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Vibration mitigation of civil structures using hybrid control strategies

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Intellectual Property Statement

The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

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Abstract

The greater scope of this thesis is to improve the safety and performance of civil engineering building-like structures which are exposed to external forces such as wind, earthquakes or other environmental factors. The current work looks at the use of mass damper technology as a potential solution for the dynamic response reduction of such structures. A comprehensive literature review of past studies and research advances is included, specifically focusing on mass damper applications on building-like structures. Using a systematic literature review approach, an up-to-date list of mass damper applications including more than 200 entries is reported, as well as a list of control algorithms commonly used in the engineering industry. The review suggested that, the mass damper systems suffer from various problems including robustness issues, high energy requirements for the active components and difficulties in the implementation of effective control algorithms. This thesis intends to tackle the identified challenges by conducting numerical simulations of a real high-rise tower. The tower is equipped with a hybrid mass damper (HMD) which possesses passive, semi-active and active capabilities. This work compares the performance of the Robust Model Predictive Control (RMPC) scheme to the well-established robust controller, H_∞. Additionally, the thesis also investigates the performance of the Deep Deterministic Policy Gradient (DDPG) reinforcement learning controller when compared to the Linear Quadratic Regulator (LQR) controller. Methods to reduce the energy consumption of the HMD system were also investigated. This thesis proposed a mode-switching control scheme using the Deep Q-Network (DQN) algorithm. This method switches between passive, semi-active, and active configurations of the system and was found to be efficient in dissipating the dynamic responses of the tower while also considerably reducing energy requirements compared to a purely active system. The current research work showed that, the proposed control algorithms and the energy consumption reduction techniques were efficient and outperformed the well-established methods rendering them novel and innovative for the field. Overall, this thesis proposes effective and practical solutions which can be used to design safe and sustainable building-like structures in the future.

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Abbreviations

A2C/A3C	Asynchronous Advantage Actor-Critic
ADP	Adaptive Dynamic Programming
AI	Artificial Intelligence
AMD	Active Mass Damper
ANN	Artificial Neural Network
ARX	Autoregressive with Exogenous Inputs
ASHMD	Active/Semi-Active Hybrid Mass Damper
ATMD	Active Tuned Mass Damper
BIM	Building Information Modelling
C51	Categorical 51-Atom DQN
CFNC	Cost Function-based Semiactive Neuro-control
CO	Clipped-Optimal
DBG	Displacement Based Ground-hook
DDPG	Deep Deterministic Policy Gradient
DOF	Degree of Freedom
DPG	Deterministic Policy Gradien
DQN	Deep Q-Network
EBP	Energy-Based Predictive
EHATMD	Enhanced Hybrid Active Tuned Mass Damper
ER	Electrorheologica
FE	Finite Element
FNN	Fuzzy Neural Network
FPA	Flower Pollination Algorithm
FSMC	Fuzzy Sliding Mode Control
GFLC	Genetic Fuzzy Logic Controller
GHTMD	Ground-Hook Tuned Mass Damper
GS	Gain Scheduling
HER	Hindsight Experience Replay
HMD	Hybrid Mass Damper

Continued

HMLD	Hybrid Mass Liquid Damper
HSMC	Hierarchical Sliding Mode Controller
I2A	Imagination-Augmented Agents
IGSA	Improved Gravitational Search Algorithm
IRA	Interstory Response Amplification
ISAMD	Impulsive Semi-Active Mass Damper
LFT	Linear Fractional Transformation
L-K	Lyapunov-Krasovskii
LMI	Linear Matrix Inequalities
LPV	Linearly Parameter Varying
LQ	Linear Quadratic
LQG	Linear Quadratic Gaussian
LQR	Linear Quadratic Regulator
LTI	Linear Time Invariant
LYAP	Lyapunov stability theory-based
MBBC	Modified Bang-Bang Controller
MBMF	Model-Based RL with Model-Free Fine-Tuning
MBVE	Model-Based Value Expansion
MDP	Markov Decision Proces
MEBNC	Modal-Energy-Based Neurocontrol
MEDA	Maximum Energy Dissipation Algorithm
MLP	Multilayer Perceptron
MPC	Model Predictive Control
MR	Magnetorheological
MSHMD	Mode-Switching Hybrid Mass Damper
MTMD	Multiple-Tuned Mass Damper
NFMPC	Novel Fast Model Predictive Control
NN	Neural Network
PA	Poll Assignment

Continued

PATMD	Passive Tuned Mass Damper
PD	Proportional Derivative
PDLT	Parameter-Dependent Lyapunov Theory
PID	Proportional Derivative Integral
PPO	Proximal Policy Optimisation
QR-DQN	Quantile Regression DQN
RBC	Rule Based Controller
ReLU	Rectified Linear Unit
RMPC	Robust Model Predictive Control
RMS	Root Mean Square
RSC	Robust Saturation Controller
SAC	Soft Actor-Critic
SATMD	Semi-Active Tuned Mass Damper
SM	Sliding Mode
SVD	Singular Value Decomposition
TD3	Twin Delayed DDPG
THSR	Taiwan High-Speed Railway
TLD	Tuned Liquid Damper
TMD	Tuned Mass Damper
TMDI	Tuned Mass Damper Inerter
TRPO	Trust Region Policy Optimisation
UBB	Uncertain But Bound
UKF	Unscented Kalman Filter
VG	Variable Gain
VGF	Variable Gain Feedback
VIV	Vortex-Induced Vibration
WFLMS	Wavelet-hybrid Feedback-Least-Mean-Square

Chapter 1

Introduction and Thesis Contributions

Chapter Outline: This chapter presents the research background and introduces the general concepts of structural control. Moreover, it includes the research aim and the main contributions of this thesis. It also includes a list of the publications that are directly related to this thesis and it describes how these are structured in order to realise the research aim.

1.1 General Introduction

Civil engineering structures vibrate. And this is acceptable until the magnitude of vibrations cause the serviceability and/or the safety limits of the structure to be compromised. However, many civil engineering structures around the world suffer from dynamic vibrations which, in many cases, deteriorate their structural integrity and thus, they fail their main objective; to provide a safe environment for the occupants. Recent wind and earthquake design codes suggest that performance-based design criteria have to be met with advanced methods without only relying on conventional methods. The conventional methods include designing the structures which are subjected to wind and earthquake loadings, for nonlinear, yielding and ductile response (Elias and Matsagar (2017)). The research area of structural control arose, aiming to develop ingenious techniques and methods in order to minimise the effect of the dynamic vibrations on civil engineering structures. Soong and Spencer (2002) mention that, the First and Second World Conferences on Structural Control held in 1994 and 1998, respectively, attracted a large audience from all over the world demonstrating the interest of the research community for the structural control field. To this date, the structural control research community developed various methods applied for structural control purposes including bearing systems, hysteric and viscoelastic devices, liquid dampers, and mass damper systems. Saaed et al. (2015) conducted an extensive review of different control systems designed for civil engineering structures and Wani et al. (2022) presented a latest critical review on control strategies used for structural vibration control.

This work will focus on the use of mass damper technologies for the vibration mitigation of civil structures. More specifically, an up-to-date literature will be included demonstrating the latest advancements in the area of structural control using mass damper systems. Additionally, a latest (and most complete) list of mass damper applications on real building-like structures will be presented along with a first-time-ever list of control algorithms applied on real systems. Although actuators are used by the control systems within this study, they will not be discussed in the literature review. Actuators and their use have been discussed significantly by Preumont (2011), Redekar et al. (2022), Zhang (2010). Moreover, various control algorithms will be investigated numerically in order to assess their performance on the vibration mitigation of a real case-study tower. With the increasing interest in the structural control field, this research work intends to serve as a valuable asset for researchers and engineering professionals by providing novel methods on dissipating the dynamic responses of civil structures using mass damper technologies.

1.2 Basic Principles of Structural Control

Mass damper technologies are employed on civil structures in order to dissipate their dynamic responses caused by external excitations. Mainly the excitations are due to wind (Jafari and Alipour (2021)) or seismic loading (Kunde and Jangid (2003)) however, excitations due to human action are broadly studied within the literature (Jones et al. (2011)). The control strategies vary between passive, semi-active, active and hybrid approaches. The passive systems are usually tuned at the fundamental frequency of the structure and they dissipate the excess energy of the civil structure without having any adapting capabilities (Housner et al. (1997)). On the other hand, the semi-active, active and hybrid systems were designed to have adapting capabilities by utilising different hardware and are depended on one or more control algorithms. Figure 1.1 shows a simple control scheme for an active tuned mass damper (ATMD). The active structural control relies mainly on the use of an actuator which applies forces that may dissipate or add energy to the mass damper. In the feedback control system shown in Figure 1.1, the control signals sent to the actuators, are a function of the response of the system which are physically measured by sensors. A control algorithm is using the measured responses in order to derive the control signal for the actuator. In real life however, full-state feedback (measuring all displacements and velocities of the system) is rarely available. Thus, it is often that observers are designed which provide a full-state estimation using the limited measurements. The same control concept applies for the semi-active and hybrid control schemes. Typically, the semi-active dampers do not add mechanical energy to the system and they require orders of magnitude less energy to operate than an active system. The semi-active mass dampers do not utilise an actuator but rather, they have damping and/or stiffness adapting capabilities. Finally, the hybrid systems are often referred to as systems which combine more than one type of control. Chapter 2 will touch on that in more detail.

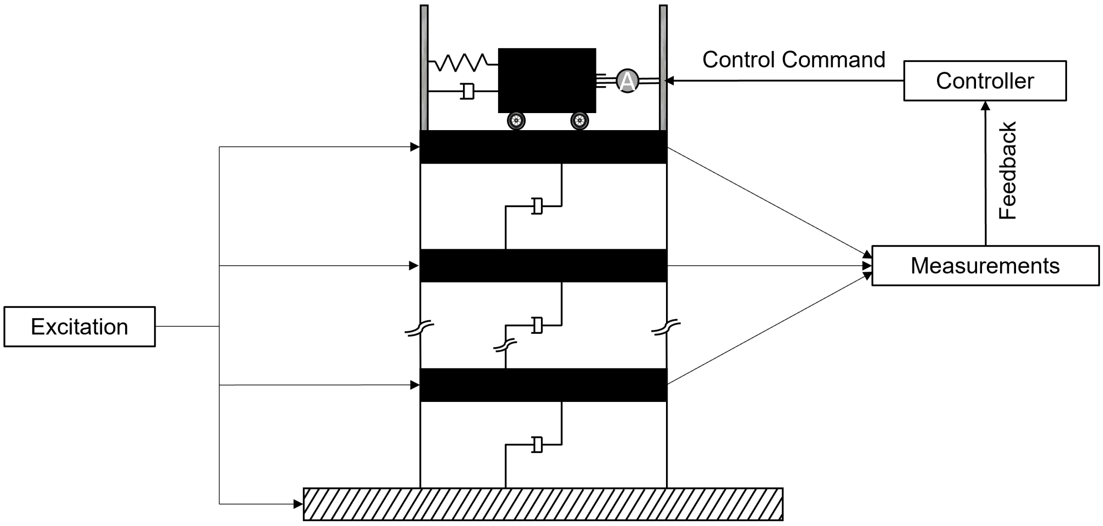


Figure 1.1: Basic diagram of an active control system installed on a building

1.3 Control Algorithms

As explained in Section 1.2, the control algorithm is the main part of a semi-active, active and hybrid system which directly affects its performance. This section will briefly introduce the main control techniques in order to provide an understanding on to where the algorithms used herein fall into.

Classical controllers are based on the Proportional-Integral-Derivative (PID) control algorithm (a feedback controller) which applies correction forces on the calculated error between the desired set-point and the measured process value (Dorf and Bishop (2000)). Classical controllers include feedback and combined feedback and feedforward controllers. It is worth noting that, the first form of feedback controllers dates back to 300BC in Greece, used for the regulation of float (Dorf and Bishop (2000)).

Optimal controllers consider the minimisation (or maximisation) of an objective function in order to achieve optimum performance. Examples of optimal controllers include algorithms where the dynamics of the system are described by a set of linear differential equations and the objective function is defined as a linear quadratic function. A popular solution for such applications is the Linear Quadratic Regulator, which is widely used within the area of structural control (Wani et al. (2022)).

Robust control algorithms are used for the cases where there is some form of uncertainty in the system. Uncertainties in the area of structural control could occur during the response measurement, modelling errors, or due to ageing and environmental effects. H_2 and H_∞ controllers are broadly used in robust control applications since, they provide a stable control solution (Doyle et al. (1989)).

Adaptive controllers are the ones which adjust their parameters based on the changes during the control process. Adaptive controllers are generally classified as feedback or feedforward adaptive controllers along with direct, indirect and hybrid methods (Cao et al. (2012)).

Intelligent control techniques involve the use of artificial intelligence algorithms such as machine learning, reinforcement learning, fuzzy logic, evolutionary computation and more, in order to control complex systems with high degree of uncertainties (Antsaklis and Passino (1993)).

This thesis will consider optimal, robust and intelligent controllers (seen in Figure 1.2) in order to investigate their performance on the control of a mass damper installed on a real high-rise tower acting as a semi-active, active and hybrid mass damper.

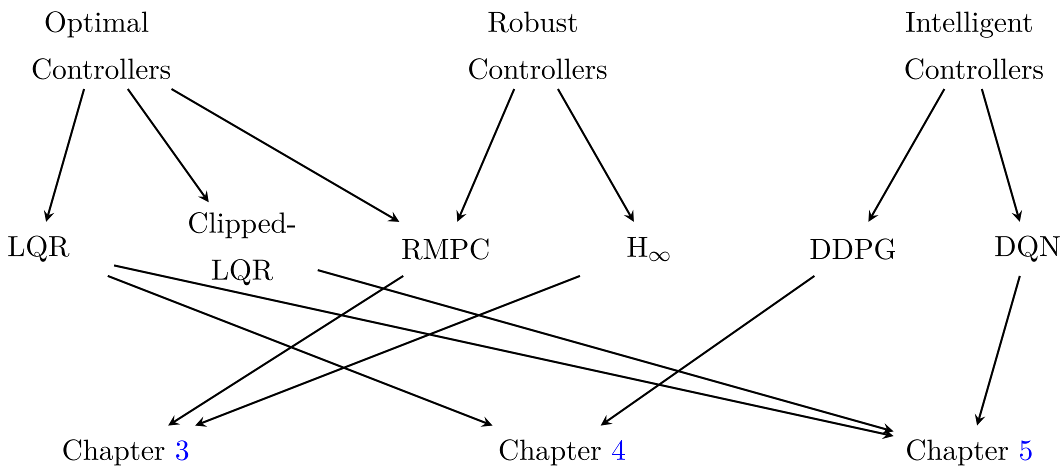


Figure 1.2: Control algorithms used within this thesis

1.4 Thesis Aim & Contributions

The aim of this work is to enhance the vibration dissipation performance of civil structures using mass damper technologies. A number of newly-proposed control algorithms within the structural control field will be implemented and their performance will be assessed against different well-established controllers within the field. The major contributions of this thesis are:

1. An up-to-date literature review reporting the research advances of the mass damper technology on civil engineering structures.

2. An up-to-date list of real-life applications of mass damper technology on building-like structures.

3. A first-time-ever list of control algorithms used for the control of mass dampers on real building-like applications.

4. Application of a newly-proposed Robust Model Predictive Controller (RMPC) for the control of a real high-rise tower using a HMD.

5. Application of a Deep Deterministic Policy Gradient (DDPG) controller for the vibration control of a real building for the first time ever.

6. Proposal of a novel passive, semi-active, active mode-switching mass damper controlled by a Deep Q-Network (DQN) controller.

Ultimately, this thesis intends to contribute to the wider field of structural engineering and design, and propose novel methods and tools to enhance the safety and stability of civil engineering structures against dynamic loads.

1.5 Thesis Structure

This thesis is submitted in accordance to the *'Protocol for the format and presentation of an alternative style of doctoral thesis including published material'* of the Faculty of Engineering and Physical Sciences of the University of Leeds. Chapters 2-5 are already prepared manuscripts with the thesis' author being the lead author of each, demonstrating original contributions. Each of these chapters includes a relevant literature review, main findings, conclusions and future work recommendations.

Chapter 2 introduces the different types of mass damper systems and explains the differences between the passive, semi-active, active and hybrid technology, including an up-to-date literature review. Moreover, using a systematic literature review approach, an updated list of mass damper applications in real building-like structures with more than 200 entries and a fist-time-ever list of control algorithms implemented on real mass dampers are presented.

Chapter 3 considers the robust control of a real high-rise tower using a HMD. Firstly, this chapter introduces the case-study specifications and dynamics that are used throughout the thesis. Moreover, an RMPC scheme is proposed and two control algorithms are designed; one considering the best displacement reduction, and one considering a reduced power and energy consumption. Their performance is compared to the well-established robust controller H_∞ in five different parametric uncertainty scenarios.

Chapter 4 presents the application of a DDPG reinforcement learning algorithm for the control of a real high-rise tower for the first time ever. The proposed algorithm is compared to a Linear Quadratic Regulator (LQR) which is a very well-established controller within the field in order to assess its performance. The two controllers are implemented in two different parametric uncertainty scenarios.

Chapter 5 proposes a novel passive, semi - active, active mode - switching HMD (MSHMD) controlled by a DQN reinforcement learning algorithm for the vibration mitigation of a real high-rise tower. The performance of the MSHMD is compared to a passive, semi-active and active tuned mass damper in order to demonstrate its vibration dissipation performance along with its reduced power and energy consumption.

Chapter 6 includes the general conclusions and contributions to knowledge that arose from this thesis. Finally, the thesis' limitations and future work recommendations are suggested based on the findings of this work.

1.6 List of Journal and Conference Papers

The journal publications and conference papers that are directly related with this thesis are:

1. L. Koutsoloukas, N. Nikitas and P. Aristidou. Control law and actuator capacity effect on the dynamic performance of a hybrid mass damper; the case of Rottweil tower, *Proceedings of the International Conference on Structural Dynamic, EURODYN*, 1:1422-1432, 2020.

2. L. Koutsoloukas, N. Nikitas and P. Aristidou. Passive, Semi-Active, Active and Hybrid Mass Dampers: A Literature Review with Associated Applications on

Building-Like Structures, *Developments in the Built Environment*, 12:100094, 2022.

3. L. Koutsoloukas, N. Nikitas, and P. Aristidou. Robust structural control of a real high - rise tower equipped with a hybrid mass damper, *The Structural Design of Tall and Special Buildings*, 31(12):e1941, 2022.

4. L. Koutsoloukas, N. Nikitas, and P. Aristidou. Structural Control of a Real High-Rise Tower Using Reinforcement Learning, 2023. (**Submitted**).

5. L. Koutsoloukas, N. Nikitas, and P. Aristidou. A Reinforcement Learning Controlled Novel Hybrid Mass Damper on A Real Tower, 2023. (**Submitted**).

References

P. J. Antsaklis and K. M. Passino, editors. *An introduction to intelligent and autonomous control*. Kluwer Academic Publishers, 1993.

C. Cao, L. Ma, and Y. Xu. Adaptive control theory and applications. *Journal of Control Science and Engineering*, 2012:2012–2014, 2012. ISSN 16875249. doi: 10.1155/2012/827353.

R. C. Dorf and R. H. Bishop. *Modern Control Systems*. Prentice Hall, Inc., USA, 9th editio edition, 2000.

J. C. Doyle, K. Glover, P. P. Khargonekar, and B. A. Francis. State-Space Solutions to Standard H2 and H_∞, Control Problems. *IEEE Transactions on Automatic Control*, 34(8):831–847, 1989. ISSN 15582523. doi: 10.1109/9.29425.

S. Elias and V. Matsagar. Research developments in vibration control of structures using passive tuned mass dampers. *Annual Reviews in Control*, 44:129–156, 2017. ISSN 13675788. doi: 10.1016/j.arcontrol.2017.09.015. URL https://doi.org/10.1016/j.arcontrol.2017.09.015.

G. W. Housner, L. A. Bergman, T. K. Caughey, A. G. Chassiakos, R. O. Claus, S. F. Masri, R. E. Skelton, T. T. Soong, B. F. Spencer, and J. T. P. Yao. Structural Control: Past, Present, and Future. *Journal of Engineering Mechanics*, 123(9):897–971, 1997. ISSN 0733-9399. doi: 10.1061/(asce)0733-9399(1997)123:9(897).

M. Jafari and A. Alipour. Methodologies to mitigate wind-induced vibration of tall buildings: A state-of-the-art review. *Journal of Building Engineering*, 33:101582, 2021. ISSN 2352-7102. doi: 10.1016/j.jobe.2020.101582. URL https://doi.org/10.1016/j.jobe.2020.101582.

C. A. Jones, P. Reynolds, and A. Pavic. Vibration serviceability of stadia structures subjected to dynamic crowd loads: A literature review. *Journal of Sound and Vibration*, 330(8):1531–1566, 2011. ISSN 0022460X. doi: 10.1016/j.jsv.2010.10.032. URL http://dx.doi.org/10.1016/j.jsv.2010.10.032.

M. Kunde and R. Jangid. Seismic behavior of isolated bridges: A-state-of-the-art review. *Electronic Journal of Structural Engineering*, 3(2):140–169, 2003.

A. Preumont. *Vibration control of active structures*, volume 179. 2011. ISBN 9789400720329. doi: 10.1007/978-94-007-2033-6_1.

A. Redekar, D. Deb, and S. Ozana. Functionality Analysis of Electric Actuators in Renewable Energy Systemsâ€”A Review. *Sensors*, 22(11):1–26, 2022. ISSN 14248220. doi: 10.3390/s22114273.

T. E. Saaed, G. Nikolakopoulos, J. E. Jonasson, and H. Hedlund. A state-of-the-art review of structural control systems. *JVC/Journal of Vibration and Control*, 21(5): 919–937, 2015. ISSN 17412986. doi: 10.1177/1077546313478294.

T. T. Soong and B. F. Spencer. Active, semi-active and hybrid control of structures. *Bulletin of the New Zealand Society for Earthquake Engineering*, 33(3):387–402, 2002. ISSN 11749857. doi: 10.5459/bnzsee.33.3.387-402.

Z. R. Wani, M. Tantray, E. Noroozinejad Farsangi, N. Nikitas, M. Noori, B. Samali, and T. Y. Yang. A Critical Review on Control Strategies for Structural Vibration Control. *Annual Reviews in Control*, (August), 2022. ISSN 13675788. doi: 10.1016/j.arcontrol.2022.09.002. URL https://doi.org/10.1016/j.arcontrol.2022.09.002.

P. Zhang. *Chapter 3 - Sensors and actuators.* Peng Zhang, first edit edition, 2010. ISBN 9781437778076. doi: 10.1016/B978-1-4377-7807-6.10003-8. URL http://dx.doi.org/10.1016/B978-1-4377-7807-6.10003-8.

Chapter 2

Passive, Semi-Active, Active and Hybrid Mass Dampers: A Literature Review with Applications on Building-Like Structures

Chapter Outline: This chapter intends to explain the differences between the passive, semi-active, active and hybrid mass dampers, and present the research advances of the structural control community. This will demonstrate the effectiveness of such systems on dissipating the dynamic responses of civil structures but also, it will identify their practical limitations. Using a systematic literature review approach, up-to-date lists of mass damper and control algorithm applications on building-like structures will be included, and discussion based on the statistical findings will be conducted.

Source: L. Koutsoloukas, N. Nikitas and P. Aristidou. Passive, Semi-Active, Active and Hybrid Mass Dampers: A Literature Review with Associated Applications on Building-Like Structures, *Developments in the Built Environment*, 12, 100094, 2022.

2.1 Abstract

In this paper, a state-of-the-art literature review is presented emphasising on the development of control variants for mass damper schemes on building-like structures. Additionally, a systematic literature review is conducted addressing three relevant questions: What type of mass damper is preferable by the associated industry? How are mass dampers distributed around the world? Is industry following research? Through the systematic literature review, updated lists of mass damper implementations and control algorithm applications in real-life structures were compiled. 208 case-studies are discussed in total. It is found that, 63% of them refer to passive tuned mass dampers, 31% to hybrid mass dampers, 4.0% to active mass dampers and only 2% to semi-active mass dampers. Regarding control algorithms, controllers of 24 structures driving semi-active, active or hybrid mass dampers are presented. It is concluded that the industry considerably lags behind latest structural control research both regarding implementations and overall management.

2.2 Introduction

Over the recent years, there has been an increasing trend of building high-rise structures around the world (CTBUH (2020)). This trend came along with the modern way of designing and constructing buildings, aiming to keep them sustainable and aesthetically pleasing. Ultimately, this evoked their slender and lightweight design. Sustainable building design is arguably an effective design approach since, less material is required for the construction of a project. However, such structures may be vulnerable to excessive vibrations caused by dynamic loadings, i.e. wind (Nikitas et al. (2011), Simiu and Yeo (2019), Solari (2017)), earthquake (Jangid and Datta (1995), Xie et al. (2020)), human action (Jones et al. (2011), Sachse et al. (2003), Živanović et al. (2005)) and traffic (Avci et al. (2021)). The need for vibration control due to dynamic loadings, forced the structural control research community to develop smart systems that will allow vibration mitigation in civil structures. The evolution of the smart control systems that are studied today, arise mainly from passive solutions. Amongst many, one technology that received a great attention is the tuned mass damper (TMD). A passive TMD (PTMD) was firstly proposed by Frahm (1911) for decreasing the rocking motion of ships. Since then, serious efforts have been made by the structural control community to enhance the performance of the PTMDs which lead to the development of semi-active, active and hybrid mass dampers.

A PTMD consists of a constant mass, spring (stiffness element), and dashpot (viscous damping element), as shown in Figure 2.1 (a). This control system is attached to a vibrating structure to reduce undesirable vibrations. When referring to buildings, it is usually located at the top floor and tuned to the fundamental frequency of the uncontrolled structure, dissipating in this way considerable amounts of external energy input. The PTMD is characterised by its mechanical simplicity, cost-effectiveness and reliable operation (Yang et al. (2022)).

The semi-active technology can be deemed as the directly evolved energy dissipating technology from passive since, it integrates adaptive, rather than constant, elements to improve performance and effectiveness, as shown in Figure 2.1 (b). The semi-active TMD (SATMD) capitalises on its adaptiveness by gathering information about the structural response and adjusting damping and/or stiffness parameters in real-time using a performance optimisation strategy. The SATMDs consist of sensor(s), a control system (controller), a stiffness and a damping device with either or both allowing adjustment of their base values. Bhaiya et al. (2019) state that the semi-active systems can be thought as being the most efficient control strategy of any alternative however, this depends on inherent limitations of SATMDs e.g. those utilising magnetorheological (MR) dampers (controllable damper that uses magnetorheological fluids to adjust their damping force (Saaed et al. (2015))) have bounds in the control force capability. Spencer and Nagarajaiah (2003) mentioned that, appropriately installed semi-active systems have a significantly enhanced performance when compared to the passive equivalents and have the potential to achieve, or surpass the performance of even fully active systems. Nagarajaiah (2009) mentions that, in semi-active control, the variation of stiffness is considered to be more efficient since, the stiffness adjustment can directly track the instantaneous tuning frequency. In the case of the damping variation, it is stated that, the damping ratio needs to change extensively, defeating in this way the main purpose of the TMD; the tuning. Thus, the damping becomes the dominant characteristic and not the tuning. The author concludes that, it is generally more desirable to use the stiffness parameter as the variable property rather than the damping unless, there are major constraints that need to be encountered, such as stroke length.

Active control systems consist of sensor(s), controller(s) (with a predetermined algorithm as in Wani et al. (2022)), and actuator(s) (seen in Figure 2.1 (c)). An active control system requires a relatively large power in order to allow the actuators to provide large control forces in real-time. Active control systems are mainly designed to increase the effective structural damping, without any major impact in the effective structural stiffness. Their sensors can be located at different positions of the structure to measure the external excitation in terms of distributed system response variables i.e. velocities, displacements, acceleration, mass damper position and the control forces. The controller receives the data from the sensors, and after analysing it, it generates a control signal to drive the actuator(s). Therefore, the controller uses a feedback function of the lagged measured data provided by the sensors and produces actuation signals. The actuators produce appropriate forces that could naturally deviate from these controller signals. Such a so-called active mass damper (AMD) was installed on a real high-rise building for the first time ever in 1989 on the Kyobashi Seiwa Building in Japan (Kobori et al. (1991)).

Elias and Matsagar (2017) state that a hybrid control system can be a combination of passive to passive, passive to active and alike control techniques. This type of systems started becoming very famous structural control options since, they aim to minimise negative characteristics that each system has when acting independently yielding a more efficient structural control system overall. Soong and Spencer (2002) mention that, the term hybrid' generally denotes a configuration that combines passive and active control systems. Additionally, they state that the passive part controls a portion of the control objective and thus, less active control effort is needed, which leads to lowering the power consumed by the active part. It is noticed that in the literature, there is an inconsistency in the terminology of mass damper systems. More specifically, researchers tend to describe their proposed systems as hybrid when referring to active tuned mass dampers (ATMD) since, the aforementioned system combines by default a passive and an active control system (as seen in Figure 2.1 (d)). Ikeda (2009) states that in Japan, it is common to refer to an ATMD as a hybrid mass damper (HMD) because, the ATMD is considered to be a derivation from either active control or passive control. Specifically, Kobori (1996) mentions that the ATMD is referred to as hybrid control since, it is the alteration of a PTMD into an active one. Moreover, they add that another form of a hybrid control system is the mounting of an AMD on a TMD. Sakamoto and Kobori (1995) report that this type of hybrid systems is popularly called

DUOX.

Previous reviews in the structural control field include the works of Housner et al. (1997) who included passive, semi-active, active and hybrid systems and Spencer and Sain (1997) who reviewed the research development of structural control systems including 24 full-scale building and 15 bridge implementations, actuator types and characteristics, and new technological and algorithmic trends. Kareem et al. (1999) presented an overview of the state-of-the-art control systems for the response reduction of civil structures, and included a list of 27 full-scale mass damper applications. Symans and Constantinou (1999) presented a state-of-the-art review of semi-active control systems for the protection of structures under earthquake loading. Buckle (2000) presented a review of the control performance of passive systems under seismic excitations. Nishitani and Inoue (2001) presented an overview of 29 buildings equipped with active and hybrid control systems in Japan. Soong and Spencer (2002) reviewed the development and assessment of passive, semi-active, active and hybrid control and included a list of 40 full-scale implementations of mass damper control systems. Spencer and Nagarajaiah (2003) reviewed the structural control schemes and presented a list of 46 building and 15 bridge mass damper applications. Datta (2003) reported an updated review of the active control systems applied on earthquake excited structures. Jung et al. (2004b) reviewed the dynamic models used for semi-active mass dampers with MR fluid dampers. Ikeda (2009) presented a list of 52 real practical applications of active and semi-active control schemes on buildings in Japan. Fisco and Adeli (2011a) presented a state-of-the-art review of active and semi-active control systems and a companion paper (Fisco and Adeli (2011b)) where the same authors reviewed the hybrid control systems and control strategies within the civil engineering field. Casciati et al. (2012) reviewed the theory and applications of active and semi-active control of civil structures. Gutierrez Soto and Adeli (2013) reviewed the PTMD research efforts and demonstrated a list of 93 real full-scale applications of PTMDs on civil structures. Basu et al. (2014) attempted to give a common frame by demonstrating the recent research and applications of structural control systems across Europe. Nagarajaiah and Jung (2014) reviewed the advances in smart TMDs which included active and semi-active mass dampers. Saaed et al. (2015) reported a review of passive, semi-active, active and hybrid control systems used for the response control of civil engineering structures. Elias and Matsagar (2017) presented a state-of-the-art review of civil structures using PTMDs . Yang et al.

(2022) reported a critical review of structural control vibration dissipation using TMDs where they focused on TMD modifications, mathematical modelling, and optimisation procedures to obtain the TMD optimal parameters. They also included active and semi-active dampers, and TMD practical realisations.

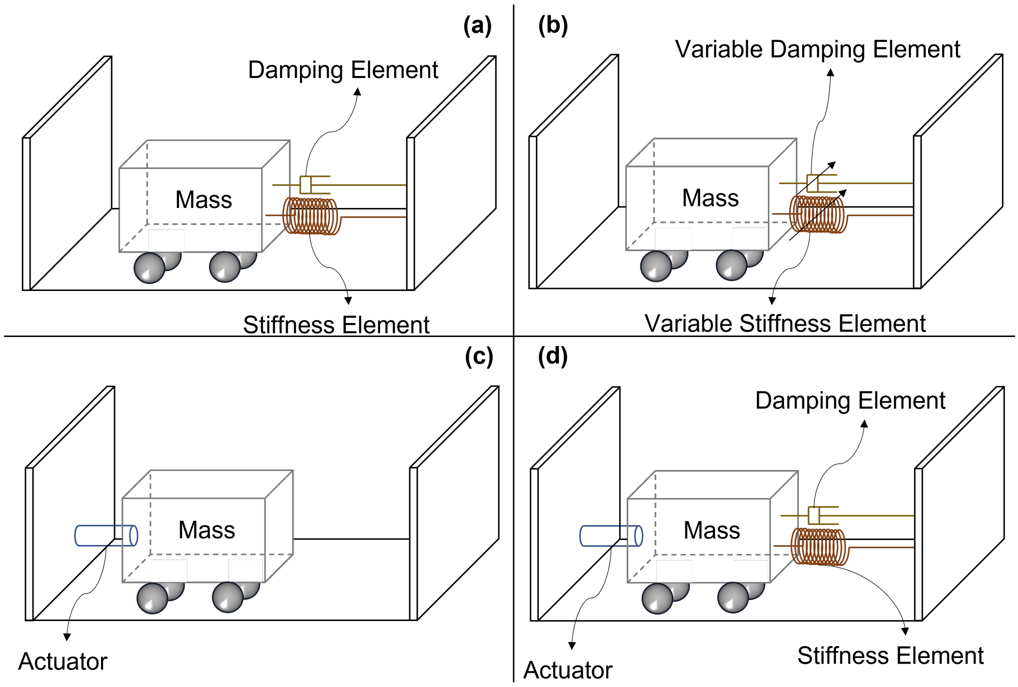


Figure 2.1: Illustration of mass damper options: a) PTMD, b) SATMD with variable stiffness and variable damping, c) AMD, d) typical HMD, combining passive and active parts, ATMD

2.3 Paper Contributions

This work aims to provide firstly, an exhaustive literature review including advances and limitations in the area of structural control using mass damper technology with a focus on theoretical and simulation based studies. Secondly, it aims to systematically gather a list of real mass damper and control algorithm applications on building-like structures around the world and draw conclusions through the application trends.

The explicit contributions of this work are:

1. Review the efforts that have been made by the structural control community in order to:
    - Include an up-to-date detailed review of studies which consider passive, semi-active, active, and hybrid mass damper control of civil structures
    - Present the state-of-the-art control algorithms that proved efficient for the control of civil structures
    - Identify the control system limitations, as these are reported in the literature
2. Carry out a systematic literature review to:
    - Report an updated list of real-life applications of mass dampers systems on building-like structures
    - List the control algorithms utilised on real buildings for the first time ever
    - Draw conclusions on the installation trends of passive, semi-active, active and hybrid mass dampers through the years
    - Understand whether the research carried out in the literature was applied in real-life applications
    - Identify potential gaps between the research trends and the needs of the associated engineering sector

2.4 Paper Structure

This work is structured as follows: Section 2.5 presents a review of studies found in the literature including the advances of passive, semi-active, active and hybrid mass dampers, while Section 2.6 reports their limitations (categorised as hardware or software-related) as these were reported previously. Section 2.7 includes the explanation of the systematic literature review approach to be pursued and emphasises on its importance. Section 2.8 discusses the findings of the systematic literature search regarding the real-life implementations of mass damper systems along with the associated control algorithms. Finally, Section 4.10 includes the conclusions of this study and puts forward suggestions for guiding future research focus.

2.5 Mass Damper Control Systems

This section includes the collection of research advances for passive, semi-active, active and hybrid mass dampers. In each subsection, the studies are organised in a chronological order.

2.5.1 Passive Tuned Mass Dampers

One amongst the first methods for the parameter determination of PTMDs was attempted by Den Hartog (1956) where expressions for the optimum damping ratio and frequency ratio of the undamped mass subjected to harmonic excitation were derived. It is worth mentioning that, the Den Hartog equations are based on the assumption that the structures are modelled as single degree of freedom (DOF) systems. To account for the damping in the main system, Falcon et al. (1967) developed a graphical method which was suitable for different types of structural vibration. Randall et al. (1981) and Ayorinde and Warburton (1980) developed various design charts in order to obtain the optimum parameters with known mass ratios and different primary system damping. Furthermore, the optimal parameters for tuned mass dampers under random excitations idealised by white noise were then proposed by Warburton (1982).

Clark (1988), studied how the use of multiple tuned mass dampers (MTMDs) on tall structures manage a significant response reduction under a seismic action. In contrast, it was stated that a single tuned mass damper is not recommended for reducing the seismic response of tall buildings. For many buildings, many of their modes of vibration are closely packed in the seismic excitation range. The first design rule is to place the TMDs at the antinode locations of the individual mode shapes. To decide on how many modes to consider, one must examine the mode shape matrix, the participation factors, the earthquake design response spectrum and the natural frequencies of the structure.

Xu et al. (1992) conducted wind-tunnel tests and theoretical analyses to investigate the vibration mitigation performance of PTMDs on tall buildings under wind excitation. They used a scaled building model (1:400) of the CAARC Standard Tall Building. They tested this model with PTMDs with different parameters in a wind tunnel to investigate the dissipation performance of the PTMDs. They concluded that, the PTMDs were effective in suppressing the wind-induced dynamic response of the building however, its performance could be enhanced with the implementation of an active control system.

Lin et al. (1994) examined the effectiveness of a PTMD in reducing the primary structural responses under stochastic environmental loadings. It was found that the PTMD was useful and it is more appropriate to a structure that its fundamental frequency is less than that of the input excitation. It was stated that an optimum PTMD can reduce both earthquake and wind induced structural responses. Finally, it was shown that the PTMD was more effective on reducing the wind induced vibrations rather than those induced by an earthquake and are useful for lightly-damped structures. Based on their numerical simulations, the authors concluded that, the PTMD was effective on reducing the seismic responses by 60% and it was even more efficient on reducing the acceleration responses than the corresponding displacements.

Kwok and Samali (1995) demonstrated the effectiveness of PTMDs in the dynamic response control of tall buildings under wind excitations. The authors concluded that the PTMD can achieve an additional 3-4% critical damping and 40-50% response reduction.

Tsai (1995) studied the performance of a TMD on base isolated structures. The authors used a 5-storey base-isolated building equipped with a PTMD under seismic loading. Their results showed that, during the first seconds of the simulation, the PTMD had a very little effect on the response of the building, however, it added damping to the structure achieving in this way a reduced structural response. Finally, it was shown that, the PTMD can be more efficient when the damping of the base-isolation system has lower damping values.

Sadek et al. (1997) proposed a method for estimating the parameters for a PTMD in the case of seismic excitation. The results show that the proposed method reduces significantly the displacement and acceleration of the buildings. The authors used their proposed method for the control of single and multi-DOF structures under seismic excitations. It was found that the PTMDs achieved a response reduction of the order of 50%. Concluding, the authors stated that this method can be applied in the vibration control of tall buildings.

Lin et al. (2000) considered the effectiveness of PTMDs on the vibration control of irregular buildings. The authors designed multi-DOF torsionally coupled shear buildings which were excited by bi-directional seismic loading. Two PTMDs were introduced at the building models and, to determine the optimum location installation and the moving direction of the PTMDs, the authors used the controlled mode shape values. The

PTMDs were used to control both the translational responses of the building models. Their simulations showed that the PTMDs were effective on reducing the responses of the a long and a square five-storey torsionally coupled buildings under five different seismic excitations.

Singh et al. (2002) presented an approach for the optimal parameter selection for the design of PTMDs for the control of torsional buildings under bi-directional earthquake loading. A genetic algorithm was used to find the optimum parameters of four PTMDs with fourteen design parameters. The PTMDs were installed in pairs in orthogonal directions. Their results demonstrated the effectiveness of the optimal parameter selection on the dynamic response control of torsional systems.

Pinkaew et al. (2003) investigated the effectiveness of the PTMD on the damage reduction of buildings under earthquake loading. The authors stated that, the effectiveness of the PTMD on decreasing the displacement of the structure after the yielding point is found to be insufficient thus, they considered the damage reduction of the structure. For their simulations, they developed a single-DOF equivalent system of a 20-storey reinforced concrete building under harmonic and the 1985 Mexico City earthquake excitations. The authors added different degrees of damage protection and collapse prevention for the assessment of their model where, it was found that the PTMD can be effective on preventing the structure from collapse and increase its yield resistance.

Wang et al. (2003) studied the application of PTMDs for the control of train-induced vibrations on bridges. For their simulations, the authors modelled the railway bridge as an Euler-Bernouli beam, and the train forces were modelled as moving forces, moving masses, and moving suspension masses in order to simulate various vehicles on the bridge. By using the simply supported bridges of Taiwan High-Speed Railway (THSR) under German I.C.E., Japanese S.K.S. and French T.G.V. trains, the authors demonstrated the effectiveness of the TMD on decreasing the vertical displacements, absolute accelerations, end rotations, and train accelerations during resonant speeds.

Lee et al. (2006a) proposed a design approach for structures with PTMDs by taking into account the states of the full dynamic system of multi-DOF structures, multiple PTMDs located on different building floors and the power spectral density function of the environmental excitations. To demonstrate the effectiveness of their method, the authors used a single-DOF and a ten-DOF model equipped with a single PTMD and a five-DOF model equipped with two PTMDs. In all scenarios the feasibility of the method was shown.

Avila and Gonçalves (2009) investigated the influence of the masses of MTMDs on the main system dynamic performance using four different arrangements of double mass dampers. By using a minimax procedure, the authors showed that small variations on MTMD parameters and the way that the masses are connected have an influence on the response of the main structure.

Lackner and Mario (2010) considered the structural control of offshore wind turbines using PTMDs. Two PTMDs were installed in the nacelle of the wind turbine, acting in two different directions. After carrying out a parametric study to obtain optimal parameters of the PTMDs, the authors demonstrated the effectiveness of the PTMDs on response control of the offshore wind turbines. Finally, it was stated that the results show the potential for active control approaches.

Bekdas and Nigdeli (2011) studied the optimal parameter determination of PTMDs using the harmony search metaheurestic optimisation method. The authors used the the peak values of first storey displacement and acceleration transfer function as the optimisation criteria. To demonstrate the effectiveness of their methodology, a ten-DOF structure was used under the El Centro (1940) NS excitation. Moreover, a second example was considered with different floor properties. The authors compared their scheme to other methodologies such as Den Hartog (1956), Warburton (1982), Sadek et al. (1997), and Hadi and Arfiadi (1998) and demonstrated the effectiveness of their scheme.

Chakraborty and Roy (2011) conducted a reliability based optimisation of PTMD parameters for the vibration control of a structure subjected to seismic accelerations considering UBB (uncertain but bound) type system parameters. It was found that the optimum PTMD parameters and associate probability of failure of the primary system have no unique values, and rather provides bounds. However, when considering the system parameter uncertainties, a change in the optimum parameters of the PTMD and the probability of failure of the primary structure was observed. Finally, the authors mentioned that, if the uncertainty which affects the parameters of the system is not considered, the PTMD performance is overestimated. Moreover, the the upper bound of response may be used in such cases for a conservative estimate of the optimum PTMD parameters.

Mohebbi and Joghataie (2012) studied the performance of PTMDs for the response control of nonlinear frame structures subjected to seismic excitations. For the optimal parameter determination of the PTMD, the authors implemented a distributed genetic algorithm. For the performance index to be minimized, the authors derived a function of the response of the nonlinear structure to be controlled. It was concluded that the proposed method was efficient on determining the optimum parameters of a PTMD capable of reducing the structural responses. The authors noted that, the simplicity and the desirable convergence behaviour of their scheme were also very important outcomes of their methodology.

Yu et al. (2013) report a reliability based robust design optimisation methodology for PTMDs. The authors mention that, in contrast to conventional stochastic design optimisation, their methodology is applicable for deterministic and or uncertain structures and it can take into account safety and quality simultaneously. A single-DOF system was used to test the performance of the PTMD designed using the proposed methodology. When compared to a conventional stochastic design optimisation procedure, the effectiveness of the proposed optimisation methodology was presented.

Stewart and Lackner (2014) considered the control of offshore wind turbines subjected to external excitation, particularly considering the effect of wind - wave misalignment on the tower loads. The authors implemented PTMDs and showed that, they managed to decrease the side-side loads caused by the windâ€“wave misalignment by over 40%. Moreover, they showed that the increase in the PTMD mass from 10,000kg to 20,000kg had little benefit on the PTMD performance. Concluding, the authors mentioned that the PTMD is a cheap and robust solution for suppressing the tower vibrations in the offshore environment.

Yang et al. (2015) proposed an innovative approach for the optimal design of distributed PTMDs. The authors compared their methodology to conventional ways for the design of distributed PTMDs. It was found that the proposed design approach demonstrates superior performance and robustness compared to the conventional methodologies, and provides a simple and straightforward way to determine the optimum parameters of the distributed PTMD system.

Marian and Giaralis (2015) proposed a control system which is a generalisation of the classical PTMD. More specifically, the authors designed a PTMD inerter to suppress the oscillatory motion of a structure. It was mentioned that this system uses the so-called 'mass amplification effect' of the inerter to enhance its performance compared to a conventional PTMD. It was found that, an optimally designed PTMD inerter outperforms the conventional PTMD when tested in the suppression of the displacements of an undamped single-DOF structure excited by white-noise. When tested in multi-DOF structures for vibration suppression, it was seen that again, the PTMD inerter was more effective on suppressing the fundamental mode of vibration compared to the classical PTMD. It was concluded that, the PTMD inerter configuration can either replace part of the PTMD vibrating mass to achieve lightweight passive vibration control solutions, or improve the performance of the classical PTMD for a given PTMD mass.

More recent studies investigate PTMD parameter optimisation by using various computational and mathematical methods. Amongst others, Elias and Matsagar (2017), developed a distributed genetic optimisation algorithm based on the minimisation of a performance index to find a set of PTMD optimal parameters, including its stiffness and damping. Khatibinia et al. (2018) proposed an optimal design procedure of a PTMD under continuous stationary critical excitation representing the most severe earthquake. The authors mentioned that optimal parameters are obtained by minimising the sum root of the mean square of story drifts defined in the frequency domain. Thus, the performance of the Improved Gravitational Search Algorithm (IGSA) using a ten story shear building with a PTMD was investigated. The results showed that the IGSA converges to better solutions when compared to other algorithms. Moreover, Kang and Peng (2019) studied the optimal parameters of large mass ratio PTMD and used numerical optimisation methods and a revised formula based on a fitting technique to achieve an enhanced version of previously existing formulas.

Yucel et al. (2019) used machine learning to achieve optimum PTMD parameters and concluded that, their equations and graphs can be easily and effectively used as a tuning tool for the PTMD parameter determination. In this paper, an Artificial Neural Network (ANN) model was proposed aiming to generate the tuning parameters of a PTMD. For the training of the ANN, the optimum parameters of several single-DOF structures were used. The optimum values were determined using a flower pollination algorithm (FPA) (i.e. optimisation method). Moreover, the ANN model was used to generate three basic tuning formulations which were tested on single-DOF and multi-DOF structures. Lastly, when the structures were tested under seismic excitation by considering the stroke of the PTMD, the parameters that occurred from the proposed model were found to be more effective than the optimum parameters that were determined from the existing formulations.

Colherinhas et al. (2019) studied the optimal parameter determination of a pendulum TMD for the control of a slender tower under random excitation. The tower was modelled as a single-DOF system. The authors used a genetic algorithm to determine the parameters (flexural stiffness/damping, mass ratio and pendulum length) of the pendulum TMD. For their fitting function, the authors chose the minimisation of the maximum frequency peaks.

Stanikzai et al. (2019) studied the control of base-isolated structures with PTMD under seismic loading. For their simulations, the authors used two-dimensional reinforced concrete multi-DOF buildings. The PTMD was located on different floors of the building in order to investigate its response control performance. It was concluded that, when the time period of the isolators was increased, the performance of the PTMD reduced. Moreover, the placement of the PTMD in low-rise buildings has no significant effect while in the case of larger structures, the placement of the PTMD has a noticeable role in the overall vibration dissipation performance.

Zucca et al. (2021) proposed a methodology for the optimization of the PTMD design for the control of a historical masonry chimney located in northern Italy. The authors derived a two-phase optimization procedure where, in the first phase, the PTMD parameters were defined by starting from the dynamic behaviour of the chimney by finite element modelling. In the second phase, the authors considered the nonlinear behaviour of the masonry by using a fiber model of the chimney. The results showed the effectiveness of the proposed methodology for the control of slender masonry structures.

2.5.2 Semi-Active Mass Dampers

Researchers have been investigating the performance of various algorithms and optimisation methods in order to achieve more efficient SATMDs.

Hrovat et al. (1983) were the first to study the performance of a SATMD in the field of structural control (Spencer and Nagarajaiah (2003), Yalla et al. (2001)). The authors proposed a SATMD for the control of wind excited tall buildings and compared its performance to a fully active system and to a traditional PTMD. It was found that the proposed SATMD had a better performance than the PTMD and similar dissipative performance to the active system. Actually, in some aspects, i.e. mass stroke requirements, it was superior to the active system without requiring high power to operate as the active system did.

ABÉ (1996) investigated the performance of a SATMD whose initial displacement varies based on the feedback. Their control algorithm was developed in a simple closed form using the perturbation solutions of vibration modes. Their proposed scheme was investigated using a single-DOF model equipped with the mass damper. The performance of the proposed SATMD was compared to a traditional PTMD under impulse and earthquake loadings. It was found that, in both cases the SATMD outperformed the PTMD showcasing its capabilities.

Ricciardelli et al. (2000) proposed an empirical algorithm for the optimisation of the SATMD performance based on the measured response. The authors mention that the proposed procedure allows for the properties of the SATMD to be updated in order to improve its vibration dissipation performance. The benefit of the proposed algorithm is the fact that the exact knowledge of the properties of the main structure is not needed neither it is bound to a particular form of excitation. The proposed algorithm requires only an estimate of the first frequency of the main structure and the smoothness of the excitation spectrum.

Setareh (2002) proposed a new class of SATMDs called the ground-hook tuned mass dampers (GHTMDs) for the control of the floor vibrations due to human movement. To obtain the optimum parameters of the GHTMD, the author used the minimisation of the acceleration response of the floor, the mass ratios, and the damping ratios of the floors. When compared to a classical PTMD, it was found that the GHTMD had a better performance of about (14%). Lastly, when tested in off-tuning conditions, the author concluded that the GHTMD demonstrated robustness compared to its passive counterpart.

Xu et al. (2003) considered the semi-active control of structures using MR dampers. The authors proposed an on-line real-time neural network (NN) algorithm which was trained on-line with the Levenberg-Marquardt algorithm. Their algorithm was designed to account for the time-delay problem that may occur in semi-active control schemes. Using a three-DOF reinforced concrete model the authors demonstrated the effectiveness of their algorithm on the response reduction of the structure under seismic loading.

Nagarajaiah et al. (2004) studied the effectiveness of a SATMD with variable stiffness. The proposed system was tested on a 76-storey building and its performance was compared to a PTMD. The tuning frequency of the proposed SATMD was determined based on an empirical mode decomposition and Hilbert transform instantaneous frequency algorithm developed by the authors. It was found that the SATMD had an enhanced performance on reducing the dynamic response of the structure when compared to the uncontrolled case and the case with the conventional TMD.

Nagarajaiah and Varadarajan (2005) proposed a new semi-active variable stiffness SATMD which aimed to continuously varying its stiffness and returning its frequency in real-time. The proposed scheme implemented a short-time Fourier transform to identify the dominant frequency of response and track its variation as a function of time to retune the SATMD. The study investigated the control performance of the proposed semi-active scheme in the case of a tall building subjected to wind excitations and compared it to a PTMD and to the uncontrolled scenario. It was found that the proposed system is effective in controlling the response of the structure when it was subjected to stiffness alternations. The authors mentioned that the proposed SATMD can achieve the performance of an ATMD while, using considerably less power.

Yan et al. (2007) developed a model predictive control (MPC) algorithm for semi-active control schemes with MR dampers in order to reduce the non-linear earthquake response of high-rise buildings. The authors demonstrated the performance of their scheme on a twenty-storey benchmark building and compared it to other semi-active control schemes on the same buildings such as linear quadratic Gaussian (LQG) by Ohtori et al. (2004), and clipped LQG by Yoshida and Dyke (2004).

Lee et al. (2010) experimentally investigated the performance of four semi-active control schemes on a full-scale five storey steel frame building structure, subjected to four historical earthquakes. The algorithms that were investigated within this study were; the clipped-optimal control algorithm (CO) proposed by Dyke et al. (1996) for controlling MR dampers; Lyapunov stability theory-based control algorithm (LYAP) where the Lyapunov function was based on Leitmann (1994), the maximum energy dissipation algorithm (MEDA) by McClamroch and Gavin (1995); and Cost Function-based Semiactive Neuro-control (CFNC) by Jung et al. (2004a) and Lee et al. (2006b). Their results showed that the LYAP and CFNC were more efficient on reducing the accelerations of the structural system where, the passive counterpart and MEDA had a good performance on decreasing the first floor displacements.

Kang et al. (2011) studied the effectiveness of a SATMD equipped with MR dampers in the response of a high-rise benchmark building under wind excitation. The authors derived a ground-hook (GH) controller for the control of their proposed scheme. Their SATMD was compared to the performance of a PTMD, a ATMD, and a SATMD with variable stiffness. Their results showed that their SATMD had a similar performance to the ATMD but with significantly lower power consumption.

Laflamme et al. (2011) developed a neurocontroller which was able to self-adapt and self-organise, and it was used in the semi-active control of uncertain systems. The authors used NNs to build the controller. Using Lyapunov stability, the adaptive rules of the controller were determined and thus, the robustness of the controller was achieved. The neurocontroller was assessed through various numerical simulations for harmonic, earthquake and wind excitations. In the case of wind excitation, it was found that the proposed controller outperformed a linear quadratic regulator (LQR) controller.

Elhaddad and Johnson (2013) studied the implementation of a hybrid MPC algorithm on semi-active control applications. The authors stated that the hybrid MPC is more suitable for semi-active control since, it can accurately model the passivity constraints by using auxiliary variables into the system model. After experimenting the proposed algorithm on a typical structure under seismic excitation, and comparing the results to the clipped LQR algorithm, it was found that the hybrid MPC was more consistent in the reduction of the objective function. However, it is mentioned that the hybrid MPC required more computational power.

Chung et al. (2013) proposed an innovative phase control methodology for the control of a SATMD applied on a simplified Taipei 101 structure model under sinusoidal and design level wind excitations. The main aim of the work was to minimise the off-tuned problems that are associated with the conventional TMDs. The results showed that, the SATMD that operated with the proposed methodology demonstrated better vibration dissipation performance and robustness compared to the PTMD, particularly in the off-tune scenario.

Aiming to enhance the proposed work in (Nagarajaiah and Varadarajan (2005)), Sun and Nagarajaiah (2014) studied the performance of a semi-active control scheme, implementing variable stiffness and damping, under seismic excitation. The damping ratio of the proposed scheme was designed to vary based on the measured SATMD displacement. Moreover, by using a short-time Fourier transform-based algorithm to analyse the tracked displacement of the structure, the stiffness of the SATMD was tuned. The authors compared the proposed scheme with an optimal PTMD to investigate its performance. It was concluded that the variable stiffness and damping SATMD outperformed the PTMD with optimal parameters. Moreover, the effect of structural damage was studied to investigate the performance of the SATMD. It was found that, the proposed scheme was able to capture the variation in the structure and thus, it remained tuned in contrast to the PTMD which remained detuned.

Demetriou et al. (2015) investigated the performance of a SATMD equipped with a Proportional Derivative Integral (PID) controller applied on a multi-storey structure subjected to earthquake excitation. The numerical results showed that, the semi-active control system presented a better performance when compared with a PTMD with optimum parameters.

Miah et al. (2015) investigated the application of the LQR algorithm equipped with an unscented Kalman filter (UKF) observer for the real-time mitigation of structural vibration on a SATMD. When they compered the LQR-UKF performance with the LQG algorithm and then validated it on a joint state-parameter estimation problem where the system model was assumed uncertain and updated in real-time; it was concluded that this method is highly promising.

Demetriou et al. (2016) studied the performance of a SATMD with different control strategies for the control of a high-rise structure under wind-loading. More specifically, the authors investigated the performance of five algorithms namely; the GH (displacement and velocity-based), clipped optimal, BANG and PID. It was found that, the algorithms that proved to be more efficient (clipped optimal, displacement-based GH and PID) sacrificed the minimisation of the damper strokes in contrast to the velocity-based GH and the BANG controllers.

In their paper, Bathaei et al. (2018) investigated the performance of a semi-active system which consisted of a PTMD and an adaptive MR damper. For the control of the MR damper, type-1 and type-2 fuzzy controllers were used. The design of the fuzzy controllers was done by using the accelerating and decelerating movements of the 11-DOF test model. From the analysis, it was concluded that, the type-2 controller which considered the uncertainties related to the input variables had a better performance than the type-1 controller. Lastly, the authors stated that the type-2 controller reduced the maximum displacement, acceleration and base shear of the structure by 11.7%, 14% and 11.2% compared to the type-1 controller.

Liu et al. (2018) numerically applied a multi-SATMD device configuration on the multi-span Poyang Lake railway steel bridge aiming to increase its fatigue life for which there were major concerns. Each SATMD device consisted of an MR damper attached to a PTMD, while the baseline PTMD scenario was also considered for comparison purposes. The control strategy employed a simplest possible fixed incremental control algorithm, while for the PTMD scenario the extreme cases of the MR devices providing constantly their minimum (voltage off) and maximum (voltage on) damping capability were examined. As reported, the multi-SATMD over doubles the considered nominal lifespan and achieves more than 15% better performance than the higher damping (MR damper voltage on) PTMD control solution.

Zelleke and Matsagar (2019) developed an energy-based predictive (EBP) algorithm for semi-active control systems. Their results showed that the SATMD equipped with the EBP algorithm can reduce the vibration response and the energy imparted on a structure as compared to a PTMD, especially with excitations with distinct frequencies.

Park et al. (2019) investigated the performance of a SATMD on the vibration mitigation of offshore wind turbines. More specifically, this study focused on the availability of a MR damper model on a PTMD and its effectiveness on the control of offshore wind turbines. The proposed scheme utilized different GH control based logics, and their performance was studied based on the frequency response. The semi-active control scheme was compared with a PTMD for the vibration control of both fixed-bottom and floating offshore wind turbines under fatigue and ultimate limit states. It was found that, the semi-active control scheme outperformed the PTMD. More specifically, the SATMD equipped with a displacement-based GH controller had the best performance by reducing the fore-aft and side-to-side damage equivalent loads by around 12% and 64% respectively.

Weber et al. (2020) investigated the performance of a tuned mass damper equipped with an inerter (TMDI). The authors mentioned that the floor on which the inerter is grounded is directly related to the performance of the TMDI. Thus, the total performance of the TMDI was assessed based on a function of the floor on which the inerter was grounded. The TMDI was tested in the response reduction of a 20-story building model. To provide a better representation of the performance of the TMDI, the authors used the classical TMD as a benchmark for their study. When they simulated for broadband and harmonic excitations of the first three bending modes, it was found that the TMDI performed better when the inerter was grounded to the earth since, the inerter force was proportional to the absolute acceleration of the PTMD rather than the relative acceleration of the two inerter terminals. They also mentioned that, in order for the TMDI to outperform the PTMD, while having the inerter anywhere below the PTMDs' floor, the inerter should be installed within approximately the first third of the building's height. Lastly, when investigating the most realistic case were the inerter is installed on the same floor as the PTMD, the TMDI had worse performance than the classical TMD.

Shih and Sung (2021) developed an impulsive semi-active mass damper (ISAMD) for the control of a high-rise building. The authors proposed a directional active joint as the breaker to lock and unlock contact between the structure and damper in order to overcome the detuning effect that a PTMD may suffer from. When the proposed scheme was tested under seismic loading it was found that, when compared to a PTMD, the ISAMD had enhanced reduction performance on the maximum and root-mean-square (RMS) displacement. Moreover the ISAMD did not experience detuning, and has a stable control effect.

Dai et al. (2021) considered the vortex-induced vibration (VIV) control on long span bridges. They mention that, even though the PTMDs are efficient on controlling the VIV, they present robustness issues especially the PTMDs with small mass ratios. The authors proposed a SATMD with MR dampers for the mitigation of VIV with slowly time-varying frequency. The authors proposed a real-time tuning and mass stroke limitation methodology for the SATMD. For the control command determination, a feedforward control named the piece-wise linear interpolation (Weber (2013)) was adopted with a kinematic Kalman filter (Jeon and Tomizuka (2007)). For the modal identification of the long-span bridge the authors used the analytical mode decomposition method which was proposed by Chen and Wang (2012) in order to improve the modal identification accuracy. From the simulations it was concluded that, the proposed SATMD demonstrated robustness and superior performance against the resonant frequency uncertainty compared to the PTMD.

Wang et al. (2021) considered the control of human-induced vibrations on footbridges using a semi-active-type mass damper. The authors mention that, the traditional PTMDs are very sensitive to frequency deviation and suffer from detuning effects. Human-induced vibrations cover a wide range of frequencies and are considered to be of stochastic nature. Moreover, they add that the human-structure interaction can change the structural characteristics of the bridge. Thus, the authors state that, the PTMD may not be efficient on controlling the human-induced vibrations on bridges and thus, they proposed a semi-active mass damper with variable mass. The proposed system operates by using a Wavelet-transform based controller which identifies the instantaneous frequency of the bridge in real time and adjusts the mass of the control scheme appropriately. The authors used a simply-supported pedestrian bridge as a case study. The effectiveness of the proposed scheme was investigated under single pedestrian periodic and stochastic walking-induced excitations, and under crowd-induced stochastic excitation. Moreover, the effect of the human-structure interaction was investigated in their schemes. It was found that, the proposed semi-active control scheme had an excellent vibration control performance and outperformed the PTMD in all cases. Moreover, they found that, the human-structure interaction may amplify or reduce the structural responses and this depends on the the type of the input loads and the pedestrian body frequencies.

2.5.3 Active/Hybrid Control

Maebayashi et al. (1992) proposed a prototype HMD for the response control of tall buildings against strong winds and moderate seismic loads. The prototype HMD consists of an auxiliary mass, multi-stage rubber bearings which support the mass, and actuators driven by AC servo motors. The control algorithm was designed using the optimal control theory. The HMD was installed on a real 7-storey building (30m tall) built in 1991 at the Institute of technology of Shimizu Corporation in Tokyo. The authors mentioned that, the HMD keeps the control force to zero when the building responses are below a prescribed level and, in the case of strong winds and earthquakes (when the building responses increase) the actuators start to operate automatically. From tests and observations during strong winds, it was concluded that the HMD is effective on suppressing the building responses during strong winds and earthquake loadings.

Taida et al. (1994) investigated the control of the bending and torsional vibrations of a six-stage structure equipped with two HMDs. For the control law of the systems, the LQ optimal control theory was used. The performance of the dampers was investigated in two cases; i) decomposing signals into bending and torsion and ii) separating the sensor signals. It was concluded that, in both cases the HMD were effective on controlling the bending and torsion of the structure. When comparing the two cases, the case (i) was proved to have a better overall performance.

Suzuki et al. (1994) presented a study on the performance of an AMD when controlling a real high-rise tower called 'Riverside Sumida Building'. For the control of the tower, the authors developed a controller based on optimal control theory. Moreover, they introduced a variable-gain algorithm allowing for the scaling of the control force based on the magnitude of the vibration of the building in order to achieve the most effective control possible. Based on vibration tests and earthquake response observations, the authors concluded that, their control approach achieved the control of multiple vibration modes without causing spillover.

Lopez-Almansa et al. (1994, 1995) investigated the implementation of predictive control on civil engineering applications. However, in this case, the authors used the predicted trajectory and the control force for one time-step only, to express their objective function.

Nagashima and Shinozaki (1997) considered the control of an AMD with the practical limit of the auxiliary mass stroke length. The authors proposed a variable-gain feedback control algorithm combined with static output feedback control. The effectiveness of the proposed hybrid control method was showcased using a single-DOF system. It was found that the proposed method had a good performance against both seismic and sinusoidal excitations with respect to the mass stroke, control power and control smoothness.

Nishimura et al. (1998) investigated the control of an active-passive composite TMD equipping an office building in Tokyo in 1993. The proposed device was installed to control random disturbances such as wind and seismic loadings. For the control of the proposed system, the authors used the acceleration feedback algorithm. Moreover, the optimum parameters, the control force minimisation, and the power and energy under various types of disturbances were obtained. The authors designed a state estimator and tuning adjustments were made possible electrically instead of mechanical stiffness adjustments. The control system application proved the feasibility of the control algorithm by comparing the observed control performance to the mathematical simulations.

Mei et al. (2001) in their study, focused on the general formulation of MPC for the real-time control of structural responses under seismic excitations. The optimisation objectives that were used in this study were; the minimization of the difference between the predicted and desired response trajectories, and the control effort based on selected constraints. The prediction model was constructed using feedforward and feedback components to achieve maximum efficiency. The feedforward loop was designed based on the Kanai-Tajimi-type model for the earthquake input representation. Moreover, an auto-regressive model was used to constantly update the earthquake ground motion based on real-time on-line observations and thus, achieve predictive and adaptive nature in the control actions. After comparing the MPC scheme with H_2 control strategies, it was concluded that the MPC scheme can provide effectiveness comparable to the optimal control.

The performance of a new HMD system which consisted of a gear-type pendulum and a linear actuator was studied by Nagashima et al. (2001). Two HMD systems were used to control the transverse-torsional coupled vibration of a 36-storey high-rise building with a bi-axial eccentricity. A variable gain feedback (VGF) control technique was developed to achieve the maximum capacity of the HMD system. It was concluded that the maximum and RMS acceleration responses were reduced to 63% and 47% respectively, confirming in this way the control performance of the system.

The implementation of MPC scheme in the control of structures under earthquake loading was again studied by Mei et al. (2002). Their scheme used the acceleration feedback to estimate the states of the structure. The optimization objectives of this study included the minimisation of the difference between the predicted and desired response trajectories, alongside the control effort based on specific constraints. To build the prediction model, accelerations measurements were contained in a feedback loop. Moreover, the states of the system were determined by a Kalman-Bucy filter state observer. Single-story and three-story buildings were tested using active tendon control and AMD control. It was concluded that the MPC scheme using acceleration feedback was an effective control method.

Mei et al. (2004) investigated the use of MPC scheme, applied on the structural control of a benchmark building which is subjected to wind excitations. The authors used an explicit prediction model of the system response to minimise the objective function and thus, determine the control actions. It is mentioned that, MPC optimisation objectives were the minimisation of the difference between the predicted and desired response trajectories, and the control effort which can be limited by various constraints. Moreover, the MPC scheme was tested in both, with and without constraint cases, and then it was compared to a LQG algorithm. The inequality constraints on the maximum control force and mass damper displacement were considered on the objective function. The authors concluded that, by using input/output hard constraints, optimal control force can be achieved through the MPC scheme which satisfies the prescribed constraints.

Kumar et al. (2007) stated that, it is a general belief that the fixed parameter controllers suffer from degradation in their performance when the system parameters are subjected to a change. It was noted that conventional controllers can become unstable with these parametric uncertainties. Generally, it is desirable that the closed-loop poles of the perturbed structural system remain at pre-specified locations for a range of system parameters. Their paper investigated the pole placement-based controller design techniques, aiming to obtain robust performance by manipulating the closed loop poles of the perturbed system. These techniques were studied on active vibration control applications. It was observed that the adaptive pole placement controllers are noise tolerant but require high actuator voltages to maintain stability. Moreover, the robust pole placement controllers require comparatively small amplitude of control voltage to maintain stability, but they are noise sensitive.

Yang et al. (2011) aimed to reduce the number of sensors required in real implementations by using the modified predictive control which was derived with the partial-state concept of direct output feedback. The proposed scheme computes the control forces by determining the actual output measurements which are then multiplied by a designated constant output feedback gain matrix. To produce the feedback gain in a symmetric and efficient manner, an off-line numerical method was introduced. Two control systems were tested, single-controller and multiple-controller, in order to validate the feasibility of the modified predictive control with direct output feedback. Moreover, the application of an AMD controlled by the proposed scheme was applied on a large-scale 5-story structural model. The results showed that the proposed scheme can achieve good performance under environmental excitations.

Banerji and Samanta (2011) in their paper investigated the mounting of a tuned liquid damper (TLD) on a secondary mass which is attached to the primary structure with a spring system. The authors state that for the hybrid mass liquid damper (HMLD) system, there is an optimum value of the spring connection system for which the HMLD can achieve maximum efficiency. Lastly, it was concluded that a HMLD with optimum design parameters can be more effective device than a standard TLD for both harmonic and broad-band earthquake motions.

Li et al. (2011) studied the performance of a hybrid control system on a nonlinear structure subjected to seismic excitation. For their hybrid system, an AMD was implemented on the top of the structure. The authors stated that, an AMD control system can cause a magnification of the interstory drift of a nonlinear building. This phenomenon is called interstory response amplification (IRA) and for its elimination, interstory dampers were utilised. The control algorithm that was used for the AMD was a fuzzy logic-based controller. Based on the numerical simulations it was concluded that the proposed hybrid system can eliminate the IRA phenomenon and achieve better vibration control when compared to a single AMD control system or to interstory dampers alone.

Noormohammadi and Reynolds (2013) developed a HMD for the vibration control of structures (i.e. stadia) subjected to human excitation. Their proposed HMD consisted of a PTMD with an actuator attached to the TMD mass. After comparing the proposed HMD to a PTMD, the authors concluded that the performance has considerably enhanced.

Mitchell et al. (2013) suggested the use of a wavelet-based fuzzy neurocontrol algorithm on a hybrid control system for the structural control of buildings under seismic excitations. The hybrid system consisted of an actuator, a TMD and viscous liquid dampers. The proposed algorithm was developed by integrating the discrete wavelet transform, an ANN and a Takagi-Sugeno fuzzy controller. When comparing the proposed system with the performance of passive viscous liquid dampers and an ATMD subjected to seismic excitations, the effectiveness of the proposed system was proven.

Li et al. (2014) proposed a fuzzy sliding mode control (FSMC) method for the control of a shear frame equipped with an ATMD. The authors mention that, their algorithm avoids the undue chattering effect which is the main disadvantage of conventional sliding mode controllers, without losing its robustness against parameter uncertainties. When compared to a PTMD and an AMD, the proposed scheme demonstrated better response control and stability.

A HMD aiming to reduce the resonant vibration amplitude of structures was proposed by Collette and Chesné (2016). The proposed hybrid system included passive and active components. In this case, the direct velocity feedback control was used, and two zeros were added to the controller allowing it to interact with the poles of the plant. When the proposed system was compared with an AMD system, it requires smaller active forces and thus less energy for a better damping performance.

Demetriou and Nikitas (2016) developed an energy and cost-efficient hybrid semi-active mass damper. For the design of this hybrid system, an active and a semi-active control component were used. After testing its performance on single and multi-DOF structures, it was found that the new configuration outperformed the conventional passive and semi-active systems. Moreover, it is stated that the performance of the new hybrid system was similar to the active configuration however, it consumed considerably less energy and reduced actuation demands. Thus, it satisfied the strict serviceability and sustainability requirements. The main difference between an ATMD and the novel hybrid system presented in this research is that, the ATMD adds and dissipates energy to the system while the proposed hybrid system just dissipates. It is noted that in this study, the semi-hybrid mass damper (SHMD) device was regulated by an optimal LQR controller, while the semi-active components were controlled via a direct output feedback displacement based ground-hook (DBG) controller. Based on the numerical results it was found that, the proposed device was effective in reducing both the steady-state and the peak frequency responses of the structural system while achieving similar performance gains to that of an ATMD-equipped structure. Lastly, it was shown that the successive action of active and semi-active elements allowed an improvement in efficiency both in terms of power and actuation demands. In a later work, Demetriou and Nikitas (2017) worked towards the optimisation of system's performance where, strict sustainability and serviceability requirements were satisfied, making it a practical and reliable control solution.

Etedali and Tavakoli (2017) studied the performance of proportional derivative (PD) and PID controllers for the seismic control of high-rise buildings. For comparison purposes, a LQR controller was also used. The numerical results showed that the PD/PID controllers performed better than the LQR in terms of reduction of the maximum top storey displacement, maximum absolute acceleration of stories as well as maximum drift of stories. Lastly, the authors concluded that, the PID had a better performance than the PD controller.

Chen et al. (2017) developed a novel fast model predictive control algorithm (NFMPC) for the control of large scale civil structures. The authors state that, most of the computation of the algorithm was done explicitly, allowing for a small amount of on-line computation, which guarantees the efficiency of the controller. When compared to a standard MPC on a ten-storey plane frame, on a three-dimensional cable-stayed bridge, and on a forty-story three-dimensional frame, the proposed NFMPC algorithm was proved to be an efficient control method.

Meinhardt et al. (2017) presented the installation of a HMD with passive, semi-active and active capabilities. It is interesting to note that, since the building was not completely built by the time their work was published, the control system was only treated as a PTMD.

Peng et al. (2017) demonstrated the effectiveness of their proposed novel fast model predictive controller with actuator saturation used for the control of a plane adjacent frame structure under seismic loading. When compared to a nominal MPC, it was found that the proposed controller is highly efficient and it is a good application for large-scale structural dynamic control problems.

Aiming to mitigate the stroke size of their previously proposed HMD system in Li and Cao (2015), Cao and Li (2018) proposed an enhanced hybrid active tuned mass dampers system (EHATMD) in order to attenuate undesirable oscillations of structures under ground acceleration. Their design consisted of two ATMDs with different mass ratios on top of each other. By employing the genetic algorithm, the effects of varying the key parameters on the optimum performance of the EHATMD were studied and compared to a hybrid mass damper (HMD) with optimum parameters. It was concluded that the proposed EHATMD outperforms the HMD and thus, it can be considered as a novel extension of the HMD.

Bhaiya et al. (2019) studied the hybrid control schemes using different combinations of MR and TMDs to minimise the seismic responses of buildings. To evaluate the performance of the proposed hybrid system, the authors used purely SATMD control systems. The responses were obtained using four control strategies i.e. LQR with clipped algorithm, passive-on, passive-off, and velocity tracking control. It was concluded that by using a combination of a TMD and fewer number of MR dampers, a

40-45% response control can be achieved.

Chang and Sung (2019) proposed a modal-energy-based neurocontrol algorithm (MEBNC) for the control of civil structures under seismic excitations. The modal energy of the structure was used as an objective function for the controller training and the control signal and modal energy were used for minimisation by the controller. The authors used a three-storey nonlinear building equipped with an AMD. It was concluded that the algorithm was efficient on decreasing the structural responses and the modal energy. Lastly, nonlinear hysteretic behaviours occurred in the uncontrolled scenario however, in the MEBNC controlled case these nonlinear behaviours were almost disappeared.

Chen and Chien (2020) proposed a machine learning based optimal control method for the control of civil structures under earthquake loading. The authors mentioned that, optimal control methods require the full state feedback which may not be available on real applications and time-delay and state estimation errors may affect the control performance. Thus, they developed a multilayer perceptron (MLP) model and an autoregressive with exogenous inputs (ARX) model in machine learning. The goal was for the algorithm to learn the control forces generated from an LQR which was designed using a symbiotic organisms search algorithm. It was concluded that, when tested on a ten-storey building, both MLP and ARX were able to estimate the LQR forces with acceleration feedback, eliminating in this way the need for state estimators. Lastly, the machine learning approach was tested experimentally, with a model equipped with an AMD under seismic excitation. It was found that both MLP and ARX had a good performance on emulating the LQR performance when compared to a LQR with a Kalman filter.

Mamat et al. (2020) developed an adaptive nonsingular terminal sliding mode control algorithm for the control of seismically excited buildings. For the control device, the authors used a hybrid control system which consists of passive and active characteristics. For their simulations, they used the El Centro and the Southern Sumatra earthquakes and compared their algorithm performance with a fuzzy logic controller and a sliding mode controller. It was found that, the adaptive nonsingular terminal sliding mode control algorithm had a superior performance compared to the other two controllers in terms of displacement responses, performance indices, and the probability of building damage.

Kayabekir et al. (2020) modified a music-inspired harmony search algorithm for the parameters of an ATMD and of a PID-type controller. The authors demonstrated the effectiveness of their scheme on a ten-storey shear building. It was found that, the ATMD could reduce maximum displacement of the structure by 53.71% and had a 22.51% better performance than a PTMD.

Xu et al. (2020) investigated the performance of ATMDs for the control of adjacent buildings under earthquake loading. The authors implemented an observer-based active vibration control law and demonstrated its performance. The proposed scheme performance was tested on a 10 and a 6-DOFs adjacent buildings with two different actuator saturations (779kN and 1000kN). From the simulations it was found that the proposed scheme was efficient on reducing the structural responses. Lastly, it was mentioned that, when the actuator saturation changed from 779kN to 1000kN the control system had an enhanced performance of 52% on the structural displacement reduction.

Koutsoloukas et al. (2020) considered the vibration control of a real high-rise tower using an ATMD. For the control of the mass damper system, the authors developed an MPC with a Kalman filter. The performance of the algorithm was compared to a LQR and to a corresponding PTMD. It was concluded that, the MPC outperformed both the LQR and the PTMD.

Yan et al. (2020) studied the translation and rotation response control of structures under earthquake loading. For their simulations, the authors used a ten-storey steel building model equipped with two ATMD or PTMD systems. For the control of the ATMDs, the authors implemented a LQR and a fuzzy neural network (FNN) control algorithm. They concluded that, the ATMD operating with both algorithms was more efficient on the response control of the structure compared to the PTMD. Lastly, when considering the performance of the two control algorithms, the authors concluded that, the FNN can replace the LQR algorithm since it is efficient in controlling the system with an uncertain mathematical model which makes it a potential practical application compared to LQR.

Chen et al. (2021) considered the active control of structures with AMD stroke limits. A variable gain state-feedback controller was designed to limit the mass strokes and relative velocities. The effectiveness of the proposed controller was demonstrated in the control of a high-rise building and a four-storey experimental structure. It was found that, the proposed scheme can limit the mass strokes while having a good response dissipation performance.

Ramírez-Neria et al. (2021) developed a generalised proportional integral observer-based active disturbance rejection control scheme for the control of seismically excited buildings. The performance of the proposed scheme was experimentally investigated on a five-storey structure equipped with an AMD. The authors concluded that the proposed scheme demonstrated an excellent vibration dissipation performance and robustness in the presence of unknown external disturbance inputs.

Concha et al. (2021) proposed an automatic tuning algorithm for a sliding mode controller based on Ackermann's formula. The algorithm was investigated in the control of a seismically excited building equipped with an ATMD. The authors mention that, their tuning algorithm selects the sliding mode controller parameters in order to guarantee sufficiently fast and damped transient responses of the structure and the ATMD. Moreover, it ensures the control force and the responses of the building and the ATMD to be within acceptable limits under the frequency band of the seismic excitation. The algorithm was experimentally investigated and compared against a LQR and an optimal sliding mode controller showcasing its effectiveness.

Zhu et al. (2021) proposed a hybrid vibration mitigation method for the control of a footbridge using a PTMD and the crowd flow control theory (Carroll et al. (2012), Helbing et al. (2002)). The authors mentioned that, they proposed their hybrid method to eliminate the detuning effect and the lack of adaptability that the PTMD has which makes it a less efficient control method for footbridges. The crowd flow control theory can alter the pedestrians' velocity and walking frequency by arranging temporary or permanent measures on the structure in strategic positions (Helbing et al. (2005), Venuti and Bruno (2013)). The authors used the eddy current technique (Liu et al. (2020)) to optimise the mitigation performance of the PTMD. To simulate the crowd load, the authors used the social force model (Helbing and Molnár (1995)) which is based on the Kurt Lewinde social psychology hypothesis (Billig (2015)). To evaluate their proposed scheme, the authors used three layouts simulating; pedestrian diversion separation; bottle neck effect; and a nonlinear layout which was a combination of the first two layouts. It was found that the hybrid control method was efficient on limiting the peak acceleration of the long-span footbridge (case-study) within the serviceability limit to avoid human discomfort.

Koutsoloukas et al. (2022) investigated the performance of an ATMD for the vibration control of a real high-rise tower. For the control law of the system, the authors derived a robust model predictive control (RMPC) algorithm. The proposed algorithm was compared to the well established robust controller within the structural control field, H_∞, and to a PTMD. To assess their robustness, four different scenarios with parametric ($\pm 2\%$ and $\pm 10\%$ in stiffness and damping) uncertainties and actuator ($\pm 5\%$) uncertainty were introduced. To demonstrate the capabilities of the proposed scheme, the authors derived two controllers, one emphasising on the vibration mitigation of the tower and one emphasising on the power consumption of the system. It was concluded that the RMPC schemes outperformed the H_∞ controller and the PTMD in all uncertainty scenarios.

Zhou et al. (2022) studied the vibration dissipation performance of an ATMD equipped on a 600m tall tower. For the control of the ATMD, the authors used a LQR with variable gain algorithm. The performance of the system was investigated during the Super Typhoon Hato and it was proven efficient for the vibration mitigation of the tower.

Koutsoloukas et al. (2023) investigated the performance of the reinforcement learning deep deterministic policy gradient (DDPG) algorithm for the vibration dissipation of a real high-rise tower using an ATMD. The performance of the DDPG was compared to a PTMD and to a LQR. To investigate the robustness of the reinforcement learning algorithm, a scenario with parametric uncertainty was introduced (-10% stiffness and damping uncertainty). It was found that, in both the nominal and the uncertain scenarios, the DDPG had a similar performance to the LQR and they both outperformed the PTMD.

2.5.4 Synopsis

Section 2.5 discussed the research done by the structural control research community for passive, semi-active, active and hybrid mass dampers. Figure 2.2 shows a summary of all the studies included within this work. When considering the semi-active, active and hybrid systems, various control algorithms were investigated. More specifically, the efficiency of control techniques such as adaptive, intelligent (e.g. AI), optimal, self-organised, robust and stochastic was presented. All the aforementioned control techniques were proven adequate on effectively controlling the responses of the considered, many time fictitious, structural systems. However, it is rather essential to investigate whether the aforementioned ingenious control techniques are adopted in real-life applications. To achieve that, a systematic evaluation of literature is conducted in a later section of this work. Furthermore, the mass damper technologies have a number of limitations which could cause hesitation in the industry professionals and building owners to invest in their installation.

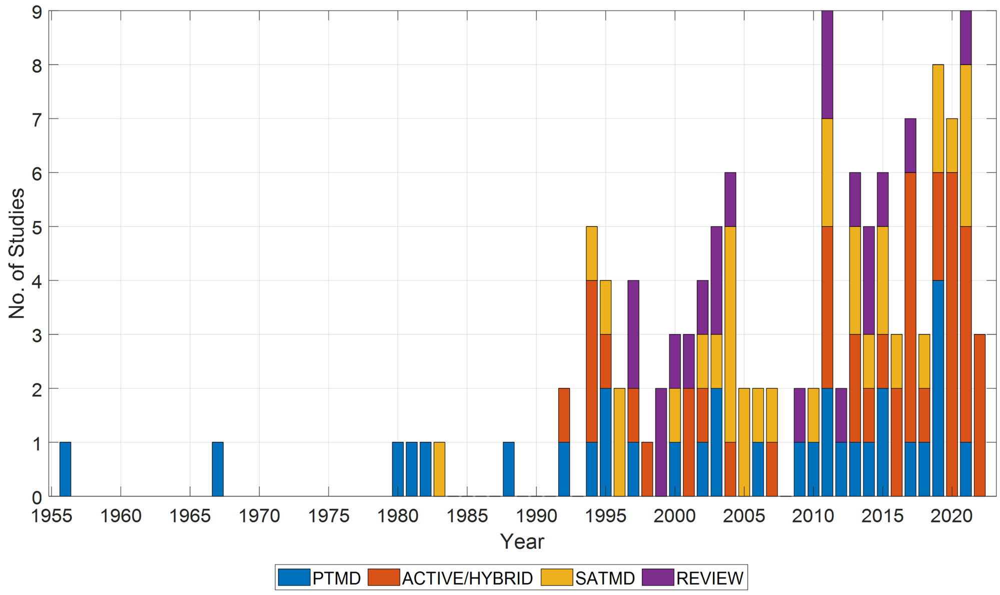


Figure 2.2: Summary of the studies included within this work.

2.6 Limitations of the Control Systems

Aside from the promising nature of the structural control schemes presented in Section 2.5, the literature includes various control limitations that cause control systems to malfunction. Thus, it is important for the structural control research community to identify in-full the limitations that each control system suffers from, and develop smart techniques to eliminate them. This section includes the limitations of the mass damper technologies that arise in the relevant literature categorised as hardware or software-related.

2.6.1 Hardware-Related Limitations

Considering the PTMDs, Bachmann and Weber (1995) showed that the effectiveness of the PTMD is much more sensitive to the error in the tuning of the PTMD frequency than the error in the tuning of its damping. Rana and Soong (1998) stated that, under seismic excitation, the PTMD system suffer from detuning. In their study, they concluded that, for a structure subjected to an earthquake motion, the effects of detuning in the parameters of the PTMD became less detrimental with increasing the mass and/or damping ratios of the PTMD. Moreover, based on the time history analyses of a single-DOF with a PTMD system, it was observed that for large damping of the structure, the PTMD did not give much response reduction. The problem of the PTMD off-tuning (detuning) is also reported in (Maślanka (2019), Noormohammadi and Reynolds (2013), Setareh (2002), Setareh et al. (2007), Shih and Sung (2021)). Gutierrez Soto and Adeli (2013) mentioned that, a disadvantage of PTMDs is that they can only be tuned in one frequency which is subject to uncertainty or it could change during ground motions. Moreover, the authors add that, the PTMDs require high installation and maintenance costs. Lastly, Elias and Matsagar (2017) advised that open research problems regarding the PTMD and multiple TMDs are; the off-tuning of the oscillations and the influence of the flexibility of the foundation.

The literature shows that, despite their promising capabilities, the active/hybrid structural control strategies are subject to several hardware-related problems that affect their performance. Firstly, Elias and Matsagar (2017) state that the operation of the active control systems is totally depended on external power supply and it requires a complex sensing and signal processing system. Ahlawat and Ramaswamy (2002) mention that, being completely depended on external power, the active systems are vulnerable to power-failure which occurs often during strong earthquakes. Moreover, due to the size of the civil engineering structures, big capacity actuators are required which translate to high costs (purchase and operation) and thus, limited interest. Demetriou and Nikitas (2016) state that the ATMDs gain their flexibility and adaptability by consuming high power and their performance is highly depended on the actuator capacity and the auxiliary mass strokes. Casciati et al. (2012) mentioned that, the actuation time lags are the main reason of causing a time delay in the control loop and thus, it has been a big concern in the research area of structural control. The authors added that, this topic is currently under review by the structural control research community. The influence of time delay was also discussed and investigated in Teng et al. (2016). Moreover, Bhaiya et al. (2019) mention that, a delay could occur due to processing feedback information which makes the active control not a reliable control method. Chen et al. (2021) mention that, it is important to limit the stroke of the AMDs since, when the mass damper has excessive strokes and its relative velocity is in the same direction as the direction of the strokes, the mass could probably collide on the anti-collision device on the building potentially causing safety problems.

2.6.2 Software-Related Limitations

It is important to note that, the control algorithm is one part of the control strategy. In order for the control algorithm to compute the required actions, information about the states of the structure in real-time is required. As explained in the Introduction, the semi-active, active and hybrid control systems require sensors located on selected areas of the structure in order to provide essential feedback regarding the state of the structure, i.e. displacements, velocities, accelerations. However, it is often that the feedback is noisy or incomplete. Incomplete feedback occurs when measurements are taken from limited DOFs of a system. For this reason, it is sometimes impossible for the control algorithm to identify all the states of the structure. To overcome this, an observer must be utilised since, it is capable of computing the full vector of structural response by using limited number of states (Miah et al. (2015)). Applications of observer algorithms in semi-active and active structural control can be found in (Azam et al. (2017), Mei et al. (2002), Miah et al. (2015), Yan et al. (2007)) where Kalman filters were utilized. Aghajanian et al. (2017), and Hillis (2010) implemented the Luenberger observer in their control schemes. Moreover, the use of the disturbance observer can be found in the control scheme of Nyawako et al. (2016). Alt et al. (2000) reported that, during an earthquake, the measured signals from the sensors may deviate from the real ones and this could result to a detrimental effect on the controlled structure.

Being highly depended on the utilised actuators, the active and hybrid mass damper control design should also take into account their explicit dynamic characteristics i.e. actuator dynamics (Wu and Yang (2004)). The effect of the actuator dynamics can be critical in the overall performance of the control system (Dyke et al. (1995)). Aiming to minimise the effect of the actuator dynamics and the computational phase delay, Nikzad et al. (1996) developed two controllers (i.e. a conventional feedforward controller and a neurocontroller) and investigated their performance. It was found that the neurocontroller was more effective on eliminating the effect of the actuator dynamics and time delay. In their study, Dyke et al. (1995) showcased the importance of accounting for the control-structure interaction and the actuator dynamics when designing a control system. The authors showed that, there is a natural velocity feedback interaction path in the case of hydraulic actuators. They concluded that, the consideration of the actuator dynamics and the control-structure interaction can lead to a considerably improved and reliable control system. However, it was mentioned that, most researchers neglect the effects from the actuator dynamics. This can result in time lag and mismatches when generating the control forces.

2.6.3 Reflection

Section 2.6 reported several limitations of passive, semi-active, active and hybrid mass dampers as these were identified in current literature. It is rather important to present these limitations of each control system in order to provide a clear direction on future research required by the community. Besides, by recognising the control systems' limitations, more accurate conclusions may be drawn in the following sections where, the installations of mass damper devices on real building-like structures will be presented and investigated.

2.7 Systematic Evaluation of Literature with Control System Applications

The concept of systematic literature review arose from the medical research field and its main use was to provide evidence-based medicine treatment (Kitchenham and Charters (2007)). The difference between a traditional, or experiential, literature review (even in very successful examples as e.g. Avci et al. (2021), Kiranyaz et al. (2021)) and a systematic one is the fact that the latter uses a structured search approach and formalised objectives. Reymert et al. (2022) state that, systematic reviews are not common in the civil and structural research fields. The systematic search provides a well-defined search methodology which helps to reduce bias and allows for generating more general conclusions (Kitchenham and Charters (2007), Petersen et al. (2008)). In this part of the current work, the use of systematic evaluation literature is considered to be essential since, it will only then allow for statistical analysis to be conducted. More specifically, by analysing the findings of the systematic evaluation, patterns and trends will be uncovered which will lead to several important conclusions around mass damper installations on real building-like structures. Other examples of the systematic literature review approach in the civil and structural engineering research area can be found in Panah and Kioumarsi (2021) where the application of building information modelling (BIM) in the health monitoring and maintenance processes was reviewed; in Kc and Gautam (2021) where the progress in sustainable structural engineering was investigated and; in Flah et al. (2021) where the application of machine learning algorithms in structural health monitoring was reviewed. Moreover, Babaei et al. (2021) used the systematic literature review approach for reporting the issues around the front-end of infrastructure megaprojects, Manzoor et al. (2021) systematically reviewed the influence of artificial intelligence in civil engineering in relation to sustainable development and Medel-Vera and Ji (2015) reviewed the seismic protection technologies applied on nuclear power plants.

To further clarify the differences between a systematic literature search and a conventional literature review, the main features addressed by Kitchenham and Charters (2007) will be discussed. Firstly, the systematic literature review starts by defining a search objective in order to express the search question. Moreover, the systematic reviews use a structured search strategy, that is documented to the readers, in order to cover as much of the relevant literature possible. After gathering the relevant literature a screening process should take place. This means that, inclusion and exclusion criteria should be set in order to discard non-applicable studies. Finally, the information to be obtained by each primary study should be clearly specified.

2.7.1 Systematic Evaluation Objectives

The objectives of this systematic evaluation is to firstly search for relevant literature which includes real-life applications of mass damper systems on building-like structures. This means that, bridges, wind turbines, and experimental schemes applied on laboratory environments are not included within this application list. Control system applications that are not mass-damper-based (i.e. even tuned liquid dampers (Ghisbain et al. (2021))) are also excluded. Moreover, any algorithms used for the control of the real-life applications will also be extracted from the relevant literature.

2.7.2 Search Strategy

The database search method used herein is based on Reymert et al. (2022), and is considered to be adequate and efficient fitting the purpose of this work. The systematic literature search was conducted by using phrase search with Boolean *AND* and *OR* operators. Table 2.1 shows how the phrase search was structured where, the *OR* operator was used between the terms of each column and the *AND* operator between each column. An iterative method was used to develop the phrase search in order to achieve an acceptable and complete literature search. At first, a Scopus search was conducted where, a broad phrase selection was used in order to assess the quantity of the relevant data and then, progressive phrase constraints were added in order to achieve satisfactory precise results. This study aims to provide two, as complete as possible, mass damper and control algorithm applications lists, widening previous coverage of the relevant literature data.

2.7.3 Screening Process

To gather the most relevant literature, a screening process was conducted. Search results that were not written in English, did not align with the objective of this systematic evaluation, or they were duplicates of existing results were excluded. Using the Table 2.1 phrase search approach, a total of 424 unique results were gathered. Moreover, due to the uniqueness of the search subject of matter, 37 more results were gathered from cited studies within the results. From the total of 461 studies, 70.5% were journal articles, 26.0% were conference papers and 3.5% were books, book chapters, and technical reports. Figure 2.3 shows a plot of the unique results based on the year they were published. From this, one may notice that, there is an increase in the interest of structural control using mass damper technology over the years, especially after 2009. Further to that, the figure shows the five countries where the most documents were produced. As it can be seen, China, Japan, United States, Taiwan and Iran produced 61.5% of the documents that were gathered through the aforementioned process. In the following sections, the data accumulated from the 461 documents will be analysed and the findings will be discussed thoroughly.

Table 2.1: Search phrase structure

	Type of Control	Specification	Results
Scopus	'Mass Damper'	'High Rise'	424
	'Mass Driver'	'Skyscraper'	
		'Practical Application'	
		'Building Application'	
		'Real Application'	
Other			37
Sum			461

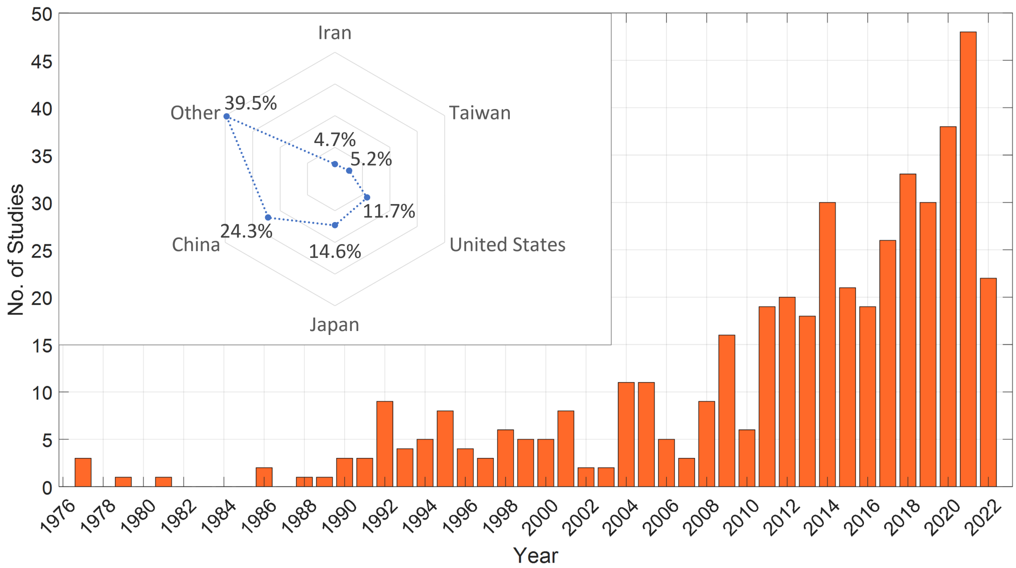


Figure 2.3: Studies gathered from the systematic literature review approach.

2.8 Literature Search Data Gathered

Over the last two decades, many significant efforts have been made to transfer theoretical structural control knowledge to real-life structures. Table 2.2, demonstrates the use of structural control systems in real-life applications organised in chronological order and the colour selection is based on the year of construction of each structure (i.e. different year designated in different background colour). As explained in the Introduction, there is an inconsistency with the terminology used by the structural control research community for describing the different types of mass dampers. Therefore, the terminology used for the control type description in this work is based on Soong and Spencer (2000) to keep consistency. Table 2.2 includes 208 building-like structures that utilise at least one type of control system i.e. passive, semi-active, active and hybrid mass dampers. It is noted that, when compared to the total number of tall structures that are being built around the world (Jafari and Alipour (2021)), the utilisation of mass damper technology is still not broadly used. Moreover, structural control applications' maps are included in Figure 2.4, which show all the control system applications listed in Tables 2.2 and 2.3. As it can be seen, Japan is the country with the most structures equipped with a control system (77). After Japan, the country with the most applications, yet with a notable difference, is the U.S.A with 37, followed by Germany with 16, making the three countries with the most structures equipped with structural control applications.

From the analysis of the accumulated data, this study aims to address three questions:

1. *What type of mass damper system is more preferred by the engineering industry?*
2. *How are mass damper systems distributed around the world?*
3. *Is the research done by the structural control research community adopted by the engineering industry?*

The consideration and discussion of the above-mentioned questions are believed to be crucial for the research area of structural control since, they will highlight gaps and future research steps to be followed.

Table 2.2: Summary of structural control applications around the world in a chronological order.

Structure	Year	Location	Type of Control
C N Tower	1973	Toronto	PTMD
John Hancock	1977	Boston	PTMD
Citicorp Building - 601 Lexington	1977	New York	PTMD
City Corp Center	1978	New York	PTMD
Sydney Tower	1980	Sydney	PTMD
Al Khobar Chimney	1980	Saudi Arabia	PTMD
Ruwais Utilities Chimney	1982	Abu Dhabi	PTMD
Deutsche Bundespost Cooling Tower	1982	Nurnberg	PTMD
Yanbu Cement Plant Chimney	1984	Saudi Arabia	PTMD
Hydro-Quebec Wind Generator	1985	Canada	PTMD
Metropolitan Tower	1985	New York City	PTMD
Chiba Port Tower	1986	Chiba	PTMD
BMW Factory floor	1988	Munich	PTMD
Arc de 124.5° Steel Scuplture	1988	Berlin	PTMD
Bin Qasim Thermal Power Station	1988	Pakistan	PTMD
Tiwest Rutile Plant Chimney	1989	Cataby	PTMD
Fukuoka Tower	1989	Fukuoka	PTMD
Henckels Zwillingwerke, Factory Floor	1989	Solingen	PTMD
Higashiyama Sky Tower	1989	Nagoya	PTMD
Kyobashi Seiwa Building	1989	Tokyo	AMD
Kajima Research Lab. # 21	1990	Tokyo	SATMD
Fernsehturm Tower	1990	Berlin	PTMD
Crystal Tower	1990	Osaka	PTMD
Huis Ten Bosch Domtoren	1990	Nagasaki	PTMD
Hibikiryokuchi Sky Tower	1991	Kitakyushu	PTMD
Shimizu Tech. Lab	1991	Tokyo	AMD
HKW Chimney	1992	Frankfurt	PTMD
BASF Chimney	1992	Antwerp	PTMD
Siemens Power Station	1992	Killingholme	PTMD
Sendagaya INTES Building	1992	Tokyo	AMD
Chifley Tower	1992	Sydney	PTMD
Applause Tower	1992	Osaka	HMD
ORC 200 Bay Tower	1992	Osaka	HMD
Kansai Int'l Airport	1992	Osaka	HMD
Rokko Island P and G	1993	Kobe	PTMD
Chifley Tower	1993	Sydney	PTMD
Al Taweeiah Chimney	1993	Abu Dhabi	PTMD
KS Project	1993	Kanasawa	HMD
Babcock, Steel Structure	1993	Munich	PTMD
Long Term Credit Bank	1993	Tokyo	HMD

Ando Nishikicho Building	1993	Tokyo	HMD
NTT Kuredo Motomach Building	1993	Hiroshima	HMD
Nishimoto Kosan Nishikicho Building	1993	Tokyo	HMD
Yokohama Landmark Tower	1993	Yokohama	HMD
Akita Tower	1994	Akita	PTMD
J City Tower	1994	Tokyo	HMD
Penta-Ocean Exp. Building	1994	Tokyo	HMD
Shinjuku Park Tower	1994	Tokyo	HMD
Dowa Fire & Marine Ins.	1994	Osaka	HMD
Hikarigaoka Office Building	1994	Tokyo	HMD
Göttingen Stack	1994	Göttingen	PTMD
Porte Kanazawa	1994	Kanazawa	AMD
Mitsubishi Heavy Ind.	1994	Yokohama	HMD
Hamamatsu ACT Tower	1994	Hamamatsu	HMD
Riverside Sumida	1994	Tokyo	AMD
Hotel Ocean 45	1994	Miyazaki	HMD
RIHGA Royal Hotel	1994	Hiroshima	HMD
Hikarigaoko J City Building	1994	Tokyo	HMD
Osaka WTC Building	1995	Osaka	HMD
Dowa Kasai Phoenix Tower	1995	Osaka	HMD
Sea Hawk Hotel and Resort	1995	Fukuoka	PTMD
Rinku Gate Tower Building	1995	Osaka	HMD
Hirobe Miyake Building	1995	Tokyo	HMD
Nissei Dowa Sonpo Phoenix Tower	1995	Osaka	HMD
Plaza Ichihara	1995	Chiba	HMD
Regensburg Siemens Building	1996	Regensburg	PTMD
Hamburg Stack	1996	Hamburg	PTMD
Nanjing Communication Tower	1996	Nanjing	AMD
Artwork The Asylum	1996	Rotterdam	PTMD
Rinku Gate Tower	1996	Izumisano	HMD
Herbis Osaka	1997	Osaka	AMD
Nisseki Yokohama Building	1997	Yokohama	HMD
Karlsruhe Building	1997	Karlsruhe	PTMD
T & C Tower	1997	Kaohsiung	HMD
Washington National Airport Tower	1997	Washington	PTMD
Petronas Twin Towers	1997	Kuala Lumpur	PTMD
Itoyama Tower	1997	Tokyo	HMD
Otis Shibyama Test Tower	1998	Chiba	HMD
Bunka Gakuen	1998	Tokyo	HMD
Oasis Hiroba 21-Oasis Tower	1998	Oita	HMD
Sendai AERU	1998	Sendai	PTMD
Kaikyo Messe Yume Tower	1998	Tokyo	HMD
Yoyogi 3-Chrome Kyodo Building	1998	Tokyo	HMD
Cooling Tower Fans	1998	Scholven Gelsenkirchen	PTMD

Odakyu Southern Tower	1998	Tokyo	HMD
Kajima Shizuoka Building	1998	Shizuoka	SATMD
Sotetsu Takashimaya Kyoto Building	1998	Yokohama	HMD
Burj Al-Arab	1999	Dubai	PTMD
JR Central Towers	1999	Nagoya	HMD
Emirates Towers	1999	Dubai	PTMD
Shinagawa Intercity Building	1999	Tokyo	HMD
Century Park Tower	1999	Tokyo	HMD
Millennium Dome	1999	London	PTMD
La Hague, SGN, Stack	1999	France	PTMD
Reichstag Spectator Balconies	1999	Berlin	PTMD
TC Tower	1999	Kaoshiung	HMD
Steel Chimney	1999	Bangkok	PTMD
Shin-Jei Building	1999	Taipei	HMD
Osaka Airport Control Tower	2000	Osaka	HMD
Cerulean Tower	2000	Tokyo	HMD
Stakis Metropole	2000	London	PTMD
Sarlux Cooling Tower Fan	2000	Sardinia	PTMD
Ube Stack	2000	Ube	PTMD
Park Tower	2000	Chicago, IL	PTMD
Incheon International Airport Control Tower	2001	Incheon	HMD
The Trump World Tower	2001	New York	PTMD
MS Deutschland, Cruise Liner	2001	Germany	PTMD
Nykredit´s New Domicil floor	2001	Denmark	PTMD
One Wall Centre Tower	2001	Vancouver	PTMD
Hotel Nikko Bayside Osaka	2001	Osaka	HMD
Dentsu Head Office Building	2001	Tokyo	HMD
Izumi Garden Tower	2002	Tokyo	HMD
Prudential Tower	2002	Tokyo	HMD
Spire of Dublin	2003	Dublin	PTMD
Nihon Terebi Tower	2003	Tokyo	HMD
Shiodome Tower	2003	Tokyo	HMD
Shiodome Media Tower	2003	Tokyo	HMD
Refab2	2003	Brazil	PTMD
Al Rostamani Tower	2003	Dubai	PTMD
Neue Terassen, Floor Slabs	2003	Dresden	PTMD
Bergen Gym Floor	2003	Bergen	PTMD
21st Century Tower	2003	Dubai	PTMD
Highcliff	2003	Hong Kong	PTMD
Roppongi T-Cube	2003	Tokyo	HMD
Kochi Airport Control Tower	2003	Kochi	HMD
Taipei 101	2004	Taipei	PTMD
Takamatsu Symbol Tower	2004	Takamatsu	HMD
Bloomberg Tower	2004	New York	PTMD

DoCoMo Telecommunications Tower	2004	Osaka	PTMD
New Kanden Building	2004	Osaka	HMD
Central Japan Airport Control Tower	2005	Aichi	HMD
NEC Tamagawa Renaissance City	2005	Kawasaki	HMD
Araucano Park	2005	Santiago de Chile	PTMD
Theatro Diana Spectator Balconies	2005	Guadalajara	PTMD
Bright Start Tower (Millennium Tower)	2005	Dubai	PTMD
Radar Tower	2005	Bilbao	PTMD
Refinery Tower	2005	Budapest	PTMD
Meteorological Radar Tower	2005	Catalunya Province	PTMD
Triumph Palace	2005	Moscow	PTMD
Akasaka Intercity	2005	Tokyo	HMD
Toranomon Towers Residence	2006	Tokyo	HMD
United States Air Force Memorial	2006	Virginia	PTMD
Anzen Building	2007	Tokyo	HMD
Grand Canyon Skywalk	2007	Arizona	PTMD
Aspire Tower	2007	Doha	PTMD
Villa Magura Odobesti	2008	Odobesti	PTMD
Al Mas Tower	2008	Dubai	PTMD
Jacky Wellhead	2008	UK	PTMD
Toronto Art Gallery Ceiling	2008	Toronto	PTMD
Shanghai World Financial Center	2008	Shanghai	HMD
Comcast Center	2008	Philadelphia, PA	PTMD
ShenZhen WuTong Mountain Tower	2009	ShenZhen	PTMD
Lanxess Chemical Plant	2009	Ontario	PTMD
Shanghai Expo Area Galleries	2009	Shanghai	PTMD
QEEC floor	2009	Doha	PTMD
Almas Tower	2009	Dubai	PTMD
Estela de la Luz	2010	Mexico City	PTMD
Danube City Tower	2010	Vienna	SATMD
Goldman Sachs Headquarters	2010	New York	PTMD
LAX Theme Building	2010	Los Angeles	PTMD
Offshore Windpark Belwind, OHVS Station	2010	Belgium	PTMD
Chimney Ramla	2010	Israel	PTMD
Singapur Skypark	2010	Singapur	PTMD
The Austonian	2010	Austin	PTMD
Canton Tower	2010	Guangzhou	HMD
Alphabetic Tower	2011	Batumi	SATMD
Kingkey Finance Tower	2011	Shenzhen	AMD
Civic Center	2011	New York	PTMD

Tokyo Skytree	2012	Tokyo	PTMD
Ivanpah Solar Tower	2012	California	PTMD
ArcelorMittal Orbit Tower	2012	London	PTMD
Windseeker-Carrowinds	2012	North Carolina	PTMD
23 Marina	2013	Dubai	PTMD
Giant Wheel - High Roller	2013	Las Vegas	PTMD
Shanghai Tower	2014	Shanghai	PTMD
Olympic Flame Monument	2014	Sochi	PTMD
Flagpole	2014	Wisconsin	PTMD
Abeno Harukas	2014	Osaka	HMD
Air Traffic Control (ATC) Tower	2015	Delhi	PTMD
432 Park Avenue	2015	New York	PTMD
Las Vegas Control Tower	2016	Las Vegas	PTMD
Socar Tower	2016	Baku	PTMD
Rottweil Test Tower	2017	Rottweil	HMD
Ping An Finance Centre	2017	Shenzhen	HMD
150 North Riverside	2017	Chicago	PTMD
Nan Shan Plaza	2018	Taipei	PTMD
111 Murray Street	2018	New York	PTMD
520 Park Avenue	2018	New York	PTMD
50 West	2018	New York	PTMD
100 East 53rd Street	2018	New York	PTMD
Muscat International Airport	2018	Oman	PTMD
Madison Square Park Tower	2018	New York	PTMD
30 Hudson Yards	2019	New York	PTMD
53 West 53rd	2019	New York	PTMD
220 Central Park South	2019	New York	PTMD
The Centrale	2019	New York	PTMD
35 Hudson Yards	2019	New York	PTMD
The Address Residence Sky View Tower 1	2019	Dubai	PTMD
Crown Sydney Hotel and Resort	2020	Sydney	PTMD
One Vanderbilt Avenue	2020	New York	PTMD
Central Park	2020	New York	PTMD
Flagpole	2021	Egypt	PTMD
Turkevi Center	2021	New York	PTMD
111 West 57th Street	2021	New York	PTMD
Greenwich	2022	New York	PTMD
The One	UC	Toronto	PTMD
M3 at M City	UC	Mississauga	PTMD
Jeddah Tower	UC	Jeddah	PTMD

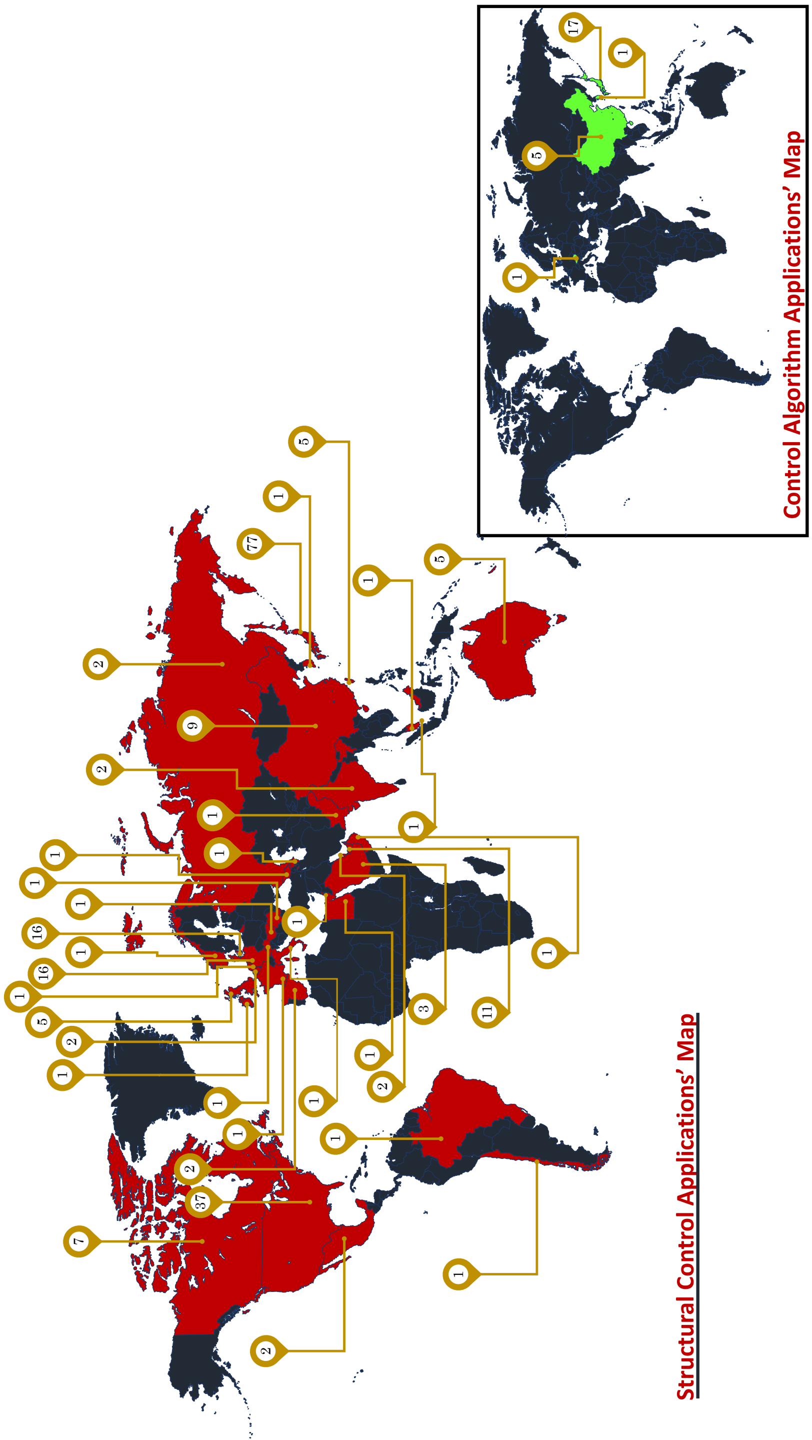


Figure 2.4: Maps of mass damper applications and control algorithms on real building-like structures.

2.8.1 What type of mass damper system is more preferred by the engineering industry?

As it can be seen in Figures 2.5-2.6, from the total number of control systems that are included in Table 2.2, the 131 are PTMDs which correspond to a 63% of the total applications included herein, the hybrid systems are 65 which correspond to the 31%, the AMDs are 8 which correspond to the 4%, and the SATMDs are 4 which correspond only to 2%. The most applications installed in a single year were 14 in 1994. Moreover, Figure 2.5 shows the number of application installations in every year since 1973 (49 years). It is observed that 55% of the total number of applications were installed within 13 years (between 1992 to 2005) which account for the 26.5% of the total years considered. This mainly occurred because, as seen in Figure 2.5, between the years 1992 and 2005, 91% of the total number of HMDs were installed. Figure 2.7 shows that, between the years 1992 and 2005, there was an increasing trend in Japan for installing HMDs. Figure 2.5 shows that, more applications were installed after 2005 than before 1992. It is noticed that, after 2005, only 7 HMDs were installed however, more PTMDs were installed than before 1992 (seen in Figure 2.5). The trend of installation of the different types of mass dampers is presented in Figures 2.6-2.7. As it can be seen, there is a positive trend in the installation of PTMDs, contrary to the AMDs and HMDs.

2.8.2 How are mass damper systems distributed around the world?

Figure 2.8 shows that, Asia is the leading continent for structural control applications with 120 applications making the 57.7% of the total control systems around the world. America (both North and South) is the continent with the second highest number of applications with 46 (22.1%), followed by Europe with 36 applications (17.3%), Australia with 5 applications (2.4%) and last Africa with 1 application (0.5%). For further comparison, the installations of systems before and after the year 2000 are presented. It is noted that, the year 2000 was selected as a benchmark year since it is associated with notable advances in various sectors, demonstrating a period of technological significance. Figure 2.9 shows that, 47% of the systems were installed before 2000 from which, 48 (49%) were PTMDs, 41 (42%) were HMDs, 7 (7%) were AMDs, and 2 (2%) were SATMDs. From the remaining 53% of the applications that were installed after 2000, 83 were PTMDs corresponding to 75.5%, 24 were HMDs corresponding to 21.8%, 2 were SATMDs corresponding to 1.8% and 1 (0.9%) was

AMD.

Taking a closer look at the installation of mass damper devices in different continents, (starting the discussion in ascending order), Africa is the continent with the fewest installations. As seen in Figure 2.9, Africa has only 1 PTMD application which was installed in 2021 in Egypt.

Australia has only 5 mass damper applications. As it can be seen in Figure 2.9, Australia has only PTMDs. More specifically, 4 applications (80%) were installed before 2000 while 1 (20%) was installed after 2000 (seen in Figure 2.10).

There is a total of 36 control systems located in Europe. Figure 2.9 shows that 94.4% are PTMDs, 2.8% are HMDs and 2.8% are SATMDs. Moreover, 18 PTMDs were installed before 2000 which correspond to 50% of the total systems installed in Europe. From the remaining 50%, 44.4% are PTMDs and the rest 5.6% is divided between the HMDs and the SATMDs (seen in Figure 2.10).

America is the second continent with the most control system applications As it can be seen in Figure 2.9, 100% of the applications in America are PTMDs. From the total of 46 systems, only 7 were installed before 2000 which is the 15.2%. Thus, the remaining 39 systems (84.8%) were installed after 2000 (seen in Figure 2.10). Figure 2.11 shows that, after 2005 there was a steady increase in the installation of mass dampers in America resulting in a strong positive trend.

Asia is the continent with the most control system applications. More specifically, there are 120 applications located in Asia which make the 57.7% of the total applications around the world. As it can be seen in Figure 2.9, 53.7% of the systems in Asia are HMDs, 37.5% are PTMDs, 6.7% are AMDs and 2.5% are SATMDs. It is noticed that, 58% of the total applications in Asia were installed before 2000. It is worth noting that, 64.2% of the total applications in Asia were installed in the Japan. As seen in Figure 2.7, there was a sudden increase in the installation of HMDs in Japanese cities such as Tokyo and Osaka after 1992. Even though Asia has the most mass damper applications since 1973, Figure 2.11 shows that there was a sudden increase in the mass damper installations between 1992 and 2005 and after that period, the installation of mass dampers was considerably decreased.

2.8.3 Is the research done by the structural control research community adopted by the engineering industry?

It is rather important to investigate the control algorithms applied within the control of real structures. This will provide an understanding on how the research done by the structural control community is incorporated in real applications. Table 2.3 includes 24 structures equipped with semi-active, active and hybrid mass dampers. More specifically, the table includes 2 structures equipped with SATMDs, 8 with AMDs and 14 with HMDs. The majority of the structures reported on the table are located in Japan (17), 5 are located in China, 1 in South Korea and 1 in Austria. The first thing to notice in this section is the lack of studies discussing the implementation of advanced mass damper systems (semi-active, active and hybrid) in real applications. More specifically, from the total of 77 semi-active, active and hybrid mass damper applications included in Table 2.2, the implementation of only 24 (31%) was presented in the literature. This demonstrates the scarcity of studies that present the real challenges that arise during and after the implementation of advanced mass damper systems on real applications.

On the algorithmic side, the majority of controllers that their performance was studied on real structures are based on the optimal control theory. Moreover, the H_∞ and the sliding mode controller were also fairly considered. As discussed in Section 2.5.4, the structural control research community studied and demonstrated the performance of adaptive, intelligent (AI), optimal, self-organised, robust and stochastic controllers. These controllers were proven to be efficient on controlling the vibrations of civil structures under wind, earthquake and human-induced excitations. However, it is noticed that the industry professionals seem to prefer algorithms which are well-established in the broadest area of control engineering. The readers are also referred to the study of Spencer and Nagarajaiah (2003) where, the algorithms employed on structural control of bridges were reviewed. From their work, it is noticed that, the majority of algorithms implemented for the control of bridges are H_∞ and optimal/sub-optimal based. The rest are fuzzy controllers, variable-gain direct velocity feedback controllers, and feedback controllers. Again, this demonstrates that the civil engineering sector is conservative in the implementation of new control techniques for mass damper applications and instead they tend to show trust on long-established controllers for which, their performance was more widely investigated and verified.

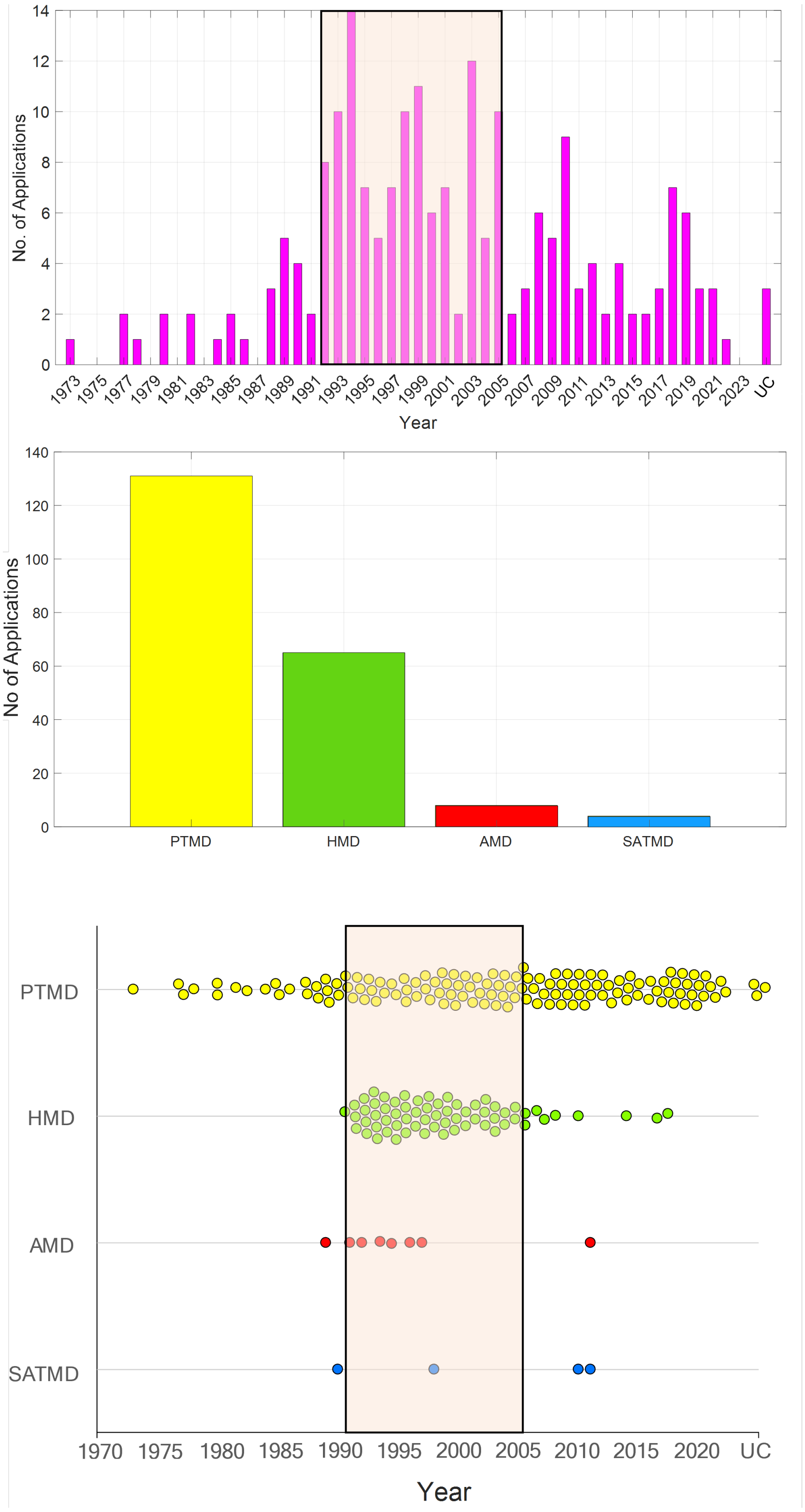


Figure 2.5: Total control system applications as per the literature.

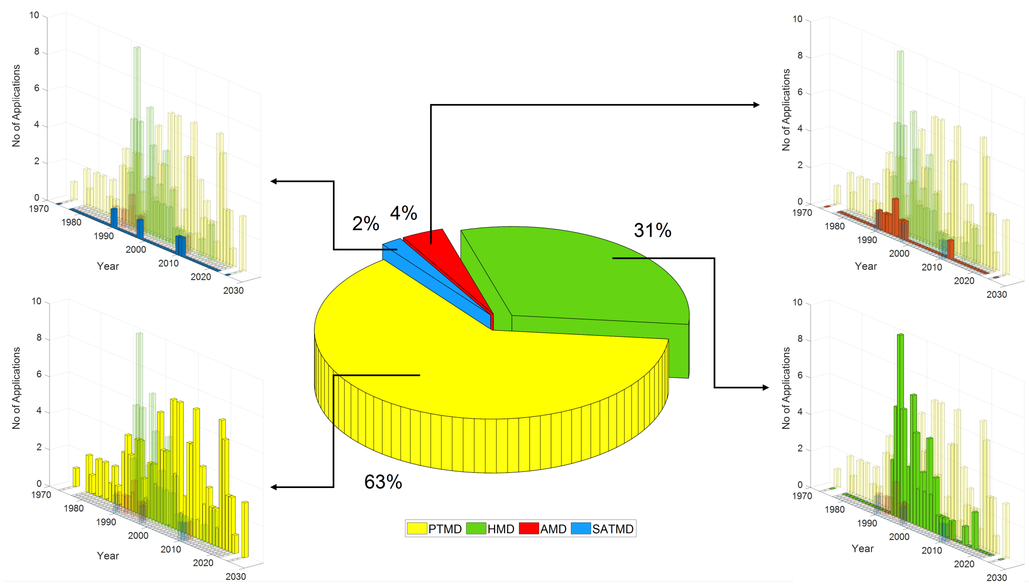


Figure 2.6: Control system application trend as per the literature.

2.8.4 Discussion

From Section 2.8.1, one may conclude that, the industry does not show trust to the active and hybrid technology and chooses the more conventional PTMDs. Despite the enhanced performance of active and hybrid mass dampers, the reason that the industry does not trust them more over the PTMDs after 2005 may be related to their high power consumption or extra costs due to the need for high-capacity actuators. There is also the possibility that the active and hybrid systems that were installed, misperformed in real-life compared to the expected performance from the simulations. If this was the

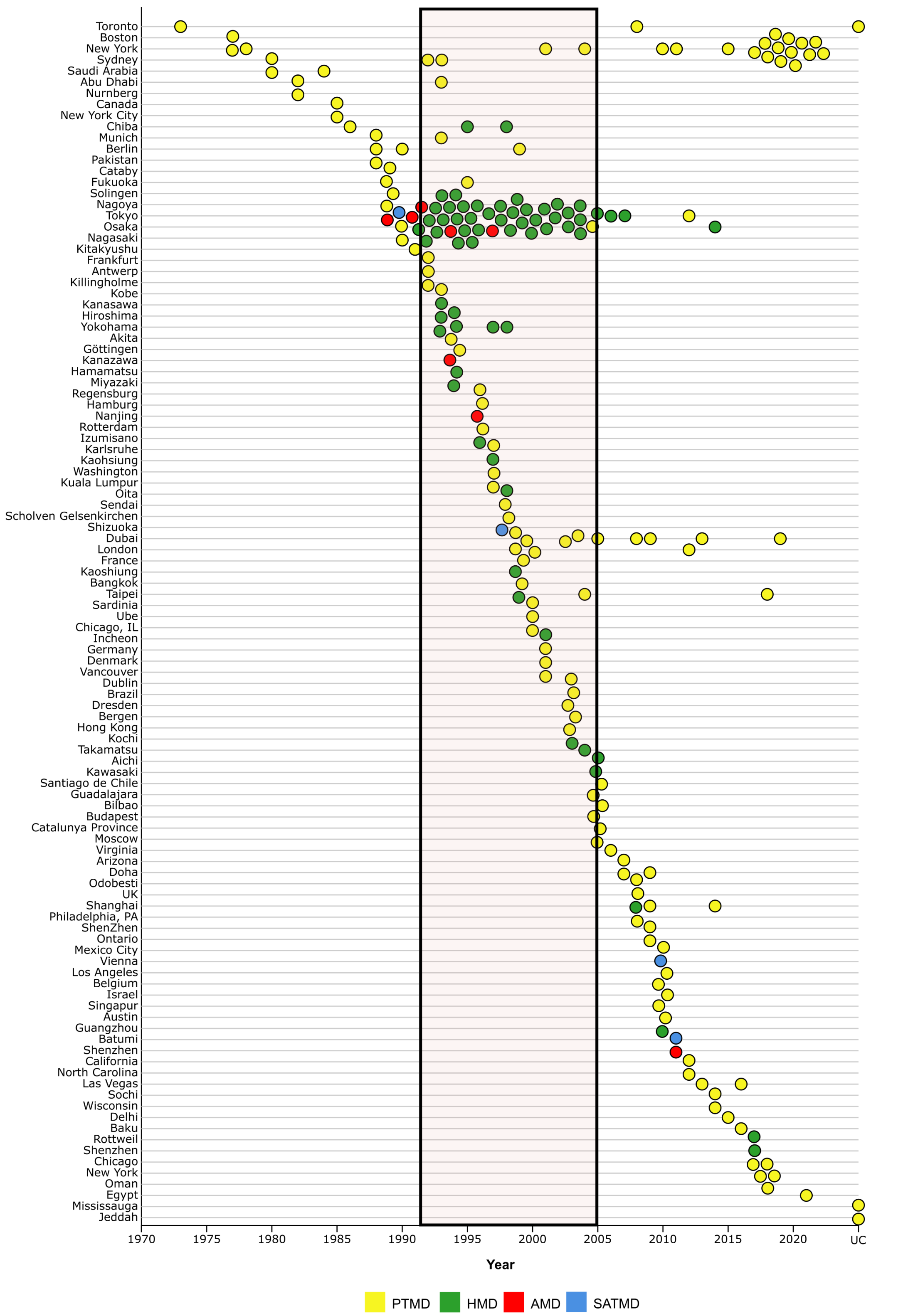


Figure 2.7: Control system applications around the world as per the literature.

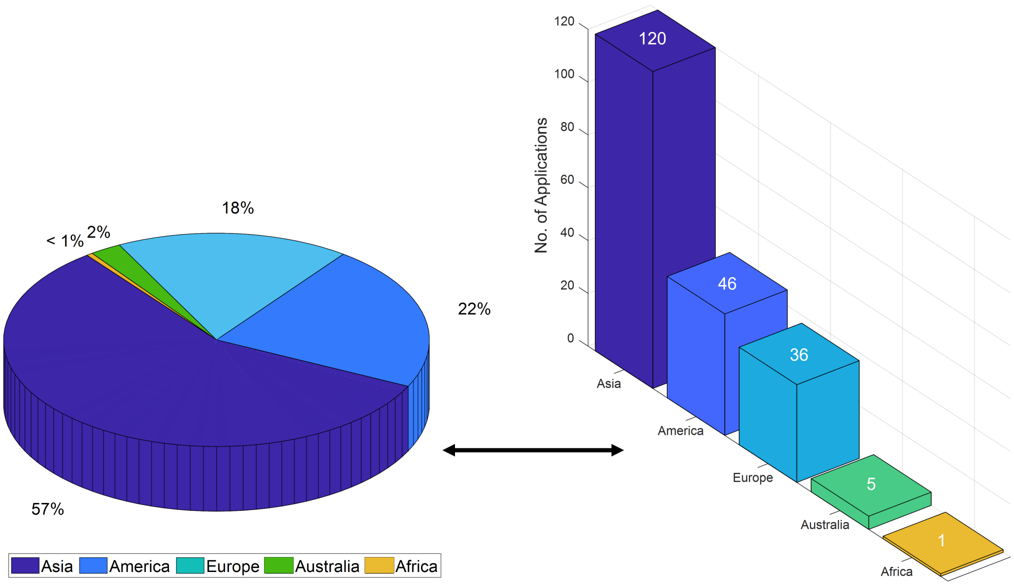


Figure 2.8: Control system applications in different continents as per the literature.

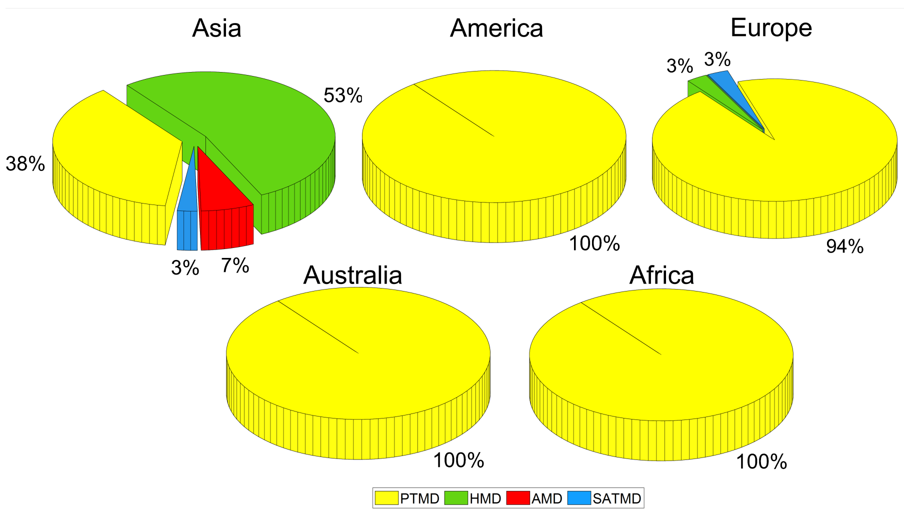


Figure 2.9: Break up of applications in different continents as per the literature.

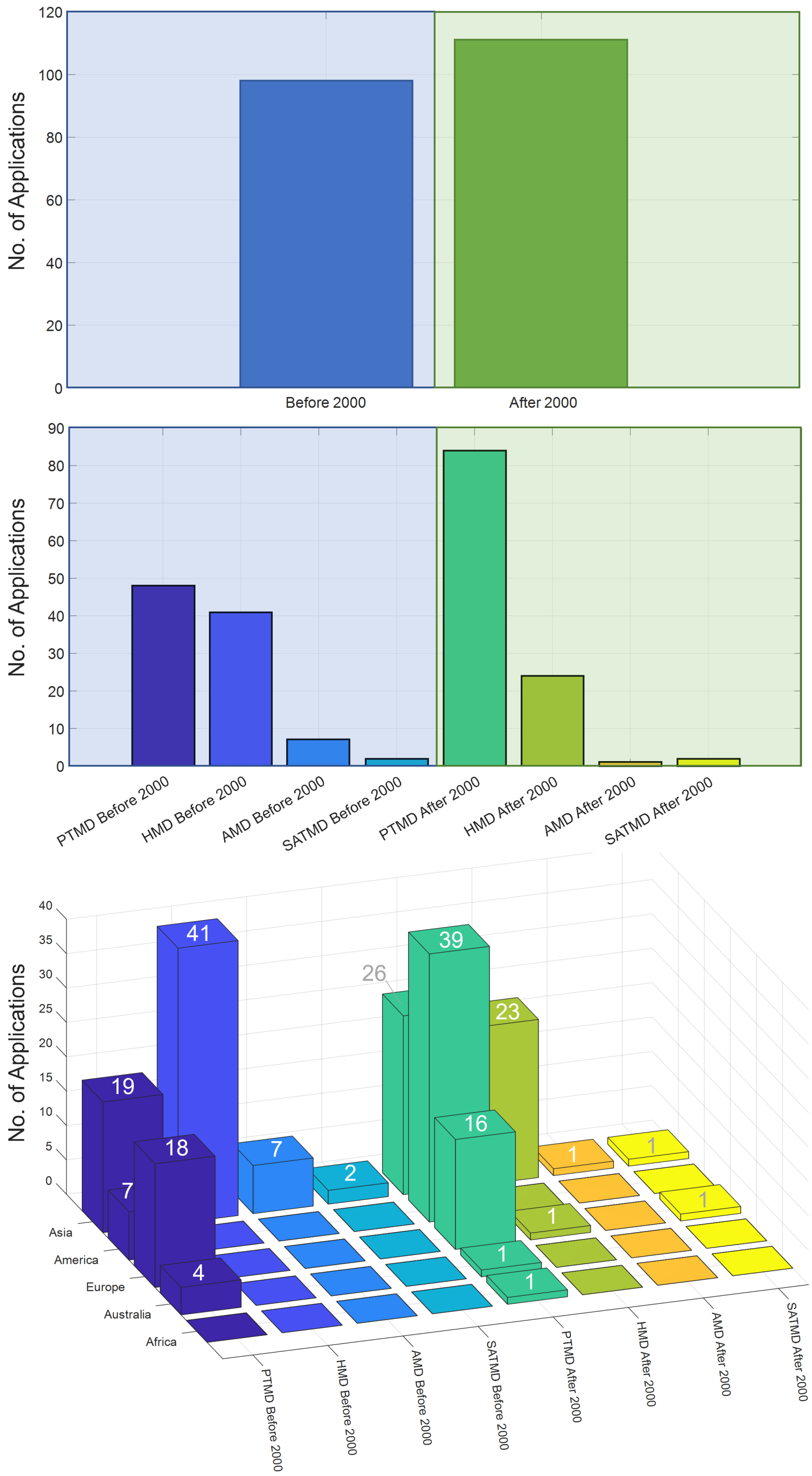


Figure 2.10: Control system applications in different continents before and after 2000 as per the literature.

Table 2.3: Algorithms considered on real building-like structures

Structure	Type of Control	Algorithm	Reference
Kyobashi Seiwa Building	AMD	LQ Optimal theory-based	Kobori et al. (1991)
			Sakamoto et al. (1992)
Yokohama Landmark Tower	HMD	LQ Optimal theory-based	Yamazaki et al. (1992)
Riverside Sumida Building	AMD	Optimal Feedback-VG	Suzuki et al. (1994)
		LQR, H_∞	Smith and Chase (1996)
Ando Nishikicho Building	HMD	Velocity-feedback optimal	Sakamoto and Kobori (1995)
Shinjuku Park Tower	HMD	LQ Optimal theory-based	Tanida et al. (1994)
Nanjing Communication Tower	AMD	LQR, Nonlinear Feedback Control	Cao et al. (1998)
		Continuous Sliding Mode	Wu and Yang (1997)
		LQG, H_∞, Continuous Sliding Mode	Wu and Yang (1998)
		LQG	Wu and Yang (2000)
ORC 200 Bay Tower	HMD	Optimal State-Feedback GS	Saito et al. (2001)
Hotel Ocean 45	HMD	Optimal State-Feedback GS	Saito et al. (2001)
Kajima Shizuoka Building	SATMD	LQR-based	Kurata et al. (1999)
Sendagaya INTES Building	AMD	LQ Optimal theory-VG	Yamamoto et al. (2001)
Applause Tower	AMD	LQ Optimal theory-based with VG	Yamamoto et al. (2001)
Porte Kanazawa	AMD	LQ Optimal theory-based with VG	Yamamoto et al. (2001)
Herbis Osaka	AMD	LQ Optimal theory-based with VG	Yamamoto et al. (2001)
Hikarigaoka Office Building	HMD	H_∞, VG	Fujinami et al. (2001)
Hirobe Miyake Building	HMD	LQ Optimal theory-based with Active-Passive SM	Nakamura et al. (2001)
Bunka Gakuen	HMD	LQ Optimal theory-based with Active-Passive SM	Nakamura et al. (2001)
Oasis Hiroba 21-Oasis Tower	HMD	H_∞ -based with Active-Passive SM	Nakamura et al. (2001)
Dentsu Head Office Building	HMD	LQR	Yamanaka and Okuda (2005)
Incheon International Airport Control Tower	HMD	H_∞ with a bilinear transform	Park et al. (2006)
Canton Tower	HMD	LQR, H_∞	Tan et al. (2012)
Shanghai World Financial Center Tower	HMD	LQ Optimal theory-based with Active-Passive SM	Lu et al. (2014)
Danube City Tower	SATMD	Adaptive nonlinear control	Weber et al. (2016)
Kingkey Finance Tower	AMD	LQR, PA, FNN, VG	Teng et al. (2014)
		VG state feedback	Chen et al. (2021)
Ping An Finance Centre	HMD	LQR, VG with Active-Passive SM	Zhou et al. (2022)

Abbreviations: **LQ**=Linear Quadratic, **VG**=Variable Gain, **SM**=Switching Mode, **LQR**=Linear Quadratic Regulator, **LQG**=Linear Quadratic Gaussian, **GS**=Gain Scheduling, **PA**=Poll Assignment, **FNN**=Fuzzy Neural Networks

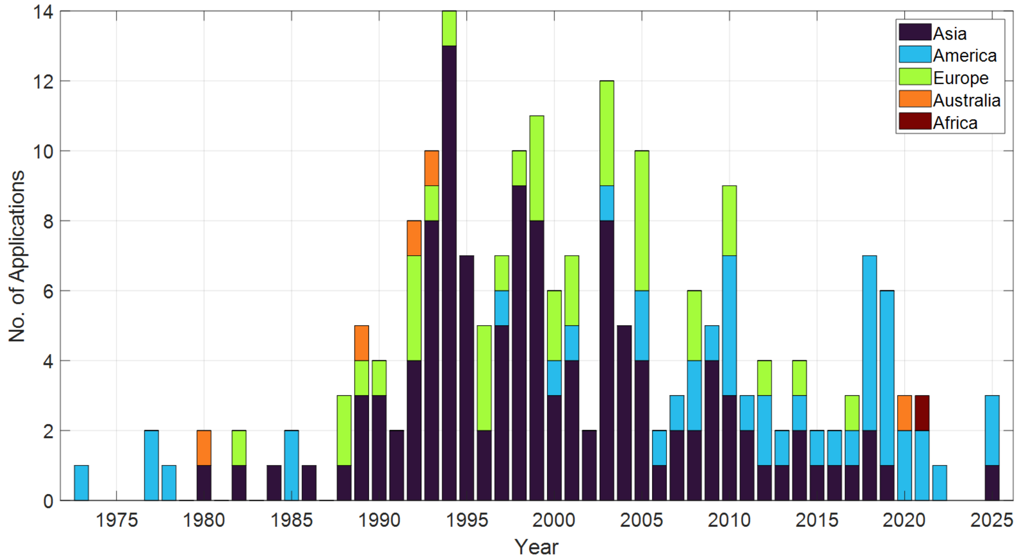


Figure 2.11: Control systems installation over the years in different continents as per the literature.

case, the active and hybrid systems may have experienced issues related to the installed actuators (e.g. actuation delays, maintenance etc). Additionally, robustness issues may have occurred due to parametric uncertainties that usually arise from modelling errors, environmental effects and structural damage. The robustness issues are directly related to the deployed control algorithm in each case. However, there is no substantial evidence in the literature that even indicates that the installed active and hybrid systems demonstrate issues that make them ineffective. One may find articles discussing the application of active, semi-active and hybrid mass dampers on real structures however, there is lack of information on how the systems perform, what their possible malfunctions are, and what their operational and management costs rise to. So, this makes it difficult to confidently reason the decrease in the use of active and hybrid technologies.

Based on the analysis that was presented in Section 2.8.2, one of the questions that comes up is, 'why the technologically advanced continent with the second highest number of control applications includes only passive systems?' The basis of the answer to this question can probably be found in Spencer and Nagarajaiah (2003). In their discussion they mentioned that, the civil engineering sector and construction industry in the U.S.A. (the country with the most applications in America) can be described as conservative and not open to the utilisation of new technologies. Moreover, it is noted that the lack of research and development expenditure by the construction industry along with the minimal to none verified analysis and design approaches make the implementation of semi-active, active and hybrid control systems in the U.S.A. almost impossible. In contrast to the U.S.A., the Japanese construction industry invests heavily in the research and development of new technologies. However, even in Japan, it is noticed that the purely active and semi-active control schemes remain in modest numbers. This demonstrates that there are still open challenges with regards to the semi-active and purely active systems in order to gain acceptance by the construction industries all over the world. Nishitani and Inoue (2001) state that, after the Kobe earthquake (1995), the use of active technology on civil structures in Japan was dramatically decreased in contrast to the base isolation devices ($\geq$700 installations). The authors explain that the reason for this was that after the earthquake, the Japanese engineering community was seeking immediate solutions on how to provide mitigation strategies for severe disasters. At the time, the active technology did not prove to be capable of controlling structures under severe natural hazards and thus, the local engineering community did not re-consider it. The authors commented that, the semi-active technology is very promising and could be inspiring the next-generation control systems. In this study, it is shown that, indeed this statement could be true when facing the development of purely active systems (i.e. AMDs). As seen in Figure 2.7, the installations of AMDs were considerably decreased after 1995 however, the installation of HMDs prospered until 2005. Spencer and Nagarajaiah (2003) mentioned that, it is a challenging task to develop control strategies for the semi-active control schemes due to their intrinsically nonlinear nature. Therefore, despite their potential effectiveness and benefits they provide, their full-scale implementation is difficult. This study shows that, to date, the full-scale installation of SATMDs remains in very low levels (only 4). This demonstrates that the advantages of the SATMDs are still not fully recognised and realised.

Trying to grasp the bigger picture, one may refer to Soong and Spencer (2002) who stated that, the acceptance of the control systems is based on a combination of their enhanced performance and their installation, maintenance and future costs. It is evident that, the structural control research community mainly emphasises on enhancing the performance of the different types of control systems without considering any related costs and practicalities. Additionally, based on the findings of Section 2.8.3, the literature lacks of studies discussing the application of advanced mass damper systems on real civil structures. This demonstrates that the community does not share experience which would be beneficial on tackling the challenges that arise. Moreover, it is evident that there are no strict methodologies to be followed for the installation of mass damper systems on real structures. On the contrary, it was noticed that, the studies considering the implementation of mass damper technologies on real structures were focusing explicitly on very custom approaches. It is possible that, the current hesitation on the installation of such technologies may be the result of the absence of solid guidelines. Finally, the lack of training of civil engineering professionals in the area of control is identified as a bottleneck and as a major reason for the hesitation in implementing advanced mass dampers within latest vibration control practices.

2.9 Conclusions

In this work, an up-to-date literature review of studies considering mass damper technology was carried out. Studies that investigated passive, semi-active, active and hybrid control using mass dampers were included and their findings were discussed. New innovative control approaches proposed by the structural control community even up to this day were presented. Moreover, the limitations of each type of control system were reported in order to highlight the research gaps that have to be tackled.

In Section 2.7, a systematic literature search was conducted in order to gather mass damper applications on building-like structures in order to provide an image of real-life applications and identify potential gaps and future research needed. Eventually, a most complete table with real-life control applications is presented. The table includes 208 structures around the world. The applications were analysed based on where they are located and when they were implemented. The studies considering the control of real building-like structures were also gathered and presented in a tabulated form. In addition to that, a novel list of control algorithms utilised on real-building like structures was devised. The main findings of this work are:

1. Asia with 120 systems is the continent with the most structural control applications, with around 3 times more applications than America that has 46. The third continent with the most structural control applications is Europe with 36, fourth is Australia with 5 and last is Africa with only 1 application

2. 47% of the total applications were installed before 2000

3. The large majority of mass damper installations were PTMDs with 131 applications (63% of the total number systems) where, the second most used system is the HMD with 65 applications (31% of total number of systems)

4. 55% of the total applications were installed between the years 1992 and 2005 which is due to the sudden increase in the installation of HMDs in Japan

5. After 2005 the installation of the HMDs has considerably decreased and a preference in PTMDs was shown even though there was an increase in HMDs research (as seen in Figure 2.2)

6. Despite the high quality research done by the structural control community (demonstrated in Section 2.5), the algorithms utilised on real applications of semi-active, active and hybrid mass dampers were mostly based on the optimal theory, H_∞ and continuous sliding mode control, most likely due to their successful establishment in many control applications outside civil engineering

7. The structural control literature lacks of experience sharing with regards to the installation and management of advanced mass damper technologies (i.e. semi-active, active and hybrid) on real applications

As discussed in Section 2.8.4, to date there are open challenges considering the active and semi-active control systems that causes scepticism in the engineering industries around the world when considering their implementation on real-life structures. The decrease in the installation of HMDs demonstrates that there are potential issues with their installation which were discussed in Section 2.8.2. Thus, the research community should understand the real problems that arise from the active, semi-active and hybrid mass dampers, and provide confidence to the industry that the aforementioned systems are more reliable and truly superior over PTMDs. Based on the findings of this work, future research should focus on:

- Development of an experience-sharing culture within the research community regarding the installation and management of advanced mass damper systems for decreasing the self-learning practice that currently occurs

- Provision of information about the performance of already installed systems and their possible performance gaps in order to form necessary new research initiatives and allow the community to tackle real practical issues
- Use of realistic control system specifications (e.g. mass size, actuator capacity, etc) and realistic (and severe) excitations within research studies
- Large-scale experimental and analytical investigation of the performance of mass dampers should be enhanced
- Consideration of the short and long-term cost associated with the control system and, methods to decrease it
- Development of energy harvesting methods which will lead to a new generation of adaptive structural control systems with minimal, or even zero, energy requirements
- Design optimally (e.g. reducing section sizes) by making mass damper systems a starting point in the design process rather than a final step add-on

References

M. ABÉ. Semi - Active Tuned Mass Dampers for Seismic Protection of Civil Structures. *Earthquake Engineering and Structural Dynamics*, 25(7):743–749, 1996. ISSN 00988847. doi: 10.1002/(sici)1096-9845(199607)25:7⟨743::aid-eqe579⟩3.3.co;2-j.

S. Aghajanian, F. Amini, and B. Moaveni. Luenberger observer application in decentralised control of civil structures. *Proceedings of the Institution of Civil Engineers: Structures and Buildings*, 170(10):765–773, 2017. ISSN 17517702. doi: 10.1680/jstbu.16.00159.

A. S. Ahlawat and A. Ramaswamy. Multi-objective optimal design of FLC driven hybrid mass damper for seismically excited structures. *Earthquake Engineering and Structural Dynamics*, 31(7):1459–1479, 2002. ISSN 00988847. doi: 10.1002/eqe.173.

T. R. Alt, F. Jabbari, and J. N. Yang. Control design for seismically excited buildings: Sensor and actuator reliability. *Earthquake Engineering and Structural Dynamics*, 29 (2):241–257, 2000. ISSN 00988847. doi: 10.1002/(SICI)1096-9845(200002)29:2⟨241::AID-EQE903⟩3.0.CO;2-Z.

O. Avci, O. Abdeljaber, S. Kiranyaz, M. Hussein, M. Gabbouj, and D. J. Inman. A review of vibration-based damage detection in civil structures: From traditional methods to Machine Learning and Deep Learning applications. *Mechanical Systems and Signal Processing*, 147:107077, 2021. ISSN 10961216. doi: 10.1016/j.ymssp.2020.107077. URL https://doi.org/10.1016/j.ymssp.2020.107077.

S. M. Avila and P. B. Gonçalves. Optimal configurations of composite multiple mass dampers in tall buildings. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 31(1):75–81, 2009. ISSN 18063691. doi: 10.1590/S1678-58782009000100011.

E. O. Ayorinde and G. B. Warburton. Minimizing structural vibrations with absorbers. *Earthquake Engineering Structural Dynamics*, 8(3):219–236, 1980. ISSN 10969845. doi: 10.1002/eqe.4290080303.

S. E. Azam, E. Chatzi, C. Papadimitriou, and A. Smyth. Experimental validation of the Kalman-type filters for online and real-time state and input estimation. *JVC/Journal of Vibration and Control*, 23(15):2494–2519, 2017. ISSN 17412986. doi: 10.1177/1077546315617672.

A. Babaei, G. Locatelli, and T. Sainati. What is wrong with the front-end of infrastructure megaprojects and how to fix it: A systematic literature review. *Project Leadership and Society*, 2:100032, 2021. ISSN 26667215. doi: 10.1016/j.plas.2021.100032. URL https://doi.org/10.1016/j.plas.2021.100032.

H. Bachmann and B. Weber. Tuned Vibration Absorbers for â€œLivelyâ€ Structures. *Structural Engineering International*, 5(1):31–36, 1995. ISSN 1016-8664. doi: 10.2749/101686695780601457.

P. Banerji and A. Samanta. Earthquake vibration control of structures using hybrid mass liquid damper. *Engineering Structures*, 33(4):1291–1301, 2011. ISSN 01410296. doi: 10.1016/j.engstruct.2011.01.006. URL http://dx.doi.org/10.1016/j.engstruct.2011.01.006.

B. Basu, O. S. Bursi, F. Casciati, S. Casciati, A. E. Del Grosso, M. Domaneschi, L. Faravelli, J. Holnicki-Szulc, H. Irschik, M. Krommer, M. Lepidi, A. Martelli, B. Ozturk, F. Pozo, G. Pujol, Z. Rakicevic, and J. Rodellar. A European Association for the Control of Structures jointperspective. Recent studies in civil structural control across Europe. *Structural Control and Health Monitoring*, 21:1414–1436, 2014. doi: 10.1002/stc.

A. Bathaei, S. M. Zahrai, and M. Ramezani. Semi-active seismic control of an 11-DOF building model with TMD+MR damper using type-1 and -2 fuzzy algorithms. *JVC/Journal of Vibration and Control*, 24(13):2938–2953, 2018. ISSN 17412986. doi: 10.1177/1077546317696369.

G. Bekdas and S. M. Nigdeli. Estimating optimum parameters of tuned mass dampers using harmony search. *Engineering Structures*, 33(9):2716–2723, 2011. ISSN

01410296. doi: 10.1016/j.engstruct.2011.05.024. URL http://dx.doi.org/10.1016/j.engstruct.2011.05.024.

V. Bhaiya, S. D. Bharti, M. K. Shrimali, and T. K. Datta. *Hybrid seismic control of buildings using tuned mass and magnetorheological dampers*. 2019. ISBN 9182335389. doi: 10.1680/jstbu.18.00090.

M. Billig. Kurt Lewin's Leadership Studies and His Legacy to Social Psychology: Is There Nothing as Practical as a Good Theory? *Journal for the Theory of Social Behaviour*, 45(4):440–460, 2015. ISSN 14685914. doi: 10.1111/jtsb.12074.

I. G. Buckle. Passive control of structures for seismic loads. *The 12th world conference on earthquake engineering*, pages 2825–2838, 2000. ISSN 11749857. doi: 10.5459/bnzsee.33.3.209-221.

H. Cao, A. M. Reinhorn, and T. T. Soong. Design of an active mass damper for a tall TV tower in Nanjing, China. *Engineering Structures*, 20(3):134–143, 1998. ISSN 01410296. doi: 10.1016/S0141-0296(97)00072-2.

L. Cao and C. Li. Enhanced hybrid active tuned mass dampers for structures. *Structural Control and Health Monitoring*, 25(2):1–13, 2018. ISSN 15452263. doi: 10.1002/stc.2067.

S. P. Carroll, J. S. Owen, and M. F. Hussein. Modelling crowd-bridge dynamic interaction with a discretely defined crowd. *Journal of Sound and Vibration*, 331(11):2685–2709, 2012. ISSN 0022460X. doi: 10.1016/j.jsv.2012.01.025. URL http://dx.doi.org/10.1016/j.jsv.2012.01.025.

F. Casciati, J. Rodellar, and U. Yildirim. Active and semi-active control of structures-theory and applications: A review of recent advances. *Journal of Intelligent Material Systems and Structures*, 23(11):1181–1195, 2012. ISSN 1045389X. doi: 10.1177/1045389X12445029.

S. Chakraborty and B. K. Roy. Reliability based optimum design of Tuned Mass Damper in seismic vibration control of structures with bounded uncertain parameters. *Probabilistic Engineering Mechanics*, 26(2):215–221, 2011. ISSN 02668920. doi: 10.1016/j.probengmech.2010.07.007. URL http://dx.doi.org/10.1016/j.probengmech.2010.07.007.

S. Chang and D. Sung. Modal-Energy-Based Neuro-Controller for Seismic Response Reduction of a Nonlinear Building Structure. *Applied Sciences (Switzerland)*, 9:4443, 2019.

C. J. Chen, Z. H. Li, J. Teng, Q. G. Wu, and B. C. Lin. A variable gain state-feedback technique for an AMD control system with stroke limit and its application to a high-rise building. *Structural Design of Tall and Special Buildings*, 30(1):1–16, 2021. ISSN 15417808. doi: 10.1002/tal.1816.

G. Chen and Z. Wang. A signal decomposition theorem with Hilbert transform and its application to narrowband time series with closely spaced frequency components. *Mechanical Systems and Signal Processing*, 28:258–279, 2012. ISSN 08883270. doi: 10.1016/j.ymssp.2011.02.002. URL http://dx.doi.org/10.1016/j.ymssp.2011.02.002.

P. C. Chen and K. Y. Chien. Machine-learning based optimal seismic control of structure with active mass damper. *Applied Sciences (Switzerland)*, 10(15), 2020. ISSN 20763417. doi: 10.3390/APP10155342.

Y. Chen, S. Zhang, H. Peng, B. Chen, and H. Zhang. A novel fast model predictive control for large-scale structures. *JVC/Journal of Vibration and Control*, 23(13): 2190–2205, 2017. ISSN 17412986. doi: 10.1177/1077546315610033.

L. L. Chung, Y. A. Lai, C. S. Walter Yang, K. H. Lien, and L. Y. Wu. Semi-active tuned mass dampers with phase control. *Journal of Sound and Vibration*, 332(15): 3610–3625, 2013. ISSN 0022460X. doi: 10.1016/j.jsv.2013.02.008. URL http://dx.doi.org/10.1016/j.jsv.2013.02.008.

A. J. Clark. Multiple passive tuned mass dampers for reducing earthquake induced building motion. *Proceedings of the Ninth World Conference on Earthquake Engineering*, 5:779–784, 1988.

G. B. Colherinhas, M. V. G. de Morais, M. A. M. Shzu, and S. M. Avila. Optimal Pendulum Tuned Mass Damper Design Applied to High Towers Using Genetic Algorithms: Two-DOF Modeling. *International Journal of Structural Stability and Dynamics*, page 1950125, 2019. ISSN 0219-4554. doi: 10.1142/s0219455419501256.

C. Collette and S. Chesné. Robust hybrid mass damper. *Journal of Sound and Vibration*, 375:19–27, 2016. ISSN 10958568. doi: 10.1016/j.jsv.2016.04.030. URL http://dx.doi.org/10.1016/j.jsv.2016.04.030.

A. Concha, S. Thenozhi, R. J. Betancourt, and S. K. Gadi. A tuning algorithm for a sliding mode controller of buildings with ATMD. *Mechanical Systems and Signal Processing*, 154:107539, 2021. ISSN 10961216. doi: 10.1016/j.ymssp.2020.107539. URL https://doi.org/10.1016/j.ymssp.2020.107539.

CTBUH. CTBUH Year in Review: Tall Trends of 2019. *CTBUH Journal*, (1):42–49, 2020.

J. Dai, Z.-D. Xu, P.-P. Gai, and Y.-W. Xu. Mitigation of Vortex-Induced Vibration in Bridges Using Semiactive Tuned Mass Dampers. *Journal of Bridge Engineering*, 26 (6):05021003, 2021. ISSN 1084-0702. doi: 10.1061/(asce)be.1943-5592.0001719.

T. Datta. A state-of-the-art review on active control of structures. *ISET Journal of earthquake technology*, 40(1):1–17, 2003. ISSN 0972-0405.

D. Demetriou and N. Nikitas. A novel hybrid semi-active mass damper configuration for structural applications. *Applied Sciences (Switzerland)*, 6(12), 2016. ISSN 20763417. doi: 10.3390/app6120397.

D. Demetriou and N. Nikitas. Hybrid Semi-Active Mass Dampers in Structures; Assessing and Optimising Their Damping Capacity. *Procedia Engineering*, 199: 3103–3108, 2017. ISSN 18777058. doi: 10.1016/j.proeng.2017.09.571. URL http://dx.doi.org/10.1016/j.proeng.2017.09.571.

D. Demetriou, N. Nikitas, and K. D. Tsavdaridis. Semi active tuned mass dampers of buildings: A simple control option. *American Journal of Engineering and Applied Sciences*, 8(4):620–632, 2015. ISSN 19417039. doi: 10.3844/ajeassp.2015.620.632.

D. Demetriou, N. Nikitas, and K. D. Tsavdaridis. Performance of fixed-parameter control algorithms on high-rise structures equipped with semi-active tuned mass dampers. *The Structural Design of Tall and Special Buildings*, 25:340–354, 2016. doi: 10.1002/tal.

J. P. Den Hartog. *Mechanical Vibrations*. McGraw-Hill, New York, NY, USA, 4 edition, 1956. ISBN 0486647854.

S. J. Dyke, B. F. Spencer, P. Quast, and M. K. Sain. Role of control-structure interaction in protective system design. *Journal of Engineering Mechanics*, 121(2):322–338, 1995. ISSN 07339399. doi: 10.1061/(ASCE)0733-9399(1995)121:2(322).

S. J. Dyke, B. F. Spencer, M. K. Sain, and J. D. Carlson. Modeling and control of magnetorheological dampers for seismic response reduction. *Smart Materials and Structures*, 5(5):565–575, 1996. ISSN 09641726. doi: 10.1088/0964-1726/5/5/006.

W. M. Elhaddad and E. A. Johnson. Hybrid MPC: An Application to Semiactive Control of Structures. In *Topics in Dynamics of Civil Structures*, volume 4, pages 27–36. 2013. ISBN 9781461465546. doi: 10.1007/978-1-4614-6555-3.

S. Elias and V. Matsagar. Research developments in vibration control of structures using passive tuned mass dampers. *Annual Reviews in Control*, 44:129–156, 2017. ISSN 13675788. doi: 10.1016/j.arcontrol.2017.09.015. URL https://doi.org/10.1016/j.arcontrol.2017.09.015.

S. Etedali and S. Tavakoli. PD/PID Controller Design for Seismic Control of High-Rise Buildings Using Multi-Objective Optimization: A Comparative Study with LQR Controller. *Journal of Earthquake and Tsunami*, 11(3):1–23, 2017. ISSN 17937116. doi: 10.1142/S1793431117500099.

K. Falcon, B. Stone, W. Simcock, and C. Andrew. Optimization of Vibration Absorbers: A Graphical Method for Use on Idealized Systems with Restricted Damping. *Journal of Mechanical Engineering Science*, 9:374–381, 1967. doi: 10.1243/JMES.

N. R. Fisco and H. Adeli. Smart structures: Part I - Active and semi-active control. *Scientia Iranica*, 18(3 A):275–284, 2011a. ISSN 10263098. doi: 10.1016/j.scient.2011.05.034. URL http://dx.doi.org/10.1016/j.scient.2011.05.034.

N. R. Fisco and H. Adeli. Smart structures: Part II - Hybrid control systems and control strategies. *Scientia Iranica*, 18(3 A):285–295, 2011b. ISSN 10263098. doi: 10.1016/j.scient.2011.05.035. URL http://dx.doi.org/10.1016/j.scient.2011.05.035.

M. Flah, I. Nunez, W. Ben Chaabene, and M. L. Nehdi. Machine Learning Algorithms in Civil Structural Health Monitoring: A Systematic Review. *Archives of Computational Methods in Engineering*, 28(4):2621–2643, 2021. ISSN 18861784. doi: 10.1007/s11831-020-09471-9. URL https://doi.org/10.1007/s11831-020-09471-9.

H. Frahm. Device for damping vibration of bodies, 1911.

T. Fujinami, Y. Saito, M. Morishita, Y. Koike, and K. Tanida. A hybrid mass damper system controlled by H∞ control theory for reducing bending torsion vibration of an actual building. *Earthquake Engineering and Structural Dynamics*, 30(11):1639–1653, 2001. ISSN 00988847. doi: 10.1002/eqe.85.

P. Ghisbain, S. Mendes, M. Pinto, and E. Malsch. Innovative Liquid Damper for Wind-Induced Vibration of Buildings : Performance after 4 Years of Operation, and Next Iteration. *International Journal of High-Rise Buildings*, 10(2):117–121, 2021.

M. Gutierrez Soto and H. Adeli. Tuned Mass Dampers. *Archives of Computational Methods in Engineering*, 20(4):419–431, 2013. ISSN 11343060. doi: 10.1007/s11831-013-9091-7.

M. N. Hadi and Y. Arfiadi. Optimum design of absorber for MDOF structures. *Journal of Structural Engineering*, 124(11):1272–1280, 1998.

D. Helbing and P. Molnár. Social force model for pedestrian dynamics. *Physical Review E*, 51(5):4282–4286, 1995. ISSN 1063651X. doi: 10.1103/PhysRevE.51.4282.

D. Helbing, I. Farkas, and P. Molnar. Simulation of pedestrian crowds in normal and evacuation situations. *Pedestrian and evacuation dynamics*, 21(2):21–58, 2002.

D. Helbing, L. Buzna, A. Johansson, and T. Werner. Self-organized pedestrian crowd dynamics: Experiments, simulations, and design solutions. *Transportation Science*, 39(1):1–24, 2005. ISSN 00411655. doi: 10.1287/trsc.1040.0108.

A. J. Hillis. Active motion control of fixed offshore platforms using an extended state observer. *Proceedings of the Institution of Mechanical Engineers. Part I: Journal of Systems and Control Engineering*, 224(1):53–63, 2010. ISSN 09596518. doi: 10.1243/09596518JSCE847.

G. W. Housner, L. A. Bergman, T. K. Caughey, A. G. Chassiakos, R. O. Claus, S. F. Masri, R. E. Skelton, T. T. Soong, B. F. Spencer, and J. T. P. Yao. Structural Control: Past, Present, and Future. *Journal of Engineering Mechanics*, 123(9):897–971, 1997. ISSN 0733-9399. doi: 10.1061/(asce)0733-9399(1997)123:9(897).

D. Hrovat, P. Barak, and M. Rabins. Semiâ€Active versus Passive or Active Tuned Mass Dampers for Structural Control. *Journal of Engineering Mechanics*, 109(3): 691–705, 1983. ISSN 0733-9399. doi: 10.1061/(asce)0733-9399(1983)109:3(691).

Y. Ikeda. Active and semi-active vibration control of buildings in Japan-Practical applications and verification. *Structural Control and Health Monitoring*, 16:703–723, 2009. doi: 10.1002/stc.

M. Jafari and A. Alipour. Methodologies to mitigate wind-induced vibration of tall buildings: A state-of-the-art review. *Journal of Building Engineering*, 33:101582, 2021. ISSN 2352-7102. doi: 10.1016/j.jobe.2020.101582. URL https://doi.org/10.1016/j.jobe.2020.101582.

R. Jangid and K. Datta. Seismic behaviour of base-isolated buildings: a state-of-the-art review. 110(2):186–203, 1995.

S. Jeon and M. Tomizuka. Benefits of acceleration measurement in velocity estimation and motion control. *Control Engineering Practice*, 15(3 SPEC. ISS.):325–332, 2007. ISSN 09670661. doi: 10.1016/j.conengprac.2005.10.004.

C. A. Jones, P. Reynolds, and A. Pavic. Vibration serviceability of stadia structures subjected to dynamic crowd loads: A literature review. *Journal of Sound and Vibration*, 330(8):1531–1566, 2011. ISSN 0022460X. doi: 10.1016/j.jsv.2010.10.032. URL http://dx.doi.org/10.1016/j.jsv.2010.10.032.

H.-J. Jung, H.-J. Lee, W.-H. Yoon, J.-W. Oh, and I.-W. Lee. Semiactive Neurocontrol for Seismic Response Reduction Using Smart Damping Strategy. *Journal of Computing in Civil Engineering*, 18(3):277–280, 2004a. ISSN 0887-3801. doi: 10.1061/(asce)0887-3801(2004)18:3(277).

H. J. Jung, B. F. Spencer, Y. Q. Ni, and I. W. Lee. State-of-the-art of semiactive control systems using MR fluid dampers in civil engineering applications. *Structural Engineering and Mechanics*, 17(3-4):493–526, 2004b. ISSN 12254568. doi: 10.12989/sem.2004.17.3_4.493.

J. Kang, H.-S. Kim, and D.-G. Lee. Mitigation of wind response of a tall building using semi-active tuned mass dampers. *The Structural Design of Tall and Special Buildings*, 20:552–565, 2011. doi: 10.1002/tal.

Y. J. Kang and L. Y. Peng. Optimisation Design and Damping Effect Analysis of Large Mass Ratio Tuned Mass Dampers. *Shock and Vibration*, 2019, 2019. ISSN 10709622. doi: 10.1155/2019/8376781.

A. Kareem, T. Kijewski, and Y. Tamura. Mitigation of motions of tall buildings with specific examples of recent applications. *Wind and Structures, An International Journal*, 2(3):201–251, 1999. ISSN 12266116. doi: 10.12989/was.1999.2.3.201.

A. E. Kayabekir, G. Bekdas, S. M. Nigdeli, and Z. W. Geem. Optimum design of PID controlled active tuned mass damper via modified harmony search. *Applied Sciences (Switzerland)*, 10(8), 2020. ISSN 20763417. doi: 10.3390/APP10082976.

S. Kc and D. Gautam. Progress in sustainable structural engineering: a review. *Innovative Infrastructure Solutions*, 6(2):1–23, 2021. ISSN 23644184. doi: 10.1007/s41062-020-00419-3. URL https://doi.org/10.1007/s41062-020-00419-3.

M. Khatibinia, H. Gholami, and R. Kamgar. Optimal design of tuned mass dampers subjected to continuous stationary critical excitation. *International Journal of Dynamics and Control*, 6(3):1094–1104, 2018. ISSN 21952698. doi: 10.1007/s40435-017-0386-7. URL https://doi.org/10.1007/s40435-017-0386-7.

S. Kiranyaz, O. Avci, O. Abdeljaber, T. Ince, M. Gabbouj, and D. J. Inman. 1D convolutional neural networks and applications: A survey. *Mechanical Systems and Signal Processing*, 151:107398, 2021. ISSN 10961216. doi: 10.1016/j.ymssp.2020.107398. URL https://doi.org/10.1016/j.ymssp.2020.107398.

B. Kitchenham and S. Charters. Guidelines for performing Systematic Literature Reviews in Software Engineering. Technical report, 2007.

T. Kobori. Future direction on research and development of seismic-response-controlled structures. *Computer-Aided Civil and Infrastructure Engineering*, 11(5):297–304, 1996. ISSN 10939687. doi: 10.1111/j.1467-8667.1996.tb00444.x.

T. Kobori, N. Koshika, K. Yamada, and Y. Ikeda. Seismicâ€responseâ€controlled structure with active mass driver system. Part 1: Design. *Earthquake Engineering Structural Dynamics*, 20(2):133–149, 1991. ISSN 10969845. doi: 10.1002/eqe.4290200204.

L. Koutsoloukas, N. Nikitas, P. Aristidou, and C. Meinhardt. Control law and actuator capacity effect on the dynamic performance of a hybrid mass damper; the case of rottweil tower. *Proceedings of the International Conference on Structural Dynamic , EURODYN*, 1:1422–1432, 2020. ISSN 23119020. doi: 10.47964/1120.9115.19241.

L. Koutsoloukas, N. Nikitas, and P. Aristidou. Robust structural control of a real high-rise tower using a hybrid mass damper. *Structural Design of Tall and Special Buildings*, 31(12):e1941, 2022. doi: 10.1002/tal.1941.

L. Koutsoloukas, N. Nikitas, and P. Aristidou. Structural Control of a Real High-Rise Tower Using Reinforcement Learning. *Submitted*, 2023.

R. Kumar, Moinuddin, S. Singh, S. S. Bedi, and S. Kumar. Pole placement techniques for active vibration control of smart structures: A feasibility study. *Turkish Acoustical Society - 36th International Congress and Exhibition on Noise Control Engineering, INTER-NOISE 2007 ISTANBUL*, 4(October 2007):2230–2240, 2007. doi: 10.1115/1.2748474.

N. Kurata, T. Kobori, M. Takahashi, N. Niwa, and H. Midorikawa. Actual Seismic Response Control Building with Semi-Active Damper System. *Earthquake engineering and structural dynamics*, 28(11):1427–1447, 1999.

K. C. Kwok and B. Samali. Performance of tuned mass dampers under wind loads. *Engineering Structures*, 17(9):655–667, 1995. ISSN 01410296. doi: 10.1016/0141-0296(95)00035-6.

M. A. Lackner and R. A. Mario. Passive structural control of offshore wind turbines. *Wind Energy*, 14:373–388, 2010. doi: 10.1002/we.

S. Laflamme, J. J. Slotine, and J. J. Connor. Wavelet network for semi-active control. *Journal of Engineering Mechanics*, 137(7):462–474, 2011. ISSN 07339399. doi: 10.1061/(ASCE)EM.1943-7889.0000248.

C. L. Lee, Y. T. Chen, L. L. Chung, and Y. P. Wang. Optimal design theories and applications of tuned mass dampers. *Engineering Structures*, 28(1):43–53, 2006a. ISSN 01410296. doi: 10.1016/j.engstruct.2005.06.023.

H. J. Lee, G. Yang, H. J. Jung, B. F. Spencer, and I. W. Lee. Semi-active neurocontrol of a base-isolated benchmark structure. *Structural Control and Health Monitoring*, 13(2-3):682–692, 2006b. ISSN 15452255. doi: 10.1002/stc.105.

H. J. Lee, H. J. Jung, S. J. Moon, S. K. Lee, E. C. Park, and K. W. Min. Experimental investigation of MR damper-based semiactive control algorithms for full-scale five-story steel frame building. *Journal of Intelligent Material Systems and Structures*, 21(10):1025–1037, 2010. ISSN 1045389X. doi: 10.1177/1045389X10374162.

G. Leitmann. Semiactive control for vibration attenuation. *Journal of Intelligent Material Systems and Structures*, 5(6):841–846, 1994. ISSN 1045389X. doi: 10.1177/1045389X9400500616.

C. Li and B. Cao. Hybrid active tuned mass dampers for structures under the ground acceleration. *Structural Control and Health Monitoring*, 22:757–773, 2015. doi: 10.1002/stc.

L. Li, G. Song, and J. Ou. Hybrid active mass damper (AMD) vibration suppression of nonlinear high-rise structure using fuzzy logic control algorithm under earthquake excitations. *Structural Control and Health Monitoring*, 19:698–709, 2011. doi: 10.1002/stc.

Z. Li, S. Zuo, and Y. Liu. Fuzzy sliding mode control for smart structure with ATMD. *Proceedings of the 33rd Chinese Control Conference, CCC 2014*, pages 21–25, 2014. ISSN 21612927. doi: 10.1109/ChiCC.2014.6896589.

C. C. Lin, C. M. Hu, J. F. Wang, and R. Y. Hu. Vibration control effectiveness of passive tuned mass dampers. *Journal of the Chinese Institute of Engineers, Transactions of the Chinese Institute of Engineers,Series A/Chung-kuo Kung Ch'eng Hsuch K'an*, 17(3):367–376, 1994. ISSN 21587299. doi: 10.1080/02533839.1994.9677600.

C. C. Lin, J. M. Ueng, and T. C. Huang. Seismic response reduction of irregular buildings using passive tuned mass dampers. *Engineering Structures*, 22(5):513–524, 2000. ISSN 01410296. doi: 10.1016/S0141-0296(98)00054-6.

J. Liu, W. Qu, N. Nikitas, and Z. Ji. Research on extending the fatigue life of railway steel bridges by using intelligent control. *Construction and Building Materials*, 168:532–546, 2018. ISSN 09500618. doi: 10.1016/j.conbuildmat.2018.02.125. URL https://doi.org/10.1016/j.conbuildmat.2018.02.125.

S. Liu, Z. Lu, P. Li, S. Ding, and F. Wan. Shaking table test and numerical simulation of eddy-current tuned mass damper for structural seismic control considering soil-structure interaction. *Engineering Structures*, 212:110531, 2020. ISSN 18737323. doi: 10.1016/j.engstruct.2020.110531.

F. Lopez-Almansa, R. Andrade, J. Rodellar, and A. M. Reinhorn. Modal predictive control of structures. II: Implementation. *Journal of Engineering Mechanics*, 120(8): 1761–1772, 1994. ISSN 07339399. doi: 10.1061/(ASCE)0733-9399(1994)120:8(1743).

F. Lopez-Almansa, R. Andrade, J. Rodellar, and A. M. Reinhorn. Modal predictive control of structures. I: Formulation. *Journal of Engineering Mechanics*, 120(8): 1743–1760, 1995.

X. Lu, P. Li, X. Guo, W. Shi, and J. Liu. Vibration control using ATMD and site measurements on the Shanghai World Financial Center Tower. *The Structural Design of Tall and Special Buildings*, 23:105–123, 2014. doi: 10.1002/tal.

K. Maebayashi, K. Shiba, A. Mita, and Y. Inada. Hybrid Mass damper system for response control building. *Tenth World Conference on Earthquake Engineering*, pages 2359–2364, 1992.

N. Mamat, F. Yakub, S. A. Z. Shaikh Salim, and M. S. Mat Ali. Seismic vibration suppression of a building with an adaptive nonsingular terminal sliding mode control. *JVC/Journal of Vibration and Control*, 26(23-24):2136–2147, 2020. ISSN 17412986. doi: 10.1177/1077546320915324.

B. Manzoor, I. Othman, S. Durdyev, S. Ismail, and M. H. Wahab. Influence of Artificial Intelligence in Civil Engineering toward Sustainable Development-A Systematic Literature Review. *Applied System Innovation*, 52(4):1–17, 2021.

L. Marian and A. Giaralis. Optimal design of a novel tuned mass-damper-inerter (TMDI) passive vibration control configuration for stochastically support-excited structural systems. *Probabilistic Engineering Mechanics*, 38:156–164, 2015. ISSN 18784275. doi: 10.1016/j.probengmech.2014.03.007. URL http://dx.doi.org/10.1016/j.probengmech.2014.03.007.

M. Maślanka. Optimised semi-active tuned mass damper with acceleration and relative motion feedbacks. *Mechanical Systems and Signal Processing*, 130:707–731, 2019. ISSN 10961216. doi: 10.1016/j.ymssp.2019.05.025.

N. H. McClamroch and H. P. Gavin. Electrorheological dampers and semi-active structural control. *Proceedings of the IEEE Conference on Decision and Control*, 4(January):3528–3533, 1995. ISSN 01912216. doi: 10.1109/cdc.1995.479131.

C. Medel-Vera and T. Ji. Seismic protection technology for nuclear powerplants a systematic review. *Journal of Nuclear Science and Technology*, 52(5):607–632, 2015.

G. Mei, A. Kareem, and J. C. Kantor. Real-time model predictive control of structures under earthquakes. *Earthquake Engineering and Structural Dynamics*, 30(7):995–1019, 2001. ISSN 00988847. doi: 10.1002/eqe.49.

G. Mei, A. Kareem, and J. C. Kantor. Model predictive control of structures under earthquakes using acceleration feedback. *Journal of Engineering Mechanics*, 128(5): 574–585, 2002. ISSN 07339399. doi: 10.1061/(ASCE)0733-9399(2002)128:5(574).

G. Mei, A. Kareem, and J. C. Kantor. Model Predictive Control of Wind-Excited Building: Benchmark Study. *Journal of engineering mechanics*, pages 459–465, 2004. doi: 10.1061/(ASCE)0733-9399(2004)130. URL http://link.aip.org/link/?JENMDT/130/1195/1.

C. Meinhardt, N. Nikitas, and D. Demetriou. Application of a 245 metric ton Dual-Use Active TMD System. *Procedia Engineering*, 199:1719–1724, 2017. ISSN 18777058. doi: 10.1016/j.proeng.2017.09.384. URL http://dx.doi.org/10.1016/j.proeng.2017.09.384.

M. S. Miah, E. N. Chatzi, and F. Weber. Semi-active control for vibration mitigation of structural systems incorporating uncertainties. *Smart Materials and Structures*, 24(5):55016, 2015. ISSN 1361665X. doi: 10.1088/0964-1726/24/5/055016. URL http://dx.doi.org/10.1088/0964-1726/24/5/055016.

R. Mitchell, Y. Kim, T. El-Korchi, and Y. J. Cha. Wavelet-neuro-fuzzy control of hybrid building-active tuned mass damper system under seismic excitations. *Journal of Vibration and Control*, 19(12):1881–1894, 2013. ISSN 10775463. doi: 10.1177/1077546312450730.

M. Mohebbi and A. Joghataie. Designing optimal tuned mass dampers for nonlinear frames by distributed genetic algorithms. *The Structural Design of Tall and Special Buildings*, 21:57–76, 2012. doi: 10.1002/tal.

S. Nagarajaiah. Adaptive passive, semiactive, smart tuned mass dampers: identification and control using empirical mode decomposition, hilbert transform, and short-term fourier transform. *Structural Control and Health Monitoring*, 16:800–841, 2009. doi: 10.1002/stc.

S. Nagarajaiah and H.-J. Jung. Smart tuned mass dampers: recent developments. *Smart Structures and Systems*, 13(2):173–176, 2014.

S. Nagarajaiah and N. Varadarajan. Short time Fourier transform algorithm for wind response control of buildings with variable stiffness TMD. *Engineering Structures*, 27(3):431–441, 2005. ISSN 01410296. doi: 10.1016/j.engstruct.2004.10.015.

S. Nagarajaiah, N. Varadarajan, and M. Asce. Wind Response Control of Building with Variable Stiffness Tuned Mass Damper Using Empirical Mode Decomposition/ Hilbert Transform. *Journal of Engineering Mechanics*, 130(4):451–458, 2004. doi: 10.1061/ÍŚASCEÍŠ0733-9399ÍŚ2004ÍŠ130:4ÍŚ451ÍŠ.

I. Nagashima and Y. Shinozaki. Variable gain feedback control technique of active mass damper and its application to hybrid structural control. *Earthquake Engineering and Structural Dynamics*, 26(8):815–838, 1997. ISSN 00988847. doi: 10.1002/(SICI) 1096-9845(199708)26:8⟨815::AID-EQE678⟩3.0.CO;2-E.

I. Nagashima, R. Maseki, Y. Asami, J. Hirai, and H. Abiru. Performance of hybrid mass damper system applied to a 36-storey high-rise building. *Earthquake Engineering and Structural Dynamics*, 30(11):1615–1637, 2001. ISSN 00988847. doi: 10.1002/eqe.84.

Y. Nakamura, K. Tanaka, M. Nakayama, and T. Fujita. Hybrid mass dampers using two types of electric servomotors: AC servomotors and linear-induction servomotors. *Earthquake Engineering and Structural Dynamics*, 30(11):1719–1743, 2001. ISSN 00988847. doi: 10.1002/eqe.89.

N. Nikitas, J. H. Macdonald, and J. B. Jakobsen. Identification of flutter derivatives from full-scale ambient vibration measurements of the Clifton Suspension Bridge. *Wind and Structures*, 14(3):221–238, 2011. ISSN 12266116. doi: 10.12989/was.2011. 14.3.221.

K. Nikzad, J. Ghabouss, and S. L. Paul. Actuator Dynamics and Delay Compensation Using Neurocontrollers. *Journal of Engineering Mechanics*, 122:966–975, 1996.

I. Nishimura, T. Yamada, M. Sakamoto, and T. Kobori. Control performance of active-passive composite tuned mass damper. *Smart Materials and Structures*, 7(5):637–653, 1998. ISSN 09641726. doi: 10.1088/0964-1726/7/5/008.

A. Nishitani and Y. Inoue. Overview of the application of active/semiactive control to building structures in Japan. *Earthquake Engineering and Structural Dynamics*, 30 (11):1565–1574, 2001. ISSN 00988847. doi: 10.1002/eqe.81.

N. Noormohammadi and P. Reynolds. Experimental investigation of dynamic performance of a prototype hybrid tuned mass damper under human excitation. *Active and Passive Smart Structures and Integrated Systems 2013*, 8688:266–278, 2013. doi: 10.1117/12.2010656.

D. Nyawako, P. Reynolds, and E. Hudson. Incorporating a disturbance observer with direct velocity feedback for control of human-induced vibrations. *Active and Passive Smart Structures and Integrated Systems 2016*, 9799:529–541, 2016. ISSN 1996756X. doi: 10.1117/12.2219383.

Y. Ohtori, R. E. Christenson, B. F. Spencer, and S. J. Dyke. Benchmark Control Problems for Seismically Excited Nonlinear Buildings. *Journal of Engineering Mechanics*, 130(4):366–385, 2004. ISSN 0733-9399. doi: 10.1061/(asce)0733-9399(2004)130:4(366).

R. S. Panah and M. Kioumarsi. Application of building information modelling (BIM) in the health monitoring and maintenance process: A systematic review. *Sensors (Switzerland)*, 21(3):1–26, 2021. ISSN 14248220. doi: 10.3390/s21030837.

S. Park, M. A. Lackner, P. Pourazarm, A. Rodríguez Tsouroukdissian, and J. Crossâ€Whiter. An investigation on the impacts of passive and semiactive structural control on a fixed bottom and a floating offshore wind turbine. *Wind Energy*, (September 2018):1451–1471, 2019. ISSN 1095-4244. doi: 10.1002/we.2381.

W. Park, K. S. Park, H. M. Koh, and D. H. Ha. Wind-induced response control and serviceability improvement of an air traffic control tower. *Engineering Structures*, 28 (7):1060–1070, 2006. ISSN 01410296. doi: 10.1016/j.engstruct.2005.11.013.

H. Peng, F. Li, S. Zhang, and B. Chen. A novel fast model predictive control with actuator saturation for large-scale structures. *Computers and Structures*, 187:35–49,

2017. ISSN 00457949. doi: 10.1016/j.compstruc.2017.03.014. URL http://dx.doi.org/10.1016/j.compstruc.2017.03.014.

K. Petersen, R. Feldt, S. Mujtaba, and M. Mattsson. Systematic mapping studies in software engineering. *12th International Conference on Evaluation and Assessment in Software Engineering, EASE 2008*, (June), 2008. doi: 10.14236/ewic/ease2008.8.

T. Pinkaew, P. Lukkunaprasit, and P. Chatupote. Seismic effectiveness of tuned mass dampers for damage reduction of structures. *Engineering Structures*, 25(1):39–46, 2003. ISSN 01410296. doi: 10.1016/S0141-0296(02)00115-3.

M. Ramírez-Neria, J. Morales-Valdez, and W. Yu. Active vibration control of building structure using active disturbance rejection control. *Journal of Vibration and Control*, page 107754632110093, 2021. ISSN 1077-5463. doi: 10.1177/10775463211009377.

R. Rana and T. T. Soong. Parametric study and simplified design of tuned mass dampers. *Engineering Structures*, 20(3):193–204, 1998. ISSN 01410296. doi: 10.1016/S0141-0296(97)00078-3.

S. E. Randall, D. M. Halsted, and D. L. Taylor. Optimum vibration absorbers for linear damped systems. *Journal of Mechanical Design, Transactions of the ASME*, 103(4):908–913, 1981. ISSN 10500472. doi: 10.1115/1.3255005.

S. Reymert, A. Rönnquist, and O. Øiseth. Systematic Metadata Analysis of Wind-Exposed Long-Span Bridges for Road Vehicle Safety Assessments. *Journal of Bridge Engineering*, 27(2):1–7, 2022. ISSN 1084-0702. doi: 10.1061/(asce)be.1943-5592.0001822.

F. Ricciardelli, A. Occhiuzzi, and P. Clemente. Semi-active tuned mass damper control strategy for wind-excited structures. *Journal of Wind Engineering and Industrial Aerodynamics*, 88(1):57–74, 2000. ISSN 01676105. doi: 10.1016/S0167-6105(00)00024-6.

T. E. Saaed, G. Nikolakopoulos, J. E. Jonasson, and H. Hedlund. A state-of-the-art review of structural control systems. *JVC/Journal of Vibration and Control*, 21(5):919–937, 2015. ISSN 17412986. doi: 10.1177/1077546313478294.

R. Sachse, A. Pavic, and P. Reynolds. Human-structure dynamic interaction in civil engineering dynamics: A literature review. *Shock and Vibration Digest*, 35(1):3–18, 2003. ISSN 05831024. doi: 10.1177/0583102403035001624.

F. Sadek, B. Mohraz, A. w. Taylor, and R. M. Chung. A method of estimating the parameters of tuned mass dampers for seismic applications. *Earthquake Engineering and Structural Dynamics*, 26:617–635, 1997. ISSN 00063444. doi: 10.1093/biomet/37.1-2.173.

T. Saito, K. Shiba, and K. Tamura. Vibration control characteristics of a hybrid mass damper system installed in tall buildings. *Earthquake Engineering and Structural Dynamics*, 30(11):1677–1696, 2001. ISSN 00988847. doi: 10.1002/eqe.87.

M. Sakamoto and T. Kobori. Research, development and practical applications on structural response control of buildings. *Smart Materials and Structures*, 4(1A):A58, 1995. ISSN 09641726. doi: 10.1088/0964-1726/4/1A/008.

M. Sakamoto, K. Sasaki, and T. Kobori. Active structural response control system. *Mechatronics*, 2(5):503–519, 1992.

M. Setareh. Floor vibration control using semi-active tuned mass dampers. *Canadian Journal of Civil Engineering*, 29(1):76–84, 2002. ISSN 03151468. doi: 10.1139/l01-063.

M. Setareh, M. Asce, J. K. Ritchey, T. M. Murray, and J.-h. Koo. Semiactive Tuned Mass Damper for Floor Vibration Control. *Journal of Structural Engineering*, 133(2): 242–250, 2007. ISSN 0733-9445. doi: 10.1061/(ASCE)0733-9445(2007)133:2(242).

M. H. Shih and W. P. Sung. Seismic resistance and parametric study of building under control of impulsive semi-active mass damper. *Applied Sciences (Switzerland)*, 11(6), 2021. ISSN 20763417. doi: 10.3390/app11062468.

E. Simiu and D. Yeo. *Wind effects on structures. Modern structural design for wind.* Wiley-Blackwell, 4 edition, 2019. ISBN 9781119375906. doi: 10.1243/pime_proc_1970_185_038_02.

M. P. Singh, S. Singh, and L. M. Moreschi. Tuned mass dampers for response control of torsional buildings. *Earthquake Engineering and Structural Dynamics*, 31(4):749–769, 2002. ISSN 00988847. doi: 10.1002/eqe.119.

H. A. Smith and J. G. Chase. Comparison of LQR and H∞ algorithms for vibration control of structures in seismic zones. *Structures Congress - Proceedings*, 2(December): 1164–1171, 1996.

G. Solari. Wind Loading of Structures: Framework, Phenomena, Tools and Codification, 2017. ISSN 23520124.

T. T. Soong and B. F. Spencer. Active, semi-active and hybrid control of structures. *Bulletin of the New Zealand Society for Earthquake Engineering*, 33(3):387–402, 2000. ISSN 11749857.

T. T. Soong and B. F. Spencer. Supplemental energy dissipation: State-of-the-art and state-of-the-practice. *Engineering Structures*, 24(3):243–259, 2002. ISSN 01410296. doi: 10.1016/S0141-0296(01)00092-X.

B. F. Spencer and S. Nagarajaiah. State of the Art of Structural Control. *Journal of Structural Engineering*, 129(7):845–856, 2003. ISSN 0733-9445. doi: 10.1061/(asce) 0733-9445(2002)128:8(965).

B. F. Spencer and M. K. Sain. Controlling Buildings: A New Frontier in Feedback. *IEEE Control Systems Magazine on Emerging Technology*, 17(6):19–35, 1997. ISSN 10990682. doi: 10.1002/cber.190904203162.

M. H. Stanikzai, S. Elias, V. A. Matsagar, and A. K. Jain. Seismic response control of base-isolated buildings using tuned mass damper. *Australian Journal of Structural Engineering*, 20(4):310–321, 2019. ISSN 13287982. doi: 10.1080/13287982.2019. 1635307. URL https://doi.org/10.1080/13287982.2019.1635307.

G. M. Stewart and M. A. Lackner. The impact of passive tuned mass dampers and wind-wave misalignment on offshore wind turbine loads. *Engineering Structures*, 73:54–61, 2014. ISSN 01410296. doi: 10.1016/j.engstruct.2014.04.045. URL http://dx.doi.org/10.1016/j.engstruct.2014.04.045.

C. Sun and S. Nagarajaiah. Study on semi-active tuned mass damper with variable damping and stiffness under seismic excitations. *Structural Control and Health Monitoring*, 21:890–906, 2014. doi: 10.1002/stc.

T. Suzuki, M. Kageyama, A. Nobata, O. Yoshida, and S. Inaba. Active Vibration Control System Installed In A High-Rise Building. *Proc. 1st World Conf. on Struct. Control*, pages 3–11, 1994.

M. D. Symans and M. C. Constantinou. Semi-active control systems for seismic protection of structures: A state-of-the-art review. *Engineering Structures*, 21(6):469–487, 1999. ISSN 01410296. doi: 10.1016/S0141-0296(97)00225-3.

K. Taida, Y. Koike, M. Mutaguchi, T. Kakutani, T. Tachibana, and Y. Arai. Control of Bending-Torsion Structural Vibration Using a Pair of Hybrid Mass Dampers. *JSME International Journal*, 37(3):477–481, 1994.

P. Tan, Y. Liu, F. L. Zhou, and J. Teng. Hybrid mass dampers for canton tower. *CTBUH Journal*, (1):24–29, 2012. ISSN 19461186.

K. Tanida, M. Mutaguchi, Y. Koike, T. Murata, T. Kobori, K. Ishii, Y. Takenaka, and T. Arita. Development of V-shaped hybrid mass damper and its application to high-rise buildings. *Journal of Robotics and Mechatronics*, 6(3):249–255, 1994.

J. Teng, H. B. Xing, Y. Q. Xiao, C. Y. Liu, H. Li, and J. P. Ou. Design and implementation of AMD system for response control in tall build. *Smart Structures and Systems*, 13(2):235–255, 2014.

J. Teng, H. B. Xing, W. Lu, Z. H. Li, and C. J. Chen. Influence analysis of time delay to active mass damper control system using pole assignment method. *Mechanical Systems and Signal Processing*, 80:99–116, 2016. ISSN 10961216. doi: 10.1016/j.ymssp.2016.04.008.

H. C. Tsai. The effect of tuned-mass dampers on the seismic response of base-isolated structures. *International Journal of Solids and Structures*, 32(8-9):1195–1210, 1995. ISSN 00207683. doi: 10.1016/0020-7683(94)00150-U.

F. Venuti and L. Bruno. Mitigation of human-induced lateral vibrations on footbridges through walkway shaping. *Engineering Structures*, 56:95–104, 2013. ISSN 01410296. doi: 10.1016/j.engstruct.2013.04.019. URL http://dx.doi.org/10.1016/j.engstruct.2013.04.019.

J. F. Wang, C. C. Lin, and B. L. Chen. Vibration suppression for high-speed railway bridges using tuned mass dampers. *International Journal of Solids and Structures*, 40(2):465–491, 2003. ISSN 00207683. doi: 10.1016/S0020-7683(02)00589-9.

L. Wang, S. Nagarajaiah, W. Shi, and Y. Zhou. Semi-active control of walking-induced vibrations in bridges using adaptive tuned mass damper considering human-structure-interaction. *Engineering Structures*, 244(June):112743, 2021. ISSN 18737323. doi: 10.1016/j.engstruct.2021.112743. URL https://doi.org/10.1016/j.engstruct.2021.112743.

Z. R. Wani, M. Tantray, E. Noroozinejad Farsangi, N. Nikitas, M. Noori, B. Samali, and T. Y. Yang. A Critical Review on Control Strategies for Structural Vibration Control. *Annual Reviews in Control*, (August), 2022. ISSN 13675788. doi: 10.1016/j.arcontrol.2022.09.002. URL https://doi.org/10.1016/j.arcontrol.2022.09.002.

G. B. Warburton. Optimum absorber parameters for various combinations of response and excitation parameters. *Earthquake Engineering and Structural Dynamics*, 10(3):381–401, 1982. ISSN 10969845. doi: 10.1002/eqe.4290100304.

F. Weber. Bouc-Wen model-based real-time force tracking scheme for MR dampers. *Smart Materials and Structures*, 22(4), 2013. ISSN 09641726. doi: 10.1088/0964-1726/22/4/045012.

F. Weber, P. Huber, H. Distl, and C. Braun. Real-Time Controlled TMD of Danube City Tower. *Council on Tall Buildings and Urban Habitat*, pages 1145–1152, 2016.

F. Weber, P. Huber, F. Borchsenius, and C. Braun. Performance of tmdi for tall building damping. *Actuators*, 9(4):1–13, 2020. ISSN 20760825. doi: 10.3390/act9040139.

J. C. Wu and J. N. Yang. Continuous sliding mode control of a TV transmission tower under stochastic wind. *Proceedings of the American Control Conference*, pages 883–887, 1997.

J. C. Wu and J. N. Yang. Active Control of Transmission Tower under Stochastic Wind. *Journal of Structural Engineering*, 124(11):1302–1312, 1998. ISSN 0733-9445. doi: 10.1061/(asce)0733-9445(1998)124:11(1302).

J.-c. Wu and J. N. Yang. LQG control of lateral-torsional motion of Nanjing TV transmission tower. *Earthquake Engineering and Structural Dynamics*, 29:1111–1130, 2000.

J.-C. Wu and J. N. Yang. Modified Sliding Mode Control for Wind-Excited Benchmark Problem. 130:499–504, 2004.

Y. Xie, M. Ebad Sichani, J. E. Padgett, and R. DesRoches. The promise of implementing machine learning in earthquake engineering: A state-of-the-art review. *Earthquake Spectra*, 36(4):1769–1801, 2020. ISSN 87552930. doi: 10.1177/8755293020919419.

L. Xu, Y. Cui, and Z. Wang. Active tuned mass damper based vibration control for seismic excited adjacent buildings under actuator saturation. *Soil Dynamics and Earthquake Engineering*, 135:106181, 2020. ISSN 02677261. doi: 10.1016/j.soildyn.2020.106181. URL https://doi.org/10.1016/j.soildyn.2020.106181.

Y. L. Xu, K. C. Kwok, and B. Samali. Control of wind-induced tall building vibration by tuned mass dampers. *Journal of Wind Engineering and Industrial Aerodynamics*, 40(1):1–32, 1992. ISSN 01676105. doi: 10.1016/0167-6105(92)90518-F.

Z. D. Xu, Y. P. Shen, and Y. Q. Guo. Semi-active control of structures incorporated with magnetorheological dampers using neutral networks. *Smart Materials and Structures*, 12(1):80–87, 2003. ISSN 09641726. doi: 10.1088/0964-1726/12/1/309.

S. K. Yalla, A. Kareem, and J. C. Kantor. Semi-active tuned liquid column dampers for vibration control of structures. *Engineering Structures*, 23(11):1469–1479, 2001. ISSN 01410296. doi: 10.1016/S0141-0296(01)00047-5.

M. Yamamoto, S. Aizawa, M. Higashino, and K. Toyama. Practical applications of active mass dampers with hydraulic actuator. *Earthquake Engineering and Structural Dynamics*, 30(December 1999):1697–1717, 2001. doi: 10.1002/eqe.88.

M. Yamanaka and H. Okuda. Dentsu head office damping systems, Tokyo, Japan. *Structural Engineering International: Journal of the International Association for Bridge and Structural Engineering (IABSE)*, 15(1):44–47, 2005. ISSN 10168664. doi: 10.2749/101686605777963369.

S. Yamazaki, N. Nagata, and H. Abiru. Tuned active dampers installed in the Minato Mirai (MM) 21 Landmark Tower in Yokohama. *Journal of Wind Engineering and Industrial Aerodynamics*, 41-44:1937–1948, 1992. ISSN 13408062. doi: 10.1299/jsmec1993.37.450.

G. Yan, B. Sun, and Y. Lü. Semi-active model predictive control for 3rd generation benchmark problem using smart dampers. *Earthquake Engineering and Engineering Vibration*, 6(3):307–315, 2007. ISSN 16713664. doi: 10.1007/s11803-007-0645-2.

X. Yan, Z. D. Xu, and Q. X. Shi. Fuzzy neural network control algorithm for asymmetric building structure with active tuned mass damper. *JVC/Journal of Vibration and Control*, 26(21-22):2037–2049, 2020. ISSN 17412986. doi: 10.1177/1077546320910003.

C.-S. W. Yang, L. L. Chung, L. Y. Wu, and N.-H. Chung. Modified predictive control of structures with direct output feedback. *Structural Control and Health Monitoring*, 18:922–940, 2011. doi: 10.1002/stc.

F. Yang, R. Sedaghati, and E. Esmailzadeh. Optimal design of distributed tuned mass dampers for passive vibration control of structures. *Structural Control and Health Monitoring*, 22:221–236, 2015. doi: 10.1002/stc.

F. Yang, R. Sedaghati, and E. Esmailzadeh. Vibration suppression of structures using tuned mass damper technology: A state-of-the-art review. *JVC/Journal of Vibration and Control*, 28(7-8):812–836, 2022. ISSN 17412986. doi: 10.1177/1077546320984305.

O. Yoshida and S. J. Dyke. Seismic Control of a Nonlinear Benchmark Building Using Smart Dampers. *Journal of Engineering Mechanics*, 130(4):386–392, 2004. ISSN 0733-9399. doi: 10.1061/(asce)0733-9399(2004)130:4(386).

H. Yu, F. Gillot, and M. Ichchou. Reliability based robust design optimization for tuned mass damper in passive vibration control of deterministic/uncertain structures. *Journal of Sound and Vibration*, 332(9):2222–2238, 2013. ISSN 0022460X. doi: 10.1016/j.jsv.2012.12.014.

M. Yucel, G. BekdaÅŸ, S. M. Nigdeli, and S. Sevgen. Estimation of optimum tuned mass damper parameters via machine learning. *Journal of Building Engineering*, 26:100847, 2019. ISSN 23527102. doi: 10.1016/j.jobe.2019.100847. URL https://doi.org/10.1016/j.jobe.2019.100847.

D. H. Zelleke and V. A. Matsagar. Energy-based predictive algorithm for semi-active tuned mass dampers. *Structural Design of Tall and Special Buildings*, 28(12):e1626, 2019. ISSN 15417808. doi: 10.1002/tal.1626.

K. Zhou, J. W. Zhang, and Q. S. Li. Control performance of active tuned mass damper for mitigating wind-induced vibrations of a 600-m-tall skyscraper. *Journal of Building Engineering*, 45(November 2021):103646, 2022. ISSN 23527102. doi: 10.1016/j.jobe.2021.103646. URL https://doi.org/10.1016/j.jobe.2021.103646.

Q. Zhu, W. Yang, Q. Zhang, and Y. Du. A hybrid vibration mitigation method based on the crowd flow control and tuned mass damper on a footbridge. *Engineering Structures*, 245:112972, 2021. ISSN 18737323. doi: 10.1016/j.engstruct.2021.112972. URL https://doi.org/10.1016/j.engstruct.2021.112972.

S. Živanović, A. Pavic, and P. Reynolds. Vibration serviceability of footbridges under human-induced excitation: A literature review. *Journal of Sound and Vibration*, 279 (1-2):1–74, 2005. ISSN 0022460X. doi: 10.1016/j.jsv.2004.01.019.

M. Zucca, N. Longarini, M. Simoncelli, and A. M. Aly. Tuned Mass Damper Design for Slender Masonry Structures: A Framework for Linear and Nonlinear Analysis. *Applied Sciences*, 11(8):3425, 2021. doi: 10.3390/app11083425.

Chapter 3

Robust Structural Control of a Real High-Rise Tower Equipped With a Hybrid Mass Damper

Chapter Outline: Chapter 2 presented various algorithms that are studied within the structural control literature and mentioned the limitations of each control system. Among others, the robustness of the control systems is of major importance since, modelling errors and the ever-changing environmental conditions could add parametric uncertainties which cause deterioration on the vibration dissipation performance of the mass dampers. This chapter will investigate the performance of robust controllers in the presence of parametric and actuator uncertainties. The robust model predictive control scheme will be introduced and compared to the well established H_∞ controller. Five different parametric uncertain scenarios will be studied and various performance indices will be introduced for the multifaceted assessment of the controllers.

Source: L. Koutsoloukas, N. Nikitas, and P. Aristidou. Robust structural control of a real high - rise tower equipped with a hybrid mass damper, *The Structural Design of Tall and Special Buildings*, 31(12), 2022.

3.1 Abstract

In this paper, the robust control of a real high-rise tower is studied, using a newly proposed, in the structural control field, Robust Model Predictive Control scheme (RMPC). Two RMPC controllers were designed considering either displacement mitigation ($RMPC_1$) or power consumption efficiency ($RMPC_2$). The two controllers were compared to the benchmark, robustness-wise, H_∞ control scheme to demonstrate their relative performance. A number of stiffness and damping uncertainty scenarios were designed based on a broad study of the relevant literature, in order to estimate the robustness of each of the three controllers. In all scenarios, variable actuator uncertainty of ±5% was introduced. It was found that all controllers are effective in controlling the tower and demonstrate robustness against parametric and actuator uncertainties with different relative merits over each other. Indicatively, when considering RMS and peak displacement and acceleration reduction, the H_∞ had an average performance reduction of 24%, the $RMPC_1$ 31% and the $RMPC_2$ 28% against their uncontrolled equivalent.

3.2 Introduction

Over the last decades, the structural control sector has gained great attention aiming to propose solutions on suppressing structural vibrations due to wind and earthquake excitations (Ding et al. (2013), Wang et al. (2020a), Yang et al. (2004b)) or due to human action (Wang et al. (2020b, 2021)). Applications of passive and active structural control systems are effectively employed on buildings and bridges all around the world (Koutsoloukas et al. (2022), Lim et al. (2006), Mohtat et al. (2010)). When considering the real-life control of civil structures, one expects to face various types of uncertainties within the design process. The introduction of uncertainty within the simulations is of high importance since, in most cases, simulation conditions are considered to be highly idealised, which is far from a realistic scenario where randomness and uncertainty seem to prevail. Forrai et al. (2003) mentioned that, even extremely detailed models are likely to contain parameter uncertainties and, to deal with this phenomenon, robust control schemes are required. The main types of uncertainty that are considered within the structural control literature are parameter uncertainties that occur due to modelling errors, environmental effects and structural damage, and input uncertainties that occur mainly due to noisy feedback signals and unknown force parameters. In the literature, there are various studies which consider robust algorithms and methodologies, and the performance of passive (Venanzi (2015)), semi-active (Demetriou et al. (2016), Wang et al. (2019a, 2020c)), active (Hillis (2010)) and hybrid (Demetriou and Nikitas (2016)) structural control systems is investigated. In this work, some examples of robust control that can be found in the literature are included and they are organized based on the type of uncertainty they are considering. Figure 3.1 summarizes all the studies included within this document to clearly demonstrate the algorithms used for a given type of uncertainty.

This study will investigate the performance of Robust Model Predictive Control (RMPC) and compare it to a well established robust controller benchmark within the structural control field, the H_∞ (Aggumus and Guclu (2020), Forrai et al. (2003), Huo et al. (2008, 2016), Stavroulakis et al. (2006), Wang et al. (2001, 2004), Yang et al. (2004b)), in order to asses its performance. The RMPC was already implemented in various applications outside the structural control field. For example, Tettamanti et al. (2014) studied the performance of a RMPC scheme for the control of urban road traffic networks. More specifically, they developed an algorithm with the objective of minimizing the queue lengths within an urban road network under uncertain conditions concluding that the RMPC is an appropriate choice for the specific control application. Mirzaei et al. (2012) implemented a RMPC for the rotor control of a wind turbine. To demonstrate its effectiveness, the authors compared its performance with a standard Proportional-Integral (PI) controller. Langthaler and del Re (2008) developed a RMPC scheme for the control of a diesel engine airpath since in the diesel engine control schemes, it is frequent to come across uncertainties and model-plant mismatch. They showed that their RMPC implementation can be efficient in controlling the diesel engine airpath under the considered uncertainties. Alexis et al. (2016) implemented a RMPC for the flight control of an unmanned aircraft under uncertain conditions. They demonstrated the performance of their algorithm by experimentally evaluating it in real-time using two unmanned rotorcraft configurations. They concluded that the proposed scheme demonstrated robustness since it effectively dealt with forcible disturbances while having a minimum deviation from the reference trajectory. Maasoumy et al. (2014) developed a RMPC solution for the robust control of an energy efficient building with box-constrained disturbance uncertainties. The authors compared the

RMPC with a nominal MPC and a Rule Based Controller (RBC) to establish their relative performance. They concluded that, when their model uncertainty was between 30-67%, the RMPC had the best overall performance, while in the case with lower uncertainty, the nominal MPC was more efficient and in the case with higher uncertainty (≥67%), the RBC had the best performance. Nagpal et al. (2019) developed their RMPC with linear matrix inequalities for the climate control of a building with uncertain model parameters. When comparing the performance of the RMPC to a nominal MPC, which was synthesized without accounting for any model uncertainties, it was found that, the RMPC had a better tracking performance by 24% when considering 70% variation in the system parameters. Additionally, in the presence of severe uncertainty with sinusoidal variations, the RMPC had a 17% better tracking performance than the nominal MPC controller.

In general, various examples of MPC applications can be found in the literature specific to civil engineering control systems, demonstrating the effectiveness of the actual scheme (Chen et al. (2017), Elhaddad and Johnson (2013), Koutsoloukas et al. (2020), Lopez-Almansa et al. (1994, 1995), Mei et al. (2000, 2001, 2002, 2004), Peng et al. (2017, 2018, 2020)). To the authors' best knowledge, the RMPC has not been applied for the vibration mitigation of a real high-rise building application before. For this reason, the effectiveness of the RMPC will be demonstrated within this study, by developing two controllers; one designed for the best possible response mitigation performance, and one designed for reduced power consumption.

In terms of uncertainty, this study will investigate the vibration control of a real tower with parametric and actuator uncertainties. In civil engineering, parametric uncertainties are associated with deviations between the real structure and its mathematical description used for the control design (Lim et al. (2006), Wang et al. (2009)). Parameter uncertainties can also occur due to the random and distributed nature of applied loads (Acampora et al. (2014)), due to structural degradation and due to damage (Chase et al. (1996)). The effect of parameter misalignment between model and real structure may result to poor control design where performance is compromised, and potentially stability issues may arise (Aggumus and Guclu (2020)). As stated by Lago et al. (2019), the damping characteristics of the structural systems are highly uncertain until the building is complete. Moreover, they state that to increase the building's sustainability, it is important to account for the structural model variability.

Uncertainty in the actuator performance may occur in the manufacturing process, which results to individual differences between nominally similar actuators. Moreover, the performance of an actuator can degrade due to long-term use (Yonezawa et al. (2020a,b)). Additionally, it is often that the actuators installed on structures are only periodically inspected/calibrated leading to poor performance (Alt et al. (2000)). The actuator uncertainty could be associated with instability and poor control performance (Yonezawa et al. (2020a,b)) thus, it is crucial to also consider its effect within the simulation process.

This work is structured as follows: Section 3.2.1 and 3.2.2 include an extended review of studies which dealt with parametric and input uncertainty, respectively. Sections 3.3.1 to 3.3.3 include the mathematical derivation of the system dynamics and the detailed description of the novel controller that is used within this study. Section 3.4 describes the real-life application that is used as a case study. Sections 3.5 and 3.6 discuss the results and compare the associated simulations of the simulations while the final Section 3.7 concludes the study highlighting the most critical findings.

3.2.1 Parametric uncertainty

Wang (2004) proposed a Linear Quadratic Gaussian-α (LQG-α) algorithm that aimed to provide robust control to earthquake and wind-excited benchmark problems (Ohtori et al. (2004), Yang et al. (2004a)) while accounting for $\pm15\%$ stiffness variation with an additional large -25% stiffness perturbation in the wind excitation scenario. They developed the controller so that it provides adjustable relative stability and introduces a gain parameter via a LQG design. The relative stability not only delivers a guaranteed settling time for the system but also increases the controlled system robustness. The author states that in both wind and earthquake loading cases, the proposed algorithm further improves the control performance of the system when compared to a regular LQG. In the case of earthquake, it was mentioned that the LQG-α needed a higher control force than the LQG controller. When the two controllers were saturated to the same control force, it was found that the LQG-α demonstrated robustness also to saturation effects.

Yang et al. (2004b) proposed two H_∞ control strategies for the control of a 76-storey benchmark building (Yang et al. (2004a)) under wind excitation, and a long-span benchmark bridge (Dyke et al. (2003)) subjected to earthquake(s). Their first H_∞ based control strategy was designed to deal with an energy-bounded class of excitations. Their second control strategy was designed for a class of excitations with a specified bounded peak. Both control strategies were compared to a LQG control scheme and simulations were carried out for three different sets of stiffness uncertainty $(0\%, -15\%, +15\%)$. It was concluded that the newly proposed control schemes outperformed the LQG controller demonstrating in this way their effectiveness.

Stavroulakis et al. (2006) considered the active control of a two-dimensional 8-storey building structure by studying the performance of three algorithms namely, the Linear Quadratic Regulator (LQR), the H_2 and the H_∞. They stated that, the LQR and H_2 cannot explicitly account for system uncertainties and thus, the H_∞ was also considered. The authors introduced parametric uncertainties by using the linear fractional transformation (LFT) method with percentage perturbations. To derive the nominal values for the mass, stiffness and damping matrices, Finite Element (FE) models were used. For their control scheme, the authors introduced four actuators co-located with the sensors on the structure. When tested under periodic sinusoidal horizontal loading pressure on each joint, the maximum displacement reduction percentages achieved with the LQR, H_2 and H_∞ were 69.5%, 93.1% and 86.2% respectively, always with reference to the uncontrolled case. Their conclusions mention that, even though all the control solutions have proven to be effective, the H_2 and the H_∞ were preferred since they demonstrated enhanced robustness properties.

Lim (2008) proposed a robust saturation controller (RSC) that is designed by using Lyapunov robust stability for an uncertain linear time invariant (LTI) system. To improve the control performance, the author proposed a method that considers the optimization of linear matrix inequalities (LMI). The author experimentally tested the proposed controller using a 2-DOF model with parameter (stiffness) uncertainty. The stiffness uncertainty was bounded between ± 20%. The controller with and without the LMI optimization method was tested and compared against other previously designed controllers (i.e. a LQR controller and a modified bang-bang controller (MBBC)). It was found that the proposed controller method reduced peak drifts of each story by 30.66% and 34.99% for the nominal system against the uncontrolled case. Moreover, it was shown that, as the bounds of the parameter uncertainties were increasing, the MBBC had a better performance than the RSC, while the LQR had the worst performance. When the algorithms were compared in ±20% stiffness uncertainty scenarios, it was concluded that the MBBC could not be used efficiently in an uncertain system even though in most cases it had superior performance over the RSC since, in one of the uncertain scenarios considered, the algorithm lost its robustness due to an unstable mode.

Huo et al. (2008) investigated a general implementation of the H_∞ controller for an active mass damper (AMD). Their aim was to keep a good vibration dissipation performance while having structural mass and stiffness uncertainties. To model the uncertainties in the system, they used LFT. Moreover, for the design of the H_∞ controller, an efficient solution procedure based on LMI was utilized. For their testing model, a two-storey flexible structure testbed with an AMD was used and tested under ground accelerations. In their experiment, they introduced a 10% uncertainty in the mass and 40% on the stiffness and damping matrices. For comparison purposes, they designed a pole-placement controller and they showed that, the H_∞ controller had a better performance when having stiffness and mass variation in the model, showcasing in this way the robustness of the controller. More specifically, four uncertain cases were considered experimentally with different mass uncertainty values and it was shown that, the reduction ratios of the proposed H_∞ controller and the pole-placement controller with respect to the uncontrolled case were ≈63% and ≈52% respectively, in the case with no additional mass and, ≈58% and ≈20% respectively, with uneven additional mass on both floors.

Narasimhan (2009) developed a single hidden layer non-linearly parametrized neural network (NN) with a proportional derivative type controller for the the active control of a highway bridge benchmark study (Agrawal et al. (2009)) with bi-linear isolation devices. The direct Lyapunov approach was used in order to derive adaptive parameter update laws. The proposed control scheme provides robustness since the controller parameters are updated on-line. The author mentioned that, the main advantage of the proposed controller is the fact that there is no need for identification before using the controller. Finally, when the controller was used in the control of the highway bridge benchmark, it was concluded that it was efficient in reducing the critical responses.

Mohtat et al. (2010) investigated the trade-off between nominal performance and robustness in both conventional and intelligent (Vassilyev et al. (2017)) structural control schemes. The authors proposed a systematic treatment on stability robustness and performance robustness by taking into account uncertainty that arises from structural parameters. To demonstrate their results, they used a truss bridge under seismic excitation. For the control of their active tuned mass damper (ATMD), the authors developed a genetic fuzzy logic controller (GFLC), reduced-order observer-based controllers based on pole-placement and LQR schemes. It was found that, the fuzzy logic controller was the best choice in terms of compromise between performance and robustness.

Du et al. (2012) studied the application of Lyapunov-Krasovskii (L-K) approach to develop a sampled data controller for a linearly parameter varying (LPV) model. The controller was investigated on a three-storey shear building with an active bracing system. The authors utilized ±40% stiffness and damping uncertainties. It was concluded that the proposed controller is effective on the disturbance attenuation of the model with parameter uncertainty and actuator saturation.

Ding et al. (2013) proposed a controller based on parameter-dependent Lyapunov theory (PDLT) and the LMI technique for the control of a linear parameter varying model of a three-storey building model equipped with an active brace system. The authors utilized mass, stiffness and damping uncertainty up to ±40%. Moreover, the actuator saturation and control forces input time-delay were also taken into account for the control scheme. When the system was tested under seismic excitation, it was found that the proposed controller decreases the building responses, while, being simple and practical making it this way a good option for real applications.

Aly (2014) firstly proposed a design approach for a passive tuned mas damper (PTMD) to be efficient in parametric uncertainties. Thus, the effectiveness of the optimum parameter PTMD design was demonstrated, and then the robust parameters of the PTMD were presented for a structure with ±10% stiffness uncertainty. The proposed approach was tested on a high-rise building under wind excitation. Due to the slenderness of the building, an actuator was introduced to dissipate the responses in one direction, resulting to an ATMD. Two algorithms were tested for the control of the ATMD namely, LQG and fuzzy logic controller. It was concluded that, regarding the PTMD with predetermined optimal parameters that take into account structural uncertainties, the system presented robustness. In the case of the ATMD, the fuzzy logic controller demonstrated higher robustness than the LQG. More specifically, when considering the peak displacement reductions, it was shown that the PTMD managed to reduce the displacements by 47.45%, 28.50% and 47.78% for 0%, -10% and +10% stiffness uncertainty, respectively. For the same uncertain scenarios the LQG managed to reduce the peak displacements by 52.25%, 45.19% and 52.60% whereas, the fuzzy logic controller achieved a reduction of 45.80%, 27.60%, and 51.06%, respectively. The fuzzy logic controller managed to reduce (over the LQG controller) the required RMS control forces up to 25.66%.

Giron and Kohiyama (2014) proposed a robust decentralized control method for the reduction of vibrations on buildings based on the Lyapunov-control function. Moreover, an expression for semi-active control was also proposed by the authors. Using a single-DOF system, the authors demonstrated the effectiveness of the algorithm and its robustness against ±15% stiffness and mass uncertainties.

Huo et al. (2016) proposed an H_∞ controller for civil engineering structures. For their controller design, the authors used the D-K iteration procedure (Skogestad and Postlethwaite (2005)). To extract the parametric uncertainties from the model matrices, the LFT approach was used. The authors introduced ±10%, ±20% and ±30% uncertainty on the mass, damping and stiffness components. To validate the robustness of their proposed controller, the authors used a 4-DOF mathematical building model and a two-storey experimental physical building tested on a seismic table.

Gill et al. (2017) investigated the robustness of their proposed distributed tuned mass dampers and compared their performance to a single tuned mass damper (TMD) and to multiple TMDs installed at the top of a building. For their simulations, they used a 20-storey benchmark building (Spencer Jr. et al. (1998)) subjected to seismic loading. To demonstrate the robustness of their scheme, ±15% stiffness and damping uncertainties were introduced within their simulations. It was found that, the distributed TMDs outperformed the other aforementioned control systems, and their performance in presence of parametric uncertainties was found to be better than the other schemes, especially in the drift and acceleration responses.

Aggumus and Guclu (2020) investigated the semi-active control of a ten-story building using a magnetorheological (MR) damper equipped TMD, operating with an H_∞ controller. For their control scheme, they took into account the effects on the system response with uncertainties caused by high frequencies that are not taken into account in their reduced model. The authors studied their control scheme experimentally on a shaking table to assess its performance. It was found that, the H_∞ semi-active controlled scheme outperformed the PTMD in the response reduction of the system. As an example, the best semi-active control scheme had an inter-storey drift ratio of 0.236

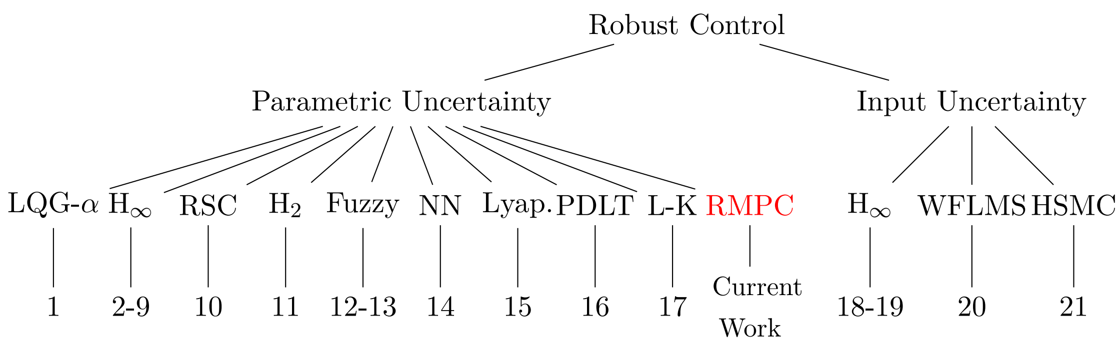
with respect to the uncontrolled case while, the PTMD achieved 0.256.

3.2.2 Input uncertainty

Wang et al. (2001, 2004) developed a robust controller that considers parameter, control effort, and input (disturbance) uncertainties. The authors state that, they considered two types of uncertainties, structured and unstructured (Doyle (1985)) for parameter and input, respectively. For the control part, the authors proposed a robust H_2 optimality together with robust H_∞ disturbance attenuation and robust relative stability. It is noted that, the authors considered a singular value decomposition (SVD) for all structured uncertainties. For the demonstration of the performance of the controller, the authors used a 4-DOF mathematical model with $\pm$ 10% uncertainty in the mass, stiffness and damping matrices.

Adeli and Kim (2004) proposed a wavelet-hybrid feedback-least-mean-square (WFLMS) algorithm for the robust control of a benchmark study (Spencer et al. (1998)) for a 3-DOF system with an AMD and a system with an ATMD (Kim and Adeli (2004)), respectively. It is noted that, the original hybrid feedback-least-mean-square algorithm was proposed in their companion paper (Kim and Adeli (2004)). The authors mention that, what makes the algorithm robust is the fact that it takes into account different external disturbances and a large frequency range of vibrations. More specifically, the authors used a low-pass filter that allows all the lower frequency signal components to pass unchanged. The authors add that, the high frequency components obstruct the stabilization of filter coefficients (introduced in their companion paper) and thus, by keeping them out it allows the hybrid feedback-LMS control algorithm to adapt its coefficients in a more stable fashion. In the civil engineering area, this can be effective since, typically the high frequencies of the external excitations do not affect considerably the structural response. Based on their results, it was found that, in order to have the best control performance, the cut-off frequency should be 1.5-2 times higher than the largest significant natural frequency. Finally, since the proposed algorithm can be used alongside a feedback controller (i.e. LQR, LQG), it was concluded that the proposed model can be used to enhance the performance of other feedback controllers.

Zhang et al. (2020) proposed a robust controller which was based on two disturbance observers. More specifically, the authors considered the active control of an offshore



1: Wang (2004); **2-9:** Aggumus and Guclu (2020), Huo et al. (2008, 2016), Stavroulakis et al. (2006), Wang et al. (2001, 2004), Yang et al. (2004b); **10:** Lim (2008); **11:** Stavroulakis et al. (2006); **12-13:** Aly (2014), Mohtat et al. (2010); **14:** Narasimhan (2009); **15:** Giron and Kohiyama (2014); **16:** Ding et al. (2013); **17:** Du et al. (2012); **18-19:** Wang et al. (2001, 2004); **20:** Adeli and Kim (2004); **21:** Zhang et al. (2020)

Figure 3.1: Summary of the studies included within this document indicating the gap this study aims to cover

wind turbine. For their control scheme, they firstly initialised two types of disturbances, matched and mismatched for wind and wave loading, respectively. Two nonlinear disturbance observers were independently designed to estimate and counteract the unknown disturbances with additional noise. Then a hierarchical sliding mode controller (HSMC) was designed for the control of the wind turbine. It was found that the two disturbance observers had high estimation accuracy and the control algorithm had strong robustness and great vibration mitigation effectiveness.

3.3 Control Strategy

3.3.1 Equations of Motion

This section includes the equations of motion of a multi-DOF tower equipped with a mass damper under wind excitation. Equation 3.1 describes the dynamics of the tower equipped with the mass damper. $M, \hat{C}$ and K denote the mass, structural damping and stiffness matrices with size $n_{tmd} \times n_{tmd}$ where, n_{tmd} represents the dimensionality of the structure with the mass damper. $u_n(t)$ is an m-sized control vector including the actuator uncertainty. $u_n(t) = u(t) + w(t)$ where, $u(t)$ is the actuator force and $w(t)$ is the process noise. $\hat{D}$ is a $n_{tmd} \times m$ matrix describing how the control force is entering the system. The external excitations are represented with the r-sized vector $f(t)$ and, matrix E with size $n_{tmd} \times r$ describes the way that the excitations are entering the system. $q(t)$ is the n_{tmd}-sized displacement vector and the over-dots represent derivatives with respect to time. Lastly, (t) denotes the continuous time variable (Takács and Rohal-Ilkiv (2012)).

$$M\ddot{q}(t) + \hat{C}\dot{q}(t) + Kq(t) = \hat{D}u_n(t) + Ef(t) \tag{3.1}$$

Equation 3.1 can be formulated in an equivalent state-space form with the Equations 3.2 and 3.3.

$$\dot{x}(t) = Ax(t) + Bu_n(t) + Hf(t) \tag{3.2}$$

$$y(t) = Cx(t) + Du_n(t) + v(t) \tag{3.3}$$

where,

$$x(t) = \begin{bmatrix} q(t) \\ \dot{q}(t) \end{bmatrix} A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}\hat{C} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ M^{-1}\hat{D} \end{bmatrix} H = \begin{bmatrix} 0 \\ M^{-1}E \end{bmatrix} \tag{3.4}$$

$y(t)$, C, D, and v represent the measured outputs, the output matrix, the feed-through matrix and the white measurement noise, respectively. Moreover, 0 and I in the matrices in Equation 3.4 represent the null and identity matrices of appropriate dimensions respectively, and the superscript '-1' represents the inverse matrix operator.

3.3.2 Kalman Filter

To estimate the states of the system based on measured response data only and to eliminate potential inaccuracies and statistical noise, a Kalman filter is implemented within this work. Using the Equations 3.2 and 3.3, the Kalman state estimator is shown in Equation 3.5.

$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + L(y(t) - C\hat{x}(t) - Du(t)) \tag{3.5}$$

where, $\hat{x}(t)$ is the estimated state vector and L is the Kalman gain matrix (Dyke et al. (2003), Ricciardelli et al. (2003), Yalla et al. (2001), Yang et al. (2004a)).

3.3.3 Robust Model Predictive Control

The minimax approach for the RMPC design is adopted within this study since, it is considered one of the most efficient design techniques (Tettamanti et al. (2014)). Equations 3.6 and 3.7 show augmented linear discrete-time prediction model for the RMPC scheme (Langthaler and del Re (2008)).

$$x(k+1) = A_d\hat{x}(k) + B_d u(k) + Gw_1(k) \tag{3.6}$$

$$y(k) = C\hat{x}(k) + Du(k) \tag{3.7}$$

The above system is constrained with, $\hat{x}(k) \in \mathbb{X}$ and $u(k) \in \mathbb{U}$ where the sets $\mathbb{X}$ and $\mathbb{U}$ are assumed to be polyhedrons. A_d and B_d are the discrete-time zero-order-hold counterparts of matrices A and B (Jeon and Tomizuka (2007), Lin et al. (2010), Soong (1990)) and $k = \frac{t}{\Delta t}$ is the integer time instant where, Δt is the sampling time (Yang et al. (2004a)). G, and $w_1(k)$ represent the actuator uncertainty locator matrix and the uncertainty vector, respectively. $w_1(k)$ is unknown but bounded in some measure, $w_1(k) \in \mathbb{W}_1$ where, $\mathbb{W}_1$ is the set of possible uncertainties. The final optimisation problem is highly depended on the set $\mathbb{W}_1$ (Löfberg (2012)). Lofberg (2003), proposed a box-constrained problem with a single inequality for the set of numbers w_1 such that $\|w_1\|_\infty \leq 1$, as seen in Equation 3.8.

$$\mathbb{W}_1 = \mathbb{W}_\infty = \{w_1 : \|w_1\|_\infty \leq 1\} \tag{3.8}$$

Moreover, Lofberg (2003) proposed a methodology to avoid the intractable problems that occur due to the exponential increase in the computational complexity that will result if, the future control effort $u(k+1)$ is to be computed optimally over a control horizon $N_{RMPC} - 1$, using the available $\times(k+1)$. Thus, to solve the minimax problem, decision variables $u^{(i)}(\cdot|k)$ and state realization $\times^{(i)}(\cdot|k)$ are introduced for every possible uncertainty realization $w_1^{(i)}(\cdot|k)$, where the i superscript denotes the realization index. Finally, the minimax problem is to solve the objective function in Equations 3.9-3.12. It is noted that the performance measure ℓ is typically assumed to be convex in $\times(k+j|k)$ and $u(k+j|k)$ when considering the minimax MPC scheme (Löfberg (2003)).

$$\min_{\tau, u^{(i)}(\cdot|k)} \tau \tag{3.9}$$

subject to:

$$\ell\Big(\hat{x}^{(i)}(k|k), u^{(i)}(k|k), ..., x^{(i)}(k+N_{RMPC}-1|k), u^{(i)}(k+N_{RMPC}-1|k)\Big) \leq \tau \tag{3.10}$$

$$x^{(i)}(k+j|k) \in \mathbb{X} \tag{3.11}$$

$$u^{(i)}(k+j|k) \in \mathbb{U} \tag{3.12}$$

$$\text{for} \quad j = 0,\ 1,\ 2, ...,\ N_{RMPC}-1$$

It is noted that the controllers were designed in Matlab using the YALMIP toolbox (Löfberg (2004)) and the Gurobi optimizer (Gurobi Optimization (2021)). This work will not include the full derivation of the H_∞ control scheme for civil engineering structures since, it is extensively used in literature. For the full derivation of the algorithm, the reader can refer to Refs [Aggumus and Guclu (2020), Palazzo and Petti (1999), Wu et al. (2006)]

3.4 Application description

The tower application considered within this study is the 245m tall Rottweil tower located in Germany, which is a test tower for high-speed elevators. The tower was designed to satisfy specific requirements when experiencing wind-induced vibrations. Based on observations, the speed of the wind excitation can reach 15.3-16.7m/s, referring to ground values at a height of 10m. The wind induced vibrations are primarily of vortex shedding nature and they are expected to cause human discomfort and impact the structural integrity of the tower, especially in terms of long term fatigue (Meinhardt et al. (2017)).

To guarantee human comfort while ensuring structural integrity, a uni-directional hybrid mass damper (HMD) was installed which is not an unusual case in buildings, see Refs [Cao et al. (1998), Lu et al. (2014), Nagashima et al. (2001)]. The term hybrid, arises from the fact that the system combines a passive mass damper, two actuators, orthogonal along the principal axes, with a maximum capacity of 35kN, and semi-active capabilities with adjustable damping and stiffness parameters. In this paper, only the passive and active components of the control system will be considered and thus, the system will operate either as a PTMD and/or as an ATMD. It is noted that, in the ATMD configuration, the actuators will be adding forces on top of the passive one generated by the naturally moving mass. The installed actuators' capacity is considered to be relatively small when compared to other actuators that are applied on similarly sized structures. For reference, the control system installed on the Nanjing TV tower has an actuator capacity of 100kN (Cao et al. (1998)) and the Shanghai World Financial Center Tower 142.5kN (Lu et al. (2014)). The mass of the system was chosen to be 240t based on closed form formulas (Den Hartog (1956)), which corresponds to a mass ratio of 1.3%. The tower is equipped with four uni-axial MEMS accelerometers which capture the horizontal accelerations of the tower and the mass damper. Additionally, the displacement of the actuators is monitored using string pot transducers and an inductive length measuring system integrated within the linear motors (ANCO (2017)).

For the simulations of this paper, the authors used a reduced-order model with 15-DOF which was provided by the design company. It is mentioned that in this study, the two planes of the building are considered decoupled (i.e. no aeroelastic coupling contribution) and thus, only one plane is considered, which further discards all torsional vibrations. The originally bi-directional HMD is herein used as a uni-directional control system, without though any loss of generality. For the derivation of the reduced-ordered model, the authors followed the same procedure described in (Koutsoloukas et al. (2020)) where, a nominal MPC was designed for the control of the same tower and its performance was compared against an LQR and the equivalent PTMD. The damping matrix was determined using the Rayleigh approximation with damping ratio of 1% of critical for modes 1 (0.17Hz) and 5 (5.88Hz). The two mode shapes are presented in Figure 3.2 in order to provide a visual representation of the structural dynamics. The first mode represents the fundamental frequency of the structure and it is directly associated with the overall stability of the structure. Furthermore, the fifth mode demonstrates the higher-frequency vibrations of the structure. It also provides information on localised responses that may occur due to external forces. All dynamic characteristics are from an updated FE model, while in what is shown later displacements are considered to be the dynamic part-only of the total displacement; the latter incorporating also the static wind component (Nikitas et al. (2011)).

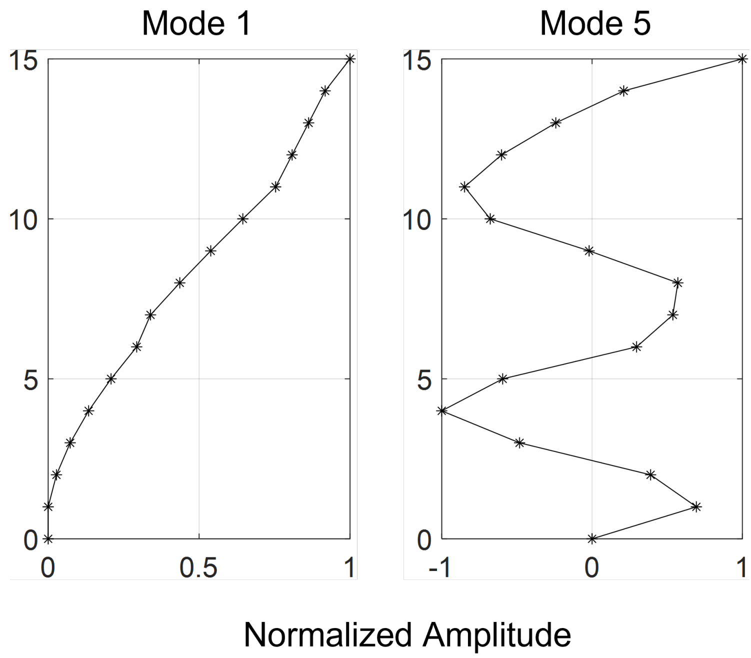


Figure 3.2: First and fifth mode shapes of the tower.

3.5 Numerical simulations of the tower and results

This section includes the results of three simulation scenarios with actuator, stiffness and damping uncertainties. In all scenarios, the peak and root-mean-square (RMS) responses of the tower on the first, top, and two intermediate floors are presented. Moreover, as it was mentioned in Section 3.4, the Rottweil tower is used to test high-speed elevators. In order for the elevators to operate properly, the top floor dynamic displacement cannot exceed a manufacturer's tolerance of 200mm. Thus, a top floor dynamic displacement limit of 200mm is introduced within this study.

The selected RMPC objective function for the control of the Rottweil tower can be seen in Equation 3.13 subjected to the constraints in Equations 3.14-3.16.

$$\min_{u} \max_{w_1} \sum_{j=0}^{N_{RMPC}-1} \|Q_{RMPC}\hat{x}(k)\|_{\infty} + \|R_{RMPC}u(k)\|_{\infty} + aS \tag{3.13}$$

subject to,

$$w_1(k+j|k) \in \mathbb{W}_1 \tag{3.14}$$

$$u_{min} \leq u(k) \leq u_{max} \tag{3.15}$$

$$q_{min} - S \leq q(k) \leq q_{max} + S \tag{3.16}$$

Q_{RMPC} and R_{RMPC} are weighting matrices of appropriate dimensions. S is a slack variable used to minimize the soft constraint violation with a being a very large scalar weight. The full algorithm derivation on how the above optimization problem is solved can be found in Löfberg (2003). The robust optimization is carried out by developing the so-called 'robust counterpart' of the uncertain system. The robust counterpart is derived by removing the uncertainty within the system. The full method on developing the robust counterpart of the proposed system can be found in Löfberg (2012).

By using two different combinations of Q_{RMPC} and R_{RMPC}, two different RMPC controllers are developed. RMPC_1 is designed to account for the best displacement response dissipation while, RMPC_2 is designed for a reduced power consumption (P_{act}) (Yang et al. (2004a)) by penalizing the control effort ($u(k)$) and the actuator velocity ($\dot{q}_{act}(k)$) in the the total integration time (Ts) where,

$$P_{act}(k) = \dot{q}_{act}(k)u(k) \tag{3.17}$$

$$RMS(P_{act}) = \left\{ \frac{1}{\frac{Ts}{\Delta t}+1} \sum_{k=0}^{\frac{Ts}{\Delta t}} [P_{act}(k)]^2 \right\}^{1/2} \tag{3.18}$$

In the RMPC scheme, hard and soft constraints were introduced within the algorithms, as seen in equations 3.15 and 3.16, respectively. To force the algorithm keep the top floor displacement ($q_{15}(k)$) within the desired limit, the q_{min} and q_{max} were set to -200mm and 200mm respectively and, the control input limits u_{min} and u_{max} were set to -35kN and 35kN, respectively. Moreover, due to the tower's architecture, only the top storey is usable by humans. Since the floor accelerations are directly related to human comfort (Soong and Spencer (2002)), the top floor accelerations are considered of relatively more significance within this study. A schematic diagram is included in Figure 3.3 showcasing the wind loading on the first, an intermediate (7th), and the top (15th) floor. Based on the literature, the parametric uncertain scenarios in this work were selected to be −2% and +2% to account for environmental effects and minor modelling errors and, +10% and −10% to account for major modelling errors and damage. In all cases, the uncertainties were introduced directly within the stiffness and damping matrices. It is noted that, in all scenarios, a random actuator uncertainty within ±5% (based on the actuator specifications) was considered. This means that, for every control signal calculated by the controller, the final actuator force was randomly ranging between 95%-105% of it. All simulations within this study were carried out in Matlab.

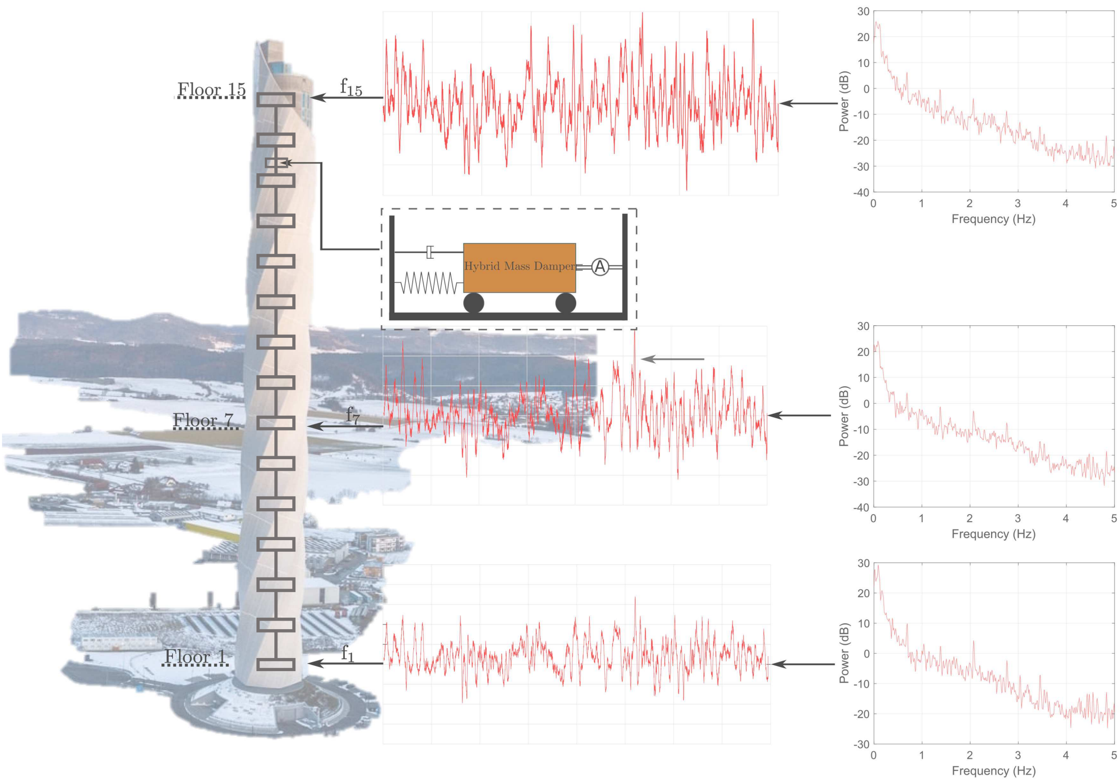


Figure 3.3: Schematic diagram of the wind loading applied on the first, intermediate (7) and top (15) floors.

3.5.1 Scenario 1

As it can be seen in Tables 3.1 and 3.2, the PTMD and the three controllers had good performance on dissipating the RMS and peak responses of the tower compared to the uncontrolled case. As seen in Table 3.1, in the uncontrolled case and in the case with the PTMD, the top floor displacement exceeded the 200mm limit that was initially set. This is actually the very reason the Rottweil tower needs incorporating a more effective vibration mitigation solution than the PTMD. When considering the controllers, the H_∞ could not decrease the top floor displacement within the desired limits, even if marginally away from it, while, the two RMPC controllers did manage to decrease the top floor displacement below 200mm. More specifically, the $RMPC_1$ had the best overall response control performance when considering the RMS and peak displacements. Figure 3.4 shows the top floor displacements of the PTMD, H_∞, $RMPC_1$ and $RMPC_2$, respectively, against the uncontrolled case. As seen therein, all the control schemes demonstrated response reduction when compared to the uncontrolled case. The effectiveness of the control systems is also showcased in the auto power spectral densities where, the frequency peak at 0.17Hz in the uncontrolled case is considerably suppressed with all control schemes. When considering the top floor accelerations, the $RMPC_1$ had the best performance on decreasing the RMS top floor accelerations, while, the $RMPC_2$ had the best performance on decreasing the maximum absolute acceleration value; note that acceleration was not included explicitly within the controller objective function. Figure 3.5 shows the top floor acceleration responses of the PTMD and the three controllers compared to the uncontrolled case, and the corresponding power spectra for each case. It is noticed that in the RMPC schemes, there was an observable increase in the acceleration power spectrum in the higher order modes, something quite different to how a PTMD would perform. When considering the power consumption of the controllers, the $RMPC_2$ had the lowest RMS value with 2.36kW and a peak value of 19.9kW. The H_∞ RMS and peak power consumption were, 3.65kW and 16.5kW, respectively where, the equivalent $RMPC_1$ values were 6.60kW and 30.7kW, respectively. It can be noticed that in order for the $RMPC_2$ to keep the top floor displacement limit of 200mm and satisfy the soft constraint that was initially set, it required a higher power consumption than the H_∞ scheme. The power consumption of the three controllers against time and the actuator energy consumption in absolute values are presented in Figure 3.6. It is noted that, the energy consumption was calculated as the integral of the absolute of power over time and thus, it does not alone distinguish between adding or extracting energy from mass damper, and it does not account for additional hardware energy loses (e.g. see actuator efficiency rating). The total actuator energy consumption using the H_∞ controller was 1.05×10^4kJ from which, the actuators required 4.4×10^3kJ to remove energy and 6.1×10^3kJ to add energy to the mass damper motion. When using the $RMPC_1$, the total actuator energy consumption was 1.91×10^4kJ where, the actuators required 7.7×10^3kJ to remove energy from the mass damper and 1.14×10^4kJ to add energy to it. Lastly, the total actuator energy consumption using the $RMPC_2$ was 4.52×10^3kJ from which, the actuators required 2.3×10^3kJ to remove energy and 2.2×10^3kJ to add energy to the moving mass. This balance of energy that is spent towards dissipating the mass damper, is quite an interesting feature for the purpose of this particular hardware setup. Potentially it could be handled by a semi-active device on much lower energy expenditure.

Table 3.1: Maximum and RMS displacement values for the nominal system (0% parameter uncertainty) with ±5% actuator uncertainty.

	RMS					MAX				
Floor	**No Control**	**PTMD**	**H_∞**	**$RMPC_1$**	**$RMPC_2$**	**No Control**	**PTMD**	**H_∞**	**$RMPC_1$**	**$RMPC_2$**
1	0.05	0.039	0.037	0.035	0.037	0.18	0.16	0.15	0.13	0.14
5	1.43	1.13	1.09	1.03	1.08	5.32	4.83	4.39	3.96	4.12
10	4.31	3.39	3.27	3.10	3.26	16.1	14.6	13.3	11.9	12.4
15	6.65	5.24	5.04	4.79	5.03	24.8	22.6	20.5	18.5	19.0

All units in *cm*

Table 3.2: Maximum and RMS acceleration values for the nominal system (0% parameter uncertainty) with ±5% actuator uncertainty.

	RMS					MAX				
Floor	**No Control**	**PTMD**	**H_∞**	**$RMPC_1$**	**$RMPC_2$**	**No Control**	**PTMD**	**H_∞**	**$RMPC_1$**	**$RMPC_2$**
15	6.54	4.10	3.84	3.28	3.92	20.3	17.1	15.5	14.5	12.7

All units in cm/s^2

3.5.2 Scenario 2

Scenario 2 was developed in order to investigate the performance and robustness of the two controllers and the PTMD in the presence of minor modelling errors and errors possibly relating to light environmental effects as quoted before. As seen in Tables 3.3-3.6, the three controllers, H_∞, $RMPC_1$ and $RMPC_2$ demonstrate robustness and

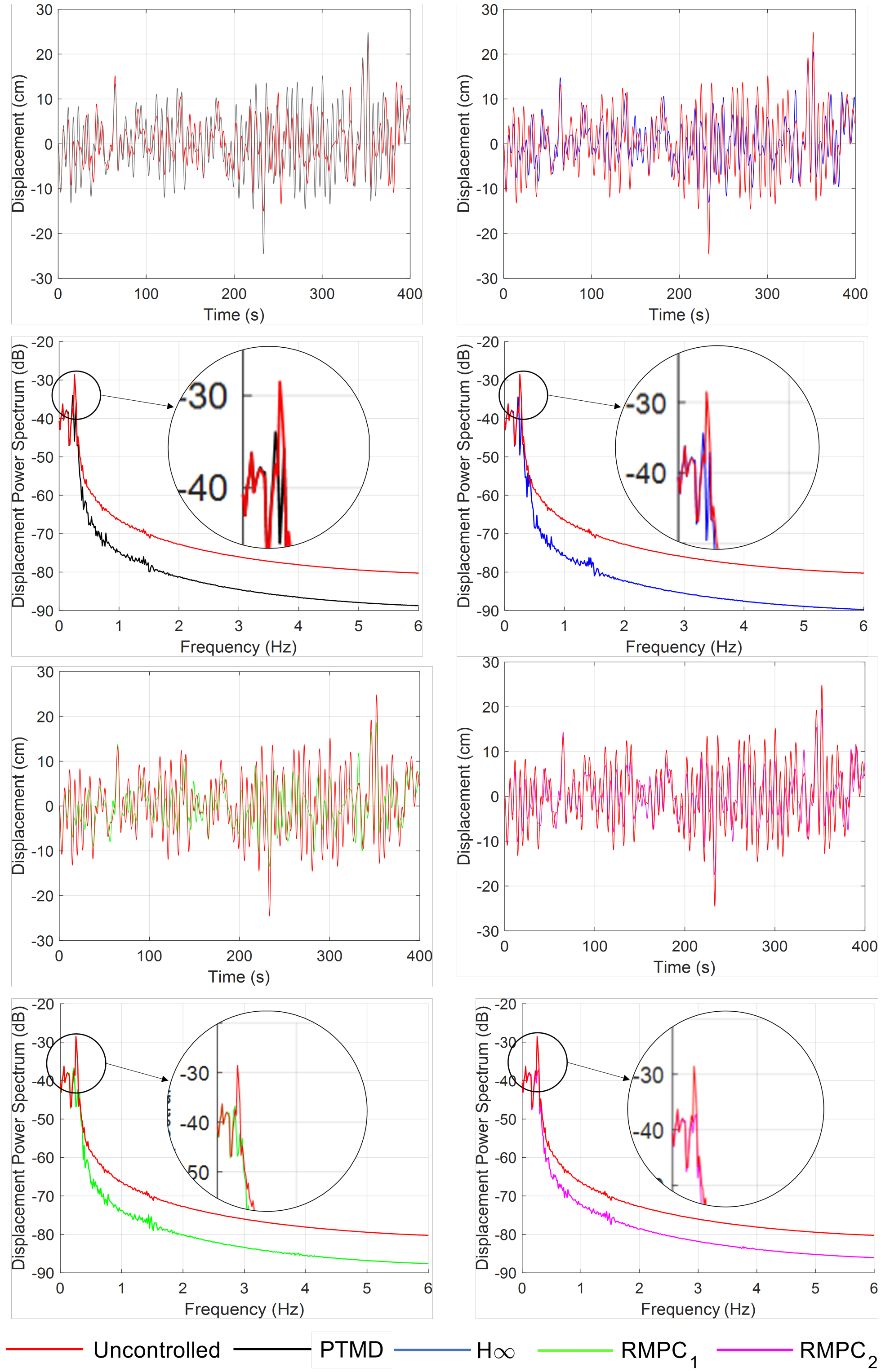


Figure 3.4: Time and Frequency analysis of the displacement responses in the controlled and uncontrolled cases.

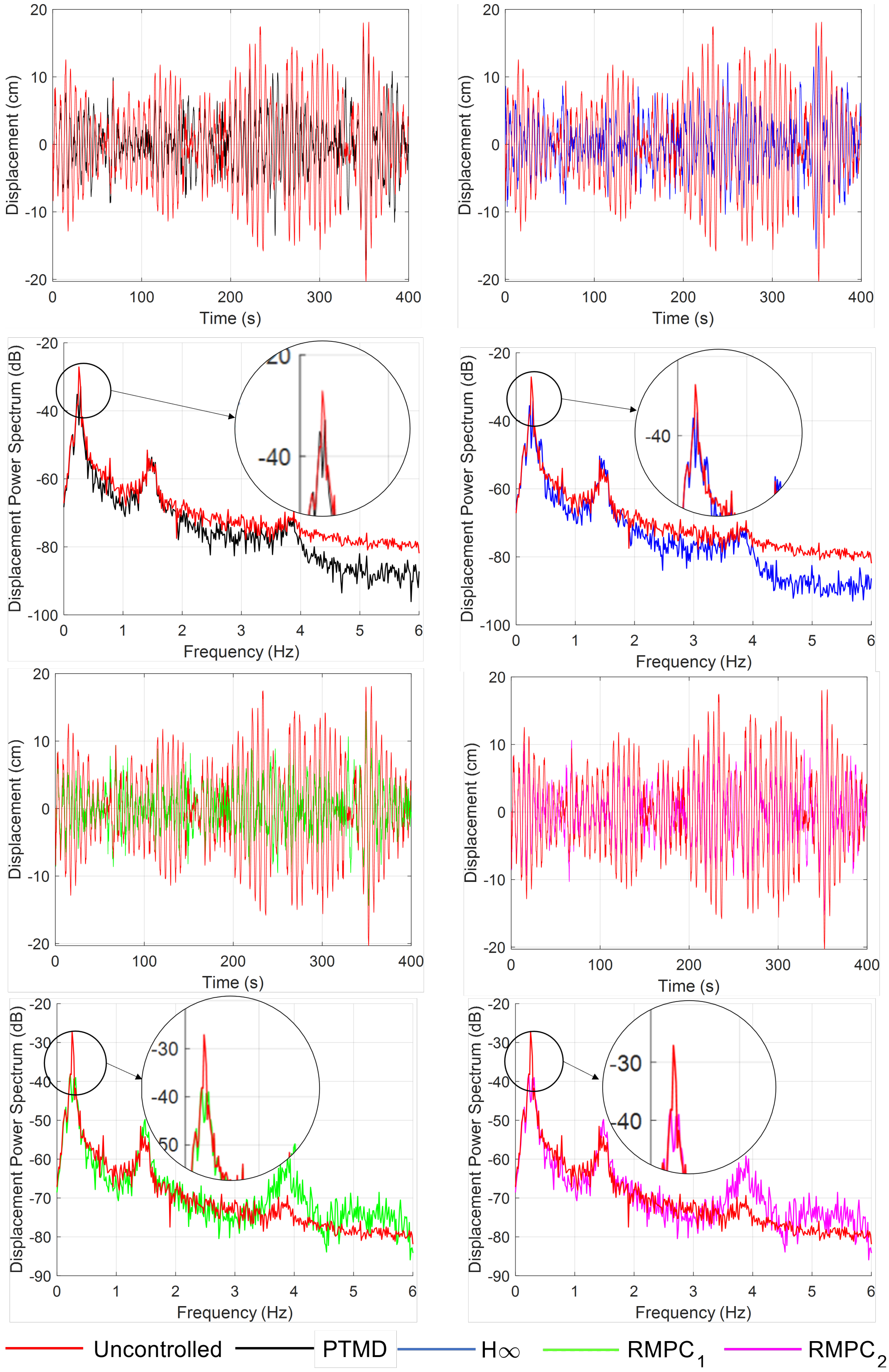


Figure 3.5: Time and Frequency analysis of the acceleration responses in the controlled and uncontrolled cases.

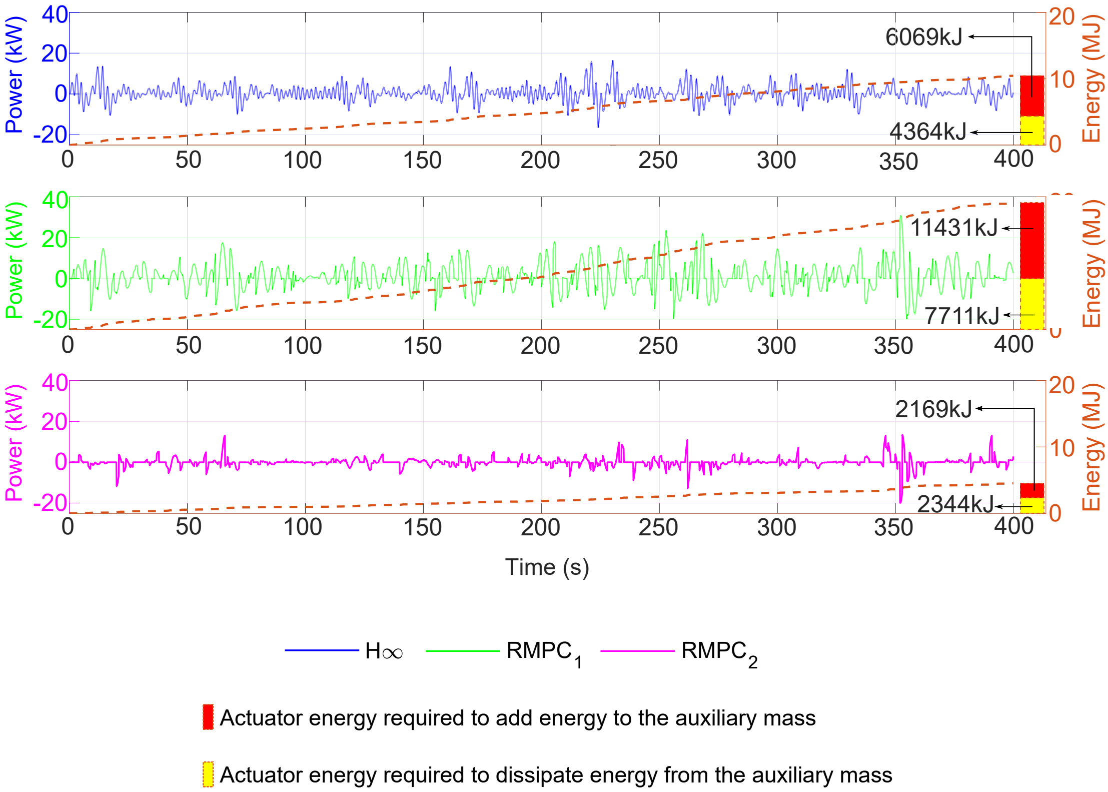


Figure 3.6: Power and energy consumption over time for the active control schemes for the nominal system.

are effective in controlling the RMS and peak displacements and accelerations of the tower. However, in all cases, again the H_∞ could not keep the top floor displacements within the desired limit, in contrast to the two RMPC controllers. It is noted that, when the parameter uncertainty was set to -2%, the peak acceleration recorded in the case with the PTMD was higher even than the one recorded in the uncontrolled case despite the fact that the RMS acceleration was still decreased. One could expect these phenomena since, as it was shown in Rana and Soong (1998), the detuning of a PTMD could worsen structural responses. Moreover, as mentioned in Refs [Wang et al. (2019a,b)], even small deviations of the primary structure may lead to considerable decrease in performance of PTMDs. Namely, as filed in Table 3.6, the maximum acceleration recorded in the uncontrolled case was 17.0cm/s^2 where, in the case with the PTMD, the maximum acceleration was 17.5cm/s^2 which corresponds to 4.6% increase. However, the RMS acceleration was considerably decreased from 6.37cm/s^2 in the uncontrolled case to a 4.17cm/s^2 with the PTMD, which corresponds to a 34.5% decrease. When considering the controllers, the RMPC$_1$ had the best performance on decreasing the RMS and peak accelerations in both uncertainty cases. When investigating the power consumption of the three controllers in the case where the uncertainty was set to +2%, the RMPC$_2$ had the lowest RMS and peak power consumption with 2.13kW and 15.8kW, respectively whereas, the H_∞ achieved 5.04kW and 18.1kW respectively, and the RMPC$_1$ 6.42kW and 26.0kW, respectively. In the case where the uncertainty was -2%, the average power consumption for the RMPC$_2$, H_∞ and RMPC$_1$ were, 2.28kW, 5.03kW and 7.19kW, respectively, while the peak power consumptions for the three controllers were 22.3kW, 17.7kW and 32.1kW, respectively. The total energy requirements for the RMPC$_1$ in the case with +2% was 1.8×10^4kJ, from which 7.5×10^3kJ were required for the actuators to remove energy from the damper mass and 1.1×10^4kJ were required to add energy to it. The H_∞ required a total of 1.4×10^4kJ from which 6.6×10^3kJ were used to remove energy from the mass damper and 7.3×10^3kJ were used to add energy to it. Finally, when using the RMPC$_2$, the total energy requirements were 4.3×10^3kJ from which 2.1×10^3kJ were used to remove energy from the mass damper and 2.2×10^3kJ were used to add energy to it. In the case were the uncertainty was set to -2%, the total requirements for the RMPC$_1$, H_∞ and RMPC$_2$ were 2.1×10^4kJ, 1.5×10^4kJ and 4.1×10^3kJ, respectively. The energy required for the three controllers to act as effective break was 8.2×10^3kJ, 7.1×10^3kJ and 2.1×10^3kJ, respectively where, the energy required to act as actuation to the mass damper was 1.3×10^4kJ, 7.9×10^3kJ and 2.0×10^3kJ, respectively.

Table 3.3: Maximum and RMS values for the system with +2% damping and stiffness uncertainty and ±5% actuator uncertainty.

	RMS					MAX				
Floor	**No Control**	**TMD**	**H_∞**	**$RMPC_1$**	**$RMPC_2$**	**No Control**	**TMD**	**H_∞**	**$RMPC_1$**	**$RMPC_2$**
1	0.049	0.037	0.036	0.034	0.038	0.19	0.15	0.14	0.13	0.14
5	1.45	1.09	1.08	1.01	1.13	5.53	4.67	4.51	4.00	4.21
10	4.38	3.28	3.25	3.02	3.41	16.6	14.14	13.6	12.1	12.7
15	6.76	5.06	5.01	4.67	5.26	25.6	21.8	21.0	18.7	19.6

All units in *cm*

Table 3.4: Maximum and RMS acceleration values for the system with +2% damping and stiffness uncertainty and ±5% actuator uncertainty.

	RMS					MAX				
Floor	**No Control**	**TMD**	**H_∞**	**$RMPC_1$**	**$RMPC_2$**	**No Control**	**TMD**	**H_∞**	**$RMPC_1$**	**$RMPC_2$**
15	6.91	4.03	3.85	3.30	3.98	19.8	16.7	15.5	14.4	15.2

All units in cm/s^2

Table 3.5: Maximum and RMS values for the system with -2% damping and stiffness uncertainty and ±5% actuator uncertainty.

	RMS					MAX				
Floor	**No Control**	**TMD**	**H_∞**	**$RMPC_1$**	**$RMPC_2$**	**No Control**	**TMD**	**H_∞**	**$RMPC_1$**	**$RMPC_2$**
1	0.048	0.039	0.039	0.036	0.040	0.18	0.17	0.16	0.14	0.14
5	1.43	1.17	1.15	1.05	1.18	5.29	5.01	4.85	3.9	4.08
10	4.32	3.52	3.48	3.17	3.56	15.86	15.1	14.6	11.7	12.3
15	6.67	5.44	5.37	4.906	5.50	24.4	23.4	22.7	18.1	19.1

All units in *cm*

3.5.3 Scenario 3

Scenario 3 models the uncertainty that could, as quoted, occur due to major modelling errors and possibly more severe cumulative degradation and damage phenomena. Tables 3.7-3.10 collect as above all dynamic response outputs. In Table 3.9, even for the case of -10% uncertainty, the $RMPC_1$ and $RMPC_2$ showed relatively good performance on decreasing the top floor displacement, yet the 200mm limit was not satisfied. This demonstrates that the low actuator capacity impels the controller to violate the

Table 3.6: Maximum and RMS acceleration values for the system with -2% damping and stiffness uncertainty and ±5% actuator uncertainty.

	RMS					MAX				
Floor	**No Control**	**TMD**	**H_∞**	**$RMPC_1$**	**$RMPC_2$**	**No Control**	**TMD**	**H_∞**	**$RMPC_1$**	**$RMPC_2$**
15	6.36	4.17	4.04	3.30	3.89	17.0	17.5	16.3	13.2	13.4

All units in cm/s^2

soft constrain that was initially set as a key requirement of the simulation. In MPC schemes, hard constraints are typically used in control input since, it is directly related to physical limitations. For the states, soft constraints are used instead since, in most of the times they can not be enforced due to the disturbances that are acting on the system (Zeilinger et al. (2010), Zhao et al. (2012)). Additionally, adding a hard constraint on states may result to an infeasible optimization problem (Schwenzer et al. (2021)). Moreover, it is noted that, in the case where the damping and stiffness uncertainties are set to +10%, the top floor displacement in the case with the PTMD was slightly increased compared to the uncontrolled scenario. More specifically, and almost counter-intuitively, as seen in Table 3.7, the maximum displacement recorded at the top floor with the PTMD was 19.5cm were, in the uncontrolled case it was 19.1cm, demonstrating again a detuning effect. However, even though there was a slight increase in the peak values (2.05%), the PTMD managed to decrease the corresponding RMS value by 29.2%. When considering the performance of the three controllers, the $RMPC_1$ had again the best performance on decreasing the RMS and peak displacement values of the tower in all the uncertainty cases. Moreover, the $RMPC_1$ was the most efficient in decreasing the RMS and peak accelerations in the case where the uncertainty was set to −10% (Table 3.10). In the case where the uncertainty was set to +10%, the $RMPC_1$ had the best performance on decreasing the RMS accelerations and the $RMPC_2$ was the most efficient in limiting the peak accelerations (Table 3.8). Finally, the RMS power consumption of the $RMPC_2$, H_∞ and $RMPC_1$ for the case where the uncertainty was set to +10% was 1.87kW, 4.66kW and 6.46kW respectively where, the corresponding peak values were 11.2kW, 17.7kW and 30.5kW, respectively. In the case were the uncertainty was set to −10%, the RMS power with the $RMPC_2$ controller was 2.79kW, with the H_∞ was 5.77kW, and with the $RMPC_1$ was 7.52kW. The corresponding peak power values were 18.8kW, 19.6kW and 30.2kW, respectively. The total energy requirements for the $RMPC_1$, H_∞ and $RMPC_2$ controllers in the case where the uncertainty was set to +10% were, 1.8×10^4kJ, 1.3×10^4kJ and 3.8×10^3kJ, respectively while in the case where the uncertainty was set to -10%, the total energy requirements were, 2.2×10^4kJ, 1.7×10^4kJ and 5.2×10^3kJ. In the case with +10% uncertainty, the energy required for the control system to remove energy from the auxiliary mass using the three controllers was 7.8×10^3kJ, 6.0×10^3kJ and 2.0×10^3kJ where, in the case with -10% uncertainty, it was 8.5×10^3kJ, 8.1×10^3kJ and 2.3×10^3kJ, respectively. The energy required by the actuators to add energy to the auxiliary mass using the three controllers in the +10% uncertainty case was 1.1×10^4kJ, 6.7×10^3kJ and 1.8×10^3kJ, respectively where, in the case were the parameter uncertainty was set to -10%, the energy required to literally actuate the auxiliary mass using the three controllers was 1.3×10^4kJ, 8.8×10^3kJ and 2.8×10^3kJ, respectively.

Table 3.7: Maximum and RMS values for the system with +10% damping and stiffness uncertainty and ±5% actuator uncertainty.

	RMS					MAX				
Floor	**No Control**	**TMD**	**H_∞**	**$RMPC_1$**	**$RMPC_2$**	**No Control**	**TMD**	**H_∞**	**$RMPC_1$**	**$RMPC_2$**
1	0.046	0.034	0.032	0.031	0.035	0.14	0.14	0.13	0.12	0.12
5	1.38	0.98	0.96	0.90	1.01	4.19	4.16	3.92	3.43	3.55
10	4.17	2.95	2.87	2.69	3.11	12.5	12.6	11.8	10.2	10.7
15	6.43	4.55	4.44	4.15	4.80	19.2	19.5	18.3	15.7	16.5

All units in *cm*

Table 3.8: Maximum and RMS acceleration values for the system with +10% damping and stiffness uncertainty and ±5% actuator uncertainty.

	RMS					MAX				
Floor	**No Control**	**TMD**	**H_∞**	**$RMPC_1$**	**$RMPC_2$**	**No Control**	**TMD**	**H_∞**	**$RMPC_1$**	**$RMPC_2$**
15	7.15	3.95	3.60	3.12	4.00	18.8	16.3	14.6	15.3	13.3

All units in cm/s^2

Table 3.9: Maximum and RMS values for the system with -10% damping and stiffness uncertainty and ±5% actuator uncertainty.

	RMS					MAX				
Floor	**No Control**	**TMD**	**H_∞**	**$RMPC_1$**	**$RMPC_2$**	**No Control**	**TMD**	**H_∞**	**$RMPC_1$**	**$RMPC_2$**
1	0.051	0.047	0.045	0.041	0.042	0.19	0.19	0.18	0.16	0.16
5	1.5	1.41	1.35	1.20	1.24	5.88	5.68	5.52	4.70	4.91
10	4.52	4.24	4.08	3.61	3.75	17.8	17.2	16.7	14.2	14.8
15	6.99	6.56	6.31	5.57	5.78	27.4	26.5	25.8	21.9	22.8

All units in *cm*

Table 3.10: Maximum and RMS acceleration values for the system with -10% damping and stiffness uncertainty and ±5% actuator uncertainty.

	RMS					MAX				
Floor	**No Control**	**TMD**	**H_∞**	**$RMPC_1$**	**$RMPC_2$**	**No Control**	**TMD**	**H_∞**	**$RMPC_1$**	**$RMPC_2$**
15	5.88	4.82	4.57	3.96	4.64	20.2	18.3	16.5	15.1	16.9

All units in cm/s^2

3.6 Summary

Figures 3.7 and 3.8 show a summary of the peak and RMS responses, respectively, in different uncertainty realisations for the uncontrolled case, the PTMD, the H_∞, the $RMPC_1$ and the $RMPC_2$ schemes. Moreover, Figure 3.9 shows the maximum and RMS power consumption of the H_∞, the $RMPC_1$ and the $RMPC_2$ control schemes along with the energy requirements of each controller. To further compare more holistically the performance of the three controllers and the PTMD, a performance index, $J_{control}$, is introduced (Equation 3.19) which considers the control efficacy of each controller in all five uncertain cases (p), against the baseline of the uncontrolled case where, $q_{(i)}$ and $q_{u(i)}$ represent the displacement of the controlled and uncontrolled case in the corresponding floor (i), and $\ddot{q}_{(15)}$ and $\ddot{q}_{u(15)}$ the top floor acceleration in the controlled and uncontrolled case, respectively. The $\frac{1}{4}$ and $\frac{1}{5}$ coefficients are used as averaging terms for the number of the considered floors and parametric uncertain scenarios, respectively. It is noted that the smaller the performance index, the better the performance of the control system is.

$$J_{control} = \frac{1}{5}\sum_{p=1}^{5}\Bigg(\frac{1}{4}\sum_{i} q_{(i)}/q_{u(i)} + \frac{1}{4}\sum_{i}\text{RMS}(q_{(i)})/\text{RMS}(q_{u(i)}) + \ddot{q}_{(15)}/\ddot{q}_{u(15)} + \text{RMS}(\ddot{q}_{(15)})/\text{RMS}(\ddot{q}_{u(15)})\Bigg)_{(p)} \quad (3.19)$$

$$\text{for} \quad i = 1,\ 5,\ 10,\ 15$$

As seen in Figure 3.10, the $RMPC_1$ had the best overall control dynamic output performance with a performance index $J_{control} = 0.69$ while, having the highest power consumption. The H_∞ had a performance index $J_{control} = 0.76$ while, the $RMPC_2$ had a performance index almost right in the middle at $J_{control} = 0.72$. The $RMPC_2$ had the lowest RMS power consumption in all cases and the lowest peak consumption in the $-10\%, +2\%$ and $+10\%$ uncertainty cases. It is noted that in the remaining cases, the controller sacrificed the power consumption in order to satisfy the soft constrain set for the top floor displacements. As expected, the PTMD had the worst performance of all control devices with a performance index $J_{control} = 0.80$. This roughly indicates that the distance from the PTMD to H_∞ is rather impressively equal to the one from the H_∞ to the less aggressive from the RMPC options.

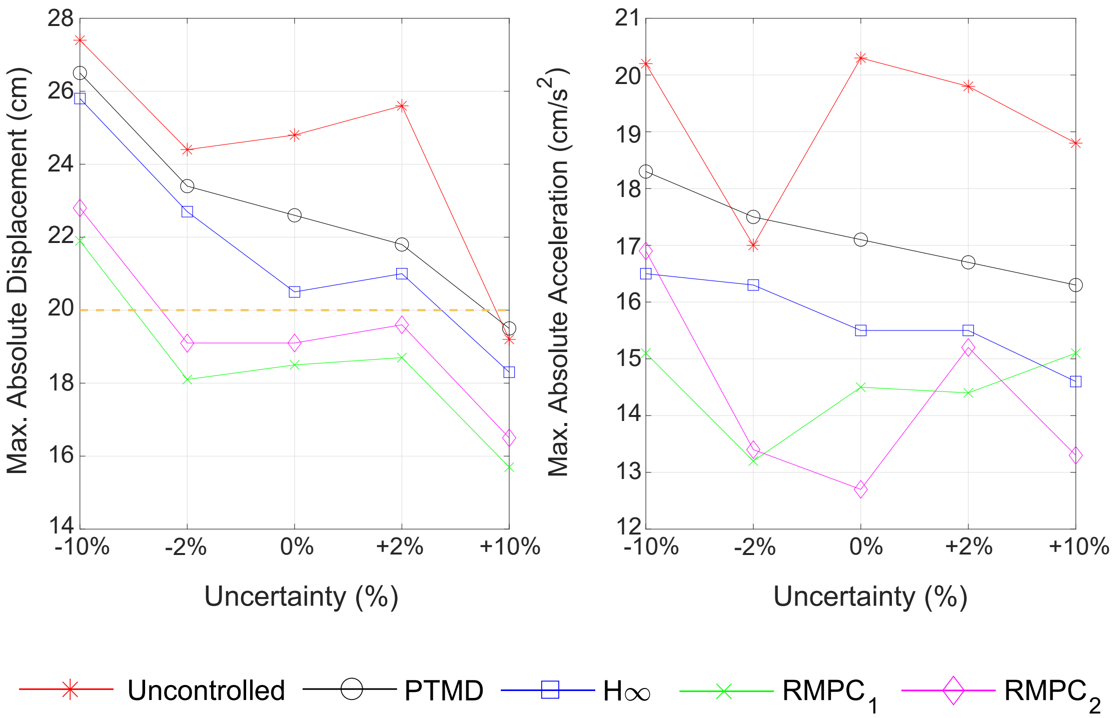


Figure 3.7: Summary of the maximum top floor responses.

3.7 Conclusions

This study considered the robust control of the 245m tall Rottweil tower using a 2D reduced-ordered model. Two Robust Model Predictive controllers were developed and compared against the well-established H_∞ control scheme, that is widely considered of benchmark value. A so-called $RMPC_1$ controller was designed to account for the best possible displacement control of the tower while, a so-called $RMPC_2$ was designed for reduced power consumption. To account for parameter uncertainties, three different control scenarios were constructed aligning with similar literature studies. In all scen-

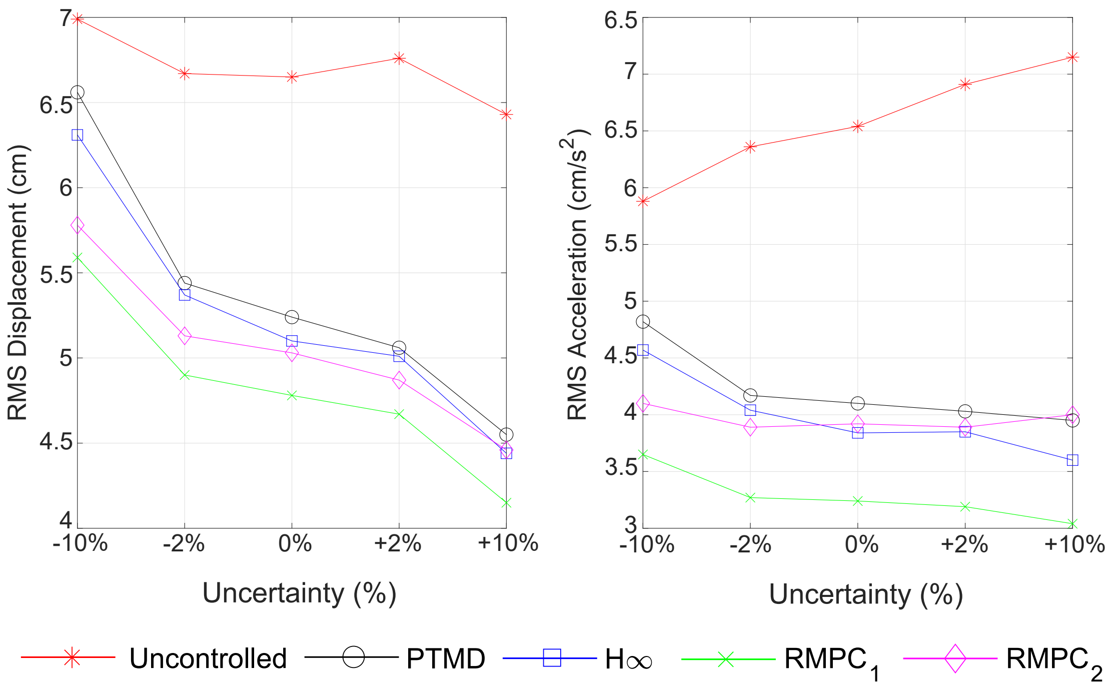


Figure 3.8: Summary of the RMS top floor responses.

arios, the nominal design wind load (i.e. the only force consideration) was kept the same and no aeroelastic and other intricate response amplitude effects were considered explicitly within the simulations. In all cases, the energy expenditure of the controllers was assessed in detail separating instances of adding to extracting energy to the mass damper.

Scenario 1 considered the nominal reduced-order model of the tower (0% uncertainty). In Scenario 2, ±2% damping and stiffness uncertainties were introduced to simulate minor modelling errors, light environmental effects or even human occupancy. Lastly, Scenario 3 simulated more extensive modelling errors such as those linked to cumulative ageing, and structural damage and thus, it considered ±10% damping (a value within, or even lower than, the accuracy of tracking damping) and stiffness uncertainties. Moreover, in all scenarios a variable actuator uncertainty randomly ranging between ±5% was introduced, which is the maximum expected uncertainty of the installed actuators. It was found that, all three controllers demonstrated robustness and effectiveness on dissipating the displacement and acceleration responses of the actual tower in all parametric scenarios. As expected, the PTMD did not demonstrate con-

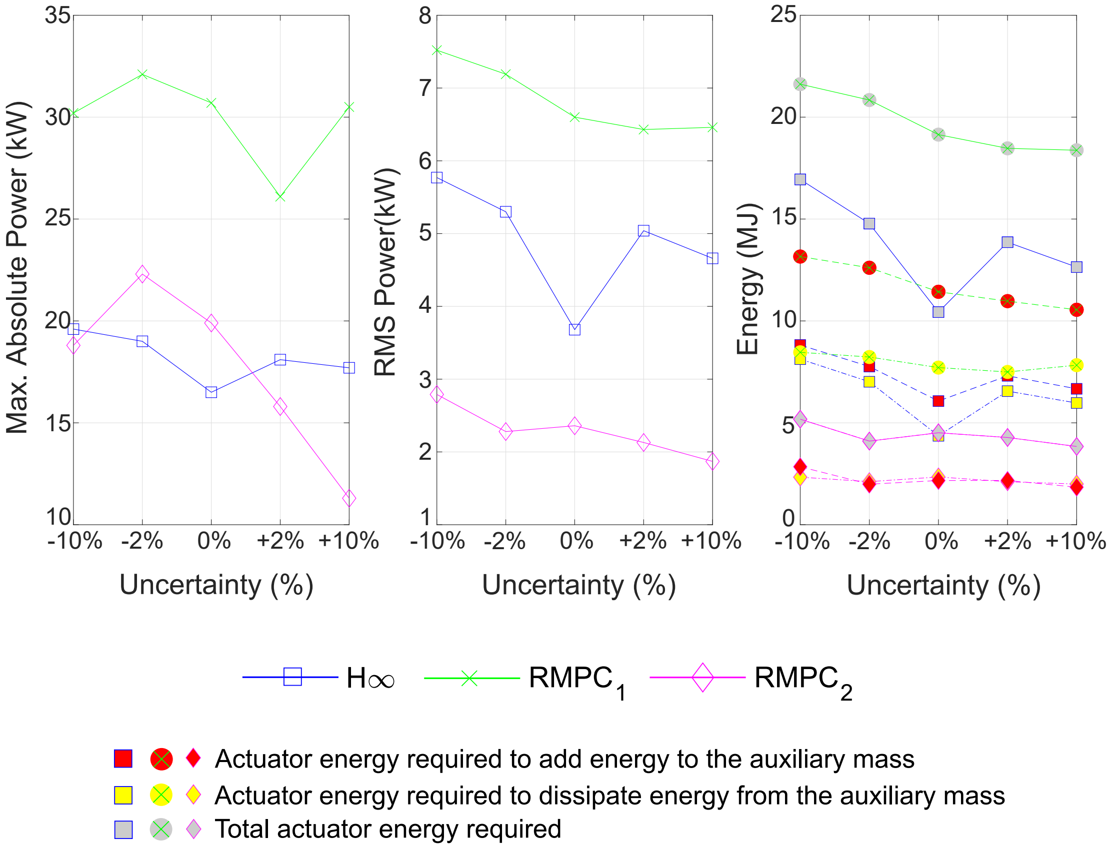


Figure 3.9: Summary of the Maximum & RMS Power, and the energy consumption for each controller.

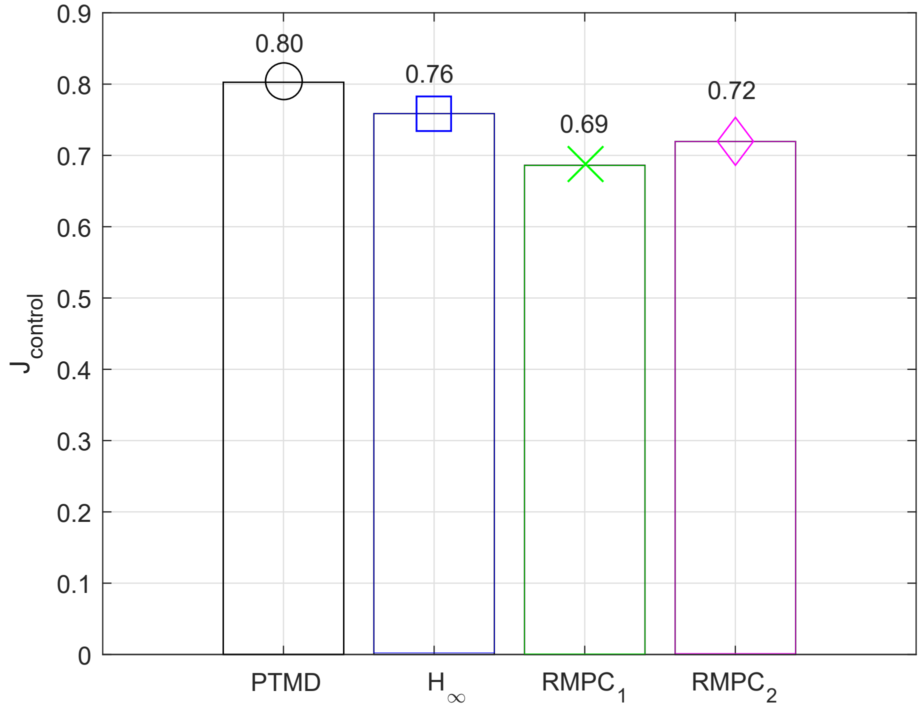


Figure 3.10: Performance index for the control schemes.

sistent robustness since, in Scenario 2 with −2% damping and stiffness uncertainty, the top floor accelerations were more severe when compared to the uncontrolled case and, in Scenario 3 with +10% damping and stiffness uncertainty, the peak displacements at the highest floors were again increased compared to the uncontrolled case.

When considering the newly proposed controllers, the RMPC_1 had the best overall performance on dissipating the displacement and acceleration responses of the tower while, having the highest power consumption. The RMPC_2 had the second best control performance while, being the controller with the least power consumption in almost all cases. In contrast to the two RMPC schemes, the H_∞ could not keep the top floor displacements within the desired limit even though it had a good response dissipation performance. It is noted that, in the case were the parameter uncertainty was set to −10%, the small actuator capacity drove even the best of the two RMPC controllers to violate the tolerance requirement set for keeping the top floor dynamic displacements within ±200mm. Yet, the relative performance over the H_∞ is probably sufficient motivation for exploring robust algorithms that might perform even better.

It is concluded that the RMPC scheme is a very effective and powerful control method for civil engineering real mega-building applications. Future work will expand to consider, i) the semi-active capabilities of the hybrid system, which will be integrated within the control scheme in order to reduce the actuator energy requirements for dissipating the energy from the structure as shown in Figure 3.6, while, allowing for control algorithm coupling between active and semi-active operating modes; ii) an energy harvesting system, which will be designed in order to take advantage of the dissipative part of the energy, and decrease the energy requirements of the active control system and; iii) artificial intelligence inspired controllers, which will be developed in order to account for non-linearities beyond uncertainty, and will be compared to conventional controllers in order to asses their performance.

References

A. Acampora, J. H. Macdonald, C. T. Georgakis, and N. Nikitas. Identification of aeroelastic forces and static drag coefficients of a twin cable bridge stay from full-scale ambient vibration measurements. *Journal of Wind Engineering and Industrial Aerodynamics*, 124:90–98, 2014. ISSN 01676105. doi: 10.1016/j.jweia.2013.10.009. URL http://dx.doi.org/10.1016/j.jweia.2013.10.009.

H. Adeli and H. Kim. Wavelet-hybrid feedback-least mean square algorithm for robust control of structures. *Journal of Structural Engineering*, 130(1):128–137, 2004. ISSN 07339445. doi: 10.1061/(ASCE)0733-9445(2004)130:1(128).

H. Aggumus and R. Guclu. Robust H∞ control of STMDs used in structural systems by hardware in the loop simulation method. *Actuators*, 9(3), 2020. ISSN 20760825. doi: 10.3390/ACT9030055.

A. Agrawal, P. Tan, S. Nagarajaiah, and J. Zhang. Benchmark structural control problem for a seismically excited highway bridge-Part I: Phase I Problem definition. *Structural Control and Health Monitoring*, 16:509–529, 2009. ISSN 15452255. doi: 10.1002/stc. URL http://dx.doi.org/10.1002/stc.456.

K. Alexis, C. Papachristos, R. Siegwart, and A. Tzes. Robust Model Predictive Flight Control of Unmanned Rotorcrafts. *Journal of Intelligent and Robotic Systems: Theory and Applications*, 81(3-4):443–469, 2016. ISSN 15730409. doi: 10.1007/s10846-015-0238-7.

T. R. Alt, F. Jabbari, and J. N. Yang. Control design for seismically excited buildings: Sensor and actuator reliability. *Earthquake Engineering and Structural Dynamics*, 29 (2):241–257, 2000. ISSN 00988847. doi: 10.1002/(SICI)1096-9845(200002)29:2⟨241::AID-EQE903⟩3.0.CO;2-Z.

M. A. Aly. Proposed robust tuned mass damper for response mitigation in buildings exposed to multidirectional wind. *The Structural Design of Tall and Special Buildings*, 23:664–691, 2014. ISSN 15417794. doi: 10.1002/tal.

ANCO. Users Guide: GERB TMD Tower Control System. Technical report, ANCO ENGINEERS, 2017.

H. Cao, A. M. Reinhorn, and T. T. Soong. Design of an active mass damper for a tall TV tower in Nanjing, China. *Engineering Structures*, 20(3):134–143, 1998. ISSN 01410296. doi: 10.1016/S0141-0296(97)00072-2.

G. Chase, A. Smith, and T. Suzuki. Robust H∞ Control Considering Aactuator Saturation. II: Applications. *Journal of Engineering Mechanics*, 122(10):984–993, 1996.

Y. Chen, S. Zhang, H. Peng, B. Chen, and H. Zhang. A novel fast model predictive control for large-scale structures. *JVC/Journal of Vibration and Control*, 23(13): 2190–2205, 2017. ISSN 17412986. doi: 10.1177/1077546315610033.

D. Demetriou and N. Nikitas. A novel hybrid semi-active mass damper configuration for structural applications. *Applied Sciences (Switzerland)*, 6(12), 2016. ISSN 20763417. doi: 10.3390/app6120397.

D. Demetriou, N. Nikitas, and K. D. Tsavdaridis. Performance of fixed-parameter control algorithms on high-rise structures equipped with semi-active tuned mass dampers. *The Structural Design of Tall and Special Buildings*, 25:340–354, 2016. doi: 10.1002/tal.

J. P. Den Hartog. *Mechanical Vibrations*. McGraw-Hill, New York, NY, USA, 4 edition, 1956. ISBN 0486647854.

Y. C. Ding, F. L. Weng, and Z. A. Yu. Actuator saturation and control design for buildings structural systems with improved uncertainty description. *Shock and Vibration*, 20(2):297–308, 2013. ISSN 10709622. doi: 10.3233/SAV-2012-00745.

J. C. Doyle. Structured Uncertainty in Control System Design. *Proceedings of the IEEE Conference on Decision and Control*, pages 260–265, 1985. ISSN 01912216. doi: 10.1109/cdc.1985.268842.

H. Du, N. Zhang, B. Samali, and F. Naghdy. Robust sampled-data control of structures subject to parameter uncertainties and actuator saturation. *Engineering Structures*, 36:39–48, 2012. ISSN 01410296. doi: 10.1016/j.engstruct.2011.11.024. URL http://dx.doi.org/10.1016/j.engstruct.2011.11.024.

S. J. Dyke, J. M. Caicedo, G. Turan, L. A. Bergman, and S. Hague. Phase I Benchmark Control Problem for Seismic Response of Cable-Stayed Bridges. *Journal of Structural Engineering*, 129(7):857–872, 2003. ISSN 11228385. doi: 10.1002/stc.23.

W. M. Elhaddad and E. A. Johnson. Hybrid MPC: An Application to Semiactive Control of Structures. In *Topics in Dynamics of Civil Structures*, volume 4, pages 27–36. 2013. ISBN 9781461465546. doi: 10.1007/978-1-4614-6555-3.

A. Forrai, S. Hashimoto, H. Funato, and K. Kamiyama. Robust active vibration suppression control with constraint on the control signal: Application to flexible structures. *Earthquake Engineering and Structural Dynamics*, 32(11):1655–1676, 2003. ISSN 00988847. doi: 10.1002/eqe.293.

D. Gill, S. Elias, A. Steinbrecher, C. Schröder, and V. Matsagar. Robustness of multimode control using tuned mass dampers for seismically excited structures. *Bulletin of Earthquake Engineering*, 15(12):5579–5603, 2017. ISSN 15731456. doi: 10.1007/s10518-017-0187-6.

N. Giron and M. Kohiyama. A robust decentralized control method based on dimensionless parameters with practical performance criterion for building structures under seismic excitations. *Structural Control and Health Monitoring*, 21:907–925, 2014. ISSN 15452255. doi: 10.1002/stc. URL http://dx.doi.org/10.1002/stc.456.

L. Gurobi Optimization. Gurobi Optimizer Reference Manual, 2021.

A. J. Hillis. Active motion control of fixed offshore platforms using an extended state observer. *Proceedings of the Institution of Mechanical Engineers. Part I: Journal of Systems and Control Engineering*, 224(1):53–63, 2010. ISSN 09596518. doi: 10.1243/09596518JSCE847.

L. Huo, G. Song, H. Li, and K. Grigoriadis. H∞ robust control design of active structural vibration suppression using an active mass damper. *Smart Materials and Structures*, 17(1), 2008. ISSN 09641726. doi: 10.1088/0964-1726/17/01/015021.

L. Huo, C. Qu, and H. Li. Robust control of civil structures with parametric uncertainties through D-K iteration. *The Structural Design of Tall and Special Buildings*, 25:158–176, 2016. ISSN 15417794. doi: 10.1002/tal.

S. Jeon and M. Tomizuka. Benefits of acceleration measurement in velocity estimation and motion control. *Control Engineering Practice*, 15(3 SPEC. ISS.):325–332, 2007. ISSN 09670661. doi: 10.1016/j.conengprac.2005.10.004.

H. Kim and H. Adeli. Hybrid feedback-least mean square algorithm for structural control. *Journal of Structural Engineering*, 130(1):120–127, 2004. ISSN 07339445. doi: 10.1061/(ASCE)0733-9445(2004)130:1(120).

L. Koutsoloukas, N. Nikitas, P. Aristidou, and C. Meinhardt. Control law and actuator capacity effect on the dynamic performance of a hybrid mass damper; the case of rottweil tower. *Proceedings of the International Conference on Structural Dynamic , EURODYN*, 1:1422–1432, 2020. ISSN 23119020. doi: 10.47964/1120.9115.19241.

L. Koutsoloukas, N. Nikitas, and P. Aristidou. Passive, Semi-Active, Active and Hybrid Mass Dampers: A Literature Review with Associated Applications. *Developments in the Built Environment*, 12:100094, 2022. ISSN 2666-1659. doi: 10.1016/j.dibe.2022.100094. URL https://doi.org/10.1016/j.dibe.2022.100094.

A. Lago, D. Trabucco, and A. Wood. *Damping Technologies for Tall Buildings*. 2019. ISBN 9780128159637. doi: 10.1016/b978-0-12-815963-7.00001-4.

P. Langthaler and L. del Re. *Robust Model Predictive Control of a Diesel Engine Airpath*, volume 41. IFAC, 2008. ISBN 9783902661005. doi: 10.3182/20080706-5-kr-1001.01603. URL http://dx.doi.org/10.3182/20080706-5-KR-1001.01603.

C. W. Lim. Active vibration control of the linear structure with an active mass damper applying robust saturation controller. *Mechatronics*, 18(8):391–399, 2008. ISSN 09574158. doi: 10.1016/j.mechatronics.2008.06.006.

C. W. Lim, Y. J. Park, and S. J. Moon. Robust saturation controller for linear time-invariant system with structured real parameter uncertainties. *Journal of Sound and Vibration*, 294(1-2):1–14, 2006. ISSN 10958568. doi: 10.1016/j.jsv.2005.10.020.

C. C. Lin, L. Y. Lu, G. L. Lin, and T. W. Yang. Vibration control of seismic structures using semi-active friction multiple tuned mass dampers. *Engineering Structures*, 32 (10):3404–3417, 2010. ISSN 01410296. doi: 10.1016/j.engstruct.2010.07.014. URL http://dx.doi.org/10.1016/j.engstruct.2010.07.014.

J. Lofberg. Approximations of closed-loop minimax MPC. *42nd IEEE International Conference on Decision and Control*, pages 1438–1442, 2003.

J. Löfberg. *Minimax Approaches to Robust Model Predictive Control*. 2003. ISBN 9173736228. URL http://www.control.isy.liu.se/research/reports/Ph.D.Thesis/PhD812.pdf.

J. Löfberg. YALMIP: A toolbox for modeling and optimization in MATLAB. *Proceedings of the IEEE International Symposium on Computer-Aided Control System Design*, pages 284–289, 2004. doi: 10.1109/cacsd.2004.1393890.

J. Löfberg. Automatic robust convex programming. *Optimization Methods and Software*, 27(1):115–129, 2012. ISSN 10556788. doi: 10.1080/10556788.2010.517532.

F. Lopez-Almansa, R. Andrade, J. Rodellar, and A. M. Reinhorn. Modal predictive control of structures. II: Implementation. *Journal of Engineering Mechanics*, 120(8): 1761–1772, 1994. ISSN 07339399. doi: 10.1061/(ASCE)0733-9399(1994)120:8(1743).

F. Lopez-Almansa, R. Andrade, J. Rodellar, and A. M. Reinhorn. Modal predictive control of structures. I: Formulation. *Journal of Engineering Mechanics*, 120(8): 1743–1760, 1995.

X. Lu, P. Li, X. Guo, W. Shi, and J. Liu. Vibration control using ATMD and site measurements on the Shanghai World Financial Center Tower. *The Structural Design of Tall and Special Buildings*, 23:105–123, 2014. doi: 10.1002/tal.

M. Maasoumy, M. Razmara, M. Shahbakhti, and A. S. Vincentelli. Handling model uncertainty in model predictive control for energy efficient buildings. *Energy and Buildings*, 77:377–392, 2014. ISSN 03787788. doi: 10.1016/j.enbuild.2014.03.057. URL http://dx.doi.org/10.1016/j.enbuild.2014.03.057.

G. Mei, A. Kareem, and J. C. Kantor. Model Predictive Control For Wind Excited Buildings : A Benchmark Problem. *14th Engineering Mechanics Conference*, 2000.

G. Mei, A. Kareem, and J. C. Kantor. Real-time model predictive control of structures under earthquakes. *Earthquake Engineering and Structural Dynamics*, 30(7):995–1019, 2001. ISSN 00988847. doi: 10.1002/eqe.49.

G. Mei, A. Kareem, and J. C. Kantor. Model predictive control of structures under earthquakes using acceleration feedback. *Journal of Engineering Mechanics*, 128(5): 574–585, 2002. ISSN 07339399. doi: 10.1061/(ASCE)0733-9399(2002)128:5(574).

G. Mei, A. Kareem, and J. C. Kantor. Model Predictive Control of Wind-Excited Building: Benchmark Study. *Journal of engineering mechanics*, pages 459–465, 2004. doi: 10.1061/(ASCE)0733-9399(2004)130. URL http://link.aip.org/link/?JENMDT/130/1195/1.

C. Meinhardt, N. Nikitas, and D. Demetriou. Application of a 245 metric ton Dual-Use Active TMD System. *Procedia Engineering*, 199:1719–1724, 2017. ISSN 18777058. doi: 10.1016/j.proeng.2017.09.384. URL http://dx.doi.org/10.1016/j.proeng.2017.09.384.

M. Mirzaei, N. K. Poulsen, and H. H. Niemann. Robust Model Predictive Control of a Wind Turbine. *2012 American Control Conference (ACC)*, pages 4393–4398, 2012.

A. Mohtat, A. Yousefi-Koma, and E. Dehghan-Niri. Active vibration control of seismically excited structures by ATMDS: Stability and performance robustness perspective. *International Journal of Structural Stability and Dynamics*, 10(3):501–527, 2010. ISSN 02194554. doi: 10.1142/S0219455410003592.

I. Nagashima, R. Maseki, Y. Asami, J. Hirai, and H. Abiru. Performance of hybrid mass damper system applied to a 36-storey high-rise building. *Earthquake Engineering and Structural Dynamics*, 30(11):1615–1637, 2001. ISSN 00988847. doi: 10.1002/eqe.84.

H. Nagpal, A. Staino, and B. Basu. Robust model predictive control of HVAC systems with uncertainty in building parameters using linear matrix inequalities. *Advances in Building Energy Research*, 2019. ISSN 17562201. doi: 10.1080/17512549.2019.1588165. URL https://doi.org/10.1080/17512549.2019.1588165.

S. Narasimhan. Robust direct adaptive controller for the nonlinear highway bridge benchmark. *Structural Control and Health Monitoring*, 16:599–612, 2009. ISSN 15452255. doi: 10.1002/stc. URL http://dx.doi.org/10.1002/stc.456.

N. Nikitas, J. H. Macdonald, and J. B. Jakobsen. Identification of flutter derivatives from full-scale ambient vibration measurements of the Clifton Suspension Bridge. *Wind and Structures*, 14(3):221–238, 2011. ISSN 12266116. doi: 10.12989/was.2011.14.3.221.

Y. Ohtori, R. E. Christenson, B. F. Spencer, and S. J. Dyke. Benchmark Control Problems for Seismically Excited Nonlinear Buildings. *Journal of Engineering Mechanics*, 130(4):366–385, 2004. ISSN 0733-9399. doi: 10.1061/(asce)0733-9399(2004)130:4(366).

B. Palazzo and L. Petti. Optimal Structural Control in the Frequency Domain: Control in Norm H2 and H∞. *Journal of Structural Control*, 6(2):205–221, 1999.

H. Peng, F. Li, S. Zhang, and B. Chen. A novel fast model predictive control with actuator saturation for large-scale structures. *Computers and Structures*, 187:35–49, 2017. ISSN 00457949. doi: 10.1016/j.compstruc.2017.03.014. URL http://dx.doi.org/10.1016/j.compstruc.2017.03.014.

H. Peng, Y. Chen, E. Li, S. Zhang, and B. Chen. Explicit expression-based practical model predictive control implementation for large-scale structures with multi-input delays. *JVC/Journal of Vibration and Control*, 24(12):2605–2620, 2018. ISSN 17412986. doi: 10.1177/1077546316689341.

H. Peng, F. Li, and Z. Kan. A novel distributed model predictive control method based on a substructuring technique for smart tensegrity structure vibrations. *Journal of Sound and Vibration*, 471:115171, 2020. ISSN 10958568. doi: 10.1016/j.jsv.2020.115171. URL https://doi.org/10.1016/j.jsv.2020.115171.

R. Rana and T. T. Soong. Parametric study and simplified design of tuned mass dampers. *Engineering Structures*, 20(3):193–204, 1998. ISSN 01410296. doi: 10.1016/S0141-0296(97)00078-3.

F. Ricciardelli, A. D. Pizzimenti, and M. Mattei. Passive and active mass damper control of the response of tall buildings to wind gustiness. *Engineering Structures*, 25(9):1199–1209, 2003. ISSN 01410296. doi: 10.1016/S0141-0296(03)00068-3.

M. Schwenzer, M. Ay, T. Bergs, and D. Abel. Review on model predictive control: an engineering perspective, 2021. ISSN 14333015.

S. Skogestad and I. Postlethwaite. *Multivariable Feedback Controlâ€"Analysis and Design*. John Wiley and Sons Ltd, Sussex, 2 edition, 2005.

T. T. Soong. *Active Structural Control: Theory and Practice*. John Wiley Sons, Inc, New York, 1990. ISBN 1111111111.

T. T. Soong and B. F. Spencer. Active, semi-active and hybrid control of structures. *Bulletin of the New Zealand Society for Earthquake Engineering*, 33(3):387–402, 2002. ISSN 11749857. doi: 10.5459/bnzsee.33.3.387-402.

B. F. Spencer, S. J. Dyke, and H. S. Deoskar. Benchmark problems in structural control: Part I - Active Mass Driver system. *Earthquake Engineering and Structural Dynamics*, 27(11):1127–1139, 1998. ISSN 00988847. doi: 10.1002/(SICI)1096-9845(1998110) 27:11⟨1127::AID-EQE774⟩3.0.CO;2-F.

B. F. Spencer Jr., R. E. Christenson, and S. J. Dyke. Next generation benchmark control problem for seismically excited buildings. *Second World Conference on Structural Control*, pages 1135–1360, 1998. URL http://nees.org/resources/2405/download/Report_bldg_full2.pdf.

G. E. Stavroulakis, D. G. Marinova, E. Hadjigeorgiou, G. Foutsitzi, and C. C. Baniotopoulos. Robust active control against wind-induced structural vibrations. *Journal of Wind Engineering and Industrial Aerodynamics*, 94(11):895–907, 2006. ISSN 01676105. doi: 10.1016/j.jweia.2006.06.012.

G. Takács and B. Rohal-Ilkiv. *Model Predictive Vibration Control*. 2012. ISBN 9781447123323. doi: 10.1007/978-1-4471-2333-0.

T. Tettamanti, T. Luspay, B. Kulcsar, T. Peni, and I. Varga. Robust control for urban road traffic networks. *IEEE Transactions on Intelligent Transportation Systems*, 15 (1):385–398, 2014. ISSN 15249050. doi: 10.1109/TITS.2013.2281666.

S. N. Vassilyev, A. Y. Kelina, Y. I. Kudinov, and F. F. Pashchenko. Intelligent Control Systems. *Procedia Computer Science*, 103(October 2016):623–628, 2017. ISSN 18770509. doi: 10.1016/j.procs.2017.01.088. URL http://dx.doi.org/10.1016/j.procs.2017.01.088.

I. Venanzi. Robust optimal design of tuned mass dampers for tall buildings with uncertain parameters. *Structural and Multidisciplinary Optimization*, 51(1):239–250, 2015. ISSN 16151488. doi: 10.1007/s00158-014-1129-4.

L. Wang, W. Shi, X. Li, Q. Zhang, and Y. Zhou. An adaptive-passive retuning device for a pendulum tuned mass damper considering mass uncertainty and optimum frequency. *Structural Control and Health Monitoring*, 26(7):1–21, 2019a. ISSN 15452263. doi: 10.1002/stc.2377.

L. Wang, W. Shi, and Y. Zhou. Study on self-adjustable variable pendulum tuned mass damper. *Structural Design of Tall and Special Buildings*, 28(1), 2019b. ISSN 15417808. doi: 10.1002/tal.1561.

L. Wang, S. Nagarajaiah, W. Shi, and Y. Zhou. Study on adaptive-passive eddy current pendulum tuned mass damper for wind-induced vibration control. *Structural Design of Tall and Special Buildings*, 29(15):1–23, 2020a. ISSN 15417808. doi: 10.1002/tal.1793.

L. Wang, W. Shi, Q. Zhang, and Y. Zhou. Study on adaptive-passive multiple tuned mass damper with variable mass for a large-span floor structure. *Engineering Structures*, 209(December 2019):110010, 2020b. ISSN 18737323. doi: 10.1016/j.engstruct.2019.110010. URL https://doi.org/10.1016/j.engstruct.2019.110010.

L. Wang, W. Shi, Y. Zhou, and Q. Zhang. Semi-active eddy current pendulum tuned mass damper with variable frequency and damping. *Smart Structures and Systems*, 25(1):65–80, 2020c. ISSN 17381991. doi: 10.12989/sss.2020.25.1.065.

L. Wang, S. Nagarajaiah, W. Shi, and Y. Zhou. Semi-active control of walking-induced vibrations in bridges using adaptive tuned mass damper considering human-structure-interaction. *Engineering Structures*, 244(December 2020):112743, 2021. ISSN 18737323. doi: 10.1016/j.engstruct.2021.112743. URL https://doi.org/10.1016/j.engstruct.2021.112743.

S. G. Wang. Linear quadratic Gaussian-α control with relative stability and gain parameter for the structural benchmark problems. *Journal of Engineering Mechanics*, 130(4):511–517, 2004. ISSN 07339399. doi: 10.1061/(ASCE)0733-9399(2004)130:4(511).

S. G. Wang, H. Y. Yeh, and P. N. Roschke. Robust control for structural systems with parametric and unstructured uncertainties. *Proceedings of the American Control Conference*, 2:1109–1114, 2001. ISSN 07431619. doi: 10.1109/acc.2001.945868.

S.-g. Wang, P. N. Roschke, and H. Y. Yeh. Robust Control for Structural Systems with Unstructured Uncertainties. *Journal of engineering mechanics*, 130(March):337–346, 2004.

Y. Wang, J. P. Lynch, and K. H. Law. Decentralized H∞ controller design for large-scale civil structures. *Earthquake Engineering and Structural Dynamics*, 38:377–401, 2009. doi: 10.1002/eqe.

J. C. Wu, H. H. Chih, and C. H. Chen. A robust control method for seismic protection of civil frame building. *Journal of Sound and Vibration*, 294(1-2):314–328, 2006. ISSN 10958568. doi: 10.1016/j.jsv.2005.11.019.

S. K. Yalla, A. Kareem, and J. C. Kantor. Semi-active tuned liquid column dampers for vibration control of structures. *Engineering Structures*, 23(11):1469–1479, 2001. ISSN 01410296. doi: 10.1016/S0141-0296(01)00047-5.

J. N. Yang, A. K. Agrawal, B. Samali, and J.-C. Wu. Benchmark Problem for Response Control of Wind-Excited Tall Buildings. *Journal of engineering mechanics*, 130:437–446, 2004a.

J. N. Yang, S. Lin, and F. Jabbari. H∞-based control strategies for civil engineering structures. *Structural Control and Health Monitoring*, 11(3):223–237, 2004b. ISSN 15452255. doi: 10.1002/stc.38.

A. Yonezawa, I. Kajiwara, and H. Yonezawa. Model-free vibration control based on a virtual controlled object considering actuator uncertainty. *JVC/Journal of Vibration and Control*, (June), 2020a. ISSN 17412986. doi: 10.1177/1077546320940922.

A. Yonezawa, I. Kajiwara, and H. Yonezawa. Novel Sliding Mode Vibration Controller With Simple Model-Free Design and Compensation for Actuator's Uncertainty. *IEEE Access*, 9:4351–4363, 2020b. ISSN 21693536. doi: 10.1109/ACCESS.2020.3047810.

M. N. Zeilinger, C. N. Jones, and M. Morari. Robust stability properties of soft constrained MPC. *Proceedings of the IEEE Conference on Decision and Control*, pages 5276–5282, 2010. ISSN 01912216. doi: 10.1109/CDC.2010.5717488.

Y. Zhang, X. Zhao, and X. Wei. Robust structural control of an underactuated floating wind turbine. *Wind Energy*, (October 2019):1–20, 2020. ISSN 10991824. doi: 10.1002/we.2550.

K. Zhao, X. Lu, W. Zheng, and C. Huang. Direct relaxation of hard-constraint in Model Predictive Control. *Proceedings - 2012 9th International Conference on Fuzzy Systems and Knowledge Discovery, FSKD 2012*, (Fskd):2366–2370, 2012. doi: 10.1109/FSKD.2012.6234019.

Chapter 4

Structural Control of a Real High-Rise Tower Using Reinforcement Learning

Chapter Outline: Chapter 3 presented the performance of two robust control schemes in the presence of parametric and actuator uncertainties. This chapter will investigate the use of a reinforcement learning controller for the control of the same case-study. As it will be discussed herein, the reinforcement learning control scheme is not broadly investigated in the area of structural control despite its proven efficiency on different control areas. The Deep Deterministic Policy Gradient controller will be implemented and its performance will be compared to the well established Linear Quadratic Regulator. To also assess the robustness of the two controllers, the worst-case parametric uncertain scenario that was studied in Chapter 3 will be investigated. As it will be shown, the reinforcement learning scheme can be proven efficient for structural control purposes and further investigation should be conducted.

Source: L. Koutsoloukas, N. Nikitas, and P. Aristidou. Structural Control of a Real High-Rise Tower Using Reinforcement Learning, 2023. (**Submitted**).

4.1 Abstract

This paper investigates the vibration control of a real high-rise tower using a hybrid mass damper (HMD). A Deep Deterministic Policy Gradient (DDPG) algorithm is implemented for the control of the HMD for the first time. The performance of this reinforcement learning algorithm was investigated in different scenarios in order to assess its robustness. Namely, a −10% stiffness and damping uncertainty was introduced directly in the matrices of the nominal model. For comparison purposes, the performance of the system controlled by a well established controller within the structural control field namely, the Linear Quadratic Regulator (LQR), and the performance of the system when acting as an equivalent passive-only tuned mass damper (PTMD) were also established. The simulation results showed that, the DDPG algorithm had a better overall performance than the LQR in terms of vibration dissipation, actuator displacement and velocity, power and energy consumption. More specifically, the DDPG managed to reduce the peak displacements by up to 23% and the peak accelerations by up to 32% in the nominal case when compared to the uncontrolled scenario. When parameter uncertainty was introduced in the system, the DDPG algorithm managed to reduce displacements by up to 16.4% and accelerations by up to 22.3%. It is noted that, in all cases, the DDPG controlled hybrid system outperformed the passive PTMD. When considering the practical constraints of the mass damper application (i.e. actuator displacement, velocity and force saturation, and power consumption) the DDPG was more efficient in handling them compared to the LQR. As such, the DDPG algorithm is an efficient algorithm which has merits within the structural control field.

4.2 Introduction

Accompanying advances in construction and materials, there is a drive for building more efficient and sustainable civil structures. In practice, this translates for instance to very slender high-rise buildings which are susceptible to vibrations. Such structural vibrations can be caused mainly due to strong winds, earthquakes, or human activities. Extensive research has been conducted over the last years, and various structural control techniques have been proposed to mitigate excessive vibrations. Amongst the most effective applied control techniques are the mass dampers (Koutsoloukas et al. (2022b)) which can be categorised into passive tuned mass dampers (PTMD)

(Elias and Matsagar (2017), Gutierrez Soto and Adeli (2013)), semi-active tuned mass dampers (SATMD) (Casciati et al. (2012), Demetriou and Nikitas (2016), Fisco and Adeli (2011a), Jung et al. (2004)), active mass dampers (AMD) (Datta (2003), Korkmaz (2011), Nishitani and Inoue (2001)) and hybrid mass dampers (HMD) (Fisco and Adeli (2011b), Soong and Spencer (2002)). Although the PTMDs proved to be efficient in dissipating excess dynamic structural responses in many studies (Bekdas and Nigdeli (2011), Carlo Marano et al. (2010), Ghorbani-Tanha et al. (2009), Lin et al. (1994), Singh et al. (2002), Yucel et al. (2019)), SATMDs, AMDs and HMDs were developed in order to achieve even better performance than them and eliminate their inherent weaknesses e.g. lack of adaptiveness and detuning effects (Rana and Soong (1998)). The effectiveness of SATMDs, AMDs and HMDs is also dependent upon the utilised control algorithm. Many control algorithms were investigated in the literature such as the Linear Quadratic Regulator (LQR) (Cao et al. (1998), Djajakesukma et al. (2002), Ikeda (1997), Jiang et al. (2010), Miah et al. (2015), Nagashima and Shinozaki (1997), Ou and Li (2010), Ricciardelli et al. (2003), Yang et al. (2004b)), the Model Predictive Control (MPC) (Chen et al. (2017), Koutsoloukas et al. (2020), Lopez-Almansa et al. (1994, 1995), Mei et al. (2000, 2001, 2002, 2004), Peng et al. (2017, 2020)), the H_∞ (Aggumus and Guclu (2020), Chase et al. (1996), Chen et al. (2010), Lezgy-Nazargah et al. (2020), Manjarekar and Singru (2016), Yang et al. (2004b)), the Groundhook (Demetriou et al. (2016), Ji et al. (2005), Kang et al. (2011), Setareh (2002)), the Proportional Integral Derivative (PID) (Demetriou et al. (2015), Etedali and Tavakoli (2017), Kayabekir et al. (2020)) and Fuzzy logic based controllers (Battaini et al. (1997, 1998), Burgos et al. (2004), Casciati et al. (1994, 1996), Li et al. (2014), Pourzeynali et al. (2007)), to name only a representative sample of them.

This paper will consider the active control of a real-high rise tower equipped with a HMD. For the control law of the HMD, the reinforcement learning algorithm Deep Deterministic Gradient (DDPG) (Lillicrap et al. (2015)) will be implemented. To the authors' best knowledge, the DDPG has not been applied on a real tower application within the structural control field before. The intuition for this knowledge translation step comes from the fact that reinforcement learning schemes already proved efficient in stabilising walking humanoid robots (Peters et al. (2003)), a problem alike to this of perturbed swaying structures.

4.3 Paper Contributions

This paper aims to (i) test the effectiveness of the reinforcement learning DDPG algorithm in dissipating the dynamic responses of a real high-rise tower; (ii) compare its performance against a well established controller within the structural control field, namely the LQR, and against an equivalent PTMD; (iii) use parameters of practical significance (i.e. actuator displacement, velocity, power and energy consumption) for the holistic assessment of the performance of the DDPG and; (iv) assess its robustness by introducing parameter uncertainties within the model of the tower.

4.4 Paper Structure

This work is structured as follows: Section 4.5 includes a brief explanation of the reinforcement learning scheme and Section 4.6 includes a review of reinforcement learning applications within the structural control field. Section 4.7 includes the derivation of the DDPG agent and, Section 4.8 describes the real-life application of this study. Section 4.9 demonstrates the simulation results and finally, Section 4.10 includes a reflective account of this work. It is noted that, the derivation of the LQR will not be included within this study and the reader can refer to (Djajakesukma et al. (2002), Miah et al. (2015), Ou and Li (2010), Yang et al. (2004b)) for the associated full derivation.

4.5 Reinforcement Learning

The concept of reinforcement learning emerged from two different research fields (i) optimal control using value functions and dynamic programming and (ii) animal psychology (Nian et al. (2020)). In general, as explained in Achiam (2018), reinforcement learning is the area that studies the development of a learner and decision maker called 'agent', through trial and error. The agent during its learning procedure interacts with the 'environment' which includes everything outside the agent. Reinforcement learning agents learn by using a pre-set reward function which rewards or punishes the agent for the correct or wrong decisions they took based on the desired outcome. The aim of the agent is to maximise its cumulative reward (return) function and thus, through trial and error, get trained to achieve pre-set goals. To interact with the environment, as seen in Figure 4.1, the agent receives (full or partial) state observations and takes actions based on the pre-set reward.

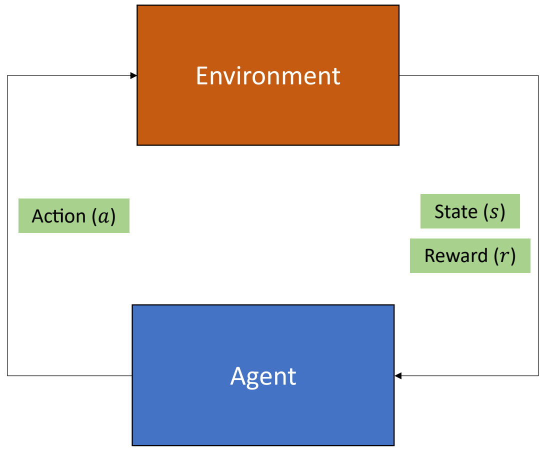


Figure 4.1: Agent-Environment Interaction

In Figure 4.1, s represents the observation vector including the states of the system, a represents the control actions taken by the reinforcement learning agent and r represents the reward provided to the agent from the interaction with the environment at each time instant t. The kind of actions that an agent is capable of taking depends on the given environment. The set of all possible actions that an agent is capable of taking is called action space. The action space is described as discrete when an agent has a finite amount of actions that can be taken within their environment. When the agent controls a physical system such as a HMD, the action space is described as continuous and the actions are vectors with real values (Masson et al. (2016)). An agent uses a rule in order to decide what actions to take. This rule is called policy and it could be deterministic or stochastic (Nagarajan et al. (2018)).

In the reinforcement learning scheme, the expected return (value) of a state or state-action pair is useful to know. Using this knowledge, the algorithm acts based on a particular policy. This is often called 'value function'. The value function can be thought of as a measure of how good it is being in a particular state, assuming optimal behaviour occurs afterwards (Nian et al. (2020)). Therefore, large values correlate to good states and small values to bad states. To estimate the value and action-value functions, the methods that are used typically are; dynamic programming, Monte Carlo, and Temporal Difference. For more information about the aforementioned methods the authors are referred to the works of (Nian et al. (2020), Sutton and Barto (1998)).

As mentioned, the effectiveness of the agent's performance is highly depended on the pre-selected reward function. The concept of selecting a function to reward or punish the behaviour of the algorithm, originates from the animal psychology (Nian et al. (2020)). The readers are referred to the work of Thorndike (1911) where, in the so called 'Law of Effect', the author explained that, actions which result in a positive effect are likely to be repeated in contrast to the ones resulting to bad outcomes which are likely to be avoided. In general, there are different types of rewards. The first type of reward is called finite-horizon undiscounted reward which is the sum of rewards obtained within a fixed step window. A reward function can also be infinite-horizon discounted return. This is the sum of all rewards obtained since the beginning of training but multiplied by a discount factor depending on when they have occurred. The discount factor is used in order to adjust the participation ratio of the future reward to the determination of the current reward (Radmard Rahmani et al. (2019)). Moreover, Nian et al. (2020) mention that, the discount factor is used in order to add uncertainty into future rewards.

In general, the algorithms within the reinforcement learning field can be categorised based on whether they require access to, or learn, from the model of the environment. The algorithms that require knowledge of the environment model to learn are often called Model-based reinforcement learning algorithms. On the other hand, reinforcement learning algorithms that do not require a model to run are called Model-free reinforcement learning algorithms.

4.5.1 Model-based vs Model-free Algorithms

In the case of Model-based reinforcement learning algorithms, the model consists of a function which predicts the rewards and the state transitions. The benefit when using a Model-based reinforcement learning algorithm is that the agent uses the knowledge of the model to investigate the possible outcomes for a range of choices, and then it decides explicitly between the choices. Moreover, the Model-based reinforcement learning algorithms tend to converge faster to optimal solutions (Polydoros and Nalpantidis (2017)). However, a real-model of the environment is not always available nor accurate. Moreover, it is noticed that, Model-based reinforcement learning algorithms may perform well during a simulation, but when applied on real applications, amenable to random uncertainties, they may perform sub-optimally or not accurate at all. Lastly, Model-based learning methods are fundamentally hard to devise and thus, they require great effort to implement (Achiam (2018), Sutton and Barto (1998)). On the other hand, Model-free reinforcement learning algorithms are considered to be easier to tune and implement. There are two main approaches in order to train an agent with a Model-free reinforcement learning algorithm namely; policy optimisation and Q-learning (Achiam (2018), Sutton and Barto (1998)).

4.5.2 Policy Optimisation

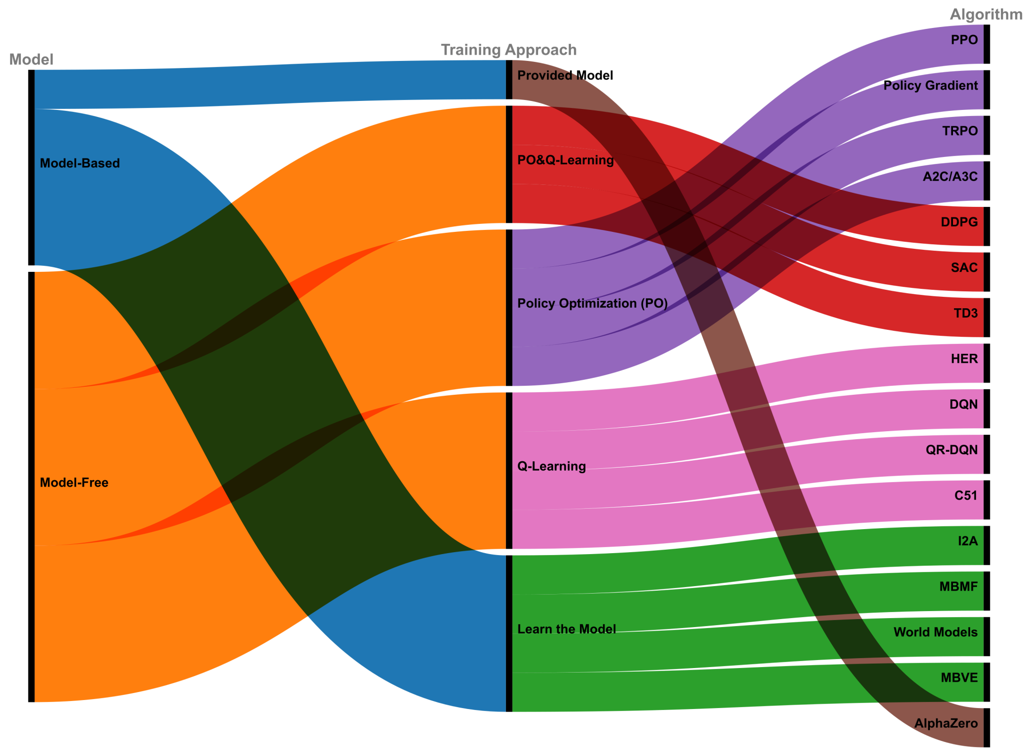
Policy optimisation methods operate around the given policy. Thus, these methods treat the mathematical problem as one of numerical optimisation. They operate by optimising the expected reward always with respect to the parameters of the given policy. Almost in all cases, the optimisation is executed on-policy, meaning that each update is based on the data collected as a result from the last version of the policy. To update the policy, it is often that these methods learn an approximator for the on-policy value function (Achiam (2018), Sutton and Barto (1998)). These approaches are often considered to not be sample-efficient (Schulman (2016)).

4.5.3 Q-Learning

'Q' in Q-learning is the expected return from a taken action to a certain state (Watkins (1989)). Q-learning is an off-policy method meaning that the optimal policy value is determined without considering the agent's actions. The algorithm learns an approximator where the optimal action-value function and the objective function is built based on the Bellman equation (Sutton and Barto (1998), Szepesvári (2010)).

4.5.4 Discussion

In general, policy optimisation algorithms tend to be stable and reliable since, they are designed to optimise over the desired goal. On the other hand Q-learning methods tend to be less stable (Sutton and Barto (1998), Tsitsiklis and Van Roy (1996)). However, once the Q-learning methods are employed, they tend to be more sample-efficient due to their ability of effectively reusing data. Figure 4.2 shows a classification of Model-based and Model-free algorithms along with their training approach. As seen, there are some algorithms that lie between the two reinforcement learning methods trading-off between the strengths and weaknesses of each. In the next sections, the reinforcement learning algorithms used within the area of structural control will be discussed. As it will be established, reinforcement learning schemes within structural control have received only modest levels of investigation.



PPO: Proximal Policy Optimisation; **TRPO**: Trust Region Policy Optimisation; **A2C/A3C**: Asynchronous Advantage Actor-Critic; **SAC**: Soft Actor-Critic; **TD3**:Twin Delayed DDPG; **HER**: Hindsight Experience Replay; **DQN**: Deep Q-Network; **QR-DQN**: Quantile Regression DQN; **C51**: Categorical 51-Atom DQN; **I2A**: Imagination-Augmented Agents; **MBMF**: Model-Based RL with Model-Free Fine-Tuning; **MBVE**: Model-Based Value Expansion;

Figure 4.2: Reinforcement learning algorithm classification [Source: Achiam (2018)]

4.6 Literature Review

In general, research and practice in structural control has not given thorough attention to reinforcement learning control schemes (Khalatbarisoltani et al. (2019)). This section includes examples of the limited reinforcement learning control applications within the structural control field, aiming to identify potential gaps. As it will be noticed, most of the algorithms included in Figure 4.2 have not been explored by the structural control research community. This makes the reinforcement learning-based structural control an open research area which could prove to be very promising.

Khalatbarisoltani et al. (2019) used a reinforcement learning scheme for the online tuning of a fuzzy-proportional-derivative controller. For their control scheme, the authors used the Q-learning algorithm. Additionally, in order to deal with time-delay effects, a state predictor was implemented in conjunction with the controller. To demonstrate the effectiveness of their control scheme, they used a reduced-order model of a 10-storey building (Pourzeynali et al. (2007)). They tested experimentally the effectiveness of their controller on a 2-degree of freedom (DOF) model equipped with an AMD. The model was tested on a shake table under different earthquake excitation. It was concluded that, the proposed scheme was more effective on the response control of the model when compared to passive, proportional-derivative, and fuzzy-proportional-derivative with reinforcement learning (without state predictor) control schemes.

Radmard Rahmani et al. (2019) proposed a model-free reinforcement learning controller for the active control of a 1-DOF moment frame. The authors used an advanced Q-learning algorithm to train their agent. To eliminate the potential instabilities and divergences that could arise in the proposed scheme, the authors put together an improved version of a Q-learning variant called Mini-batch learning (Mnih et al. (2015)). Their results show that, the proposed controller not only dissipates the displacement and acceleration responses of the system under the earthquake loading it was trained for (i.e. Landers earthquake), but it was proved to be efficient under four other earthquakes which were obtained from the NGA strong motion database PEER Center.

Gao et al. (2020) proposed an actor-critic reinforcement learning algorithm for the vibration control of a 1-DOF system equipped with an AMD. To analyse the stability of the closed-loop system, the authors used the Lyapunov direct method. The proposed algorithm was experimentally investigated under sinusoidal loading. The proposed actor-critic algorithm was compared to a passive and to a proportional-velocity control method. Their results showed that, when considering the floor displacement, all control schemes had a very similar performance. Moreover, when considering the maximum floor accelerations, the passive system was the most efficient. However, when investigating the stable range of displacement and acceleration, the reinforcement learning control scheme had the best performance. In conclusion, it is noted that, the stable range of displacement and acceleration under reinforcement learning control only accounts 28.6% and 23.7%, respectively, when compared to the corresponding proportional-velocity control values and, 26.4% and 25.3%, respectively, when compared to the passive mode values. Finally, the maximum floor acceleration was reduced by 6.9% when compared to the proportional-velocity value.

Zhang et al. (2020) investigated the active control of an offshore wind turbine using an active tuned mass damper (ATMD). For the control of their active device, the authors developed an adaptive dynamic programming (ADP) algorithm. It is noted that the large-scale machine learning platform Tensorflow was used for the development of their neural network structure. It was mentioned that, the control of the wind turbine was investigated in nominal and extreme conditions. Based on their simulations, the authors concluded that, the ADP controller had good vibration dissipation performance at both the nominal and extreme conditions. As an example, the standard deviation of platform pitch displacement was reduced by almost 40% compared to the uncontrolled case. Additionally, when compared to a H_∞ controller, the proposed scheme was found to be more effective, especially in the case of extreme conditions. Finally, the authors mentioned that, in their control scheme, there was a trade-off between the response dissipation performance and the power consumption.

Wang (2020) investigated the dynamic response control of a 1-DOF system equipped with an AMD. The author proposed a coarse-fine self-learning algorithm for the control of the AMD. It was suggested that, in the aforementioned control scheme, the exact exciting frequency of the primary structure can be obtained after several tries allowing for the AMD to dissipate the dynamic responses of the primary structure. For the control algorithm, the author used two improved techniques namely, the variable-gain frequency estimator and the variable learning rate $Q(\lambda)$-learning algorithm. The $Q(\lambda)$-learning is a combination of the Q-learning method (Watlkins (1989)) and the $TD(\lambda)$ (Sutton (1988)) return estimation method (Peng and Williams (1994)). It was concluded that, the proposed scheme was indeed capable of tracking the exact exciting frequency after several attempts of self-learning. Moreover, by tuning the AMD's natural frequency to match the obtained excitation frequency, the dynamic responses of the primary structure were considerably decreased.

Eshkevari et al. (2021) presented a novel reinforcement learning algorithm for the active control of a five-storey shear benchmark building model (Park and Noh (2017)). To design the environment for the proposed reinforcement learning controller, the authors used the Gym library (Brockman et al. (2016)). The novel algorithm uses the off-policy soft actor-critic (SAC) (Haarnoja et al. (2018)) optimisation method for updating its policy. The simulation results showed that, the proposed algorithm managed to reduce the average inter-storey drifts of the five-storey shear benchmark building by up to 65%. When compared to a Linear Quadratic Gaussian (LQG) algorithm, it was found that, the reinforcement learning algorithm demonstrated more optimal actuator forcing strategies and a further average inter-storey drift reduction of 25%.

Yuan et al. (2021) used the model-free Q-learning algorithm for the control of a 2-DOF frame structure using a semi-active control scheme possessing a magnetorheological damper. The authors tested their algorithm which was trained with three different reward functions. It was found that, the algorithm managed to decrease the maximum displacement response by up to 45.63%, the maximum speed by up to 47.73% and the maximum acceleration by up to 48.17% when compared to the uncontrolled case.

Despite the not-very-broad literature, the reinforcement learning control scheme is shown to be efficient in controlling civil engineering applications. The future of reinforcement learning is expected to be bright with many real-life applications (Yuan and Fathi (2022)). Thus, more emphasis should be given threin by the structural control research community. The next section will explain the fundamentals of the DDPG algorithm which will be investigated herein.

4.7 DDPG

In this paper, the DDPG algorithm (Lillicrap et al. (2015)) will be utilised for the dynamic control of a real civil engineering structure. The DDPG is a model-free off-policy algorithm which combines concepts of deep Q-Networks (DQN) (Mnih et al. (2015)) and Deterministic Policy Gradient (DPG) (Silver et al. (2014)) to achieve a continuous action space. Due to its powerful nature, the DDPG is implemented for the control of various systems requiring continuous action spaces such as in robotics (Vecerik et al.

(2017)), in autonomous driving (Wang et al. (2018), in building energy consumption forecasting (Liu et al. (2020)), and in control design for loop heat pipes (Gellrich et al. (2020)). As seen in Figure 4.3, the reinforcement learning problem with the current civil engineering structure is designed as a Markov Decision Process (MDP) (Otterlo and Wiering (2012)). The agent observes the state of the environment at every time instant and for every action, it receives a corresponding reward. Moreover, as seen in Figure 4.3, the DDPG algorithm consists of two deep neural networks (DNNs). The first DNN is the actor which accepts the state of the environment and outputs an action a (which is the same as the symbol u used in this thesis). However, in order to train the agent, a second DNN is used, namely, a critic, which accepts the state of the environment and the action, and outputs an estimated Q-function ($Q(s, a)$). This Q-function is an estimation of a particular reward given an action and a state. To train the agent, the value function target is then compared to the critics output ($Q(s, a)$) and a Loss function (Mean-Squared Error) is determined which is used to backpropagate and train the network. The value function target is the sum of the experienced reward and the discounted future reward. The training process involves several updates in an episode (sequence of states and actions) for many episodes. Moreover, the networks are updated by sampling mini-batches in a random order from an experience replay buffer (Lillicrap et al. (2015)). The actor learns a deterministic policy, mapping states to corresponding actions. An agent can be considered as trained when it determines a satisfactory policy. As shown in Figure 4.3, both the actor and critic DNNs consist of fully connected layers and they are activated using rectified linear unit (ReLU) functions, which are common activation functions in DNNs (Almutairi et al. (2021)). The output of the fully connected single neuron of the actor network is then passed through a hyperbolic tangent (tanh) function and a scaling layer to accommodate a continuous action space within the desired limitations. Since the DDPG uses a deterministic policy, there is possibility for the network to get stuck in local minima while training. Thus, being off-policy, DDPG can be encouraged to explore by introducing a stochastic behaviour policy. A stochastic noise model, namely an Ornestein-Uhlenbeck noise process (Uhlenbeck and Ornstein (1930)), is utilised to promote the exploration of the DDPG agent.

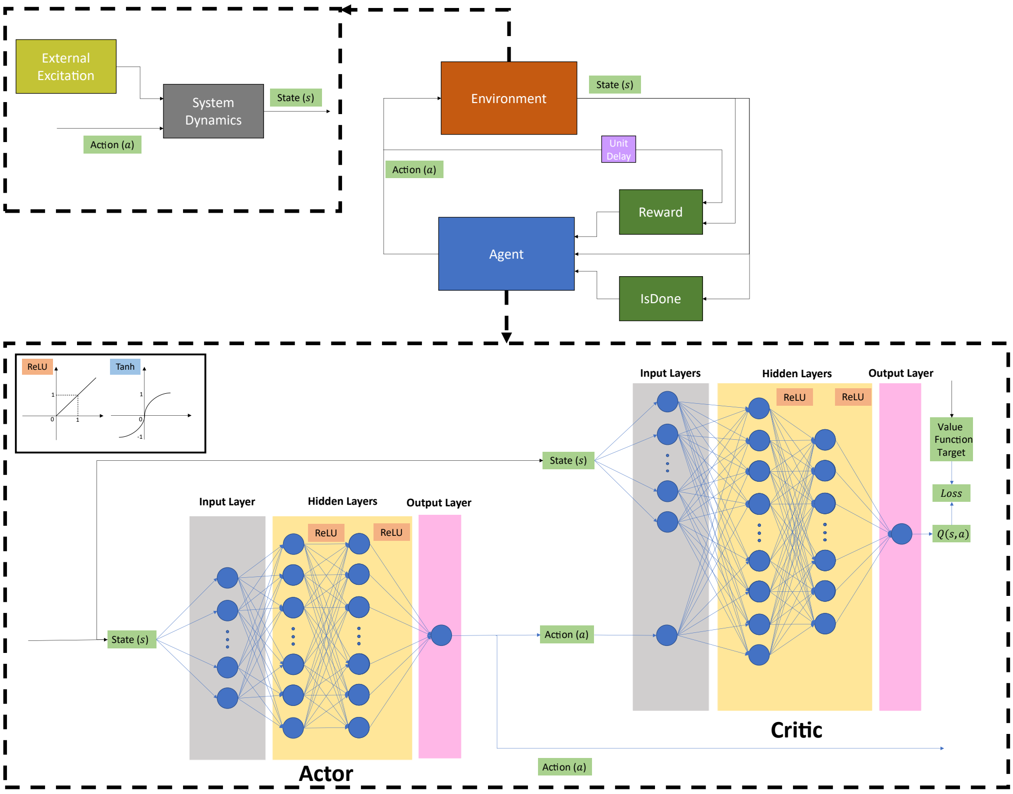


Figure 4.3: Reinforcement learning algorithm control scheme adopted within this study

4.8 Application

The case-study of this chapter is the Rottweil tower that was previously discussed in Chapter 3. To avoid repetition, the reader is referred to Section 3.4 for information about the case-study tower. Moreover, the equations of motion are also dropped in this chapter and the reader is referred to Section 3.3.1 for their full derivation.

4.8.1 Reinforcement Learning Reward Selection

As mentioned in Section 4.5, the effectiveness of the agent is highly depended on the selected reward. In this study, the main priority of the HMD is to limit the top floor sway displacement of the structure (ideally below $0.200m$). For a broader comparison, the accelerations of the tower (directly related to human comfort for instance) will also be considered. Based on the tower's nature, only the top floor of the tower is usable and this is where extremes are to be reached thus, the dynamic responses (i.e. see index 15 in the associated response metric q) of the specific floor will be primarily considered. Moreover, a penalty to the control effort will also be implement in order to decrease the power consumption of the HMD. Since the agent's aim is to maximise its cumulative return, the selected continuous reward in this case can be seen in Equation 4.1 where, β_1, β_2 and β_3 are weights equal to 100, 70 and 0.0001, respectively (i.e. defined by trial and error). Since the agent's aim is to maximise its reward, the displacement, acceleration and force terms were squared to eliminate a false reward due to opposite directionality. The term continuous means that, the selected reward varies continuously with deviations in the environment, observations and actions. A continuous reward was chosen since it can improve the convergence during the training process and it may lead to simpler networks. Reward functions within a similar concept with the one adopted herein can be found in Refs (Khalatbarisoltani et al. (2019), Radmard Rahmani et al. (2019)).

$$r = -(\beta_1 q_{15}^2 + \beta_2 \ddot{q}_{15}^2 + \beta_3 a^2) \tag{4.1}$$

4.9 Simulations

This section includes the simulation results using the DDPG agent for the control of the Rottweil tower. As described in Section 4.7, the DDPG agent is trained using a given environment and takes actions in order to satisfy its rewards. However, in civil engineering applications, it is often that parameter uncertainties may occur due to environmental effects (e.g. temperature) and phenomena such as cumulative degradation and ageing (Aggumus and Guclu (2020), Chase et al. (1996), Lago et al. (2019), Lim et al. (2006), Wang et al. (2009)) or due to the distributed and random nature of applied loads (Acampora et al. (2014), Nikitas et al. (2011)). Moreover, due to the complex nature of civil engineering structures, modelling errors may occur (Forrai et al. (2003)). This means that, the final environment to be controlled is different to the one used for the agent's training. Thus, it is important to assess whether the agent is robust against parametric uncertainties. Thus, this section will examine the performance of the DDPG agent using the nominal model and also using a model with added parametric uncertainty. In this work, a −10% stiffness and damping uncertainty

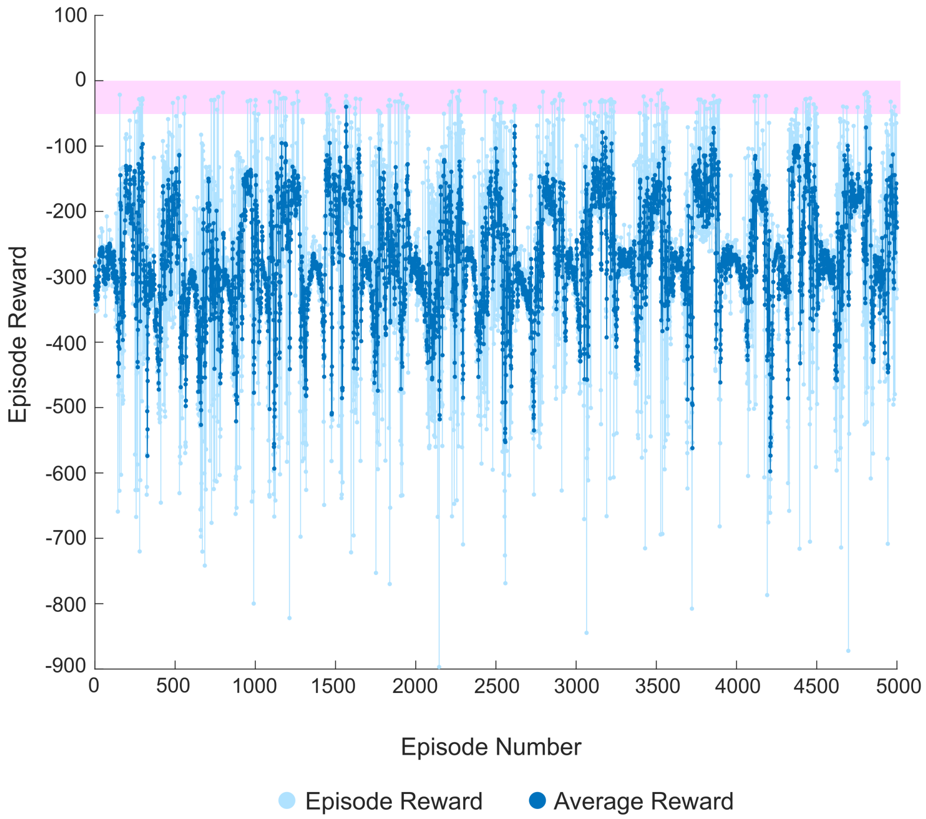


Figure 4.4: Agent reward during the training process

will be introduced within the structural model. This type of scenario was also investigated in Koutsoloukas et al. (2022a) for the control of the high-rise tower when using a RMPC scheme. It is noted that the parameter uncertainty was added directly within the stiffness and damping matrices. To evaluate the performance of the DDPG agent, a well-established control algorithm will also be considered. As shown in Koutsoloukas et al. (2022b), most of the algorithms utilized for the control of real high-rise towers around the world are based on the optimal control theory. Thus, the LQR controller is adopted. Finally, the performance of the mass damper acting solely passively, i.e. as PTMD, will be presented in both scenarios.

As mentioned in Section 3.4, the DDPG will be implemented to control the forces of the system operating as an ATMD. This means that, the forces generated by the DDPG controlled actuators will be added on top of the passive forces generated by the oscillating mass.

Figure 4.4 shows the episode and average reward gained by the agent during its training process over a total of 5000 episodes. Every average reward was computed using 5 consecutive episode rewards. The DDPG is known to be a high-variance algorithm (Xie et al. (2021)) which does not guarantee the reward to be increasing monotonically. Thus, further saving criteria were introduced in the training process in order to investigate the performance of several agents by the end of the training. The pink region in Figure 4.4 demonstrates that, all agents that achieved a reward $\geq$ -50 were considered to be good candidates for the best performance and thus, they were saved for further investigation. After assessing the performance of the saved agents, the one with the best performance was selected for implementation.

When considering the DDPG hyperparameters, the critic learning rate was set to 10^{-3}, and the actor learning rate was set to 10^{-4}. It is noted that, the critic learning rate was chosen to be larger than the actor learning rate since, it is often observed that the actor is more sensitive to the learning rate and thus, it may require a smaller learning rate (Liessner et al. (2019)). As explained in Section 4.7, during training, the algorithm randomly draws a mini-batch of samples from a replay buffer and this is used to improve the algorithm stability. In this case, the mini-batch size was chosen as 64 which is proven large enough to minimise the variance when computing gradients without considerably increasing the computational effort (Sutton and Barto (1998)). The experience buffer that the mini-batches are randomly sampled from was set to

10^5. For the update of the actor and critic parameters, a smoothing update method was selected. Thus, the target smooth factor was chosen to be 0.001 and the target update frequency was set to 1. Termination of the episodes was also added (IsDone flag in Figure 4.3), when the maximum absolute displacement or acceleration on the top floor exceeded the corresponding uncontrolled value. As expected, the rewards were negative since, the selected reward function forced the DDPG to maximise a negative sum of structural displacements, accelerations and input forces. It is noted that, all simulations were carried out in MATLAB.

4.9.1 Nominal Model Results

As seen in Figure 4.5, both the DDPG and LQR controlled system managed to decrease the top floor displacement below the desired limit (200mm), in contrast to the PTMD and the uncontrolled structure. More specifically, the maximum absolute top floor displacement recorded by the DDPG and the LQR controlled schemes were 0.191m and 0.195m, respectively. In the case where the PTMD was used, the maximum absolute top floor displacement was 0.226m and for the uncontrolled case, the corresponding value was 0.248m. As it can be noticed, the DDPG and the LQR had a very similar performance since they managed to decrease the top floor displacement by $\approx$ 23% when compared to the uncontrolled case and by a further $\approx$ 15% when compared to the PTMD.

When considering the tower's dynamic accelerations, the DDPG managed a dissipation of up to 32%. More specifically, the maximum absolute top floor acceleration in the uncontrolled case was 0.203m/s^2 where, in the active case controlled by the DDPG was 0.138m/s^2. The LQR managed to decrease the top floor dynamic acceleration to 0.142m/s^2. In the case where the PTMD was used, the dynamic accelerations were decreased to 0.171m/s^2. To achieve its performance, the DDPG satisfied the control constraint introduced during its design process as seen in Figure 4.6. The performance of the two algorithms was further compared by considering the actuator displacement and velocity. As seen in Figure 4.7, the DDPG handled the actuator displacement and velocity in a more efficient manner than the LQR. More specifically, the maximum actuator displacement and velocity when the DDPG was used were 0.549m and 0.449m/s, respectively while, when the LQR was used the corresponding values were 0.858m and 0.739m/s, respectively.

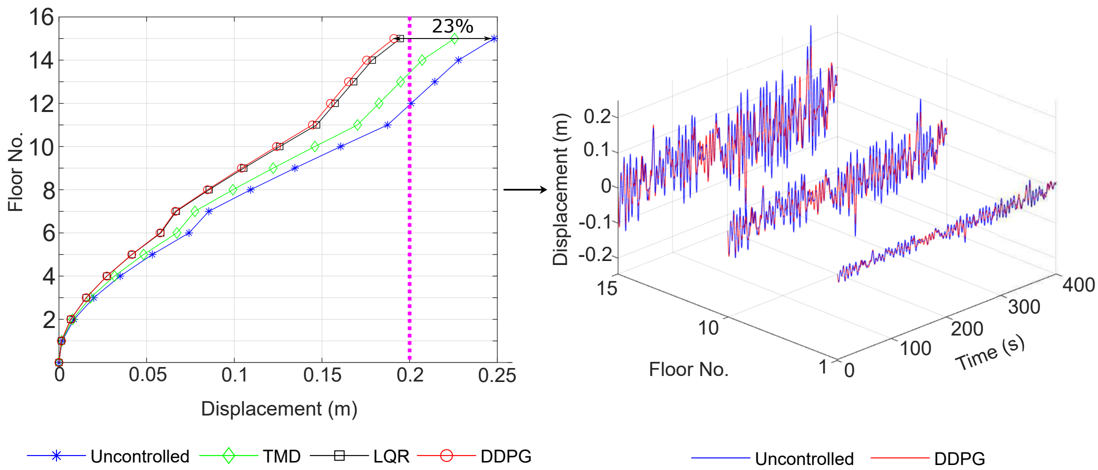


Figure 4.5: Displacement responses of the uncontrolled case and the case with DDPG controller

Figure 4.8 shows the power consumed by the system along with the absolute energy consumption. It is noted that, the negative value convention shown in this Figure represents dissipative power. The power was calculated using, Power= $\dot{q}_{ac} \cdot u(t)$ where, $\dot{q}_{ac}$ is the actuator velocity (Yang et al. (2004a)), and the energy consumption was calculated by integrating the absolute power over time. Thus this cumulative energy figure, when reviewed alone, does not distinguish between adding or extracting energy from the mass damper, and it does not also account for any additional hardware energy loses (e.g. see actuator efficiency rating). The maximum power consumption required by the DDPG controlled mass damper was 14.3kW. Moreover, the DDPG controlled system required a total of 6.6MJ. In the case where the LQR was used, for the period studied, the maximum power consumption was 22.3kW and the total energy required by the system was 7.45MJ, as shown in Figure 4.8. As it can be noticed, the DDPG achieved its performance by requiring a 35.9% lower maximum absolute power and 11.4% lower energy consumption when compared to the LQR.

4.9.2 Parametric Uncertainty

This section investigates the robustness of the DDPG agent in the case where stiffness and damping uncertainty was set to −10%. As seen in Figure 4.9, the maximum

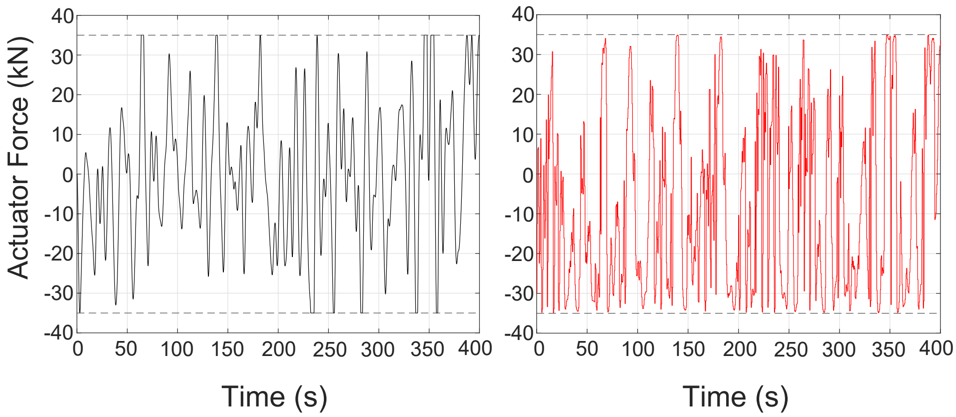


Figure 4.6: LQR (left) and DDPG (right) actuator force

absolute uncontrolled displacement was 0.274m where, in the DDPG controlled case was 0.229m. As it can be noticed, the top floor displacement exceeded the desired limit however, the algorithm demonstrated robustness since, the displacement was reduced by 16.4%. The LQR also did not manage to keep the top floor displacements within the desired limit (top floor displacement of 0.224m) even though it had a slightly better performance than the DDPG. As expected, the PTMD did not manage to keep the top floor displacement within the desired limit since, the maximum top floor displacement with the PTMD was 0.265m corresponding to a reduction of only 3.3%. It is noticed that, even with the actuator capacity limitation, the DDPG had a better performance than the PTMD with a 13.2% reduction in displacements. Moreover, as seen in Figure 4.9, in the uncontrolled case, the last five floors, i.e. 11-15, exceeded the desired tolerance limit in contrast to when the PTMD was used where the last four floors, i.e. 12-15, exceeded the desired limit. When the DDPG and LQR controlled ATMD was used, only the last two floors, i.e. 14-15, exceeded the limit. The fact that, even the actively controlled PTMD did not manage to keep the dynamic displacements within the desired limit underlines even more the small actuator capacity of the equipped system as discussed in Section 3.4 since, the agent reached the maximum allowable actuator output force (see Figure 4.10) using both algorithms. The DDPG again, handled the actuator displacement and velocity more efficiently than the LQR. As seen in Figure 4.11, the maximum actuator displacement and velocity of the DDPG were 0.622m and 0.525m/s, respectively, and using the LQR were 0.846m and 0.885m/s,

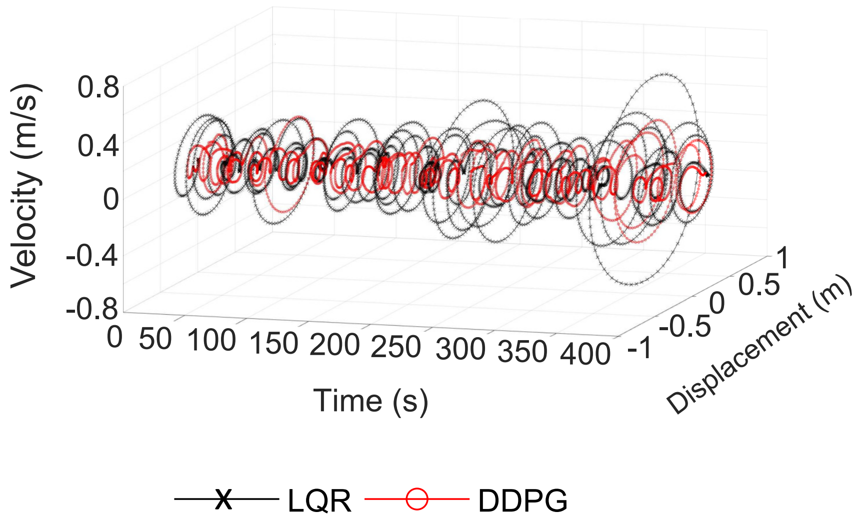


Figure 4.7: Actuator displacement and velocity for the LQR and DDPG controlled schemes

respectively.

The DDPG agent managed to reduce the dynamic top floor accelerations up to 22.3%. More specifically, in the uncontrolled case the maximum absolute acceleration was 0.202m/s^2 where, in the DDPG controlled case the corresponding value was 0.157m/s^2. The LQR had a similar performance to the DDPG algorithm. The maximum absolute top floor acceleration recorded was 0.154m/s^2. Finally, the PTMD managed to decrease the dynamic accelerations up to 9.4% (0.183m/s^2).

To achieve its performance, the DDPG agent achieved a maximum power consumption of 15.7kW and required a total energy of 7.42MJ, as seen in Figure 4.12. The LQR required a maximum power consumption of 25.2kW and a total energy consumption of 9.65MJ. As it can be noticed, the DDPG had required a considerably lower power and energy in order to achieve its performance. More specifically, the power and energy requirements of the DDPG in the parametric uncertain scenario were lower than the corresponding ones of the LQR in the nominal scenario. Overall, the DDPG had better performance than the LQR when considering all the parameters that were investigated within this study (i.e. dynamic displacement and acceleration dissipation, actuator displacement, velocity, power and energy consumption). Figure 4.13 includes a summary of the analysis results in relation to the parameters considered herein (i.e.

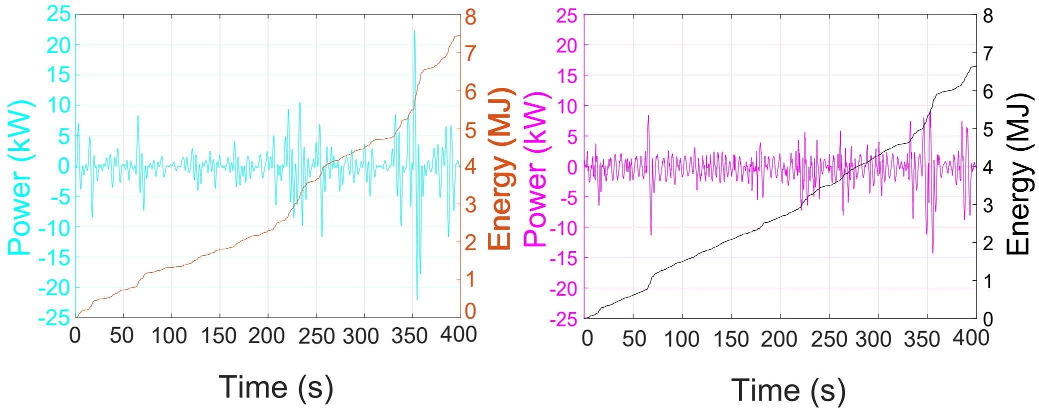


Figure 4.8: Power and energy consumption for the LQR (left) and DDPG (right) controlled schemes

displacement, acceleration, actuator saturation, displacement, velocity, power and energy consumption) for the nominal (left) and parametric uncertain (right) scenarios.

4.10 Conclusions

In this paper, a DDPG reinforcement learning algorithm was investigated for the control of a real high-rise tower equipped with a HMD. For the simulations of this work, only the passive and active capabilities of the HMD were considered making it essentially a PTMD and an ATMD, respectively. The DDPG is a model-free off-policy reinforcement learning algorithm which operates within a continuous action space. The DDPG agent was trained for 5000 episodes with the provided environment (Figure 4.4). To account for parametric uncertainties that could occur due to environmental effects, cumulative ageing, and major modelling errors, the robustness of the DDPG agent was important to be evaluated. An uncertain parametric scenario was carried out where, a -10% stiffness and damping uncertainty was introduced. For all cases, a 0.200m top floor displacement limitation was initially introduced for operational purposes of the tower. Moreover, the hard input constraint of 35kN was set during the design process of the DDPG agent to satisfy the relatively small capacity of the installed actuators. For comparison purposes, the performance of the system operating using an LQR and acting as a PTMD was demonstrated.

The simulations using the nominal model of the tower showed that, the DDPG

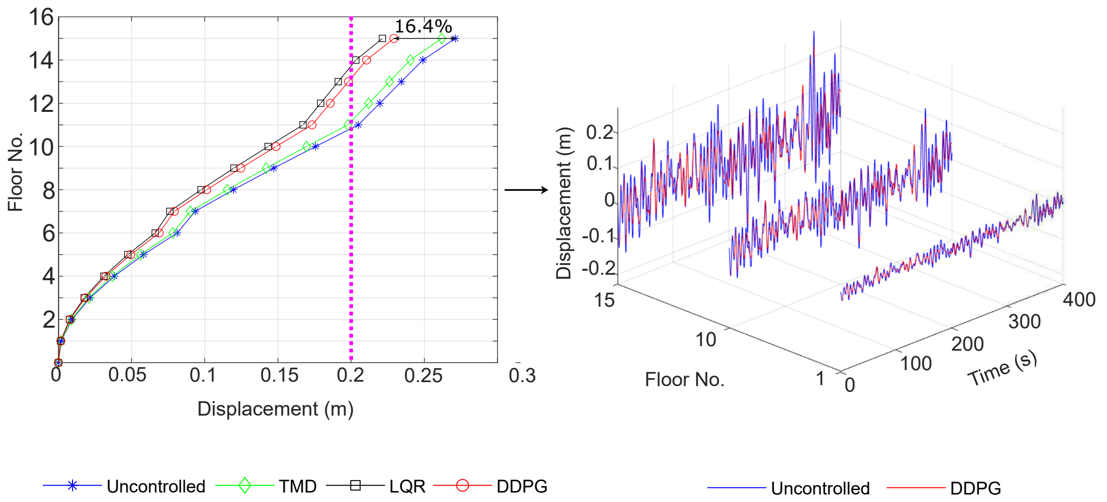


Figure 4.9: Displacement responses of the uncontrolled case and the case with DDPG controller with parametric uncertainty

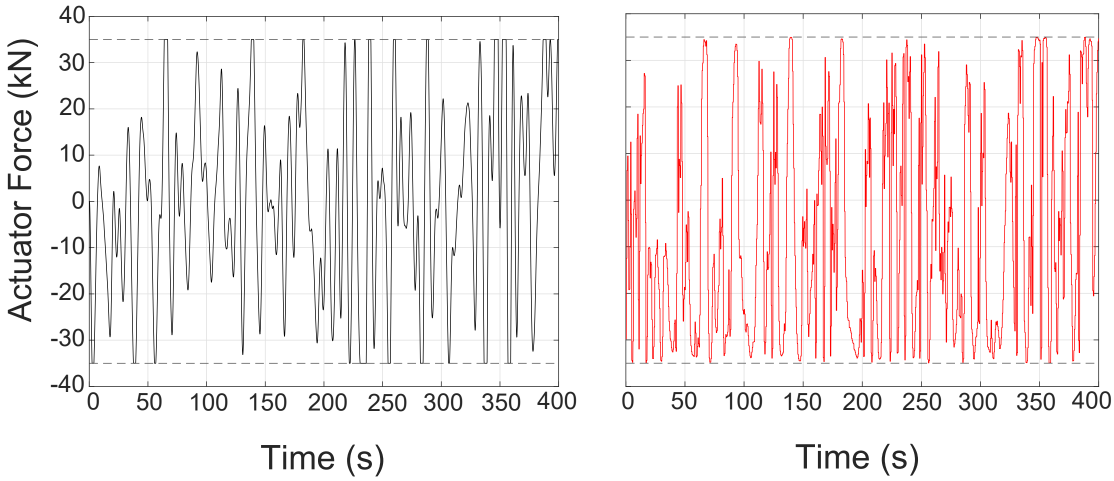


Figure 4.10: Actuator force and saturation factor for the LQR (left) and DDPG (right) controlled schemes with parametric uncertainty

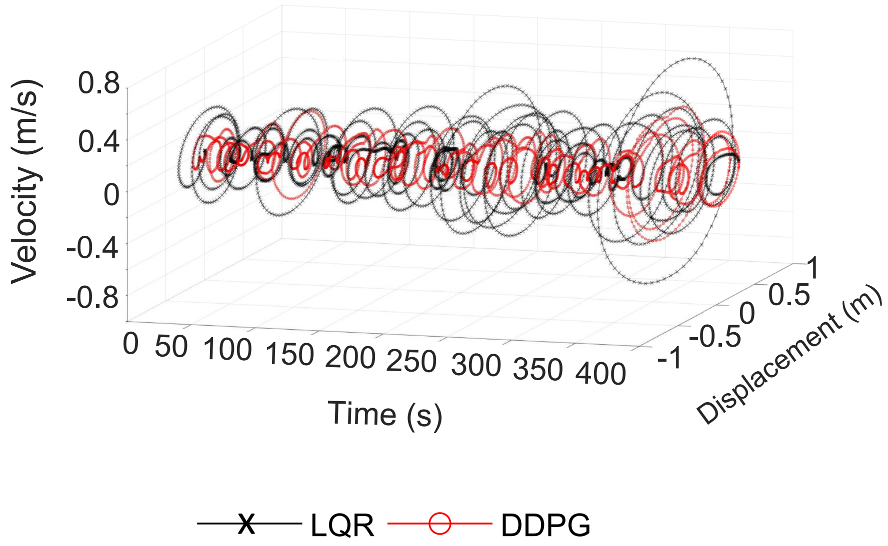


Figure 4.11: Actuator displacement and velocity for the LQR and DDPG controlled schemes with parametric uncertainty

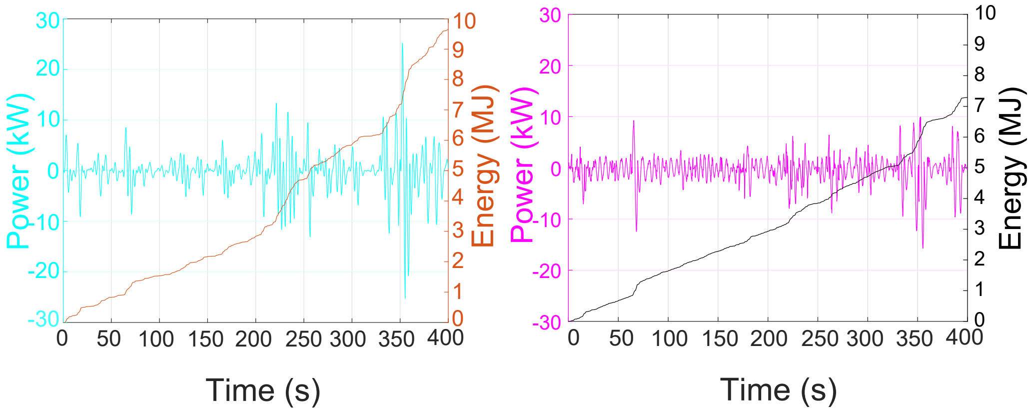


Figure 4.12: Power and energy consumption for the LQR (left) and DDPG (right) controlled schemes with parametric uncertainty

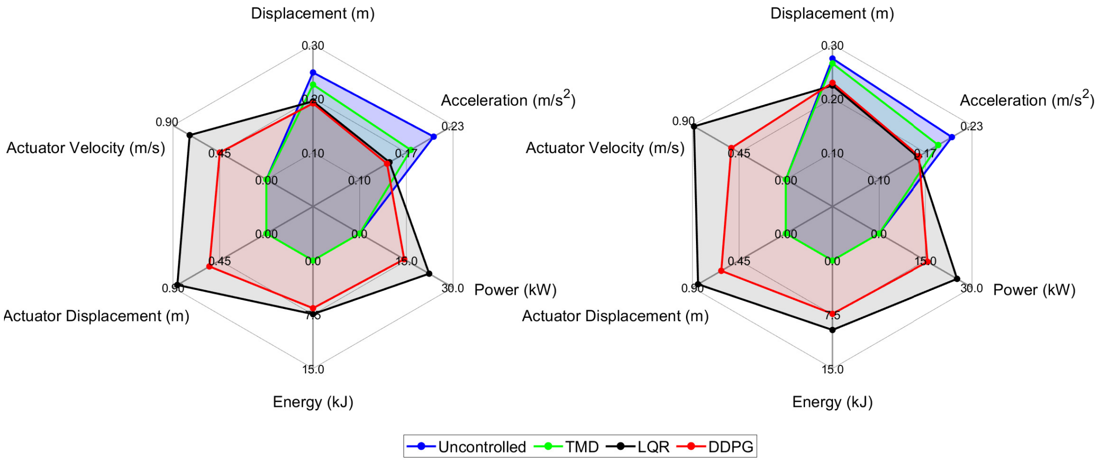


Figure 4.13: Total performance of all control schemes for the case without parameter uncertainties (left) and for the case with -10% stiffness and damping uncertainties (right)

agent had a better performance than the LQR and it managed to reduce the dynamic displacements of the tower by up to 23% where, the PTMD achieved a reduction only by up to 8.9%. Moreover, the maximum absolute top floor displacement in the DDPG controlled case was 0.191m and in the LQR controlled case was 0.195m which both satisfy the limitation that was initially set (0.200m) where, in the case with the PTMD exceeded the desired limit since it achieved a maximum absolute top floor displacement of 0.226m. The DDPG agent achieved a 32% acceleration reduction at the top floor of the tower (from 0.203m/s^2 in the uncontrolled case to 0.138m/s^2), the LQR achieved a reduction of 30% with a maximum value at the top floor of 0.142m/s^2, and the PTMD achieved a reduction of 15.8% with a maximum top floor acceleration of 0.171m/s^2. To achieve its performance, the DDPG controlled mass damper required a maximum power consumption of 14.3kW and a total energy of 6.6MJ where, the LQR required a maximum power consumption of 22.3kW and a total energy of 7.45MJ.

When the parametric uncertainty was introduced, the DDPG agent demonstrated robustness since, it managed to decrease both the dynamic displacements and accelerations of the tower. Moreover, this scenario highlighted the small actuator capacity of the installed system. More specifically, the DDPG agent managed to decrease the dynamic displacements of the tower in the presence of uncertainty by up to 16.4% (from 0.274m in the uncontrolled case to 0.229m on the top floor) and the dynamic accelerations by up to 22.3% (from 0.202m/s^2 in the uncontrolled case to 0.157m/s^2 on the top floor). The LQR had a similar performance in the dissipation of the dynamic displacements when compared to the DDPG since it achieved a maximum absolute top floor displacement of 0.224m and a maximum absolute top floor acceleration of 0.154m/s^2. The PTMD achieved a dynamic displacement reduction by only up to 3.3% and dynamic acceleration reduction by only up to 9.4%. When considering the top floor accelerations, the PTMD achieved a maximum absolute acceleration of 0.183m/s^2. As it can be noticed, the maximum absolute displacement in the DDPG and LQR controlled cases exceeded the initially set limit (0.200m). This is the effect of the small capacity of the installed actuators and the relatively small mass. Even though the DDPG agent and the LQR reached the maximum allowable force (±35kN) and consumed a maximum power 15.7kW and 25.2kW, respectively, and a total energy of 7.42MJ and 9.65MJ, respectively, they still did not manage to keep the dynamic top floor displacements within the desired limit.

It is concluded that the DDPG is an efficient algorithm for structural control and demonstrates robustness against parametric uncertainties. In this work, it was presented that, the current DDPG had a better overall performance than the LQR algorithm and the PTMD as exemplified in Figure 4.13.

Future work involves (i) investigation of different reward functions on how they influence the performance of the DDPG, (ii) implementation of different reinforcement learning algorithms and assessment of their performance, (iii) study the performance of the DDPG with different loading conditions and, (iv) introduction of a new hybrid way of operation in contrast to the current (always on passive system and adding active forces on top of the passive) by using reinforcement learning to control the HMD in a combined passive, semi-active and active mode of operation to optimise the reduction of the energy consumption of the system.

References

A. Acampora, J. H. Macdonald, C. T. Georgakis, and N. Nikitas. Identification of aeroelastic forces and static drag coefficients of a twin cable bridge stay from full-scale ambient vibration measurements. *Journal of Wind Engineering and Industrial Aerodynamics*, 124:90–98, 2014. ISSN 01676105. doi: 10.1016/j.jweia.2013.10.009. URL http://dx.doi.org/10.1016/j.jweia.2013.10.009.

J. Achiam. Spinning up in deep reinforcement learning, 2018. URL https://spinningup.openai.com/.

H. Aggumus and R. Guclu. Robust H∞ control of STMDs used in structural systems by hardware in the loop simulation method. *Actuators*, 9(3), 2020. ISSN 20760825. doi: 10.3390/ACT9030055.

M. Almutairi, N. Nikitas, O. Abdeljaber, O. Avci, and M. Bocian. A methodological approach towards evaluating structural damage severity using 1D CNNs. *Structures*, 34(September):4435–4446, 2021. ISSN 23520124. doi: 10.1016/j.istruc.2021.10.029. URL https://doi.org/10.1016/j.istruc.2021.10.029.

M. Battaini, F. Casciati, and L. Faravelli. Implementing a fuzzy controller into an active mass damper device. *Proceedings of the American Control Conference*, 2(June):888–892, 1997. ISSN 07431619. doi: 10.1109/acc.1997.609654.

M. Battaini, F. Casciati, and L. Faravelli. Fuzzy control of structural vibration. An active mass system driven by a fuzzy controller. *Earthquake Engineering and Structural Dynamics*, 27(11):1267–1276, 1998. ISSN 00988847. doi: 10.1002/(SICI)1096-9845(1998110)27:11⟨1267::AID-EQE782⟩3.0.CO;2-D.

G. Bekdas and S. M. Nigdeli. Estimating optimum parameters of tuned mass dampers using harmony search. *Engineering Structures*, 33(9):2716–2723, 2011. ISSN 01410296. doi: 10.1016/j.engstruct.2011.05.024. URL http://dx.doi.org/10.1016/j.engstruct.2011.05.024.

G. Brockman, V. Cheung, L. Pettersson, J. Schneider, J. Schulman, J. Tang, and W. Zaremba. OpenAI Gym. *arXiv preprint*, 2016.

O. T. Burgos, J. R. E. Hizon, and L. G. Sison. Comparison of classical and fuzzy control in active mass damping of a flexible structure using acceleration feedback. *IEEE Region 10 Annual International Conference, Proceedings/TENCON*, D, 2004. doi: 10.1109/tencon.2004.1415015.

H. Cao, A. M. Reinhorn, and T. T. Soong. Design of an active mass damper for a tall TV tower in Nanjing, China. *Engineering Structures*, 20(3):134–143, 1998. ISSN 01410296. doi: 10.1016/S0141-0296(97)00072-2.

G. Carlo Marano, R. Greco, and B. Chiaia. A comparison between different optimization criteria for tuned mass dampers design. *Journal of Sound and Vibration*, 329(23):4880–4890, 2010. ISSN 0022460X. doi: 10.1016/j.jsv.2010.05.015. URL http://dx.doi.org/10.1016/j.jsv.2010.05.015.

F. Casciati, L. Faravelli, and T. Yao. Application of fuzzy logic to active structural control. *Second European Coni. on Smart Structures and Materials*, pages 206–209, 1994.

F. Casciati, L. Faravelli, and T. Yao. Control of nonlinear structures using the fuzzy control approach. *Nonlinear Dynamics*, 11(2):171–187, 1996. ISSN 0924090X. doi: 10.1007/BF00045000.

F. Casciati, J. Rodellar, and U. Yildirim. Active and semi-active control of structures-theory and applications: A review of recent advances. *Journal of Intelligent Material Systems and Structures*, 23(11):1181–1195, 2012. ISSN 1045389X. doi: 10.1177/1045389X12445029.

G. Chase, A. Smith, and T. Suzuki. Robust H∞ Control Considering Aactuator Saturation. II: Applications. *Journal of Engineering Mechanics*, 122(10):984–993, 1996.

Y. Chen, W. Zhang, and H. Gao. Finite frequency H∞ control for building under earthquake excitation. *Mechatronics*, 20(1):128–142, 2010. ISSN 09574158. doi: 10.

1016/j.mechatronics.2009.11.001. URL http://dx.doi.org/10.1016/j.mechatronics.2009.11.001.

Y. Chen, S. Zhang, H. Peng, B. Chen, and H. Zhang. A novel fast model predictive control for large-scale structures. *JVC/Journal of Vibration and Control*, 23(13): 2190–2205, 2017. ISSN 17412986. doi: 10.1177/1077546315610033.

T. Datta. A state-of-the-art review on active control of structures. *ISET Journal of earthquake technology*, 40(1):1–17, 2003. ISSN 0972-0405.

D. Demetriou and N. Nikitas. A novel hybrid semi-active mass damper configuration for structural applications. *Applied Sciences (Switzerland)*, 6(12), 2016. ISSN 20763417. doi: 10.3390/app6120397.

D. Demetriou, N. Nikitas, and K. D. Tsavdaridis. Semi active tuned mass dampers of buildings: A simple control option. *American Journal of Engineering and Applied Sciences*, 8(4):620–632, 2015. ISSN 19417039. doi: 10.3844/ajeassp.2015.620.632.

D. Demetriou, N. Nikitas, and K. D. Tsavdaridis. Performance of fixed-parameter control algorithms on high-rise structures equipped with semi-active tuned mass dampers. *The Structural Design of Tall and Special Buildings*, 25:340–354, 2016. doi: 10.1002/tal.

S. L. Djajakesukma, B. Samali, and H. Nguyen. Study of a semi-active stiffness damper under various earthquake inputs. *Earthquake Engineering and Structural Dynamics*, 31(10):1757–1776, 2002. ISSN 00988847. doi: 10.1002/eqe.181.

S. Elias and V. Matsagar. Research developments in vibration control of structures using passive tuned mass dampers. *Annual Reviews in Control*, 44:129–156, 2017. ISSN 13675788. doi: 10.1016/j.arcontrol.2017.09.015. URL https://doi.org/10.1016/j.arcontrol.2017.09.015.

S. S. Eshkevari, S. S. Eshkevari, D. Sen, and S. N. Pakzad. RL-Controller: a reinforcement learning framework for active structural control. *arXiv preprint*, 2021. URL http://arxiv.org/abs/2103.07616.

S. Etedali and S. Tavakoli. PD/PID Controller Design for Seismic Control of High-Rise Buildings Using Multi-Objective Optimization: A Comparative Study with LQR

Controller. *Journal of Earthquake and Tsunami*, 11(3):1–23, 2017. ISSN 17937116. doi: 10.1142/S1793431117500099.

N. R. Fisco and H. Adeli. Smart structures: Part I - Active and semi-active control. *Scientia Iranica*, 18(3 A):275–284, 2011a. ISSN 10263098. doi: 10.1016/j.scient.2011.05.034. URL http://dx.doi.org/10.1016/j.scient.2011.05.034.

N. R. Fisco and H. Adeli. Smart structures: Part II - Hybrid control systems and control strategies. *Scientia Iranica*, 18(3 A):285–295, 2011b. ISSN 10263098. doi: 10.1016/j.scient.2011.05.035. URL http://dx.doi.org/10.1016/j.scient.2011.05.035.

A. Forrai, S. Hashimoto, H. Funato, and K. Kamiyama. Robust active vibration suppression control with constraint on the control signal: Application to flexible structures. *Earthquake Engineering and Structural Dynamics*, 32(11):1655–1676, 2003. ISSN 00988847. doi: 10.1002/eqe.293.

H. Gao, W. He, Y. Zhang, and C. Sun. Vibration Control based on Reinforcement Learning for a Flexible Building-like Structure System with Active Mass Damper against Disturbance Effects. *Proceedings of the IEEE Conference on Decision and Control*, (Cdc):2380–2385, 2020. ISSN 07431546. doi: 10.1109/CDC42340.2020.9304455.

T. Gellrich, Y. Min, S. Schwab, and S. Hohmann. Model-free control design for loop heat pipes using deep deterministic policy gradient. *IFAC-PapersOnLine*, 53(2019):1575–1580, 2020. ISSN 24058963. doi: 10.1016/j.ifacol.2020.12.2190.

A. K. Ghorbani-Tanha, A. Noorzad, and M. Rahimian. Mitigation of wind-induced motion of Milad Tower by tuned mass damper. *Structural Design of Tall and Special Buildings*, 18(4):371–385, 2009. ISSN 15417794. doi: 10.1002/tal.421.

M. Gutierrez Soto and H. Adeli. Tuned Mass Dampers. *Archives of Computational Methods in Engineering*, 20(4):419–431, 2013. ISSN 11343060. doi: 10.1007/s11831-013-9091-7.

T. Haarnoja, A. Zhou, P. Abbeel, and S. Levine. Soft actor-critic: Off-policy maximum entropy deep reinforcement learning with a stochastic actor, 2018.

Y. Ikeda. Effect of weighting a stroke of an Active Mass Damper in the linear quadratic regulator problem. *Earthquake Engineering and Structural Dynamics*, 26(11):

1125–1136, 1997. ISSN 00988847. doi: 10.1002/(SICI)1096-9845(199711)26:11⟨1125::AID-EQE697⟩3.0.CO;2-N.

H.-R. Ji, Y.-J. Moon, C.-H. Kim, and I.-W. Lee. Structural Vibration Control Using Semiactive Tuned Mass Damper. *The Eighteenth KKCNN Symposium on Civil Engineering*, 2005.

B. Jiang, X. Wei, and Y. Guo. Liner quadratic optimal control in active control of structural vibration systems. *2010 Chinese Control and Decision Conference, CCDC 2010*, (2):3546–3551, 2010. doi: 10.1109/CCDC.2010.5498552.

H. J. Jung, B. F. Spencer, Y. Q. Ni, and I. W. Lee. State-of-the-art of semiactive control systems using MR fluid dampers in civil engineering applications. *Structural Engineering and Mechanics*, 17(3-4):493–526, 2004. ISSN 12254568. doi: 10.12989/sem.2004.17.3_4.493.

J. Kang, H.-S. Kim, and D.-G. Lee. Mitigation of wind response of a tall building using semi-active tuned mass dampers. *The Structural Design of Tall and Special Buildings*, 20:552–565, 2011. doi: 10.1002/tal.

A. E. Kayabekir, G. Bekdas, S. M. Nigdeli, and Z. W. Geem. Optimum design of PID controlled active tuned mass damper via modified harmony search. *Applied Sciences (Switzerland)*, 10(8), 2020. ISSN 20763417. doi: 10.3390/APP10082976.

A. Khalatbarisoltani, M. Soleymani, and M. Khodadadi. Online control of an active seismic system via reinforcement learning. *Structural Control and Health Monitoring*, 26(3):1–18, 2019. ISSN 15452263. doi: 10.1002/stc.2298.

S. Korkmaz. A review of active structural control: Challenges for engineering informatics. *Computers and Structures*, 89(23-24):2113–2132, 2011. ISSN 00457949. doi: 10.1016/j.compstruc.2011.07.010. URL http://dx.doi.org/10.1016/j.compstruc.2011.07.010.

L. Koutsoloukas, N. Nikitas, P. Aristidou, and C. Meinhardt. Control law and actuator capacity effect on the dynamic performance of a hybrid mass damper; the case of rottweil tower. *Proceedings of the International Conference on Structural Dynamic , EURODYN*, 1:1422–1432, 2020. ISSN 23119020. doi: 10.47964/1120.9115.19241.

L. Koutsoloukas, N. Nikitas, and P. Aristidou. Robust structural control of a real high-rise tower using a hybrid mass damper. *Structural Design of Tall and Special Buildings*, 31(12):e1941, 2022a. doi: 10.1002/tal.1941.

L. Koutsoloukas, N. Nikitas, and P. Aristidou. Passive, Semi-Active, Active and Hybrid Mass Dampers: A Literature Review with Associated Applications. *Developments in the Built Environment*, 12:100094, 2022b. ISSN 2666-1659. doi: 10.1016/j.dibe.2022.100094. URL https://doi.org/10.1016/j.dibe.2022.100094.

A. Lago, D. Trabucco, and A. Wood. *Damping Technologies for Tall Buildings*. 2019. ISBN 9780128159637. doi: 10.1016/b978-0-12-815963-7.00001-4.

M. Lezgy-Nazargah, A. Elahi, and M. Pakizeh Tali. H∞ control method for seismically excited building structures with time-delay. *JVC/Journal of Vibration and Control*, 26(11-12):865–884, 2020. ISSN 17412986. doi: 10.1177/1077546319890010.

Z. Li, S. Zuo, and Y. Liu. Fuzzy sliding mode control for smart structure with ATMD. *Proceedings of the 33rd Chinese Control Conference, CCC 2014*, pages 21–25, 2014. ISSN 21612927. doi: 10.1109/ChiCC.2014.6896589.

R. Liessner, J. Schmitt, A. Dietermann, and B. Bernard. Hyperparameter Optimization for Deep Reinforcement Learning in Vehicle Energy Management. *ICAART*, 2:134–144, 2019. doi: 10.5220/0007364701340144.

T. Lillicrap, J. Hunt, A. Pritzel, N. Heess, T. Erez, Y. Tassa, D. Silver, and D. Wierstra. Continuous control with deep reinforcement learning. *arXiv:1509.02971*, 2015. ISSN 1935-8237.

C. W. Lim, Y. J. Park, and S. J. Moon. Robust saturation controller for linear time-invariant system with structured real parameter uncertainties. *Journal of Sound and Vibration*, 294(1-2):1–14, 2006. ISSN 10958568. doi: 10.1016/j.jsv.2005.10.020.

C. C. Lin, C. M. Hu, J. F. Wang, and R. Y. Hu. Vibration control effectiveness of passive tuned mass dampers. *Journal of the Chinese Institute of Engineers, Transactions of the Chinese Institute of Engineers,Series A/Chung-kuo Kung Ch'eng Hsuch K'an*, 17(3):367–376, 1994. ISSN 21587299. doi: 10.1080/02533839.1994.9677600.

T. Liu, Z. Tan, C. Xu, H. Chen, and Z. Li. Study on deep reinforcement learning techniques for building energy consumption forecasting. *Energy and Buildings*, 208, 2020. ISSN 03787788. doi: 10.1016/j.enbuild.2019.109675.

F. Lopez-Almansa, R. Andrade, J. Rodellar, and A. M. Reinhorn. Modal predictive control of structures. II: Implementation. *Journal of Engineering Mechanics*, 120(8): 1761–1772, 1994. ISSN 07339399. doi: 10.1061/(ASCE)0733-9399(1994)120:8(1743).

F. Lopez-Almansa, R. Andrade, J. Rodellar, and A. M. Reinhorn. Modal predictive control of structures. I: Formulation. *Journal of Engineering Mechanics*, 120(8): 1743–1760, 1995.

N. S. Manjarekar and P. M. Singru. A Study of H infinity and H2 synthesis for Active Vibration Control. *IFAC-PapersOnLine*, 49(1):623–628, 2016. ISSN 2405-8963. doi: 10.1016/j.ifacol.2016.03.125. URL http://dx.doi.org/10.1016/j.ifacol.2016.03.125.

W. Masson, P. Ranchod, and G. Konidaris. Reinforcement learning with parameterized actions. *30th AAAI Conference on Artificial Intelligence, AAAI 2016*, pages 1934–1940, 2016.

G. Mei, A. Kareem, and J. C. Kantor. Model Predictive Control For Wind Excited Buildings : A Benchmark Problem. *14th Engineering Mechanics Conference*, 2000.

G. Mei, A. Kareem, and J. C. Kantor. Real-time model predictive control of structures under earthquakes. *Earthquake Engineering and Structural Dynamics*, 30(7):995–1019, 2001. ISSN 00988847. doi: 10.1002/eqe.49.

G. Mei, A. Kareem, and J. C. Kantor. Model predictive control of structures under earthquakes using acceleration feedback. *Journal of Engineering Mechanics*, 128(5): 574–585, 2002. ISSN 07339399. doi: 10.1061/(ASCE)0733-9399(2002)128:5(574).

G. Mei, A. Kareem, and J. C. Kantor. Model Predictive Control of Wind-Excited Building: Benchmark Study. *Journal of engineering mechanics*, pages 459–465, 2004. doi: 10.1061/(ASCE)0733-9399(2004)130. URL http://link.aip.org/link/?JENMDT/130/1195/1.

M. S. Miah, E. N. Chatzi, and F. Weber. Semi-active control for vibration mitigation of structural systems incorporating uncertainties. *Smart Materials and Structures*, 24(5):55016, 2015. ISSN 1361665X. doi: 10.1088/0964-1726/24/5/055016. URL http://dx.doi.org/10.1088/0964-1726/24/5/055016.

V. Mnih, K. Kavukcuoglu, D. Silver, A. A. Rusu, J. Veness, M. G. Bellemare, A. Graves, M. Riedmiller, A. K. Fidjeland, G. Ostrovski, S. Petersen, C. Beattie, A. Sadik, I. Antonoglou, H. King, D. Kumaran, D. Wierstra, S. Legg, and D. Hassabis. Human-level control through deep reinforcement learning. *Nature*, 518(7540):529–533, 2015. ISSN 14764687. doi: 10.1038/nature14236. URL http://dx.doi.org/10.1038/nature14236.

P. Nagarajan, G. Warnell, and P. Stone. Deterministic Implementations for Reproducibility in Deep Reinforcement Learning, 2018. URL http://arxiv.org/abs/1809.05676.

I. Nagashima and Y. Shinozaki. Variable gain feedback control technique of active mass damper and its application to hybrid structural control. *Earthquake Engineering and Structural Dynamics*, 26(8):815–838, 1997. ISSN 00988847. doi: 10.1002/(SICI)1096-9845(199708)26:8⟨815::AID-EQE678⟩3.0.CO;2-E.

R. Nian, J. Liu, and B. Huang. A review On reinforcement learning: Introduction and applications in industrial process control. *Computers and Chemical Engineering*, 139:106886, 2020. ISSN 00981354. doi: 10.1016/j.compchemeng.2020.106886. URL https://doi.org/10.1016/j.compchemeng.2020.106886.

N. Nikitas, J. H. Macdonald, and J. B. Jakobsen. Identification of flutter derivatives from full-scale ambient vibration measurements of the Clifton Suspension Bridge. *Wind and Structures*, 14(3):221–238, 2011. ISSN 12266116. doi: 10.12989/was.2011.14.3.221.

A. Nishitani and Y. Inoue. Overview of the application of active/semiactive control to building structures in Japan. *Earthquake Engineering and Structural Dynamics*, 30(11):1565–1574, 2001. ISSN 00988847. doi: 10.1002/eqe.81.

M. V. Otterlo and M. Wiering. Reinforcement Learning and Markov Decision Processes. In *Reinforcement Learning*, pages 3–42. Springer Berlin Heidelberg, 2012.

J. Ou and H. Li. Analysis of capability for semi-active or passive damping systems to achieve the performance of active control systems. *Structural Control and Health Monitoring*, 17:778–794, 2010. doi: 10.1002/stc.

S.-K. Park and H. Y. Noh. Updating Structural Parameters with Spatially Incomplete Measurements Using Subspace System Identification. *Journal of Engineering Mechanics*, 143(7):04017040, 2017. ISSN 0733-9399. doi: 10.1061/(asce)em.1943-7889.0001226.

PEER Center. PEER Ground Motion Database. URL https://ngawest2.berkeley.edu/.

H. Peng, F. Li, S. Zhang, and B. Chen. A novel fast model predictive control with actuator saturation for large-scale structures. *Computers and Structures*, 187:35–49, 2017. ISSN 00457949. doi: 10.1016/j.compstruc.2017.03.014. URL http://dx.doi.org/10.1016/j.compstruc.2017.03.014.

H. Peng, F. Li, and Z. Kan. A novel distributed model predictive control method based on a substructuring technique for smart tensegrity structure vibrations. *Journal of Sound and Vibration*, 471:115171, 2020. ISSN 10958568. doi: 10.1016/j.jsv.2020.115171. URL https://doi.org/10.1016/j.jsv.2020.115171.

J. Peng and R. J. Williams. *Incremental multi-step Q-learning*, volume 8. Morgan Kaufmann Publishers, Inc., 1994. doi: 10.1016/b978-1-55860-335-6.50035-0. URL http://dx.doi.org/10.1016/B978-1-55860-335-6.50035-0.

J. Peters, S. Vijayakumar, and S. Schaal. Reinforcement learning for humanoid robotics. *Third IEEE-RAS International Conference on Humanoid Robots*, 2003. doi: 10.1109/NEUREL.2006.341182.

A. S. Polydoros and L. Nalpantidis. Survey of Model-Based Reinforcement Learning: Applications on Robotics. *Journal of Intelligent and Robotic Systems: Theory and Applications*, 86(2):153–173, 2017. ISSN 15730409. doi: 10.1007/s10846-017-0468-y. URL http://dx.doi.org/10.1007/s10846-017-0468-y.

S. Pourzeynali, H. H. Lavasani, and A. H. Modarayi. Active control of high rise building structures using fuzzy logic and genetic algorithms. *Engineering Structures*, 29(3):346–357, 2007. ISSN 01410296. doi: 10.1016/j.engstruct.2006.04.015.

H. Radmard Rahmani, G. Chase, M. Wiering, and C. Könke. A framework for brain learning-based control of smart structures. *Advanced Engineering Informatics*, 42

(September):100986, 2019. ISSN 14740346. doi: 10.1016/j.aei.2019.100986. URL https://doi.org/10.1016/j.aei.2019.100986.

R. Rana and T. T. Soong. Parametric study and simplified design of tuned mass dampers. *Engineering Structures*, 20(3):193–204, 1998. ISSN 01410296. doi: 10.1016/S0141-0296(97)00078-3.

F. Ricciardelli, A. D. Pizzimenti, and M. Mattei. Passive and active mass damper control of the response of tall buildings to wind gustiness. *Engineering Structures*, 25(9):1199–1209, 2003. ISSN 01410296. doi: 10.1016/S0141-0296(03)00068-3.

J. Schulman. Optimizing Expectations: From Deep Reinforcement Learning to Stochastic Computation Graphs. 2016. URL https://escholarship.org/uc/item/98384265.

M. Setareh. Floor vibration control using semi-active tuned mass dampers. *Canadian Journal of Civil Engineering*, 29(1):76–84, 2002. ISSN 03151468. doi: 10.1139/l01-063.

D. Silver, G. Lever, N. Heess, T. Degris, D. Wierstra, and M. Riedmiller. Deterministic policy gradient algorithms. *31st International Conference on Machine Learning, ICML 2014*, 1:605–619, 2014.

M. P. Singh, S. Singh, and L. M. Moreschi. Tuned mass dampers for response control of torsional buildings. *Earthquake Engineering and Structural Dynamics*, 31(4):749–769, 2002. ISSN 00988847. doi: 10.1002/eqe.119.

T. T. Soong and B. F. Spencer. Active, semi-active and hybrid control of structures. *Bulletin of the New Zealand Society for Earthquake Engineering*, 33(3):387–402, 2002. ISSN 11749857. doi: 10.5459/bnzsee.33.3.387-402.

R. Sutton and A. Barto. *An introduction to reinforcement learning.* 1998. ISBN 9781609601652. doi: 10.4018/978-1-60960-165-2.ch004.

R. S. Sutton. Learning to Predict by the Methods of Temporal Differences. *Machine Learning*, 3:9–44, 1988. doi: 10.1016/b978-1-55860-200-7.50045-3.

C. Szepesvári. Algorithms for reinforcement learning. *Synthesis Lectures on Artificial Intelligence and Machine Learning*, 9:1–89, 2010. ISSN 19394608. doi: 10.2200/S00268ED1V01Y201005AIM009.

E. L. Thorndike. *Animal intelligence*. 1911. doi: 10.54302/mausam.v22i4.5030.

J. N. Tsitsiklis and B. Van Roy. Feature-based methods for large scale dynamic programming. *Machine Learning*, 22(1-3):59–94, 1996. ISSN 08856125. doi: 10.1007/BF00114724.

G. Uhlenbeck and L. Ornstein. On the Theory of the Brownian Motion. *Physical Review*, 36(5):823– 841, 1930. doi: 10.1103/physrev.36.823.

M. Vecerik, T. Hester, J. Scholz, F. Wang, O. Pietquin, B. Piot, N. Heess, T. Rothorl, T. Lampe, and M. Riedmiller. Leveraging Demonstrations for Deep Reinforcement Learning on Robotics Problems with Sparse Rewards. *arXiv preprint*, 2017.

S. Wang, D. Jia, and X. Weng. Deep Reinforcement Learning for Autonomous Driving, 2018. URL https://arxiv.org/abs/1811.11329v3.

X. Wang. Coarse-Fine Self-Learning Active Mass Damper for Frequency Tracking Vibration Control. *International Journal of Structural Stability and Dynamics*, 20 (2):1–16, 2020. ISSN 17936764. doi: 10.1142/S0219455420500248.

Y. Wang, J. P. Lynch, and K. H. Law. Decentralized H∞ controller design for large-scale civil structures. *Earthquake Engineering and Structural Dynamics*, 38:377–401, 2009. doi: 10.1002/eqe.

C. J. C. H. Watkins. Learning from delayed rewards, 1989. ISSN 09218890.

C. J. C. H. Watlkins. *Learning from delayed rewards*. PhD thesis, 1989.

L. Xie, Y. Miao, W. Sen, P. Blunsom, Z. Wang, C. Chen, A. Markham, and N. Trigoni. Learning with Stochastic Guidance for Robot Navigation. *IEEE Transactions on Neural Networks and Learning Systems*, 21(1):166–176, 2021.

J. N. Yang, A. K. Agrawal, B. Samali, and J.-C. Wu. Benchmark Problem for Response Control of Wind-Excited Tall Buildings. *Journal of engineering mechanics*, 130:437–446, 2004a.

J. N. Yang, S. Lin, and F. Jabbari. H∞-based control strategies for civil engineering structures. *Structural Control and Health Monitoring*, 11(3):223–237, 2004b. ISSN 15452255. doi: 10.1002/stc.38.

C. Yuan and M. Fathi. Reinforcement Learning: Beyond the Basal Ganglia. In *Bridging Human Intelligence and Artificial Intelligence*, pages 235–243. Springer, 2022. ISBN 9783030847296. doi: 10.1007/978-3-030-84729-6_16.

R. Yuan, Y. Yang, C. Su, S. Hu, H. Zhang, and E. Cao. Research on Vibration Reduction Control Based on Reinforcement Learning. *Advances in Civil Engineering*, 2021, 2021.

M. Yucel, G. BekdaÅŸ, S. M. Nigdeli, and S. Sevgen. Estimation of optimum tuned mass damper parameters via machine learning. *Journal of Building Engineering*, 26:100847, 2019. ISSN 23527102. doi: 10.1016/j.jobe.2019.100847. URL https://doi.org/10.1016/j.jobe.2019.100847.

J. Zhang, X. Zhao, and X. Wei. Reinforcement Learning-Based Structural Control of Floating Wind Turbines. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, pages 1–11, 2020. ISSN 21682232. doi: 10.1109/TSMC.2020.3032622.

Chapter 5

A Reinforcement Learning Controlled Novel Mode-Switching Hybrid Mass Damper

Chapter Outline: Chapters 3 and 4 investigated the use of different controllers in the vibration dissipation of a case-study tower and assessed them using various performance measures. One of the main performance measures considered was the active energy consumption of the control system. As also mentioned in Chapter 2, the high energy requirements of the active systems renders a drawback on their practical usage. This chapter will emphasise on minimising the active energy requirements of the considered HMD using both software and hardware methods. A reinforcement learning controller will be developed in order to act as a ”decision maker” on switching between passive, semi-active and active modes-of-operation. As it will be shown, the proposed control scheme will considerably decrease the active energy requirements while maintaining an acceptable vibration mitigation performance, demonstrating in this way its effectiveness.

Source: L. Koutsoloukas, N. Nikitas, and P. Aristidou. A Reinforcement Learning Controlled Novel Hybrid Mass Damper on A Real Tower, 2023. (**Submitted**).

5.1 Abstract

This work proposes a novel passive, semi-active, active mode-switching hybrid mass damper (MSHMD) for the control of a real high-rise tower. For the mode-switching control of the system, the reinforcement learning algorithm, Deep Q-Network, was implemented. The performance of the system acting solely as a passive tuned mass damper (PTMD), a semi-active tuned mass damper (SATMD) and as an active tuned mass damper (ATMD) was also studied. For the control of the ATMD and the SATMD, the well established algorithms, Linear Quadratic Regulator (LQR) and Clipped-LQR were utilised, respectively. Simulations showed that, the proposed MSHMD had a similar performance to the ATMD while, achieving a considerable decrease in the energy demand. More specifically, the MSHMD achieved a top floor dynamic responses of up to 26.7% when compared to the uncontrolled case. Moreover, the MSHMD managed to decrease the peak power consumption and the cumulative energy consumption of the active part by up to 41% when compared to the ATMD. It was concluded that, the proposed MSHMD was efficient in controlling the dynamic responses of the tower while, considerably decreasing the active power and energy requirements of the system.

5.2 Introduction

Since 1973, the majority of the mass damper applications on real building-like structures are passive tuned mass dampers (PTMDs) (Koutsoloukas et al. (2022b)). Interestingly, despite the high-quality research done by the structural control research community, the industry professionals seem to prefer the more conventional PTMDs. In the literature, there are many cases where the effectiveness of active technology (using actuators) was highlighted either used purely as an active mass damper (AMD) (Chang and Sung (2019), Chen and Chien (2020), Li et al. (2014), Nagashima and Shinozaki (1997)) or as an active tuned mass damper (ATMD) (Cao and Li (2018), Demetriou and Nikitas (2016), Kang et al. (2011), Mitchell et al. (2013)). To eliminate the main drawback of the active technology, (i.e. the high energy requirements), the structural control community proposed a new type of control system, the semi-active tuned mass damper (SATMD). These systems are so energy efficient that they can operate using a battery as an external power source (Symans and Constantinou (1999)). The SATMDs earn their effectiveness by possessing damping and/or stiffness adaptive capabilities. Semi-active control methods include, hydraulic and solenoid valving, electrorheological (ER), magnetorheological (MR), friction and fluid viscous dampers with power requirement ranging in the order of tens of Watts compared to the kilo and mega Watts required by the active systems (Symans and Constantinou (1999)). It is reported that, in most cases, the SATMDs outperform the PTMDs, making them a trustworthy control system (Demetriou et al. (2015, 2016), Maślanka (2019), Zelleke and Matsagar (2019a,b)).

Aiming to take advantage of the positive aspects of each mass damper technology while eliminating their disadvantages, the concept of hybrid mass dampers (HMDs) was proposed. In general, it is noticed that in the literature, there is an inconsistency on the definition of the term "hybrid" when referring to mass damper systems (Koutsoloukas et al. (2022b)). Within this study, the term "hybrid" will refer to the type of systems that combine more than one type of control techniques. In most of the times, the HMDs are highly depended on the adopted control algorithm and they proved to be efficient on controlling structural vibrations. In many cases, mode-switching mechanisms are also utilised by the systems in order to serve various control objectives. For example, the Hirobe Miyake Building, the Bunka Gakuen building and the Oasis Hiroba 21-Oasis Tower utilise a similar type of HMD. The main control algorithm of the first two systems is a linear quadratic controller and for the third is a H_∞ controller. As mentioned in Nakamura et al. (2001), all three HMDs posses an active-passive mode-switching mechanism in order to ensure the safety of the system. More specifically, the mode-switching mechanism is adopted so that there will be no overloading/overheating of the motor and the driver. The authors mentioned that, in the systems with small mass, the mode-switching is achieved through the use of a magnetic clutch whereas, in the case of a larger mass, the mode-switching was achieved by simply turning the power of the motor on or off. In the case of the Shanghai World Financial Center Tower, the active-passive switching mechanisms is directly related to the excitation of the building. More specifically, the system operates as an ATMD during wind excitation and switches to passive-mode (i.e. acts as a PTMD) during earthquake loading. The purpose of this mode-switching law was to avoid having excessively large displacements of the damping device during an earthquake (Lu et al. (2014)). Finally, the HMD installed on the Ping-An Finance Centre is primarily controlled by a linear quadratic regulator (LQR) and it also possesses a working principle which changes the state of the system from stop-stage to controlled-stage and to locked stage. As mentioned in Zhou et al. (2022) the active-stage is triggered when the acceleration of the 113rd floor of the tower exceeds the limit of 1cm/s^2 for two consecutive cycles. While in the active stage, the system may turn into the locked-stage if the displacement of the damper exceeds the 220cm limit and the response acceleration is larger than 50cm/s^2.

Mode-switching control techniques used in mass damper technology allow for a fail-safe design. Many scholars report that in the event of a power-cut, especially during earthquakes, the control systems that rely only in active methods will malfunction (Ahlawat and Ramaswamy (2002), Elias and Matsagar (2017)). This highlights the importance of developing reliable control techniques which are being considerate of both structural safety and energy consumption of the system.

5.2.1 Scope of this work

In this study, the performance of a novel passive, semi-active and active mode-switching HMD (MSHMD) on controlling the dynamic responses of a real high-rise tower will be presented. The main scope of the vibration mitigation scheme herein is to keep the top floor displacements below the desired limit, while achieving minimum power and energy requirements (decreasing the use of the active part of the system). The performance of the system acting solely as a PTMD, SATMD and ATMD will be presented. Moreover, attempts on decreasing the active use of the system by proposing an active/semi-active hybrid system will also be investigated in order to compare its performance to the MSHMD. A novel control approach which combines all passive, semi-active and active techniques will be presented. For the mode-switching control of the novel MSHMD, a reinforcement learning algorithm called Deep Q-Network will be utilised for the first time ever in such an application.

5.2.2 Paper Contributions

The contributions of this paper are:

1. Demonstration of the vibration mitigation performance of a novel MSHMD possessing passive, semi-active and active mode-switching capabilities.

2. Use of the reinforcement learning algorithm called Deep Q-Network on a real structural control application for the first time ever.

3. Minimisation of the power and energy requirement of a mass damper system installed on a real high-rise tower while, maintaining high vibration mitigation performance through the use of hardware and software methods.

5.2.3 Structure of this Work

This work is structured as follows: Section 5.3 describes the general concepts of reinforcement learning and its use in the field of structural control. Section 5.4 includes the characteristics of the application and the derivation of the control algorithms used herein, and Section 5.5 presents the results that arose from the simulations that were carried out. Finally, Section 5.6 includes the conclusions of this study and mentions the future work that is required.

5.3 Reinforcement Learning

Reinforcement learning is an area of machine learning which arose from two different research fields namely; (i) the optimal control (using value functions and dynamic programming) and (ii) animal psychology (Nian et al. (2020)). Reinforcement learning algorithms involve learning how to act by trial and error. The controller, called agent, uses a reward signal pre-specified by the user in order to converge into the desired control performance. In general, the reinforcement learning algorithms can be categorised in model-based and model-free algorithms. Algorithms in the former category require knowledge of the environment (model to be controlled) whereas, algorithms in the latter category do not require any knowledge of the environment. Moreover, the reinforcement learning algorithms are also categorised based on the type of their action space (the set of all possible actions that an agent can take). Common action spaces can be continuous, discrete or continuous-discrete hybrid. Algorithms with continuous action spaces have a real-value vector outputs (actions) whereas, discrete action spaces have only a finite number actions that can be taken (Sutton and Barto (1998)).

In the area of structural control, the reinforcement learning has not gained a significance attention yet. Previous works involve the proposal of a Q-learning algorithm for the tuning of a fuzzy-proportional derivative controller with a state predictor for the control of a 10-storey building (Khalatbarisoltani et al. (2019)), the investigation of an improved version of a Q-learning variant called Mini-batch learning for the control of a reduced order model of 1 degree-of-freedom (DOF) system (Radmard Rahmani et al. (2019)), and the proposal of an actor-critic controller with a Lyapunov candidate for the control of a 1-DOF system (Gao et al. (2020)). Moreover, Zhang et al. (2020) proposed an adaptive dynamic programming algorithm for the control of an offshore wind turbine system, Wang (2020) proposed a coarse-fine self-learning algorithm for the control of a 1-DOF system and Eshkevari et al. (2021) proposed a soft actor-critic based algorithm for the control of five-storey shear benchmark building. Finally, Yuan et al. (2021) investigated the performance of a Q-learning algorithm for the control of a 2-DOF system, Koutsoloukas et al. (2023) demonstrated the performance of a Deep Deterministic Policy Gradient (DDPG) algorithm for the control of a real high-rise tower and, Sadeghi Eshkevari et al. (2023) proposed a novel data-driven control approach using policy-gradient algorithms for the control of a 3-DOF frame structure, a 5-DOF shear building and a 5-DOF nonlinear building.

The literature shows that, reinforcement learning algorithms are proven efficient on the vibration mitigation performance of civil structures. Thus, broader investigation of its implementation in structural control should be realised. In this study, the Deep Q-Network algorithm will be implemented for the control of a novel MSHMD for the vibration mitigation of a real high-rise tower. The algorithm has been successfully implemented in various control fields such as in traffic signal control (Rasheed et al. (2020)), in docking control of autonomous underwater vehicles (Anderlini et al. (2019)), in robot manipulation (Malik et al. (2022)), and in active bearing lubrication (Kazakov et al. (2022)). In all cases, the Deep Q-Network has been proven efficient on achieving the desired control goal. The following section includes the description of the application along with the derivation of the control algorithms used within this study.

5.4 Application Characteristics

The case-study of this chapter is the Rottweil tower that was previously discussed in Chapter 3. To avoid repetition, the reader is referred to Section 3.4 for information about the case-study tower. As mentioned, the capacity of the installed actuators is 35kN which is considered to be small when compared to other actuators installed on other buildings (e.g. Cao et al. (1998), Lu et al. (2014)). The operation of actuators generally is power inefficient since, even in the case where they dissipate power, they require power supply at all times (Margolis (2005)). In contrast, the semi-active configurations are more power efficient. They consume a significantly low power in order to dissipate orders of magnitude higher power from the structure. More specifically, Spencer and Nagarajaiah (2003) mention that, a device that is broadly used in the area of structural control using semi-active technology is the variable-orifice dampers which require around 50W for their operation. Moreover, the authors mention that, MR dampers can operate with a power consumption less than 50W. Kobori et al. (1993) presented a variable stiffness semi-active system for the seismic control of civil structures. For its operation, the proposed variable system device required approximately 20W. Dyke et al. (1996) developed a MR damper with force capacity of 10kN and peak power consumption of less than 10W. Spencer Jr. et al. (1997) designed a 200kN capacity MR damper for the control of civil structures which had a maximum power consumption of about 22W. Spencer et al. (1997) developed a prototype damper able to to portray the behaviour of a MR damper which had a power consumption of less than 10W. Fujitani et al. (2003) proposed a 400kN capacity MR damper applied on civil structures with a total power consumption (resulting from four DC power sources of 70W each) of 280W. Yoshida and Dyke (2004) for their control scheme, they used a MR damper with a capacity of 1000kN and a maximum power consumption of 50W. Tu et al. (2011) developed a large-scale MR damper capable of producing a 500kN damping force, designed to be applied for the control of civil structures. The proposed damper had a nominal power less than 200W. Sternberg et al. (2014) considered the manufacturing of a large-capacity MR damper to be used in conjunction with SAT-MDs applied on civil structures. The capacity of the proposed MR damper was 97ton (951kN) and its total power consumption was 144W. In this study, the power consumption of the variable damping device used in the semi-active configuration is assumed to be 50W at every action it takes. Based on the literature, this reflects to a realistic power consumption used in other real applications.

5.4.1 System Dynamics

The detailed derivation of the equations of motion are dropped in this chapter to avoid repetition, and the reader is referred to Section 3.3.1.

5.4.2 LQR

The LQR algorithm involves finding the optimal controller by minimising the cost function in Equation 5.1 where, Q_{LQR} and R_{LQR} are weights of appropriate dimensions (Ricciardelli et al. (2003)).

$$J_{LQR} = \int_0^\infty (s^T Q_{LQR} s + u_{ac}^T R_{LQR} u_{ac}) dt \tag{5.1}$$

The optimal control law is then found by Equation 5.2,

$$u_{ac}(t) = -Gs(t) \tag{5.2}$$

where,

$$G = -R_{LQR}^{-1} BP \tag{5.3}$$

In Equation 5.3, P is the solution of the Riccati equation shown in Equation 5.4. In this case, $u(t)$ in Equation 3.2 is equal to $u_{ac}(t)$.

$$PA + A^T P - PBR_{LQR}^{-1} BP + Q_{LQR} = 0 \tag{5.4}$$

5.4.3 Clipped-LQR

Semi-active control schemes, by definition, are capable of consuming power (Demetriou et al. (2016)). Thus, the control law of a semi-active device arises from the clipping (setting them equal to zero) of the active forces ($u_{ac}(t)$) generated by a controller when their direction is opposite to the relative velocity of the mass damper ($\dot{q}_{md}(t)$), as seen in Equations 5.5-5.6 where, p_{SATMD} is the relevant power dissipation of the semi-active device (Demetriou et al. (2016), Miah et al. (2015, 2016)).

$$u_{semi}(t) = \begin{cases} u_{ac}(t) : & p_{SATMD} < 0 \\ 0 : & p_{SATMD} \geq 0 \end{cases} \tag{5.5}$$

$$p_{SATMD} = (u_{ac}(t) \times \dot{q}_{md}(t)) \tag{5.6}$$

Having obtained the semi-active force (u_{semi}), the semi-active damping coefficient ($c_{semi}(t)$) should then be satisfied (Demetriou et al. (2016)) as shown in Equation 5.7.

$$c_{semi}(t) = \left| \frac{u_{semi}}{\dot{s}_{md}(t)} \right| \text{ where, } c_{min} \leq c_{semi} \leq c_{max} \tag{5.7}$$

In this study, c_{min} and c_{max} were selected as $c_{min} = 0$ and $c_{max} = 2\xi_{md}m_{md}\omega_{md}$, similar to (Zelleke and Matsagar (2019a)) where, ξ_{md}, m_{md}, and ω_{md} are the damping ratio, the mass and the angular frequency of the PTMD, respectively. Finally, in this case, $u(t)$ in Equation 3.2 is equal to $u_{semi}(t)$.

5.4.4 MSHMD

The performance of a novel MSHMD will be studied herein. The proposed control process is demonstrated in Figure 5.1. As shown, a (discrete) reinforcement learning agent is synthesised which is responsible for the mode-switching between the passive, semi-active and active modes-of-operation of the installed HMD. To achieve that, the output of the agent is restricted to 1, 2 or 3 corresponding to the passive, semi-active and active configurations, respectively. The agent is trained using the design wind loads and has no prior knowledge of the system dynamics. During training, the *IsDone* flag terminates the episode during the training if the achieved performance is worse than the uncontrolled top floor displacement or acceleration. The utilised reinforcement learning algorithm is the DQN controller. The DQN is a model-free, online, off-policy algorithm with a discrete action space. It is a variant of the Q-learning algorithm and it trains a critic to estimate the future rewards (Mnih et al. (2015)). The DQN observes the states (s) of the environment and generates an action (a). As seen in Figure 5.2, during training, the DQN artificial neural network is constructed with three convolutional layers namely; input layer, hidden layer, and output layer. The input layer represents the states and each neuron of the layer is fully-connected with the ones of the hidden layer. The hidden layer is a representation of the patterns of the high-dimensional and complex states resulted by the nonlinear functions. The neurons of the hidden layer are fully-connected to the ones of the input and output layers. The output layer represents the Q-Value of the possible actions (a) and the neurons of this layer are fully-connected to the ones in hidden layer. Afterwards, the agent receives a delayed reward for the state-action pair and updates the Q-Value of the state-action pair based on the Bellman equation (Rasheed et al. (2020)). The reward selection plays a vital role in the performance of the reinforcement learning agent (Radmard Rahmani et al. (2019)). In this study, the reward to be maximised by the DQN algorithm (J_{DQN}) was selected to be a multi-parameter quadratic cost similar to the one used in (Koutsoloukas et al. (2022a)) for the control of the mass damper using a RMPC algorithm (seen in Equation 5.8). This reward considers both the structural responses and the active/semi-active control input. Q_{DQN}, R_{DQN} and V are weights of appropriate dimensions. As explained in Section 5.4, the primary purpose of the control system installation is to decrease the dynamic displacements of the top floor (q_{top}) to be below 0.2m. Thus, a violation penalty is added to the quadratic cost (defined by Equation 5.9) in order to penalise the solutions that exceed the desired limit. Generally, the reward selection for control algorithms is an iterative process in order to achieve the best possible outcome. When also considering the large amount of computational power required for the training of a reinforcement learning algorithm, the selected quadratic cost assures a potential effectiveness of the end controller.

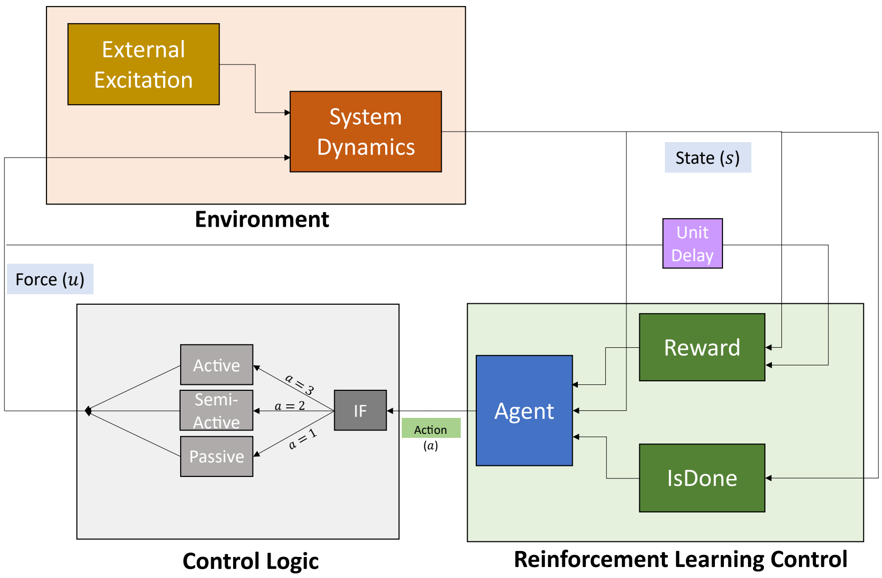


Figure 5.1: MSHMD control scheme

For the exploration and exploitation of the agent, an ϵ-greedy policy was used (Sutton and Barto (1998)). In the exploration side, by specifying a probability ϵ, a random action is chosen to update the Q-values of the potential actions to be taken by the agent and thus, identify the best action possible. Finally, for the exploitation part, using a probability $1 - \epsilon$, the best known action with the highest Q-value is selected (Rasheed et al. (2020)).

Figure 5.3 shows the training process of the DQN agent which included 2000 episodes. As it can be seen, during the first ~70 episodes, the agent received low rewards.

This suggests that, the agent was exploring solutions where, they were going against the desired control performance, possibly triggering the additional penalty in Equation 5.9. After around 400 episodes, a convergence is noticed achieving only higher rewards than the, what is seems to be, converged reward, demonstrating that the agent is capable on controlling the dynamic responses of the tower while achieving the desired performance. It is noted that, in this configuration, the semi-active and active mode-of-operation are controlled by a Clipped-LQR and a LQR, respectively. The following section will present the simulation results regarding the vibration dissipation performance of the system acting as a PTMD, SATMD, ATMD, active/semi-active HMD (ASHMD) and as a MSHMD.

$$J_{DQN} = -\int_0^\infty (s^T Q_{DQN} s + u^T R_{DQN} u + eV) dt \tag{5.8}$$

where,

$$e = \begin{cases} 0: & -0.2 \leq q_{top} \leq 0.2 \\ 1: & else \end{cases} \tag{5.9}$$

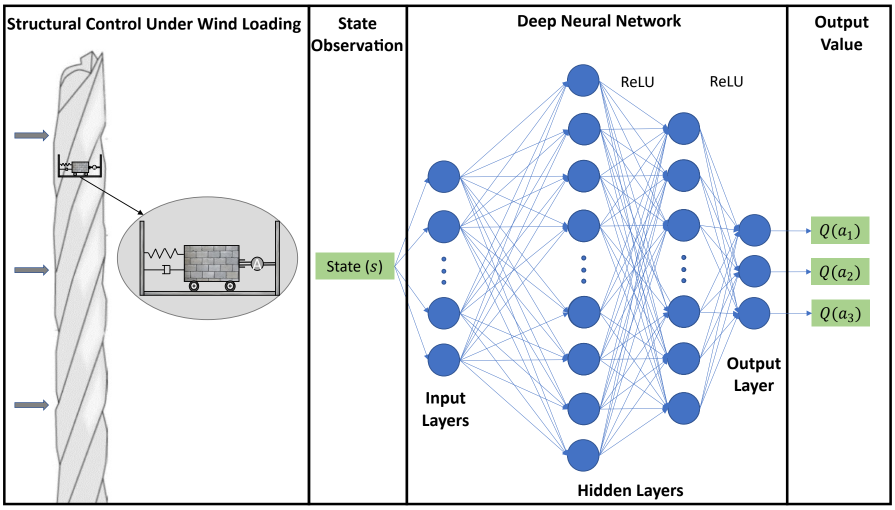


Figure 5.2: Q-Value estimation by the DQN algorithm

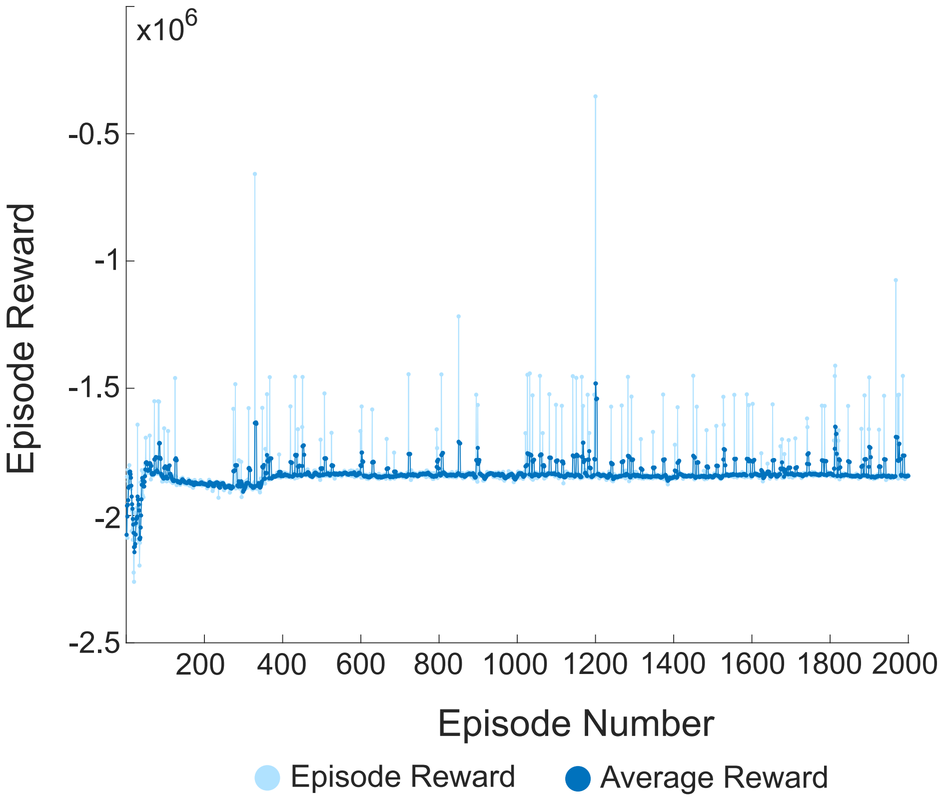


Figure 5.3: Reward of the DQN algorithm during the training process

5.5 Simulations

This section includes the performance of the systems on dissipating the dynamic responses of the Rottweil tower. As mentioned in Section 5.4, a Clipped-LQR and a LQR is used for the semi-active and active control of the system respectively while, a DQN algorithm will act as a "decision maker" for the MSHMD. For the best demonstration of the results of this study, and to highlight the performance of the novel MSHMD, the results for the PTMD, SATMD and ATMD compared to the uncontrolled case will firstly be discussed. Moreover, for further comparisons, an ASHMD system will also be proposed as a first attempt on decreasing the active energy required by the system. Then, the performance of the novel MSHMD will be presented and a summary of the results will also be included.

5.5.1 Performance of the PTMD, SATMD and ATMD

Figure 5.4 shows the top floor displacement graphs for the PTMD, SATMD and the ATMD. As it can be seen, the PTMD and the SATMD, in contrast to the ATMD, could not decrease the maximum absolute displacement of the top floor to be below the desired limit (0.2m). More specifically, the maximum absolute top floor displacement with the PTMD was 0.226m, with the SATMD was 0.210m and with the ATMD was 0.195m, compared to the uncontrolled case (0.248m). When considering the top floor accelerations, again the ATMD had the best performance with a maximum absolute value of 0.142m/s^2 compared to 0.158m/s^2, 0.171m/s^2 and 0.203m/s^2 of the SATMD, the PTMD and the uncontrolled case, respectively (seen in Figure 5.5).

The control forces generated by the SATMD and the ATMD can be seen in Figure 5.6. As seen, the maximum control force generated by the ATMD was 35kN which is the saturation of the installed actuators. The associated power and energy dissipated (and added in the case of the ATMD) can be seen in Figure 5.7. As shown, the SATMD power is negative demonstrating the "dissipative" nature of the system. In contrast, the ATMD has the ability to add and dissipate energy, as shown in the figure. The maximum absolute power dissipated by the SATMD was 9.2kW (by consuming 50W for its operation) where, in the case of the ATMD it was 22.3kW. Moreover, the total cumulative energy of the two systems without considering any additional hardware energy loses (e.g. see actuator efficiency rating) was calculated. It is noted that, in the case of the ATMD, the total absolute energy is presented including both energy

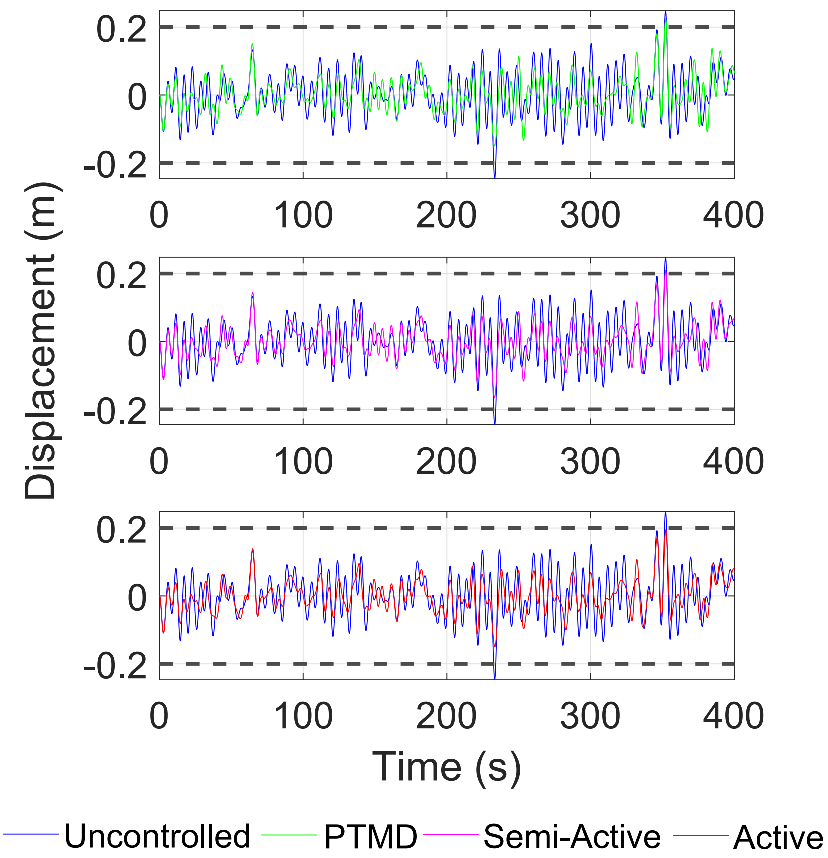


Figure 5.4: Top floor displacement graphs for the PTMD, SATMD and ATMD against the Uncontrolled case

dissipation (resulted form negative power) and energy addition (resulted from positive power). The total energy dissipated by the SATMD was 1.42MJ (by consuming a total of 200kJ for its operation) whereas, the corresponding value for the ATMD was 7.45MJ.

5.5.2 Active/Semi-Active Hybrid

The first attempt to decrease the energy required by the active part of the system is to design an ASHMD control scheme. This system will utilise the actuators (active part) only in the case where energy is to be added to the mass damper. Thus, the dissipative part will be dealt by the semi-active configuration of the system. The controllers to be used for the active and semi-active parts are the LQR and the Clipped-LQR, respectively. The proposed system indeed managed to considerably decrease the use of

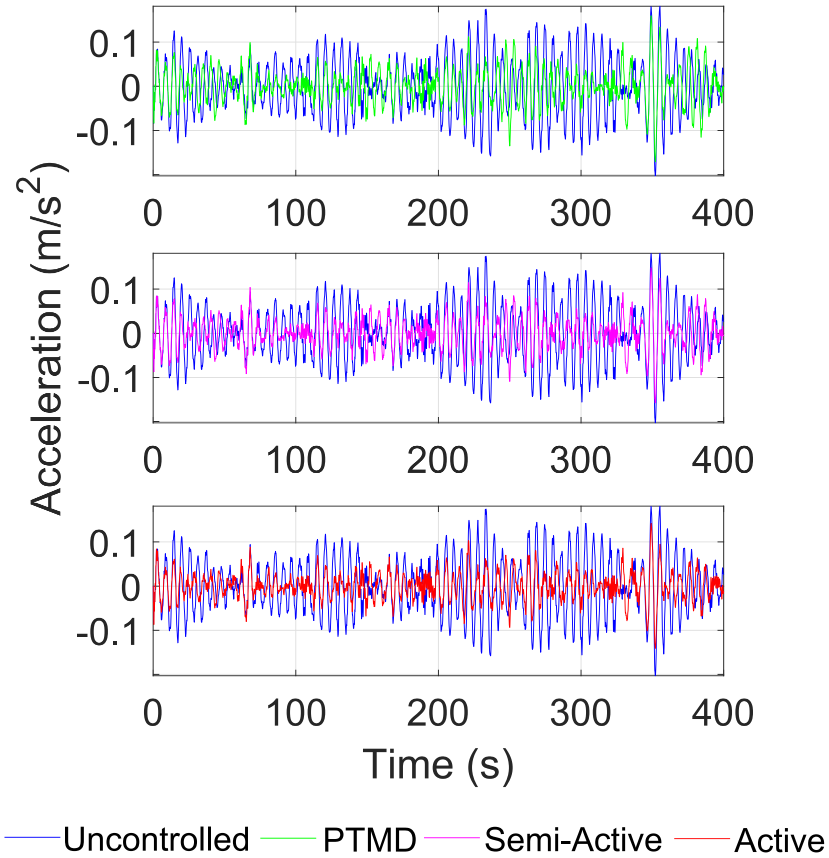


Figure 5.5: Top floor acceleration graphs for the PTMD, SATMD and ATMD against the Uncontrolled case

the active part. Figure 5.8 (top) shows the control forces generated by the ASHMD which is then broken down in the active and semi-active parts in Figure 5.8 (bottom). As seen, the proposed control scheme managed to decrease the active part usage down to 44.3%. Figure 5.9 clearly demonstrates that the active part was only used to add energy to the mass damper and the semi-active part was used to dissipate energy from the it. The active part achieved a maximum power of 23.6kW and a total energy consumption of 3.5MJ. However, the proposed system did not manage to achieve the primary target of this study, i.e. the top floor displacement to be below 0.2m. More specifically, as shown in Figure 5.10 the maximum absolute top floor displacement achieved by the system was 0.205m and the respective acceleration was 0.153m/s^2. Despite its not acceptable vibration dissipation performance, one may conclude that,

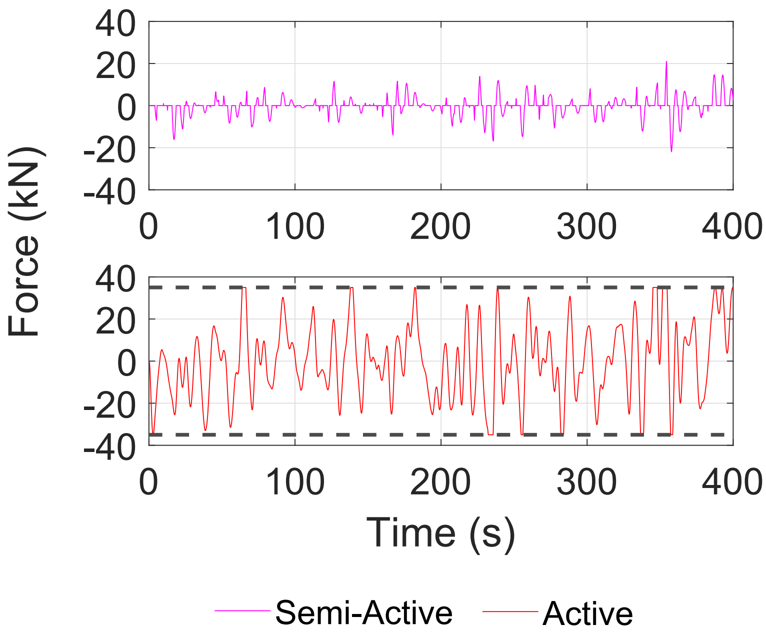


Figure 5.6: Forces generated by the SATMD and the ATMD

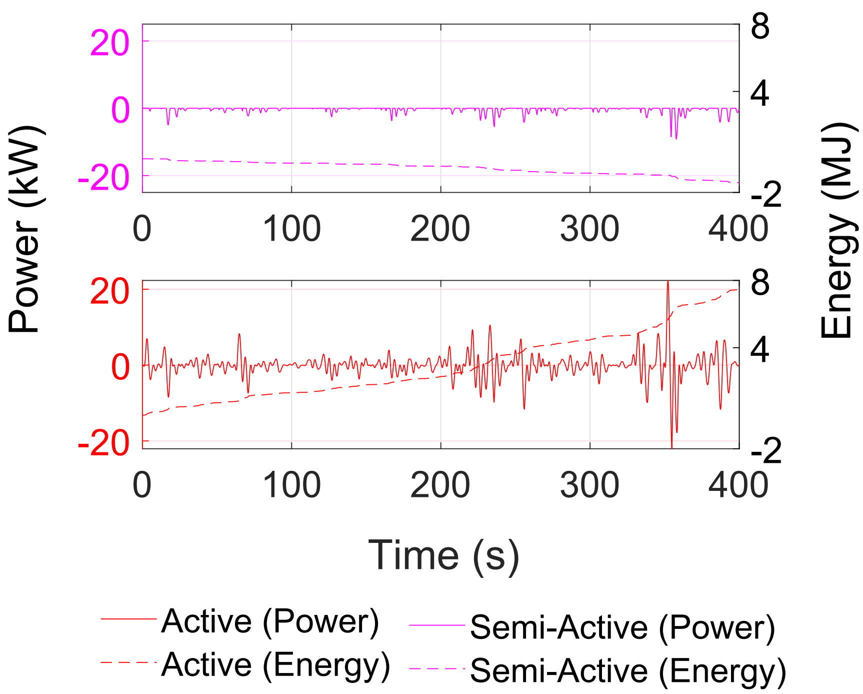


Figure 5.7: Forces generated by the SATMD and the ATMD

there is a potential on designing hybrid control systems by utilising the semi-active and active components. By decreasing the usage of the active parts of the system, which led to 47% decrease in the energy consumption of the system when compared to the ATMD, the ASHMD had a fairly good performance not managing to achieve the desired goal for just 5mm.

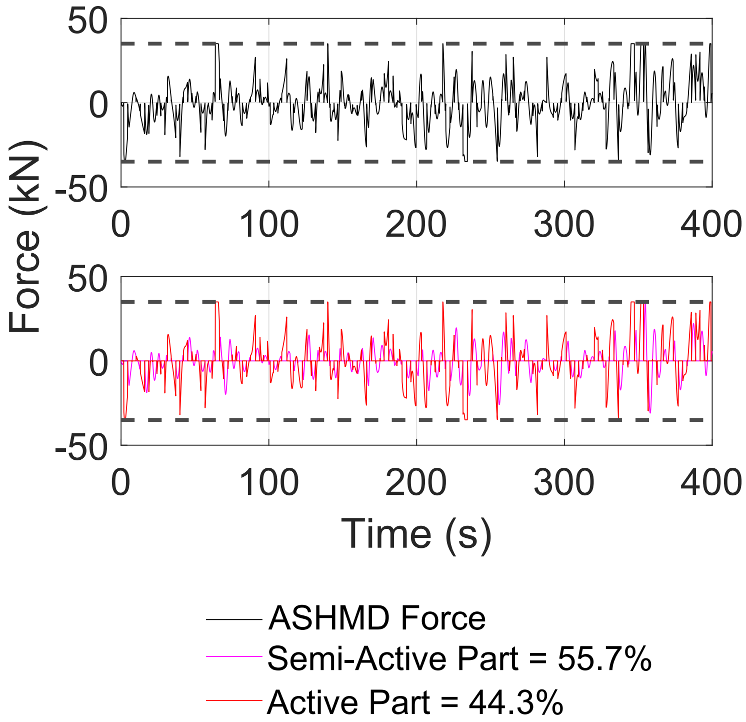


Figure 5.8: Forces generated by the Active/Semi-Active Hybrid (top) split into individual modes-of-operation (bottom)

5.5.3 Performance of the novel MSHMD

Figure 5.11 shows the displacement and acceleration response graphs of the top floor against the uncontrolled case. As it can be seen, the MSHMD managed to decrease the top floor displacements within the desired limit. More specifically, the MSHMD managed a maximum absolute top floor displacement of 0.198m (20% reduction compared to the uncontrolled case). As it can be noticed, there was a slight compromise when compared to the ATMD performance. The same thing can be seen in the performance of the system on reducing the dynamic acceleration responses. More specifically, the

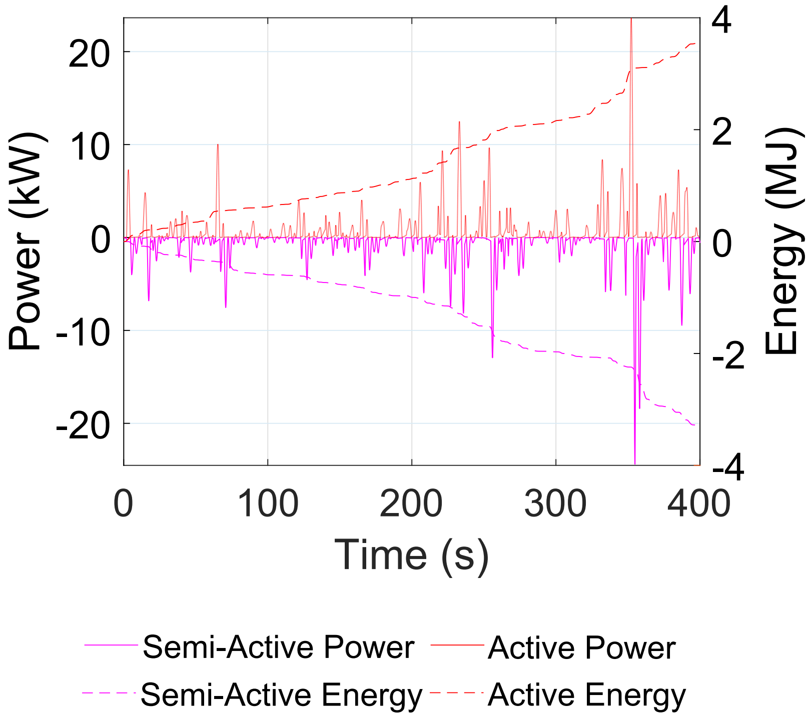


Figure 5.9: Power and energy dissipated by the Active/Semi-Active Hybrid system

maximum absolute acceleration recorded in the case of the MSHMD was 0.149m/s^2 compared to 0.203m/s^2 of the uncontrolled case (26.7% reduction).

As explained in Section 5.4.4, the DQN algorithm ”decides” which mode-of-operation to act at every time instant by outputting an action ranging between 1 to 3. When the output of the DQN is 1, the system operates as a PTMD, when it is 2 the system operates as a SATMD and when it is 3 the system acts as an ATMD. Figure 5.12 shows the DQN command for the control of the tower. For the best interpretation of the figure, a contribution factor was also introduced which shows how much each mode-of-operation was used compared to the control usage. As shown in the figure, the usage of the active mode-of-operation (i.e. acting as an ATMD) was dropped to 50.5% and still, managed to keep the top floor displacements within the desired limit. The semi-active and passive modes-of-operation usage (i.e. acting as a SATMD and as a PTMD, respectively) was 29.6% and 19.8%, respectively.

Figure 5.13 (top) shows how the MSHMD achieved its control performance, satisfying both the actuator constraint and the top floor displacement limit. To fur-

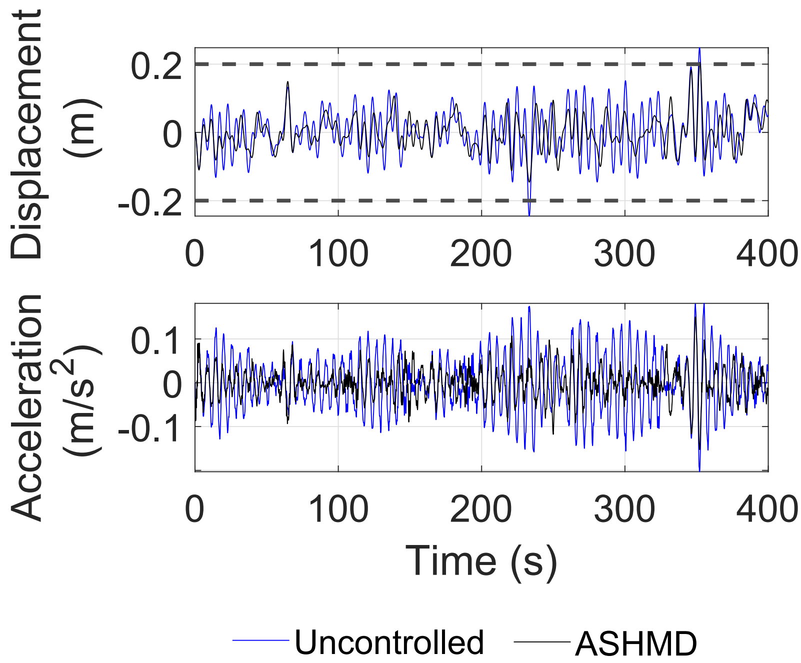


Figure 5.10: Top floor displacement and acceleration graphs of the Active/Semi-Active Hybrid system against the Uncontrolled case

ther demonstrate the individual contribution of each mode-of-operation, Figure 5.13 (bottom) shows the control forces generated by the semi-active and active modes-of-operation.

The reduced usage of the active mode-of-operation led to the decrease of energy requirements of the system. As seen in Figure 5.14, the maximum power and energy consumption of the active mode-of-operation was 14.2kW and 4.4MJ compared to 22.3kW and 7.45MJ of the ATMD system. This demonstrates that the MSHMD achieved a 36% decrease in the peak power requirement and a 41% decrease in the energy consumption. Figure 5.15 shows a summary of the performance of each system with the corresponding power and energy consumption (where applicable). One may conclude that, by having a 1.5% deteriorated performance when compared to the ATMD in the dynamic displacement mitigation, but still satisfying the main control objective, the MSHMD achieved a significant decrease in the power and energy consumption of the control system, making it an effective dynamic response control solution.

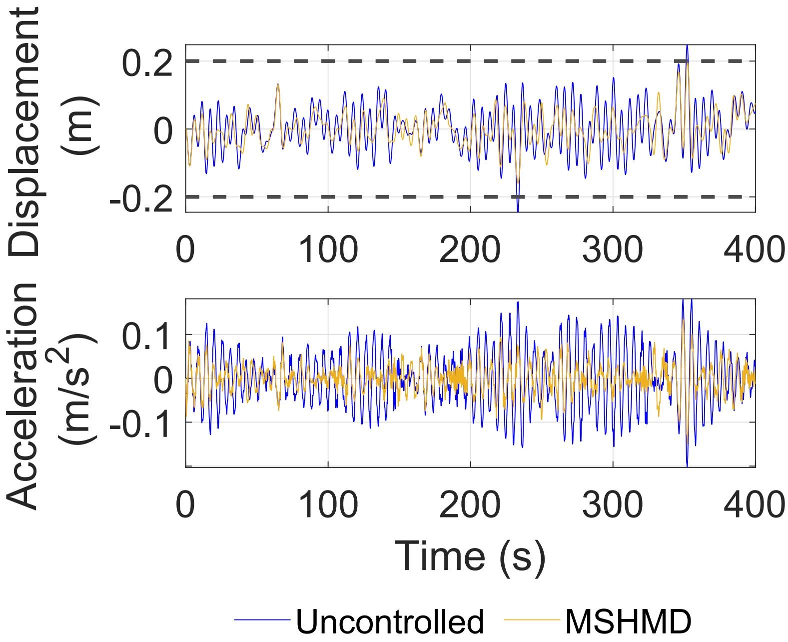


Figure 5.11: Top floor displacement and acceleration graphs for MSHMD against the Uncontrolled case

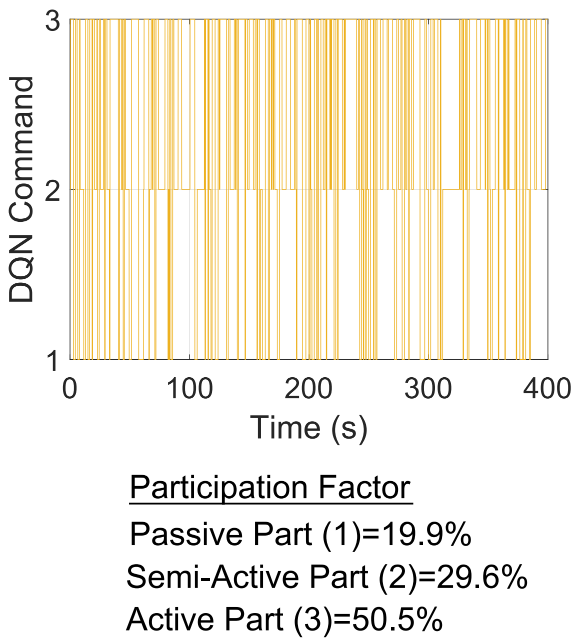


Figure 5.12: DQN output command

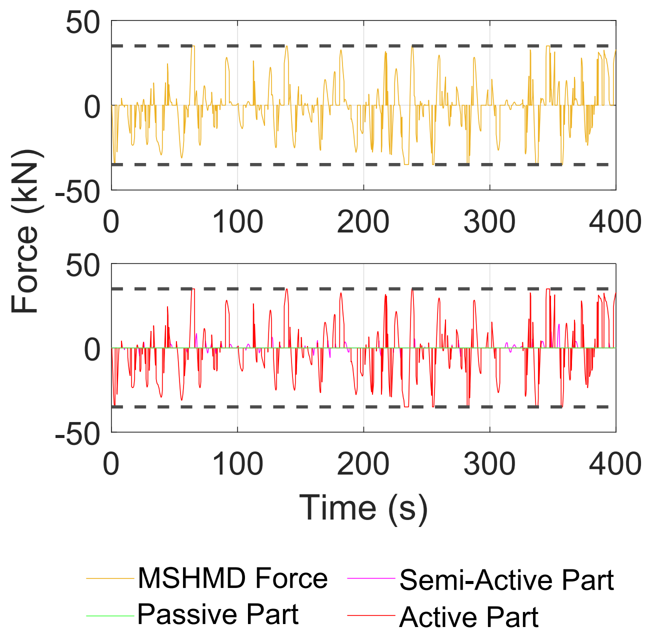


Figure 5.13: Forces generated by the MSHMD (top) split into individual modes-of-operation (bottom)

5.6 Conclusions

In this work, the dynamic displacement and acceleration response reduction of a real high-rise tower was studied. The tower is equipped with a hybrid control system capable of acting either as a PTMD, SATMD, ATMD, or as a hybrid system using a combination of them. The main control aim of this study was to decrease the dynamic displacements to be below a limit of 0.2m. Firstly, the performance of the system acting solely as a PTMD, SATMD and as an ATMD was investigated taking into account, apart from the dynamic response reduction, the power and energy consumption of the system (where applicable). For the control of the ATMD and the SATMD, the well-established algorithms LQR and clipped-LQR were used.

From the analysis of aforementioned systems, only the ATMD managed to decrease the top floor displacements to be within the desired limit. More specifically, the top floor displacements using the PTMD, SATMD and ATMD were, 0.226m, 0.210m, and 0.195m, respectively, against 0.248m of the uncontrolled case. When considering the dynamic acceleration dissipation of the top floor (the only floor used by humans) again,

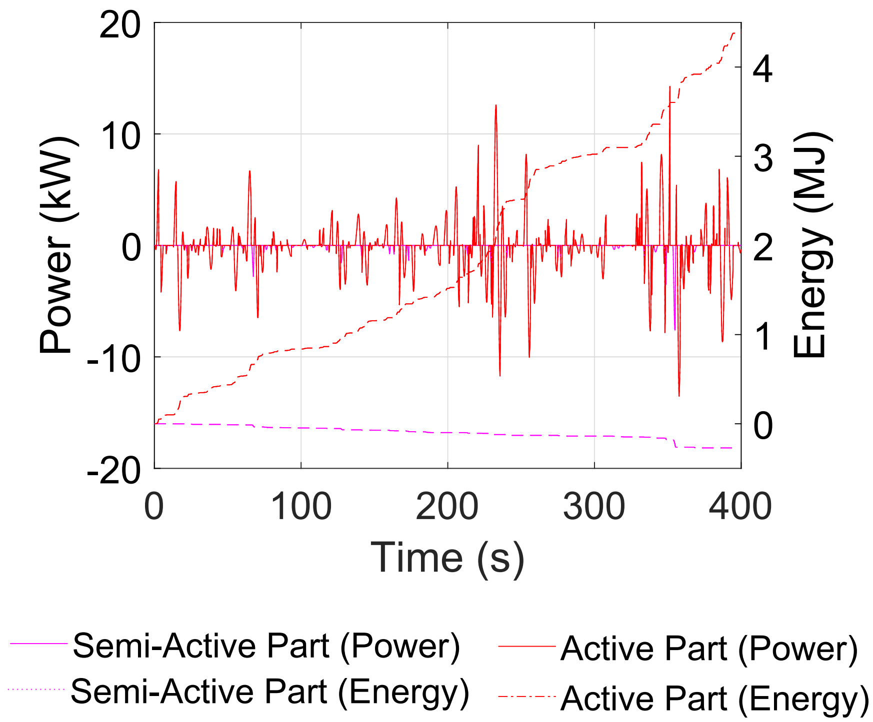


Figure 5.14: Power and energy consumption o the MSHMD when acting as a SATMD and as an ATMD

the ATMD had the best performance. More specifically, the PTMD achieved an acceleration of 0.171m/s^2, the SATMD 0.158m/s^2, and the ATMD 0.142m/s^2 where, the corresponding uncontrolled value was 0.203m/s^2. To achieve its performance, the ATMD had a maximum absolute power consumption of 22.3kW and the total cumulative energy (without accounting for any additional hardware energy loses) was 7.45MJ.

To decrease the power and energy consumption of the system firstly, an ASHMD was investigated which utilised the active and semi-active components of the system. The proposed system managed to considerably decrease the use of the active part (down to 44.3%) and thus, the system's energy consumption however, it did not manage to keep the top floor displacement within the desired limit (below 0.2m). Even though the ASHMD was not proven to be adequate, it presented that a hybrid configuration could lead to an effective system. Therefore, a novel MSHMD was proposed using the passive, semi-active and active parts of the system. For the mode-switching control of the system, a reinforcement learning algorithm called DQN was implemented. After

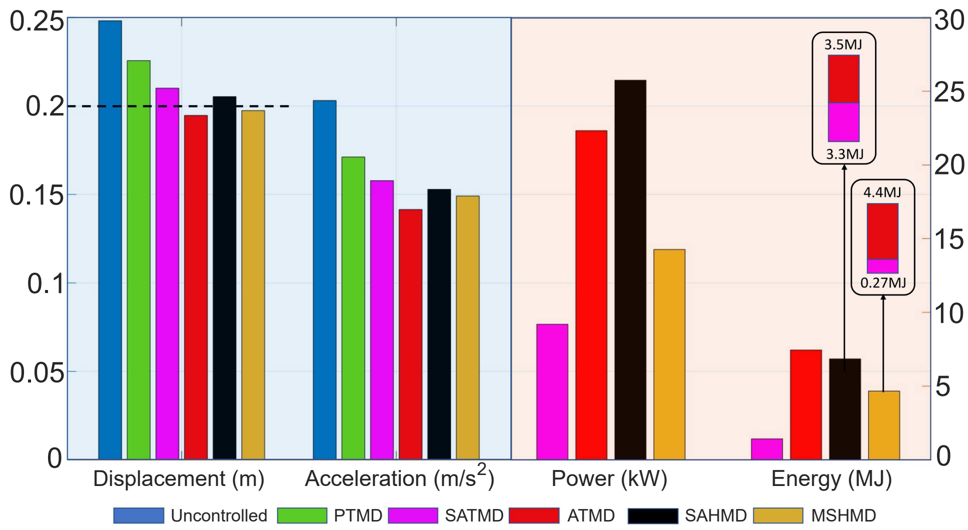


Figure 5.15: Summary of the performance of all the systems studied

training the algorithm for 2000 episodes, an agent with an acceptable performance was synthesised. When investigating the performance of the proposed system on main control objective of this study (i.e. keeping the top floor dynamic displacements below 0.2m), it was proven to be acceptable. More specifically, the maximum absolute top floor displacement achieved by the MSHMD was 0.198m. The novel system was proven to have a good performance on dissipating the top floor dynamic acceleration since, it managed to decrease it to 0.149m/s^2. As it can be noticed, the MSHMD had a slightly deteriorated performance when compared to the ATMD, even though it is considered to be within the acceptable limits. However, the MSHMD managed to decrease the usage of the active part of the system to 50.5% which considerably decreased the power and energy requirements of the system. More specifically, the maximum absolute power consumption of the active part of the MSHMD was 14.2kW and the cumulative energy was 4.4MJ, corresponding to 36% and 41%, respectively, when compared to the ATMD. Thus, the proposed system was proven to be efficient on dissipating the dynamic responses of the tower while, having low power and energy requirements.

Future work involves: (i) investigation of the effect of different control algorithms for the control of the semi-active and active parts on the performance of the MSHMD, (ii) implementation of different reinforcement learning algorithms for the mode-switching control of the MSHMD, (iii) use of different excitations to study the robustness of the control system and, (iv) development of a harvesting system in order to make the MSHMD a ”self-sustained” system.

References

A. S. Ahlawat and A. Ramaswamy. Multi-objective optimal design of FLC driven hybrid mass damper for seismically excited structures. *Earthquake Engineering and Structural Dynamics*, 31(7):1459–1479, 2002. ISSN 00988847. doi: 10.1002/eqe.173.

E. Anderlini, G. G. Parker, and G. Thomas. Docking control of an autonomous underwater vehicle using reinforcement learning. *Applied Sciences (Switzerland)*, 9(17), 2019. ISSN 20763417. doi: 10.3390/app9173456.

H. Cao, A. M. Reinhorn, and T. T. Soong. Design of an active mass damper for a tall TV tower in Nanjing, China. *Engineering Structures*, 20(3):134–143, 1998. ISSN 01410296. doi: 10.1016/S0141-0296(97)00072-2.

L. Cao and C. Li. Enhanced hybrid active tuned mass dampers for structures. *Structural Control and Health Monitoring*, 25(2):1–13, 2018. ISSN 15452263. doi: 10.1002/stc.2067.

S. Chang and D. Sung. Modal-Energy-Based Neuro-Controller for Seismic Response Reduction of a Nonlinear Building Structure. *Applied Sciences (Switzerland)*, 9:4443, 2019.

P. C. Chen and K. Y. Chien. Machine-learning based optimal seismic control of structure with active mass damper. *Applied Sciences (Switzerland)*, 10(15), 2020. ISSN 20763417. doi: 10.3390/APP10155342.

D. Demetriou and N. Nikitas. A novel hybrid semi-active mass damper configuration for structural applications. *Applied Sciences (Switzerland)*, 6(12), 2016. ISSN 20763417. doi: 10.3390/app6120397.

D. Demetriou, N. Nikitas, and K. D. Tsavdaridis. Semi active tuned mass dampers of buildings: A simple control option. *American Journal of Engineering and Applied Sciences*, 8(4):620–632, 2015. ISSN 19417039. doi: 10.3844/ajeassp.2015.620.632.

D. Demetriou, N. Nikitas, and K. D. Tsavdaridis. Performance of fixed-parameter control algorithms on high-rise structures equipped with semi-active tuned mass dampers. *The Structural Design of Tall and Special Buildings*, 25:340–354, 2016. doi: 10.1002/tal.

S. J. Dyke, B. F. Spencer, M. K. Sain, and J. D. Carlson. Modeling and control of magnetorheological dampers for seismic response reduction. *Smart Materials and Structures*, 5(5):565–575, 1996. ISSN 09641726. doi: 10.1088/0964-1726/5/5/006.

S. Elias and V. Matsagar. Research developments in vibration control of structures using passive tuned mass dampers. *Annual Reviews in Control*, 44:129–156, 2017. ISSN 13675788. doi: 10.1016/j.arcontrol.2017.09.015. URL https://doi.org/10.1016/j.arcontrol.2017.09.015.

S. S. Eshkevari, S. S. Eshkevari, D. Sen, and S. N. Pakzad. RL-Controller: a reinforcement learning framework for active structural control. *arXiv preprint*, 2021. URL http://arxiv.org/abs/2103.07616.

H. Fujitani, T. Tomurac, T. Hiwatashid, Y. Shiozakie, K. Hatac, K. Sunakodab, and S. Mopjshita. Development of 400kN Magnetorheological Damper For a Real Base-Isolated Building. *Smart Structures and Materials 2003: Damping and Isolation*, 5052(2003):265–276, 2003.

H. Gao, W. He, Y. Zhang, and C. Sun. Vibration Control based on Reinforcement Learning for a Flexible Building-like Structure System with Active Mass Damper against Disturbance Effects. *Proceedings of the IEEE Conference on Decision and Control*, (Cdc):2380–2385, 2020. ISSN 07431546. doi: 10.1109/CDC42340.2020.9304455.

J. Kang, H.-S. Kim, and D.-G. Lee. Mitigation of wind response of a tall building using semi-active tuned mass dampers. *The Structural Design of Tall and Special Buildings*, 20:552–565, 2011. doi: 10.1002/tal.

Y. N. Kazakov, A. V. Kornaev, D. V. Shutin, S. Li, and L. A. Savin. Active Fluid-Film Bearing With Deep Q-Network Agent-Based Control System. *Journal of Tribology*, 144(8), 2022. ISSN 0742-4787. doi: 10.1115/1.4053776.

A. Khalatbarisoltani, M. Soleymani, and M. Khodadadi. Online control of an active seismic system via reinforcement learning. *Structural Control and Health Monitoring*, 26(3):1–18, 2019. ISSN 15452263. doi: 10.1002/stc.2298.

T. Kobori, M. Takahashi, and K. Ogasawara. Seismic Response Controlled Structure With Active Variable Stiffness System. 22:925–941, 1993.

L. Koutsoloukas, N. Nikitas, and P. Aristidou. Robust structural control of a real high-rise tower using a hybrid mass damper. *Structural Design of Tall and Special Buildings*, 31(12):e1941, 2022a. doi: 10.1002/tal.1941.

L. Koutsoloukas, N. Nikitas, and P. Aristidou. Passive, Semi-Active, Active and Hybrid Mass Dampers: A Literature Review with Associated Applications. *Developments in the Built Environment*, 12:100094, 2022b. ISSN 2666-1659. doi: 10.1016/j.dibe.2022.100094. URL https://doi.org/10.1016/j.dibe.2022.100094.

L. Koutsoloukas, N. Nikitas, and P. Aristidou. Structural Control of a Real High-Rise Tower Using Reinforcement Learning. *Submitted*, 2023.

Z. Li, S. Zuo, and Y. Liu. Fuzzy sliding mode control for smart structure with ATMD. *Proceedings of the 33rd Chinese Control Conference, CCC 2014*, pages 21–25, 2014. ISSN 21612927. doi: 10.1109/ChiCC.2014.6896589.

X. Lu, P. Li, X. Guo, W. Shi, and J. Liu. Vibration control using ATMD and site measurements on the Shanghai World Financial Center Tower. *The Structural Design of Tall and Special Buildings*, 23:105–123, 2014. doi: 10.1002/tal.

A. Malik, Y. Lischuk, T. Henderson, and R. Prazenica. A Deep Reinforcement-Learning Approach for Inverse Kinematics Solution of a High Degree of Freedom Robotic Manipulator. *Robotics*, 11(2), 2022. ISSN 22186581. doi: 10.3390/robotics11020044.

D. Margolis. Energy regenerative actuator for motion control with application to fluid power systems. *Journal of Dynamic Systems, Measurement and Control, Transactions of the ASME*, 127(1):33–40, 2005. ISSN 00220434. doi: 10.1115/1.1870038.

M. Maślanka. Optimised semi-active tuned mass damper with acceleration and relative motion feedbacks. *Mechanical Systems and Signal Processing*, 130:707–731, 2019. ISSN 10961216. doi: 10.1016/j.ymssp.2019.05.025.

M. S. Miah, E. N. Chatzi, and F. Weber. Semi-active control for vibration mitigation of structural systems incorporating uncertainties. *Smart Materials and Structures*, 24(5):55016, 2015. ISSN 1361665X. doi: 10.1088/0964-1726/24/5/055016. URL http://dx.doi.org/10.1088/0964-1726/24/5/055016.

M. S. Miah, E. N. Chatzi, V. K. Dertimanis, and F. Weber. Real-time experimental validation of a novel semi-active control scheme for vibration mitigation. *Structural Control and Health Monitoring*, 2016. doi: 10.1002/stc.

R. Mitchell, Y. Kim, T. El-Korchi, and Y. J. Cha. Wavelet-neuro-fuzzy control of hybrid building-active tuned mass damper system under seismic excitations. *Journal of Vibration and Control*, 19(12):1881–1894, 2013. ISSN 10775463. doi: 10.1177/1077546312450730.

V. Mnih, K. Kavukcuoglu, D. Silver, A. A. Rusu, J. Veness, M. G. Bellemare, A. Graves, M. Riedmiller, A. K. Fidjeland, G. Ostrovski, S. Petersen, C. Beattie, A. Sadik, I. Antonoglou, H. King, D. Kumaran, D. Wierstra, S. Legg, and D. Hassabis. Human-level control through deep reinforcement learning. *Nature*, 518(7540):529–533, 2015. ISSN 14764687. doi: 10.1038/nature14236. URL http://dx.doi.org/10.1038/nature14236.

I. Nagashima and Y. Shinozaki. Variable gain feedback control technique of active mass damper and its application to hybrid structural control. *Earthquake Engineering and Structural Dynamics*, 26(8):815–838, 1997. ISSN 00988847. doi: 10.1002/(SICI)1096-9845(199708)26:8⟨815::AID-EQE678⟩3.0.CO;2-E.

Y. Nakamura, K. Tanaka, M. Nakayama, and T. Fujita. Hybrid mass dampers using two types of electric servomotors: AC servomotors and linear-induction servomotors. *Earthquake Engineering and Structural Dynamics*, 30(11):1719–1743, 2001. ISSN 00988847. doi: 10.1002/eqe.89.

R. Nian, J. Liu, and B. Huang. A review On reinforcement learning: Introduction and applications in industrial process control. *Computers and Chemical Engineering*, 139:106886, 2020. ISSN 00981354. doi: 10.1016/j.compchemeng.2020.106886. URL https://doi.org/10.1016/j.compchemeng.2020.106886.

H. Radmard Rahmani, G. Chase, M. Wiering, and C. Könke. A framework for brain learning-based control of smart structures. *Advanced Engineering Informatics*, 42 (September):100986, 2019. ISSN 14740346. doi: 10.1016/j.aei.2019.100986. URL https://doi.org/10.1016/j.aei.2019.100986.

F. Rasheed, K. L. A. Yau, and Y. C. Low. Deep reinforcement learning for traffic signal control under disturbances: A case study on Sunway city, Malaysia. *Future Generation Computer Systems*, 109:431–445, 2020. ISSN 0167739X. doi: 10.1016/j.future.2020.03.065. URL https://doi.org/10.1016/j.future.2020.03.065.

F. Ricciardelli, A. D. Pizzimenti, and M. Mattei. Passive and active mass damper control of the response of tall buildings to wind gustiness. *Engineering Structures*, 25(9):1199–1209, 2003. ISSN 01410296. doi: 10.1016/S0141-0296(03)00068-3.

S. Sadeghi Eshkevari, S. Sadeghi Eshkevari, D. Sen, and S. N. Pakzad. Active structural control framework using policy-gradient reinforcement learning. *Engineering Structures*, 274(October 2022):115122, 2023. ISSN 18737323. doi: 10.1016/j.engstruct.2022.115122. URL https://doi.org/10.1016/j.engstruct.2022.115122.

B. F. Spencer and S. Nagarajaiah. State of the Art of Structural Control. *Journal of Structural Engineering*, 129(7):845–856, 2003. ISSN 0733-9445. doi: 10.1061/(asce)0733-9445(2002)128:8(965).

B. F. Spencer, S. J. Dyke, M. K. Sain, and J. D. Carlson. Phenomenological Model for Magnetorheological Dampers. *Journal of Engineering Mechanics*, 123(3):230–238, 1997. ISSN 0733-9399. doi: 10.1061/(asce)0733-9399(1997)123:3(230).

B. F. Spencer Jr., J. D. Carlson, M. K. Sain, and G. Yang. On the current status of magnetorheological dampers: seismic protection of full-scale structures. *Proceedings of the American Control Conference*, pages 458–462, 1997.

A. Sternberg, R. Zemp, and J. C. de la Llera. Multiphysics behavior of a magneto-rheological damper and experimental validation. *Engineering Structures*, 69:194–205, 2014. ISSN 01410296. doi: 10.1016/j.engstruct.2014.03.016. URL http://dx.doi.org/10.1016/j.engstruct.2014.03.016.

R. Sutton and A. Barto. *An introduction to reinforcement learning.* 1998. ISBN 9781609601652. doi: 10.4018/978-1-60960-165-2.ch004.

M. D. Symans and M. C. Constantinou. Semi-active control systems for seismic protection of structures: A state-of-the-art review. *Engineering Structures*, 21(6):469–487, 1999. ISSN 01410296. doi: 10.1016/S0141-0296(97)00225-3.

J. W. Tu, J. Liu, W. L. Qu, Q. Zhou, H. B. Cheng, and X. D. Cheng. Design and fabrication of 500-kN large-scale MR damper. *Journal of Intelligent Material Systems and Structures*, 22(5):475–487, 2011. ISSN 1045389X. doi: 10.1177/1045389X11399942.

X. Wang. Coarse-Fine Self-Learning Active Mass Damper for Frequency Tracking Vibration Control. *International Journal of Structural Stability and Dynamics*, 20 (2):1–16, 2020. ISSN 17936764. doi: 10.1142/S0219455420500248.

O. Yoshida and S. J. Dyke. Seismic Control of a Nonlinear Benchmark Building Using Smart Dampers. *Journal of Engineering Mechanics*, 130(4):386–392, 2004. ISSN 0733-9399. doi: 10.1061/(asce)0733-9399(2004)130:4(386).

R. Yuan, Y. Yang, C. Su, S. Hu, H. Zhang, and E. Cao. Research on Vibration Reduction Control Based on Reinforcement Learning. *Advances in Civil Engineering*, 2021, 2021.

D. H. Zelleke and V. A. Matsagar. Semi-active algorithm for energy-based predictive structural control using tuned mass dampers. *Computer-Aided Civil and Infrastructure Engineering*, pages 1–16, 2019a. ISSN 14678667. doi: 10.1111/mice.12474.

D. H. Zelleke and V. A. Matsagar. Energy-based predictive algorithm for semi-active tuned mass dampers. *Structural Design of Tall and Special Buildings*, 28(12):e1626, 2019b. ISSN 15417808. doi: 10.1002/tal.1626.

J. Zhang, X. Zhao, and X. Wei. Reinforcement Learning-Based Structural Control of Floating Wind Turbines. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, pages 1–11, 2020. ISSN 21682232. doi: 10.1109/TSMC.2020.3032622.

K. Zhou, J. W. Zhang, and Q. S. Li. Control performance of active tuned mass damper for mitigating wind-induced vibrations of a 600-m-tall skyscraper. *Journal of Building Engineering*, 45(November 2021):103646, 2022. ISSN 23527102. doi: 10.1016/j.jobe.2021.103646. URL https://doi.org/10.1016/j.jobe.2021.103646.

Chapter 6

Conclusions and Future Work Recommendations

Chapter Outline: This chapter includes a summary of the thesis and mentions the major contributions to knowledge, highlighting the main outcome of this work. Moreover, the limitations of this research work are listed in order to allow for the accurate assessment of the findings. Finally, this chapter includes a number of future work recommendations which resulted from the findings of this thesis.

6.1 Thesis Summary

This thesis investigated the dynamic response mitigation of civil engineering structures using mass damper technology. For the simulations of this work, a real high-rise tower equipped with a hybrid mass damper (HMD) possessing passive, semi-active and active capabilities was used. A number of control algorithms arising from optimal, robust and intelligent control techniques were implemented and their performance was assessed based on various criteria.

In Chapter 2 a detailed background literature review was presented including the latest advances in the area of structural control using mass damper technology. Furthermore, using a systematic literature review approach, an up-to-date list of 208 mass damper applications on building-like structures was presented, along with a first-time-ever list of control algorithms implemented on the relevant mass dampers (including 24 listings). After analysing the data gathered within this chapter, it was shown that, Asia with 120 systems is the continent with the most structural control applications, with around 3 times more applications than America that has 46. The third continent with the most structural control applications is Europe with 36, fourth is Australia with 5 and last is Africa with only 1 application. Moreover, it was shown that 47% of the total applications were installed before 2000 and 55% of them were installed between the years 1992 and 2005. Furthermore, the large majority of mass damper installations were PTMDs with 131 applications (63% of the total number systems) where, the second most used system is the HMD with 65 applications. An observation of significance was that, after 2005 the installation of the HMDs has considerably decreased and a preference in PTMDs was shown even though there was an increase in HMDs research. Finally, the algorithms utilised on real applications of semi-active, active and hybrid mass dampers were mostly based on the optimal theory, H_∞ and continuous sliding mode control, most likely due to their successful establishment in many control applications outside civil engineering.

Chapter 3 investigated the performance of the Robust Model Predictive Control (RMPC) algorithm in the dynamic response dissipation of the Rottweil tower equipped with a HMD. More specifically, two RMPC algorithms were designed; one considering the best displacement response dissipation performance ($RMPC_1$) and; one considering the reduced power consumption ($RMPC_2$). To assess the performance of the two controllers, an H_∞ algorithm which is a well-established robust controller within the field was also implemented. Moreover, a top-floor displacement limit was introduced as an evaluation parameter for this study. Five parametric uncertain scenarios considering 0%, −2%, +2%, −10% and +10% stiffness and damping uncertainties were also investigated in order to assess the robustness of the control algorithms. It was found that, the $RMPC_1$ had the best overall response dissipation performance when compared to the rest of the controllers and the purely passive system. When considering the top floor displacement limit, the two RMPC controllers managed to satisfy the constraint in four scenarios in contrast to the H_∞ and the passive system which managed to satisfy it only in two scenarios (seen in Figure 3.7). In the −10% uncertainty scenario, non of the controllers managed to achieve the desired control objective, highlighting the small capacity actuator effect on the overall control performance of the system. Additionally, as shown in Figure 3.9, the $RMPC_2$ achieved the least power and energy consumption, and had the second best response dissipation performance only after the $RMPC_1$, demonstrating the superiority of the model predictive scheme.

Chapter 4 considered the dynamic response control of the Rottweil tower using the reinforcement learning algorithm called Deep Deterministic Policy Gradient (DDPG). For comparison purposes, the very well-established algorithm within the structural control field, Linear Quadratic Regulator (LQR), was also implemented. To investigate the robustness of the DDPG algorithm, a parametric uncertain scenario considering −10% stiffness and damping uncertainty was also implemented. Similar to Chapter 3, a top floor displacement limit was introduced for the better comparison of the two controllers. The simulation results showed that, the DDPG was efficient on reducing the dynamic responses of the tower and demonstrated robustness. More specifically, the DDPG had a similar vibration dissipation performance compared to the LQR while achieving less power and energy consumption. As shown in Figure 4.5, both controllers managed to keep the top floor displacement within the desired limit in the nominal scenario, (with the DDPG being superior to the LQR), in contrast to the parametric uncertain scenario where non of the controllers managed to reach the desired limit (seen in Figure 4.9). Moreover, when investigating the performance of the two algorithms on handling practical aspects of a HMD (i.e. actuator displacement and velocity), it was found that the DDPG had a superior performance compared to the LQR in both nominal and parametric uncertain scenarios (see Figure 4.13), demonstrating potential on implementing it within the area of structural control.

Chapter 5 aimed to decrease the energy consumption of the HMD by reducing the use of the active part of the system. To achieve that, the passive, semi-active and active parts of the system were utilised. Firstly, the performance of the system acting purely as a passive, semi-active and active system was presented. On the algorithmic side, the Clipped-LQR and LQR were used for the semi-active and active configurations, respectively. In a first attempt to decrease the active usage of the system, an active/semi-active hybrid mass damper (ASHMD) was proposed which attempted to replace the dissipative energy achieved by the active system with the semi-active configuration. Even though the proposed system managed to reduce the active energy consumption, it did not manage to meet the primary target of the study. Thus, a novel passive, semi-active, active mode-switching hybrid mass damper (MSHMD) was proposed. For the mode-switching control of the system a reinforcement learning algorithm called Deep Q-Network was implemented. When comparing the performance of the proposed system to the PTMD, the SATMD, the ATMD and the ASHMD, it was found that the MSHMD had the second best vibration dissipation performance only after the ATMD. However, the MSHMD managed to decrease the energy requirements of the active parts by 41% when compared to the ATMD, by only sacrificing 1.5% in the displacement dissipation performance (while being below the desired limit). It is noted that, only the ATMD and the MSHMD managed to decrease the top floor within the acceptable region, demonstrating the efficacy of the proposed control scheme.

6.2 Contributions to Knowledge

Each chapter discussed its contributions and novelties that arose based on the analysis that was carried out. This section will focus on the main outcome that emerges from this thesis. The primary target of this work was to develop software methods, using some of the latest algorithms, in order to considerably increase the effectiveness of a HMD installed on a real tower. Working with a real case-study signifies that various practical limitations (i.e. HMD and actuator specifications) had to be addressed and demanding control objectives (i.e. dynamic response reduction, robustness, and reduced energy consumption) had to be achieved. The considered control algorithms demonstrated effectiveness on the vibration mitigation of the case-study tower and managed to achieve control performance that could not be met with a passive configuration. In the presence of parametric uncertainties, the control algorithms were proven robust demonstrating their superiority over the passive configuration which exhibited detuning effects resulting in a deteriorated performance compared to the uncontrolled structure. The results of this thesis provide a valuable contribution to the structural control research field by presenting the feasibility of utilising advanced control algorithms for the enhancement of the mass damper performance on a real case-study tower. The current findings and recommendations can be used as a guide for engineers and researchers in the implementation of mass damper technologies in future works.

Even though the implemented control techniques had an enhanced vibration dissipation performance, the overall conclusion is that: *"The effectiveness of the software stops where the limitations of the hardware begin"*. The aforementioned statement was substantiated in Chapters 3-5, especially when parametric uncertain scenarios were investigated. More specifically, the limited actuator capacity was proven a drawback in the attempts of some of the latest control algorithms to achieve their primary control objective. Moreover, the same chapters showed that, large amounts of energy are required by active systems to achieve their performance which, in some cases can be proven to be similar to semi-active systems (which require orders of magnitude lower energy) and this causes scepticism around their application. This argument was also reviewed in chapter 2 where, the relatively low number of real-life applications of active systems was discussed. This demonstrates the importance of accurately sizing the non-traditional mass dampers (i.e. not PTMDs) by considering more parameters than just its mass, stiffness and damping. Optimisation problems can be formed where, the specifications of the actuators, the allowable stroke, the control algorithm, the total energy consumption and the total cost of the system will be used as variables, in order to achieve the best possible configuration for each specific application.

This thesis proposed novel methods to decrease the energy requirements of the mass damper system by using advanced reinforcement learning algorithms. The field of reinforcement learning is relatively new and rapidly growing, showcasing its effectiveness in various research sectors (e.g. robotics, finance, healthcare). The use of such algorithms and the consideration of both the software and hardware aspects of the system was a novel approach on mass damper applications, and their proven efficiency indicates potential for implementation on large scale applications. One of the key advantages of their implementation on the control of mass damper systems is their ability to adapt over time, leading to a continuously improving control performance while, further reducing the energy requirements of the system. Moreover, the hybridisation of the software and hardware aspects of the system that was proposed in Chapter 5, proposes a comprehensive and integrated solution on considerably decreasing the energy requirements of the system while, maintaining an acceptable vibration dissipation performance.

Finally, this thesis identified a lack of an experience sharing culture within the structural control community (in Chapter 2) in relation to the installation and management of real-life mass damper applications. It is believed that, by sharing real-life installation experience and discussing limitations that arise in each particular application, the structural control community will emphasise on solving practical problems which will broaden the acceptance of such control systems by the engineering industry. It was found that, a limited number of studied including Spencer and Sain (1997) and Koutsoloukas et al. (2022) (Chapter 2) presented lists of control algorithms that are employed on real mass damper applications. It was clear that, the engineering industry does not use the latest algorithms despite their proven efficiency. The up-to-date lists of mass damper and control algorithm implementations on real building-like structures included in Chapter 2 are considered important for the structural control field because they provide valuable information and practical insights to researchers and engineers. This will assist the structural control community to assess the acceptance of each control system by the engineering community and develop methods to increase the adoption of newly proposed smart solutions.

6.3 Thesis Limitations

To address the main research aim of this thesis, the current work was affected by a number of limitations. It it vital to identify them in order to impartially assess the findings and establish the material for future work. The limitations of this thesis are:

1. All the findings of this work are produced in a simulation environment and validation may be essential. While, simulations do not always fully embody the real-world conditions, great efforts were made in order to achieve accurate representation of realistic control conditions that may occur on the real tower by considering various types of uncertainties along with realistic control constraints.

2. The simulation work carried out within this study used design wind loads. Even though this type of loads is considered accurate enough when used in design-

ing structures, they do not include complex aerodynamic phenomena such as self-excited aerodynamic forces which may affect the dynamic properties of the structure and consequently, the vibration dissipation performance of the control system.

3. A reduced-order model was used to derive the controllers of the case-study tower which is common practice in structural control. However, the use of reduced-order models in controlling real applications includes a risk of observation spillover (Balas (1978), Nagashima and Shinozaki (1997)) which may result in control performance deterioration when used for the control of the real application.

4. Designing control algorithms may be an iterative process which often requires varying a number of parameters in order to achieve the best possible controller for a given application. All the controllers that were presented herein were proven to be efficient on achieving their control objectives. Though, it is noteworthy that the limited availability of computational power restrained the further investigation of the considered controllers.

5. This thesis investigated the energy consumption associated with the considered mass damper system (Chapters 3-5). However, a number of assumptions had to be made (e.g. did not consider any hardware energy losses) since, no actuator specification details were available to the author.

6.4 Future Works

Future work will firstly involve the derivation of a more complex wind-loading which will be a more accurate representation of the wind acting on the real structure. In a more optimistic scenario, wind data sourced from the tower's location will be acquired leading to more accurate modelling. This will also allow for the comparison of the controllers' performance using the artificial and measured wind loading, and identify the effects of the imprecise wind loading in the performance of the controllers.

Secondly, to validate the current findings, it is important to apply the proposed control schemes in experimental configurations. A scaled experimental model of the current case-study is suggested to be constructed and equipped with a model HMD. This will allow for the evaluation of the considered controllers and it will provide a testbed for different controllers and mass damper configurations to be implemented.

Thirdly, to accommodate for the observation spillover mentioned in Section 6.3, future work will investigate the use of a prefilter which electronically removes the observation spillover (Balas (1978), Nagashima and Shinozaki (1997)) or spacial modal filters (Meirovitch and Baruh (1985), Nagashima and Shinozaki (1997)) which however cause an increase in the required measurements. Moreover, the simple reduced-order model of the structure does not include any nonlinear structural behaviour due to inelastic deformations which is likely to occur in real life. More accurate modelling will also be followed by the response control of the two orthogonal axis along with the rotation and twisting of the structure.

Next, in all cases, and especially for the reinforcement learning controllers, more tests using different objective functions and tuning parameters would allow for converging in more effective controllers. Future work will involve investigating the experimented controllers with different parameters and objective functions (or rewards in the case of reinforcement learning controllers) in order to observe how their performance is influenced.

Furthermore, future work will focus on an in-detail consideration of the energy associated with the use of active and semi-active parts in mass damper configurations. Moreover, the author intends to eliminate the need of external power source by designing an energy-regeneration system. Disciplines such as aerospace (Li et al. (2016)) and automotive (Abdelkareem et al. (2018)), have already started implementing such techniques. Energy regeneration technologies have been studied by several scholars in the area of structural control (Casciati et al. (2012), Liu et al. (2016), Marian and Giaralis (2017), Takeya et al. (2016), Tang and Zuo (2011a,b)) demonstrating the effectiveness of their applications. Thus, it is suggested that the next milestone to be met is working towards turning the considered HMD into a self-sustained control system.

Finally, the economic cost associated with the installation, management and maintenance of mass damper systems installed on real building-like structures will be studied. This will provide further understanding on the economic implications and feasibility of the mass damper systems along with the long-term viability and cost-effectiveness of these technologies. Moreover, this analysis will provide valuable information in relation to the acceptance and adoption of the mass damper systems by the engineering industry.

References

M. A. Abdelkareem, L. Xu, M. K. A. Ali, A. Elagouz, J. Mi, S. Guo, Y. Liu, and L. Zuo. Vibration energy harvesting in automotive suspension system: A detailed review. *Applied Energy*, 229(July):672–699, 2018. ISSN 03062619. doi: 10.1016/j.apenergy.2018.08.030. URL https://doi.org/10.1016/j.apenergy.2018.08.030.

M. J. Balas. Active control of flexible systems. *Journal of Optimization Theory and Applications*, 25(3):415–436, 1978. ISSN 00223239. doi: 10.1007/BF00932903.

S. Casciati, L. Faravelli, and Z. Chen. Energy harvesting and power management of wireless sensors for structural control applications in civil engineering. *Smart Structures and Systems*, 10(3):299–312, 2012. ISSN 17381991. doi: 10.12989/sss.2012.10.3.299.

L. Koutsoloukas, N. Nikitas, and P. Aristidou. Passive, Semi-Active, Active and Hybrid Mass Dampers: A Literature Review with Associated Applications. *Developments in the Built Environment*, 12:100094, 2022. ISSN 2666-1659. doi: 10.1016/j.dibe.2022.100094. URL https://doi.org/10.1016/j.dibe.2022.100094.

D. Li, Y. Wu, A. Da Ronch, and J. Xiang. Energy harvesting by means of flow-induced vibrations on aerospace vehicles. *Progress in Aerospace Sciences*, 86:28–62, 2016. ISSN 03760421. doi: 10.1016/j.paerosci.2016.08.001. URL http://dx.doi.org/10.1016/j.paerosci.2016.08.001.

Y. Liu, C. C. Lin, J. Parker, and L. Zuo. Exact H2 Optimal Tuning and Experimental Verification of Energy-Harvesting Series Electromagnetic Tuned-Mass Dampers. *Journal of Vibration and Acoustics, Transactions of the ASME*, 138(6), 2016. ISSN 15288927. doi: 10.1115/1.4034081.

L. Marian and A. Giaralis. The tuned mass-damper-inerter for harmonic vibrations suppression, attached mass reduction, and energy harvesting. *Smart Structures and Systems*, 19(6):665–678, 2017. ISSN 17381991. doi: 10.12989/sss.2017.19.6.665.

L. Meirovitch and H. Baruh. The implementation of modal filters for control of structures. *Journal of Guidance, Control, and Dynamics*, 8(6):707–716, 1985. ISSN 07315090. doi: 10.2514/3.20045.

I. Nagashima and Y. Shinozaki. Variable gain feedback control technique of active mass damper and its application to hybrid structural control. *Earthquake Engineering and Structural Dynamics*, 26(8):815–838, 1997. ISSN 00988847. doi: 10.1002/(SICI)1096-9845(199708)26:8⟨815::AID-EQE678⟩3.0.CO;2-E.

B. F. Spencer and M. K. Sain. Controlling Buildings: A New Frontier in Feedback. *IEEE Control Systems Magazine on Emerging Technology*, 17(6):19–35, 1997. ISSN 10990682. doi: 10.1002/cber.190904203162.

K. Takeya, E. Sasaki, and Y. Kobayashi. Design and parametric study on energy harvesting from bridge vibration using tuned dual-mass damper systems. *Journal of Sound and Vibration*, 361:50–65, 2016. ISSN 10958568. doi: 10.1016/j.jsv.2015.10.002. URL http://dx.doi.org/10.1016/j.jsv.2015.10.002.

X. Tang and L. Zuo. Simulation and experiment validation of simultaneous vibration control and energy harvesting from buildings using tuned mass dampers. *Proceedings of the American Control Conference*, 11794:3134–3139, 2011a. ISSN 07431619. doi: 10.1109/acc.2011.5991018.

X. Tang and L. Zuo. Enhanced vibration energy harvesting using dual-mass systems. *Journal of Sound and Vibration*, 330(21):5199–5209, 2011b. ISSN 0022460X. doi: 10.1016/j.jsv.2011.05.019. URL http://dx.doi.org/10.1016/j.jsv.2011.05.019.