Extending the sound of the guzheng

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Abstract

The guzheng is a representative Chinese traditional musical instrument with more than 2000 years of history. However, the acoustics of the instrument have not been investigated to the same extent as some other Chinese instruments. This work sets out to advance and develop the guzheng, by extending its sonic potential, via the application of the technology. In this dissertation, current transformation, modelling, recording and production techniques are discussed for extending the capacities of the instrument. Recordings of the guzheng including the impulse response measurement of the instrument that capture the acoustic characteristics of the guzheng are presented. An additive synthesis model and physical modelling synthesis model of the guzheng are presented to simulate guzheng tones in Max/MSP. Guzheng recordings and synthetic results have been applied to the production of a famous traditional guzheng piece 'Yu Zhou Chang Wan' and this work is described here. The research is intended to contribute to the inheritance and development of the guzheng. By extending its timbre and pitch range, guzheng compositions and performances can be more diversified.

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Author's declaration

I declare that I am the sole author of this dissertation. This work has not been published before in any form. This work has not previously been presented for an award at this, or any other, University. All sources are acknowledged as References.

Chapter One – Introduction

The inheritance and development of traditional music is an important music research subject in modern society. With the background of globalization and cultural pluralism, absorbing different types of music is an inevitable trend of developing traditional music. There have been many people calling for the revitalization of Chinese traditional music since the 1980s in China (Xia, Yun, 2008: 158). Inheritance and innovation are both important for the development of traditional music. Art will gradually disappear without innovation and innovation must be, to a certain extent, based on inheritance.

With the popularization of electronic music in China, Chinese traditional music with full-bodied eastern characteristics combined with electronic music has appeared in China in recent years. For example, Twelve Girls Band which is a band famous for combining Chinese traditional musical instruments with pop and electronic music has drawn more and more attention (Xia, Yun, 2008: 159). Supported by modern technology, their music emphasizes visual effects and lighting. Although some people regard it as a distortion of traditional music, their music is really helpful for propagating Chinese traditional musical instruments, and they achieve this by being able to play those traditional instruments. With the development of science and technology, increasing numbers of scholars pay attention to applying new technologies to Chinese traditional musical instruments. For instance, Liang Shengfu et al. (1999) and Välimäki et al. (2006) discuss sound synthesis of the pipa and guqin (Chinese traditional plucked-string instruments with four strings and seven strings respectively). Taking the aesthetic demand of the masses into account, combining new techniques and new timbres with their traditional counterparts is needed.

The purpose of this research is to extend the sonic potential of the guzheng by transformation, modelling, recording and production techniques. There are some prior works of sound synthesis of Chinese traditional musical instruments, including the guqin and pipa. Although a few playing techniques are included in the guqin and pipa tone synthesis, the guzheng has its own specific structure and many different playing techniques. They are synthetic versions of the guzheng commercially available, but there is little research on the synthesis of the guzheng.

As a representative Chinese traditional musical instrument, inheritance and innovation of the guzheng plays a vital role. There is a clear understanding of the role of the guzheng in Chinese culture. However, the acoustics of the instrument are less well understood. Pan, Guangyu (2009) presents that, compared with western musical instruments, the guzheng is harder to play with other musical instruments or be integrated with other timbres in electronic music because of its strong Chinese feature and personalized expressive force (Pan, Guangyu, 2009: 117). Plus the limitation of the range of the guzheng, it is unlikely to meet increasing aesthetic requirements of the audience and it is not beneficial to make new compositions with the guzheng as well. Compositions of Chinese traditional musical instruments including the guzheng are lagging behind. Many famous pieces have used electronic instruments such as the *Turangalila-Symphony* by French composer Olivier

Messiaen (1908–1992) which was composed about 65 years ago. However, there are no famous and typical pieces composed for guzheng and electronic music currently.

On the aspect of compositions for the guzheng, the research results can provide composers with more space and choices to compose brand-new musical pieces of the guzheng. The research will be beneficial to the inheritance and development of the guzheng as well. The study will contribute to the development of the guzheng and Chinese traditional music by developing a greater understanding of its timbre, and by extending that timbre.

In order to achieve the goal of the research, some questions need to be considered. What are the history, structure, musical notation, tuning and playing techniques of the guzheng? What are the acoustical characteristics of the guzheng? What factors of the instrument that affect the acoustic of guzheng should be considered? Can the capabilities of the guzheng be effectively extended using current transformation and modelling techniques? What software and synthesis methods can be used? What recording techniques and microphones are suitable for guzheng recording? How can the drawbacks of adopted methods be avoided to improve the recording and synthetic results? How can the recording and synthetic sounds be applied effectively into the production and composition of the guzheng?

The dissertation is organised as follows: The theoretical background of the research is presented in Chapter Two, including an overview of the guzheng, spectral modelling synthesis and physical modelling synthesis theories, previous recordings and productions of the guzheng. Electronic music compositions with the guzheng and new technical developments of the guzheng are also introduced in this chapter.

Chapter Three presents the techniques and setup for guzheng recording. To capture the guzheng accurately, it was recorded in two places, the Trevor Jones studio and anechoic chamber respectively in the University of York. The recording results are discussed as well. Additive synthesis and physical modelling synthesis are adopted to simulate the acoustic guzheng in Max/MSP and the synthetic results are discussed in Chapter Four. In Chapter Five, the production of a famous traditional guzheng piece 'Yu Zhou Chang Wan', which uses recordings of the guzheng and synthetic results to extend the sound of the instrument, is introduced. Finally, the conclusion and ideas for further research are presented in the last chapter.

Chapter Two – Theoretical background

2.1 The guzheng

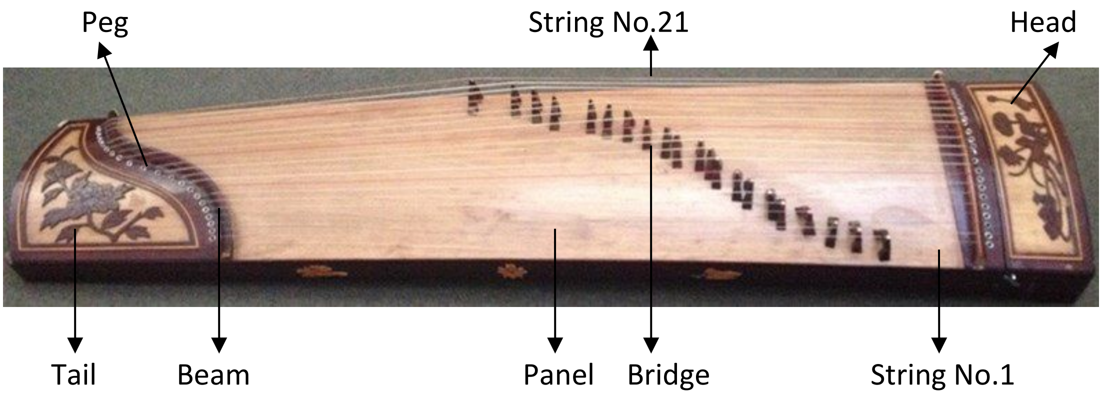
2.1.1 The history of guzheng

The guzheng is one of the most ancient Chinese plucked-string instruments with more than 2000 years of history. It was originally called "Zheng" or "Qinzheng", because it was widely spread in Qin State during the Warring States period (450 B.C. – 221 B.C.). "Gu" means "ancient" and "zheng" means "zither" in Chinese. The origin of the guzheng is a mystery. According to historical records, the earliest literature which mentioned the guzheng is *Records of the Grand Historian* in 237B.C. Therefore, it is an incontrovertible fact that the guzheng appeared earlier than 237 B.C.（Zhao, Manqin, 1981: 68）.

In ancient China, the guzheng used to have differing numbers of strings from five to twenty-six during different periods. Duan, Lili (2006) presents the earliest five-string guzheng evolved into twelve strings in the Han Dynasty (202 B.C. – 220 A.D.), and then it evolved into thirteen strings in the Sui and Tang Dynasty (581 A.D. – 907 A.D.). The guzheng was introduced to Japan by the Japanese envoy in the Tang Dynasty. The Koto which is a traditional Japanese musical instrument originated from the thirteen-string guzheng. The fourteen-string guzheng appeared in the Ming Dynasty (1368–1644) and then was augmented to sixteen stings in the Qing Dynasty (1616–1911). Most guzheng players used the strings made of twisted silk or metal by the twentieth century. Since the mid-twentieth century, flatwound steel strings with nylon were widely used which increased the capabilities and volume of the instrument. The number of guzheng strings gradually increased to twenty-one because of the rapid development of new musical pieces and playing techniques after the 1960s which expanded the range of the guzheng（Duan, Lili, 2006: 57）.

2.1.2 Guzheng acoustics

The modern standard guzheng generally has twenty-one strings and twenty-one movable bridges. The thinnest string with highest pitch is called String No.1 and the rest can be called in the same manner, String No.2, String No.3 etc. (Jin, 2011: 64). The guzheng can be made from many sorts of woods. The old mahogany and rosewood are always the best choice because of their good sound quality. The old mahogany and rosewood are very stable and the timbre of them is quite bright. This kind of timbre is suitable for not only traditional pieces, but also modern pieces. Figure 1 shows the structure of guzheng. The picture of guzheng was taken by the author. The whole length of it is approximately 160cm.



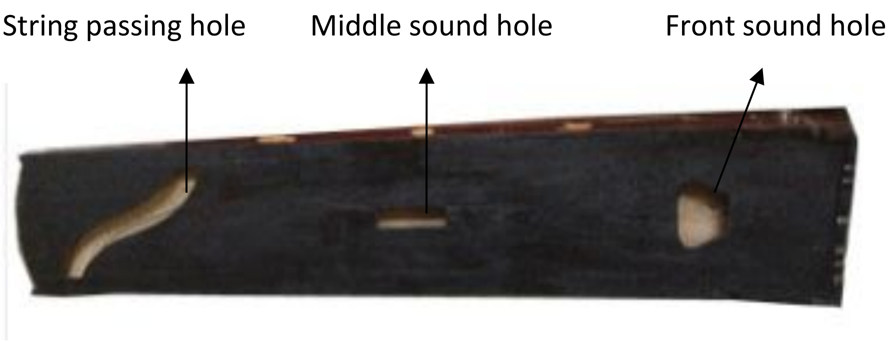


Figure 1: The structure of guzheng

The guzheng, as a traditional Chinese plucked-string instrument, is made up of four components which is similar to other plucked-string instruments: excitation system, vibration system, conduction system and resonance system. Wang Zhonglin et al. (2012) describe the excitation system as the energy source of vibration for stringed instruments, and the pick is the excitation system of the guzheng. The vibration system of the guzheng is the string which is the core part of making a sound. However, making a sound through the vibration of the string can not meet the demand of the guzheng performance. Consequently, the bridge is required to become the conduction system, conveying the vibration of the string to the resonance system of the guzheng – sound box. The sound box of the guzheng is not only regarded as the resonance system which increases the volume of the guzheng, but also determines the timbre of the guzheng because of its unique shape (Wang Zhonglin et al., 2012: 564). Figure 2 shows the simplified model of sound generating principle of the guzheng. This is a simplified model that does not incorporate flow of energy back into strings.

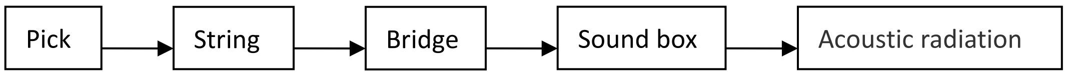


Figure 2: Simplified model of sound generating principle of the guzheng. Reproduced from Wang Zhonglin et al., 2012.

Some scholars put forward some suggestions to improve the sound box of the guzheng. Wang Zhonglin et al. (2012) propose that changing the current position of the sound hole of the guzheng can increase its volume (Wang Zhonglin et al., 2012: 566). Zhang Yongxiang (2008) indicates three sound beams which are made of wood such as red sandalwood for transmitting the vibration to the panel can be arranged inside the sound box of the guzheng to improve the volume. Their opinions provide the direction and theoretical basis for further improvement of guzheng structure.

2.1.3 Numbered musical notation (Jianpu)

Music scores of guzheng are written in Numbered musical notation (called Jianpu （简谱)). Numbers from one to seven represent music notes: 1 = do, 2 = re, 3 = mi, 4 = fa, 5 = sol, 6 = la, 7 = si. Adding dots above or below the number represents an octave higher or lower respectively. For example, one dot added above means one octave higher. Two dots added below means two octaves lower. Figure 3 shows the comparison between Numbered musical notation and Staff. Note length is indicated by adding lines below the note number or adding dashes to the right of the number （Carol Chang, 2011). Figure 4 depicts the note length comparison between Numbered musical notation and Staff.

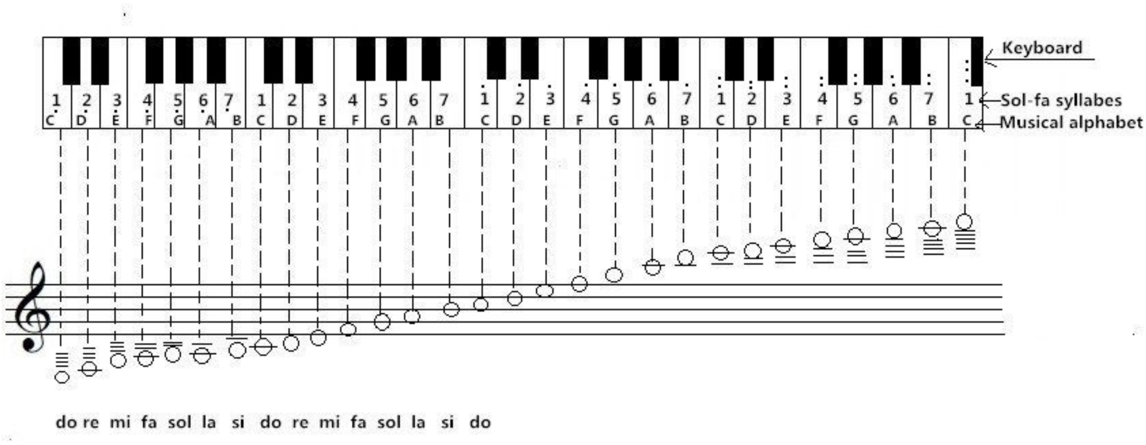


Figure 3: Comparison between Numbered musical notation and Staff. Redrawn from Huang, Yangbo, 1992.

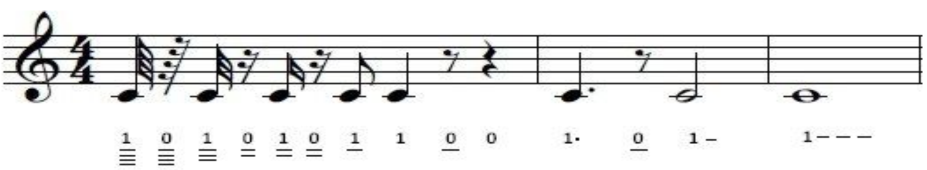


Figure 4: The note length comparison between Numbered musical notation and Staff.

2.1.4 Tuning

The guzheng has a broad range of four octaves. Strings are generally tuned as a pentatonic scale (C, D, E, G, A). Figure 5 shows the standard tuning of the guzheng. The pentatonic scale in D major is the basic and common tuning for the guzheng （Chang, 2011). In D major, String No.21 is tuned as D and String No.1 is tuned as d^3 as shown in Figure 6, and it can be changed to different majors by moving bridges. Moving it to right means higher pitch, and moving it to left means lower pitch. Bridges divide the instrument into two sides: the player uses the right side to pluck the string, while the left side is used to produce specific techniques, such as bending and vibrato (Yan, Li, 1992: 16).

Figure 5: Standard tuning of the guzheng. Reproduced from Gaywood, 1997.

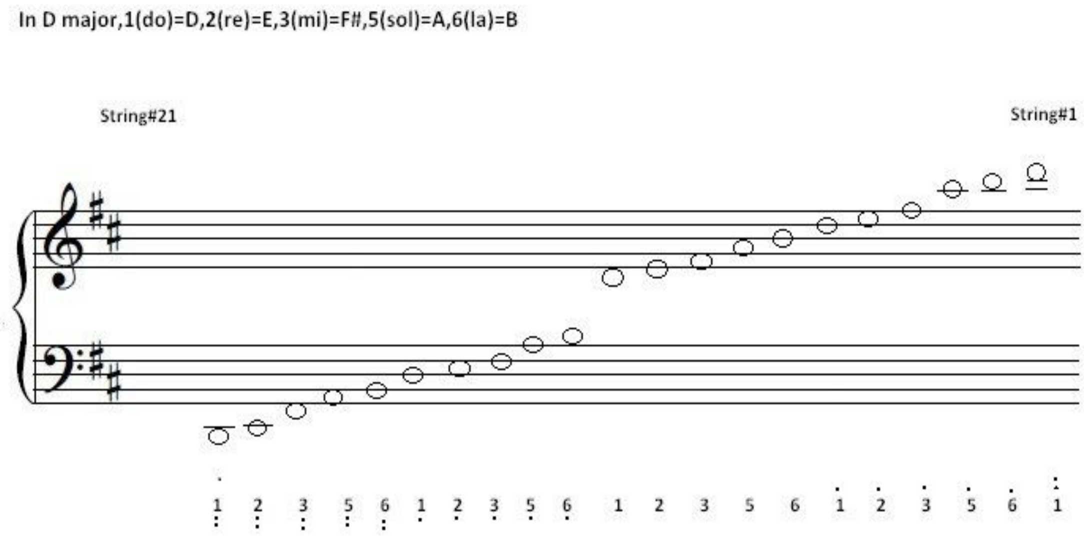


Figure 6: Tuning of the guzheng in D major. Redrawn from Chang, 2011.

As a plucked-string instrument, the guzheng changes its pitch frequently. It is mainly due to two reasons: movements of bridges and variation in atmospheric conditions. Therefore, putting the guzheng in a low-humidity without direct sunshine location is needed. Covering the guzheng with a piece of thick cloth is also helpful.

2.1.5 Playing techniques

The player is asked to use picks when they play the instrument. There are four picks in a set because the little finger does not need to wear the pick. The right hand must wear picks while whether to wear picks for left hand depends on players. Picks are often made out of the shells of hawksbill, and adhesive tapes are adopted to fix picks above the first knuckle of the fingers to make sure that both tapes and picks do not hinder the movement of the first knuckle.

Plucking is a basic technique of the guzheng. Both right hand and left hand can be used to pluck the string on the right side of the bridge. Plucking different strings in sequence continuously with different fingers sometimes can create chords and this technique is called arpeggio. Glissando is plucking across the strings upward from bass to treble notes using the index finger or downward from treble to bass notes using the thumb (Chang, 2011). Plucking the same string outward and inward repeatedly in a really short interval is known as tremolo. Tremolo is played only by the right hand and tremolo with thumb is frequently used. The wrist of right hand is the key to control tremolo (Yang, Nani, 1999: 26).

Plucking the string on the right side with the right hand first and then slightly vibrating the same string on the left side with the left hand up and down is vibrato. Vibrato is really free and players can add it by themselves to express their emotions. Harmonics are used to produce a soft tone that is an octave higher. This technique controls the amplitude of the vibrating string and makes higher harmonics with low amplitudes express more. To achieve this, the left hand slightly presses the string near the bridge and the right hand plucks the string. The position of left hand should be accurate because its position determines the pitch (Yan, Li, 1992: 47).

Bending is also a basic technique which is commonly used. The right hand is used to pluck the sting and left hand to press the left side of the same string. Plucking first and then pressing the same string or pressing first then plucking the same string are two kinds of bending which are called forward portamento and backward portamento respectively. Close the three fingers without thumb and little finger of the left hand and use these three fingers together for both vibrato and bending (Yang, Nani, 1999: 30).

The playing techniques introduced above are traditional playing techniques, some new techniques which bring special sound effects appeared from the 1980s. For instance, pitches on the left side of the guzheng were regarded as noise because pitches on the left side are out of order and have no specific majors. The left side of the guzheng is only played with the left hand and used for ornaments such as bending and vibrating. But now strings on the the left side are used for more playing techniques in particular guzheng pieces.

Beating and tapping is a highly expressive playing technique including slapping the string or bridge with the palm. This technique used playing techniques of percussion instruments for reference. Rubbing the string with the palm or pick is also an emerging playing technique. Although these special playing techniques are not widely used, the particular type of sound they produce can not be replaced by traditional playing techniques. For instance, beating and tapping is able to create a festive atmosphere. Using the left side to play glissando can make a nervous and exciting atmosphere. These techniques make the guzheng composition and performance more interesting, and provide more options for the player to perform the piece (Xu,Weiru, 2012).

2.2 Sound synthesis

2.2.1 Spectral modelling synthesis

Fourier analysis is the most prevalent method of spectrum analysis. The method gets its name from the French engineer and aristocrat Jean Baptiste Joseph, Baron de Fourier (1768-1830). He published a theory that 'arbitrarily complicated periodic signals could be represented as a sum of many simultaneous simple signals' (Roads, 1996: 1075). Scholars modelled the Fourier analysis into the short-time Fourier transform (STFT) to adapt Fourier analysis to the practical world of sampled, finite-duration, time-varying signals. There are basically two categories of spectrum analysis: harmonic analysis and formant analysis. The short-time Fourier transform (STFT) is a typical example of harmonics analysis (Miranda, 1998: 51).

Spectrum analysis is very important for spectral modelling synthesis and some methods have been created to analyse the spectrum of sounds. The static spectrum plot is a two-dimensional image which has frequency along the horizontal axis and amplitude along the vertical axis. Figure 7 shows the spectrum of a recorded guzheng tone. The plot is generated with the spectrum analyser in Wavelab. The analysis window length is 2048 samples and a Blackman smoothing window is used. The sample rate of the recorded string is 44.1 kHz.

Plotting a spectrogram (or sonogram) is a way to display a time-varying spectrum. The spectrogram has time along the horizontal axis and frequency along the vertical axis, and the amplitude of the signal at any given time and frequency is plotted in terms of the darkness of the trace. Conventionally, frequency components with more energy are plotted darkly while frequency components with less energy are plotted lightly (Roads, 1996: 541). The spectrogram of a recorded guzheng tone is shown in Figure 8 which is plotted from the spectrogram function in Matlab (This software is introduced in Chapter Three on page 57) with the following settings: 'Plucking of String No.13' is the analysed file and its sampling rate is 44.1 kHz. The window length of each frame of the short-time Fourier analysis is 4096 and the amount that each frame overlaps is 4000.

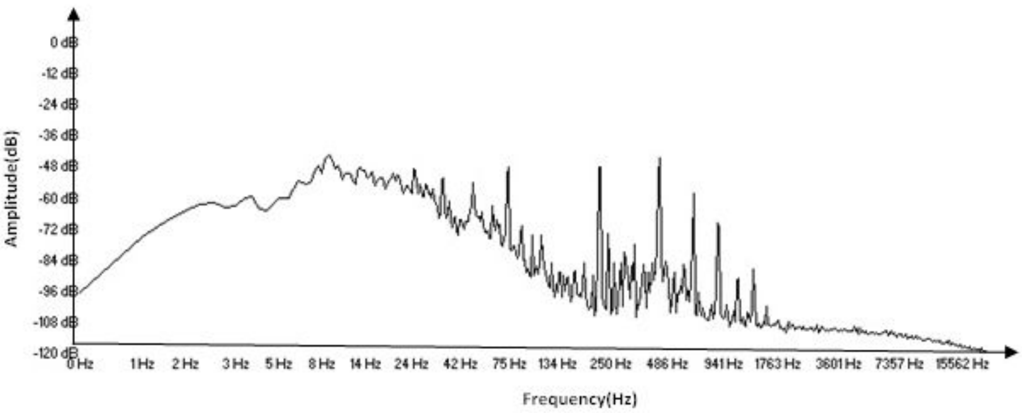


Figure 7: The spectrum of a recorded guzheng tone.

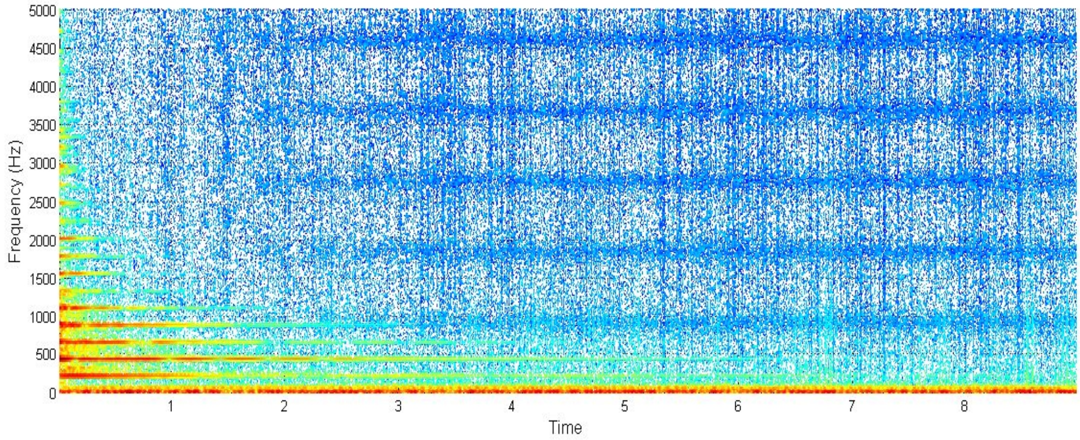


Figure 8: The spectrogram of a recorded guzheng tone.

Additive synthesis technique is one of the oldest synthesis techniques and it has been adopted since the early stage of electrical and electronic music （Cahill 1897, Douglas 1968, die Reihe 1955, Stockhausen 1964. Additive synthesis is considered a powerful and flexible spectral modelling method which assumes that ‘any periodic waveform can be modelled as a sum of sinusoids at various amplitude envelops and time-varying frequencies’ (Miranda, 1998: 125). Roads (1996) defines that additive synthesis is ‘a class of sound synthesis techniques based on the summation of elementary waveforms to create a more complex waveform’ (Roads, 1996: 134).

Each spectral component of a sound can be represented by its amplitude and frequency functions. The synthesis of a tone requires a separate sinusoidal oscillator for each partial with applying its amplitude and frequency functions (Figure 9). The sound is generated by adding the output of some sinusoidal oscillators. Each of oscillators has different amplitudes and frequencies.

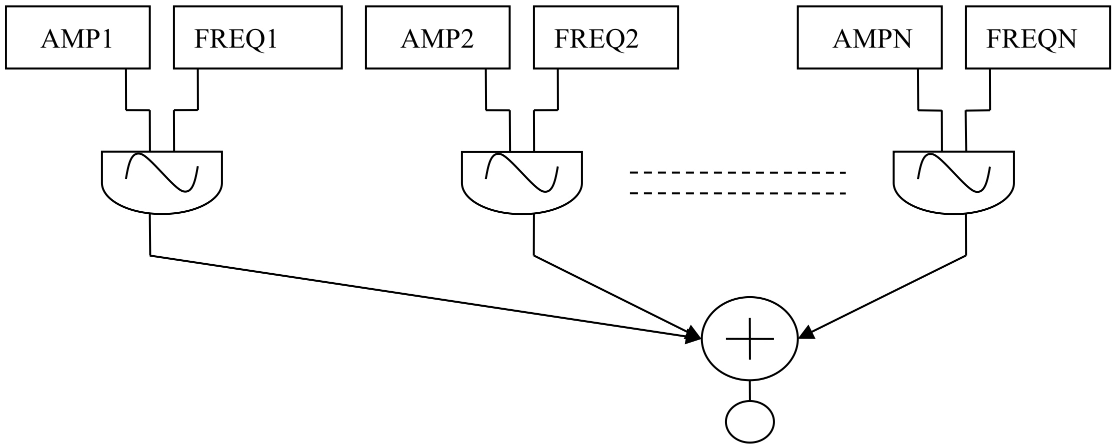


Figure 9: Basic configuration for additive synthesis. Redrawn from Dodge and Jerse, 1997.

An advantage of additive synthesis is that it provides complete, independent control over the behaviour of each spectral component. However, it is difficult to control and time-consuming, because music timbres are made up of a large number of time-varying partials, including harmonic, non-harmonic and noise components. Accordingly, it requires numerous oscillators, noise generators and envelopes to obtain a realistic simulated sound (Dodge and Jerse, 1997: 89; Miranda, 1998: 125).

Spectral modelling synthesis (SMS) is a synthesis technique that 'models time-varying spectra as a collection of sinusoids controlled through time by piecewise linear amplitude and frequency envelopes and a time-varying filtered noise component' (Serra and Smith, 1990: 12). The basic spectral modelling technique models sound as the sum of sinusoids (partials) plus noise (residual component). Serra and Smith (1990) define the sinusoidal component as the 'deterministic component' and the noise part the 'residual or stochastic component'

(Serra and Smith, 1990: 12).

> The analysis procedure detects partials by studying the time-varying spectral characteristics of a sound and represents them with time-varying sinusoids. These partials are then subtracted from the original sound and the remaining "residual" is represented as a time-varying filtered white noise component. The synthesis procedure is a combination of additive synthesis for sinusoidal part, and subtractive synthesis for the noise part.
>
> (Serra, 1997: 91)

2.2.2 Physical modelling

Physical modelling of musical instruments has become a popular research area since the 1980s. "Physical modelling" refers to the mathematical or computational simulation of sound production mechanism of musical instruments (Välimäki, 1996: 331). Miranda (1998) claims that there are three main kinds of methods of physical modelling: the classic approach, the functional approach and the recirculating wavetable approach.

> The classic physical modelling approach simulates the behaviour of vibrating media using a network of interconnected mechanical units, called mass and spring. This approach has the ability to capture two essential physical properties of vibrating media: density and elasticity. Density is relative to pitch whilst elasticity is relative to amplitude and duration. The functional approach is based on the principle that the behaviour of an instrument is determined by two main components: source and resonator. The resonator acts as a filter (or a bank of filters) applied to a non-linear source signal. The recirculating wavetable approach uses a time-varying

> lookup table to simulate the behaviour of a vibrating medium. The basic functioning of this method starts with a lookup table of a fixed length, filled with random samples.
>
> (Miranda, 1998: 92)

The Karplus-strong technique is a classic example of the recirculating wavetable approach to physical modelling. Roads (1996) describes ‘Interest in applying waveguides to synthesis was provoked by the discovery of Karplus-Strong plucked-string algorithm’ (Roads, 1996: 268). The Karplus-Strong algorithm for plucked-string instrument synthesis is an efficient technique based on the principle of delay line or recalculating wavetable (Karplus and Strong, 1983; Jaffe and Smith, 1983). The basic and typical tone of the plucked-string instrument is made of a short attack and a long decay.

The basic Karplus-Strong algorithm for plucked string instrument (Figure 10) starts with a wavetable filled with random values or noises to represent the pluck effect which are then read out of the wavetable from the right. Kevin Karplus and Alex Strong who devised the original Karplus-Strong algorithm at Stanford University suggest using a delay line to represent the waves on the string. Then they modify it with a simple low pass filter which is an averaging of the current sample with the previous sample to simulate the decay in the high-frequency harmonics over time (Roads, 1996: 293). After this, the result is fed back to the left side and then starts back at the beginning. The result of this algorithm is the sound bursts with a loud, bright quality, and then it darkens and turns into a single sinusoidal type of sound which is really like the acoustics of plucking strings. When the string is plucked, the string is highly energized and a sound wave with rich harmonics is created, and then the string's energy is exhausted which generates a tone with fewer harmonics because of the friction between the air and the string. After a period of time, the string stops vibrating with all of the energy gone (Burk et al., 2005). The decay of the sound normally depends on the length of the wavetable. However, the decay length is able to be controlled through adding time-stretching mechanisms to the original Karplus-Strong algorithm (Miranda, 2002: 78).

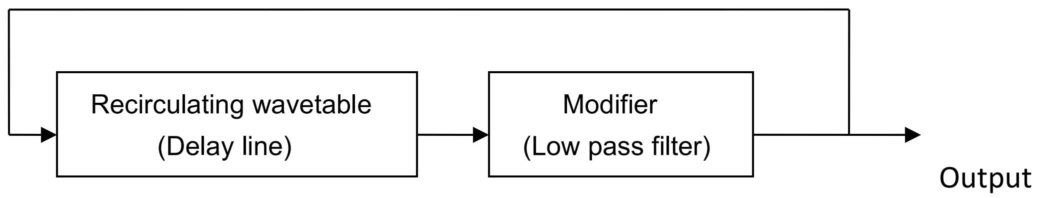


Figure 10: Basic Karplus-Strong algorithm for the plucked-string instrument.

The waveguide filtering technique is a typical functional approach to physical modelling. Waveguides are efficient algorithms of physical modelling synthesis introduced by Yamaha and Korg in 1993 and 1994 as the engine of synthesizers (Roads, 1996: 282). A waveguide (or waveguide filter) is a computation model of a wave-travelling medium, such as strings, tubes, rods, membranes and so on. The basic element of a waveguide is a pair of digital delay lines. A vital aspect of waveguide synthesis is the feedback interaction between the excitation and the filter.

Figure 11 shows a generic waveguide instrument model capable of simulating stringed or wind instruments (Cook, 1992; Roads, 1996:283).

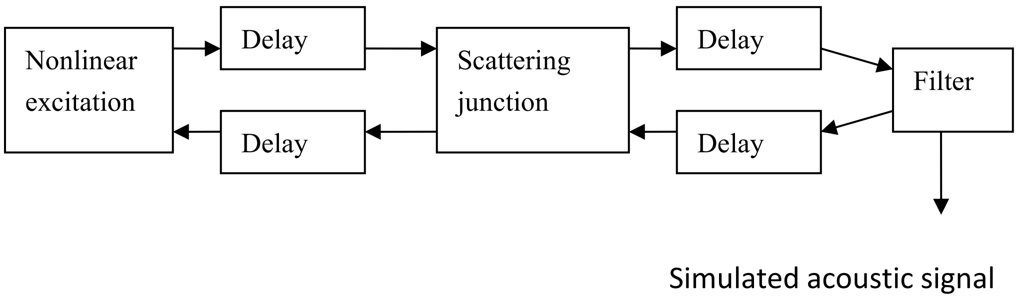


Figure 11: A generic waveguide instrument model capable of simulating stringed or wind instruments. Reproduced from Roads, 1996.

> A nonlinear excitation injected into the upper delay line travels until it hits the scattering junction, which models the losses and dispersion of energy that occur at junctions in acoustical systems. Some energy returns to the oscillator junction, and some passes on to the output junction, modelled by a filter. The scattering junction is a linear or nonlinear filter that models the effect of a finger or bows pressing on a string, or a tonehole on a wind instrument. The filter at the end models the effect of the bridge, body, or bell of the instrument.
>
> (Roads, 1996: 283)

With the digital waveguide technique, the wave travelling on the string is transferred to a delay line. A fractional delay filter is needed to generate a continuous and accurate output frequency which is similar with the allpass filter applied in Karplus-Strong synthesis (Välimäki, 1995: 37). The characteristics of string stiffness can be modelled with an allpass filter (Välimäki and Smith, 2010: 406). A damping filter is required in the waveguide model for the tone decay time (Karjalainen, Välimäki, Janosy, 1993: 56).

2.2.3 Model-based sound synthesis of plucked string instruments

The instrument is generally divided into two parts, namely, exciter and resonator. Roads (1996) presents 'the interaction between an exciter and a resonator is a basic principle of physical modelling. An excitation is an action that causes vibration, such as plucking the string. A resonance is the response of the body of an instrument to the excitation vibration' (Roads, 1996: 268).

> The exciter has a nonlinear behaviour, while the resonator has a linear behaviour. Plucked string instruments can be conveniently treated as linear system (strings and instrument body), where the "pluck" is simply described as a non-equilibrium initial condition (i.e., the pluck gives a string a non-zero displacement distribution and a null velocity distribution).
>
> (Avanzini, 2006:2)

The interaction between exciter and resonator can be feedforward and feedback. A feedforward scheme for plucked string instruments means the vibration of the resonating part does not feed back to the excitation part (Avanzini, 2006: 3). From a signal-processing point of view, the body acts as a time - invariant filter applied to the excitation signal.

Model-based sound synthesis has practical advantages over other sound synthesis methods. For example, wide variations of the synthesized sound are allowed by a natural set of control parameters in model-based synthesis (Karjalainen, Välimäki, Janosy, 1993: 56). The plucked string instrument model is shown in Figure 12.

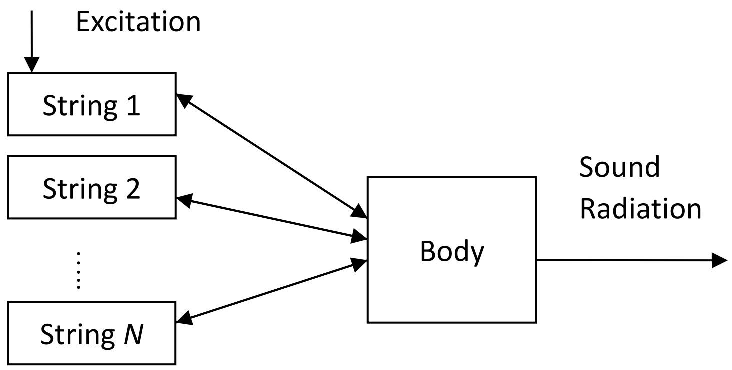


Figure 12: Model for a plucked string instrument. Redrawn from Välimäki et al., 1993.

Välimäki et al. (1996) state that ‘the general solution of the wave equation for a vibrating string is made of two independent transversal waves travelling in opposite directions. The waves reflect back with inverted polarity at the terminations of the string and form standing waves’. In this system, the losses damp the vibration of the string. The string can be described as a waveguide, which is a bidirectional discrete-time delay line (Smith, 1987). Therefore, this system may be modelled using a pair of delay lines and a pair of reflection filters, as illustrated in Figure 13.

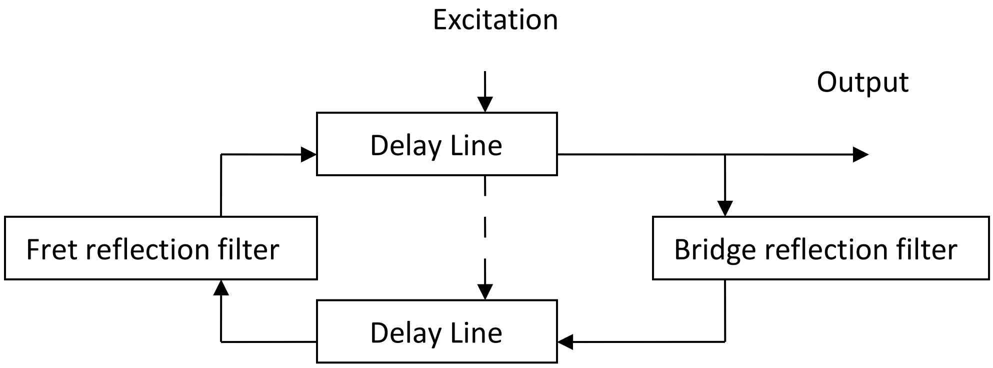


Figure 13: Waveguide model for vibrating lossy string. Redrawn from Välimäki et al., 1996.

There are many methods of modelling the body resonator for different kinds of instruments. A spectral-based body model which uses the average of the excitation signal spectra of open strings to make body model filter is proposed (Penttinen et al., 2006: 4058). It is flexible with simple computation and fit for plucked-string instruments. This body model filter roughly contains the spectral envelope modelled with a fourth-order linear prediction model and two low-frequency modes of the body modelled with second-order peak filters (Penttinen et al., 2006: 4058).

There are some prior works of plucked-string instruments sound synthesis including synthesis of a Chinese plucked-string instrument - guqin. Penttinen et al. (2006) present a model-based sound synthesis algorithm for the guqin. 'A version of the digital waveguide synthesis approach is used, where the string length is time-varying and its energy is scaled properly'. Laurson et al. (2007) have dealt with both the notation part and synthesis part of the guqin. Their paper describes a project with the control part including control of glides and vibrato of guqin synthesizer. However, there is no related research on analysis and synthesis of the guzheng.

2.2.4 Impulse response measurement of stringed instruments

A starting point for body modelling is to measure the body impulse response in an anechoic room (Karjalainen and Smith, 1996). The impulse response of the instrument measured contains all the characteristics of the timbre and reverberation. Türckheim et al. (2010) argue that impulse response measurement techniques for string instruments should meet certain requirements:

> (i) A high degree of reliability is required in order to allow the comparison of measurements as well as the exact repetition of measurements at different times or places. (ii) Particularly for investigations on musical instruments a high validity is necessary. (iii) The excitation signal has to have an adequate linear and broadband frequency behaviour. (iv) In the case of acoustic recordings, the excitation mechanism should be as quiet as possible. (v) The excitation mechanism must not add additional mass or affect the instrument's vibration characteristics in any other way. This demand is especially important for stringed instruments because of their complex and sensitive resonance behaviour.
>
> (Türckheim et al. , 2010:222)

Various impulse response measurement techniques have been proposed. For example, Bradley and Stewart (1970) propose driving methods where a machine simulating hand bowing is used to excite the instruments in a natural manner, but this method is very complex and time-consuming. Farina et al. (1995) use MLS (Maximum Length Sequence) technique to measure impulse response of violins. The approach applied the MLS excitation signal to the bridge of the violin by a transducer. The response is sampled and then cross-correlated with the original signal which obtains a result close to the impulse response. However, the MLS technique does not meet the fifth requirement mentioned above (Türckheim et al., 2010). Hence, the most reliable and practical methods are the “Impact hammer method” and the “Copper wire method”.

Karjalainen and Smith (1996) explore the method of measuring the impulse response of an acoustic guitar. An impulse hammer was used to tap the bridge vertically with damped strings for the impulse response measurement. The microphone was placed one metre in front of the sound hole (Karjalainen and Smith, 1996: 233). Erkut et al. (1999) propose the approach to measure the impulse response of the Tanbur which is an Asian long-necked string instrument. A hard-tipped metallic object with a diameter of 0.5mm was used. All strings were damped and a microphone was located one metre normal to the soundboard. Three directions were measured: vertical, horizontal and longitudinal direction.

Türckheim et al. (2010) state that the impact hammer method does not take the bridge motion in longitudinal direction and the tensional vibrations which occur due to the string deflection into consideration. The impact angle, speed and the exact point of excitation is hard to reproduce. Bridge backward motion may lead to double hits (Türckheim et al., 2010: 223). Consequently, a new method is required to obtain better impulse response measurement results.

A new impulse response measurement approach of stringed instruments which uses a thin copper wire is proposed. The procedure is very inexpensive and the principle is really simple. This method uses a thin copper wire which pulls a string aside at the bowing or plucking position until the wire breaks, and then an impulse runs along the string and hits the bridge. The method is easy to repeat because the plucking point, pulling direction, angle between the wire and string and the level of stress of breaking the wire are easily definable (Türckheim et al., 2010: 223).

Türckheim et al. (2010) use this method to measure the impulse response of the violin. Copper wires with diameters between 0.09mm and 0.19mm are used, because a larger diameter may lead to the string being pulled down from the bridge. A small rubber mat was placed near the start of the fingerboard to damp all strings. The small rubber mat is the best choice because the fingerboard modes are not influenced by the light rubber. 'The pulling direction is set to the respective bowing direction' (Türckheim et al., 2010: 2). Türckheim et al. (2010) decide to use a driving point at a distance of 10mm from the bridge. A vibration-free steel instrument called a quadrochord is adopted to measure the input signal.

Smit et al. (2010) introduce a simple automated plucking apparatus to trigger the excitation which can be used in the copper wire impulse response measurement. This excitation mechanism can exclude human error factors and avoid related noise. Owing to the acoustic radiation characteristics of a violin, the sound is different between the player's two ears. Therefore, binaural impulse responses are measured with a near-field artificial head microphone. Türckheim et al. (2010) also compare the wire excitation with the impact hammer excitation and point out that the comparison between the copper wire method and impact hammer method is an important task for impulse response measurement of string instruments and needs further research (Türckheim et al., 2010: 3).

2.3 Recording and production

2.3.1 Recording of the guzheng

Xu, Yiran and Zhu, Xiaotian (2012) investigate acoustic space distribution of the guzheng by analyzing frequency spectra in the semi-anechoic and normal recording studio. The characteristic of acoustic space distribution of the guzheng means there are different characteristics of timbres in different places when the guzheng produces sound. The frequency characteristics of the guzheng in different positions are compared and analysed. They argue that the position in front of the guzheng is more sensitive to high frequency and the position near bottom sound hole is more sensitive to middle and low frequency (Xu, Yiran and Zhu, Xiaotian, 2012: 77).

Different recording methods of the guzheng are adopted by different sound engineers. Hu, Taoyuan (2012) argues putting the microphone in front of the guzheng is better. He prefers to choose 20-25cm spaced pair technique to record the guzheng. Wang, Yichi (2008) suggests using two omnidirectional microphones beyond one metre in front of the guzheng to record the guzheng in stereo. Also large-diaphragm condenser microphones are commonly used and able to obtain satisfying recordings. The reason will be explained in detail in Chapter Three. Hu, Taoyuan (2012) and Wang Yichi (2008) claim that another way to record the guzheng is to put the microphone near the sound hole which means putting the microphone under the guzheng. The sound is very clear, but the resonance will not be enough. Too many low frequencies are easily generated through this method as well, and the reflected sound between the floor and guzheng can be recorded which makes the sound muddy. To solve this problem, the microphone can be located farther from the sound hole (Wang, Yichi, 2008: 28).

2.3.2 Electronic music composition and production of the guzheng

Xiaoyong, Chen composed many pieces for the guzheng, such as 'duet for violin and guzheng', 'invisible landscape', 'Yun', 'Fusion', 'Yang Shen' and so on which considerably extend the sound potential of the instrument by the use of new playing techniques and new tunings.

Electronic music composition with the guzheng is also an effective way to extend the capabilities of the instrument. Meng, Lei (2013) states that production and composition of Chinese traditional musical instruments with the background of electronic music elements appeared since the 1980s which aims to pursue a combination of classical and modern style (Meng, Lei， 2013： 6). With the rapid development of science and technology, combining traditional musical instruments with electronic music is an inevitable trend. Pan, Guangyu (2009) argues applying the timbre of Chinese traditional musical instruments to electronic music is controversial among scholars. Some people regard this type of music as the inheritance and development of traditional musical instruments. Others claim that it will result in losing Chinese traditional musical culture. However, it is undeniable that this kind of new style music has been accepted by a large number of people, because it is not only an efficient way to combine Chinese traditional music with modern electronic music, but also beneficial to promoting Chinese traditional music to the whole world (Pan, Guangyu, 2009: 118）.

Pan, Guangyu (2009）highlights redeveloping traditional musical instruments from the perspective of computer music has its particular advantages. For example, people can change playing techniques of musical instruments and integrate playing techniques of electronic musical instruments or western musical instruments into Chinese traditional musical instruments through the sampler. The timbre of musical instruments can be changed according to the musical piece by the equalization. By sampling synthesis, the range of traditional musical instruments can be expanded. By producing software instruments of Chinese traditional musical instruments, musicians from all over the word can use timbres of these instruments for their compositions.

Meng, Lei (2013) classifies the way of applying traditional musical instruments' timbres to electronic music into two categories: using software instruments or electronic musical instruments; adopting sounds of real traditional musical instruments by recording and live performance. With convenient software instruments, composers are able to choose suitable timbres or use the equalization to create particular timbres for their works. Current major software instruments which offer guzheng include China Kong Audio， Sample Tank, Digital Sample Arts, Best Service-Yellow River Sound (Ma, Min, 2011: 92).

Ma, Min (2011) describes abundant playing techniques of the guzheng in Kong Audio and some short samples of musical pieces are also included. The software is easy to operate and its interface is simple and beautiful with national characteristics. However, its sample rate is not high (Ma, Min, 2011: 92). Cao, Zhengyu (2012) claims Kong Audio is one of the best Chinese traditional software instruments. Samples from the real guzheng bring good sound quality which can meet the demand of the high-quality guzheng music production. More and more music producers from all over the world have paid attention to Kong Audio. In the theme song of the Chinese film *Huo Yuanjia* shown in 2006, timbres of traditional musical instruments in Kong Audio were used (Cao, Zhengyu, 2012: 17).

Cao, Zhengyu (2012) presents Sample Tank is a software instrument produced by IK Multimedia company which includes a powerful sound library of Chinese traditional musical instruments. Sample Tank has its own effects including EQ, delay, reverb, phase shift and so on to produce suitable timbre and also has excellent editing and storage functions. Other merits of Sample Tank are that it occupies very little system resources and supports multi channel MIDI (Cao, Zhengyu, 2012: 17). Ma, Min (2011) describes the obvious feature of Digital Sample Art is its high sample rates (24 bit/96Khz). It supports EXS24, Giga and Kontakt formats and can be directly used in Apple's Logic Pro (Ma, Min, 2011: 92).

The Chinese company "Anda Audio" actively cooperated with Best Service and produced a high-quality software instrument for the guzheng called Yellow River Sound in 2010. Yellow River Sound specializes in guzheng timbres rather than containing many timbres of different musical instruments. It is also the first guzheng software instrument produced by Chinese producers who may have a better knowledge of the guzheng than foreign producers. Hence, it has almost all the advantages mentioned above which include various playing techniques, high sample rates, different dynamics and so on. Therefore, it is currently considered to be the best software instrument for guzheng (Cao, Zhengyu, 2012: 18).

Some software instruments contain guzheng timbres, but they are not widely used because of few guzheng playing techniques and low sound quality, such as Quantum Leap Silk produced by East West, Asian Dreams, Heart of Asia and Logic Pro 7 (Ma, Min, 2011: 92).

Meng, Lei (2013) argues another way to apply traditional musical instruments' timbres to electronic music is adopting sounds of real traditional musical instruments by recording and live performance. Electronic music composition integrated with the guzheng can be divided into two types: tape music and timbres of guzheng in interactive electroacoustic music. Composers can prepare the sound design before the performance with tape music. Another way is to adopt traditional acoustic musical instruments, computer system and modern audio equipment. The performer (or composer) cooperates with the computer programmer to complete musical composition by human–computer interaction (Meng, Lei, 2013: 7).

In the same paper, Meng, Lei (2013) introduces a musical piece called 'Zhao Jun Hui Sai' (9'12'') as an example of applying the timbre of the guzheng to interactive electroacoustic music. The sound of this piece can be divided into two parts: the real sound of playing the guzheng and electronic sounds. The guzheng player plays two guzhengs with different majors which consist of two voice parts of the guzheng. The performer sometimes needs to play the two guzhengs at the same time. The electronic music part is mainly about sound design of the guzheng timbre including prepared electronic music and using different effects when the player performs. The composer uses effects such as reverb, delay and flanger to change the timbre of the guzheng. Different kinds of sound effects such as the sound of bell, wind, drum, running horse are adopted to create certain atmosphere (Meng, Lei, 2013: 7).

'Qixi Festival' - composed for guzheng and electronic music is a music piece played by a famous young guzheng player Wu Yang. It was composed by Zhou Jiaojiao in 2006. The piece has a length of nine minutes. The composer used Cubase VST and Protools to edit the guzheng timbre. Using a great number of samples from the real guzheng, the composer processed playing techniques of the guzheng such as bending, taping and beating with electronic elements to obtain more expressive acoustics (Zhou, Jiaojiao, 2006).

'Qiong Lou Yin' was composed by Wang Hefei for guzheng and electronic music with the length of 11'19'' in 2010. He received an award from Beijing international electronic music composition competition through this piece of music. All electronic materials are from real guzheng samples. The composer tried to get a new connection between the original guzheng timbre and the synthesized guzheng sound. The composer made use of the Sonar system and did not employ too many electronic technologies because of aiming to regard the guzheng as a relatively independent part. Reversing, delaying and pasting the guzheng sound were used to transform the guzheng timbre. Flange was used to create a metal-like timbre. The interesting part of this piece is the drum-like timbre processed from the original guzheng timbre which is similar with the timbre of Chinese traditional drum (Zhu, Wei, 2013: 7).

'Constellations for guzheng and electroacoustic sounds' was composed by French composer Marc Battier which is his fifth piece writing for Asian instruments. It was first performed in Sound Motion - opening concert of musicacoustica-Beijing 2012.

> In this piece, the electronic parts are transformed koto sounds. They are around the audience, and are composed like a painter would paint clouds in the sky. The instrument represents the human activity, sometimes harmonious, sometimes chaotic, sometimes violent, sometimes sweet and calm. At the end, the sounds of the electronic part are transformed into voice-like textures, singing but unseen, as if the instrument itself was singing. The poetic of the piece is based on the meeting of an actual performer, on stage, playing a delicate and lyrical instrument, and the electroacoustic sounds around her. The sounds are like a decor, a background. It creates a scenography upon which the instrument is mostly on the foreground until, in the last section, the guzheng shifts behind the artificial vocal sounds.

(Marc Battier, 2012)

This piece combines guzheng and electronic music which is relatively innovative. The first half of the piece is the guzheng solo. From the middle of the piece, the electronic music accompanies with the guzheng solo. The electronic parts are transformed from Koto sounds and human voice. However, the electronic parts and the guzheng still sound like two separate parts, and the electronic parts are more like background music. More natural integration and electronic timbres can be adopted to the composition.

'Natural Boundary' (6'30'') was composed for guzheng, violin, cello and electronics and premiered in 2006 in Darmstadt, Germany. The composer is Zhao Jingwen. The electronics is based on the granular synthesis technique developed by Center for Computer Research in Music and Acoustics in Stanford University, as well as the Erhu Synthesis software newly explored by Computer Music laboratory in National Cheng Kung University in Taiwan (Wang, Jianwei, 2013: 6).

2.3.3 New technical development of the guzheng

iGuzheng is a guzheng simulator app which supports many playing techniques as a true guzheng. There are full twenty-one strings whose spacing is adjustable by zooming the scroll bar and tuning as any major pentatonic. "Actual Instrument Size" and "Fit All Strings on Screen" as two display modes can be used. Songs can be recorded and shared via iTunes or email. Some guzheng samples and demo videos are included as well. Many playing techniques can be played in iGuzheng. Touching and moving on the string horizontally can play the "shake" technique; the "bending" technique can be played by sliding the left pitch slider; moving the left pitch slider backwards and forwards generates the “vibrato” technique (*iGuzheng* website).

The guzheng is relatively expensive, so most amateurs are not able to buy a real guzheng. People from all over the world can feel the charm of the guzheng and people without formal musical training can play simple guzheng pieces by iGuzheng. However, some parts need to be improved as well especially bending. The bending technique is really stiff and does not show the lingering charm of the guzheng bending. The pitch of bending is hard to control and easy to cause out of tone.

The Roland GU-10 is an effects processor developed for the guzheng. It adopts a patented simulation technique and reproduces natural resonance of the guzheng. The pickup and preamplifier specially developed for the guzheng are used to amplify the original sound of the guzheng. The effects such as chorus, flanger, octave and reverb make the live performance more excellent. The octave can expand the range of the guzheng, especially expand low pitches. Power supply through the battery or AC power adapter is convenient for live performances. The left and right pedals can be used for switch on/off. The guzheng player is able to concentrate on the performance because of its simple operation. In addition, the GU-10 can not only apply to the guzheng, but also other string instruments which increases the application fields of Chinese traditional musical instruments (Zhu, Lu; Huang, Wei, 2011: 65).

Chapter Three – Recording the guzheng

3.1 Microphone selection

Microphones for recording are generally classified into three types: dynamic, ribbon and condenser. The condenser microphone is commonly used on acoustic instruments, cymbals and studio vocals, while dynamics are used typically on drums and guitar amps. The dynamic range is calculated as the difference between the noise floor and the maximum sound pressure level which the microphone can handle. Sensitivity expresses the microphone's ability to convert acoustic pressure to electric voltage. Sound pressure level (SPL) is the result of the pressure variations in the air achieved by the sound waves. Large diaphragm microphones have lower self noise, SPL handling capability and dynamic range, higher sensitivity, narrower frequency range, larger influence on sound filed than small diaphragm microphones (*DPA Microphone* website). The large-diaphragm condenser microphone is preferred for studio vocals and acoustic instruments. The small-diaphragm condenser microphone with good transient response and detail is a good choice for close miking acoustic instruments, such as cymbals, acoustic guitar and piano (Bartlett and Bartlett, 2009).

Xia Yang (2012) tries to prove the adaptability of three different microphones with different types of frequency response characteristics (Neumann U87, AKG C3000B, Schoeps MK 5 ＆ CMC 6U respectively) in recording Chinese traditional musical instruments with the method of Matlab/Simulink spectrum analysis and the comparison of the harmonic relationship between the audio spectrum and the sound characteristics of Chinese traditional musical instruments. The author concludes the Neumann U87 microphone is one of the most suitable microphones for recording Chinese traditional musical instruments (Xia Yang, 2012:54).

The Neumann U87 microphone is able to record relatively complete fundamental frequency and harmonics. The fundamental frequency range of the guzheng is 74-1180Hz. The spectrum frequency range of the guzheng is 74Hz-16kHz (Han, Baoqiang, 2003). The microphone has a relatively complete response between 20Hz and 20 kHz and can record every harmonic of a guzheng tone. It can not only record the main harmonic components of the sound, but also has good response for high frequencies and harmonics. These characteristics result from its high sensitivities, the flat frequency response below 5 kHz and the increased frequency response above 5 kHz (Figure 14). The basic timbre of the musical instrument can be preserved. At the same time, harmonics in the high frequency region will be strengthened which adds more detail to the sound (Xia Yang, 2012: 56).

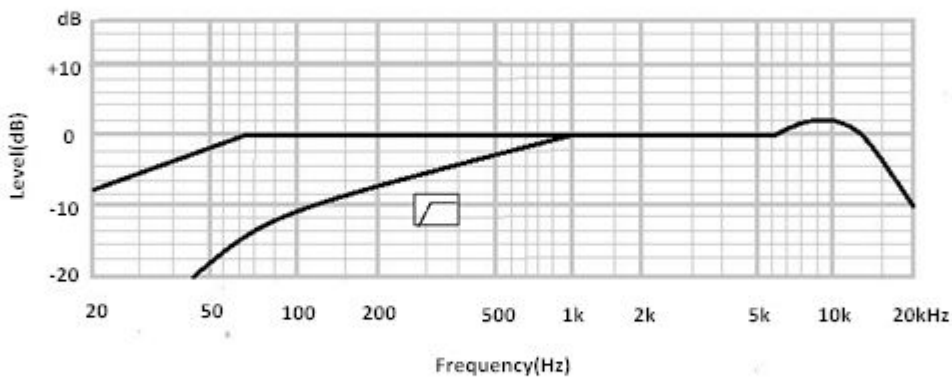


Figure 14: Neumann U87 frequency response-cardioid. Redrawn from Xia, Yang, 2012.

This microphone is a large-diaphragm condenser microphone with three directional patterns: omnidirectional, cardioid and figure of eight. The cardioid pickup pattern has broad-angle pickup of sources in front of the microphone and helps to reject room acoustics, background noise and leakage, especially sound approaching the rear of the microphone (Bartlett and Bartlett, 2009). Therefore, the cardioid pickup pattern was chosen for the guzheng recording.

The Earthworks M30 microphone was used for the impulse response measurement as well. The Earthworks M30 is the small-diaphragm omnidirectional microphone designed for measurement purposes with a wide flat frequency response from 5Hz to 30 kHz. It has a good transient response, consistent polar pattern and amplitude response across a wide frequency range. These characteristics make it ideally suited for different kinds of acoustical measurements.

The spaced pair (AB stereo) technique was adopted to record the guzheng (Figure 15). The technique uses two cardioid or omnidirectional microphones set a few feet apart in front of the sound source. As shown in Figure 15(a), one microphone was located in the middle of the guzheng, and the other was located on the right side of the instrument. Two microphones are panned in left and right configuration to capture the stereo audio of the instrument. The distance between the two microphones mainly depends on the physical size of the sound source, the room it is performing in and the sound engineer’s preference. Hu, Taoyuan (2012) presents the best distance between two microphones to record the single guzheng is 20-25cm using spaced pair technique.

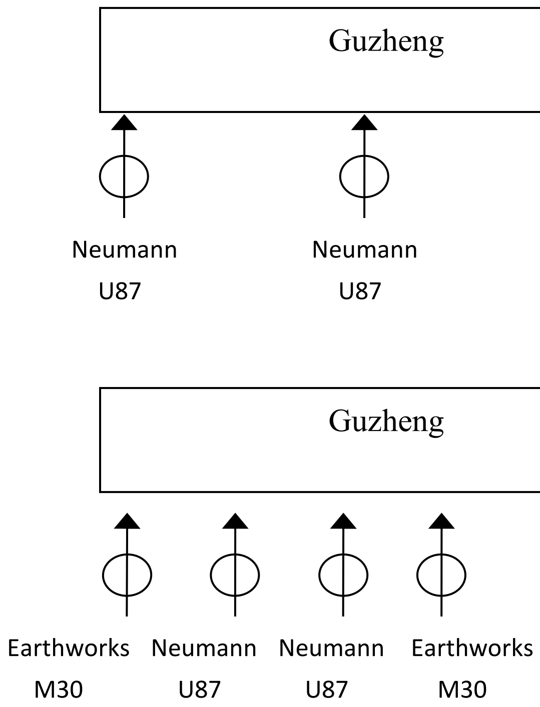


Figure 15: Microphones located in the guzheng recording.

3.2 Recordings in the Trevor Jones studio

One of the most famous traditional guzheng musical pieces 'Yu Zhou Chang Wan (The Song of Fishing Boats at Dusk)' was recorded in the Trevor Jones studio in the University of York. The player of all the guzheng recordings is the author. The recording was made with two Neumann U87 microphones (cardioid pickup pattern) in stereo. The spaced pair technique was adopted (Figure 15(a)). Two microphones were placed at a distance about one metre above the soundboard in front of the guzheng. One microphone was located in the middle of the guzheng and the other was located on the right side of the instrument, because the right side was mainly played. The signals were recorded with 48 kHz sampling rate and 24 bits resolution.

The setup (Figure 16) is beneficial to obtain good quality sound and avoid too much noise or body vibration.

Figure 16: The picture of the studio recording.

Different playing techniques were also recorded in the Trevor Jones studio for the innovative guzheng production which include plucking and tremolo of each string and arpeggio for each octave. Playing techniques of each string and octave were edited and saved as isolated sound files in order to analyse and use the sound precisely.

3.3 Recordings in the anechoic chamber

The impulse response of the guzheng was recorded in the anechoic chamber at the University of York to model the acoustic guzheng. The microphones were located in the anechoic chamber as shown in Figure 15(b). The copper wire method was adopted for the impulse response measurement. The string was pulled in the direction of plucking by the copper wire until the wire broke. Here, the wire was used for excitation. The angle between the wire and the string was approximately 90 degrees and the wire was parallel to the floor. This method is repeatable and relatively accurate because of the definable plucking point, pulling direction, angle between the wire and string and the level of stress of breaking the wire, and the procedure is simple (Türckheim et al., 2010: 223). Türckheim et al. (2010) put forward that the conventional enameled copper wire with the diameter between 0.09 mm and 0.19 mm is the best choice for excitation, because a larger diameter will lead to the string being pulled down from the bridge.

Moreover, the bridge of the guzheng is easily dislodged, so the bridge was pressed vertically by hand to keep the bridge unmovable during the measurement. The string was damped by means of two small rubbers located near both sides of the bridge. This kind of damping has a minimum weight and does not affect the soundboard modes. The distance between the small rubber and the bridge is chosen such that the string is completely damped (Figure 17). With such a setting, an impulse run along the string and hit the bridge when the wire breaks.

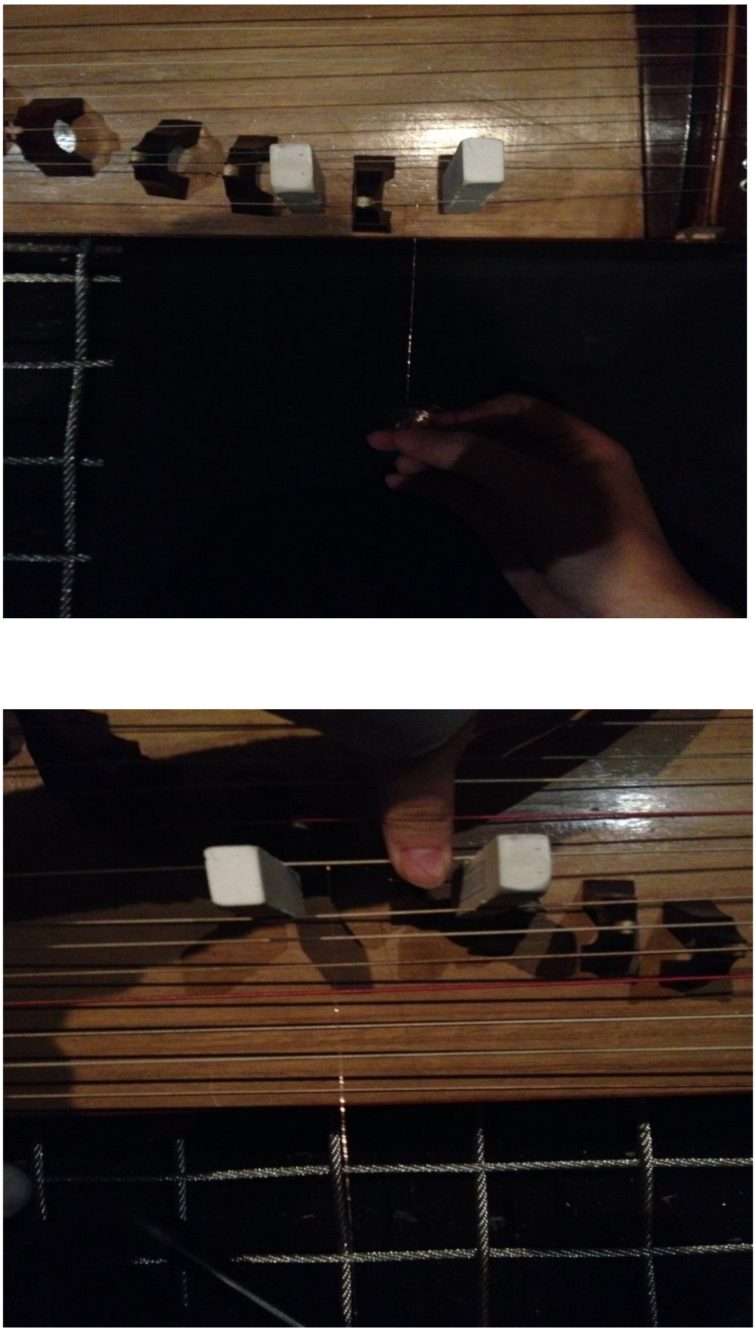


Figure 17: The picture of the impulse response measurement.

The responses were recorded with four microphones, namely two Earthworks M30 and two Neumann U87 microphones (cardioid pickup pattern). Two Neumann U87 microphones were put on the right and left side of the guzheng respectively and two Earthworks M30 microphones were put between them (in the middle). Four microphones were located in one line in front of the guzheng and perpendicular to the soundboard with a distance of one metre. The impulse response of each string was recorded using the Tascam_DR-680 which is an eight-track portable field audio recorder (Figure 18). The signals were recorded with 44.1 kHz sampling rate and 24 bits resolution. All recordings are made with 44.1 kHz or higher and they are presented on disks at 44.1 kHz to provide CD quality audio.

Figure 18: The picture of the anechoic chamber recording.

A variety of playing techniques were recorded in the anechoic chamber as well including plucking, bending, vibrato and harmonics. Impulse responses and playing techniques of each string were edited and saved as isolated sound files in order to be analysed and used conveniently.

3.4 The recording results

There is a noise with low frequency content under 200Hz from the surroundings of the anechoic chamber and recording equipments (Figure 19) existing in the recordings which has a negative effect on the quality of the recordings. This plot is generated using the spectrum analyser in Wavelab. It shows the spectrum of the recording made in the anechoic chamber without any instrument sound which is just the background and equipment noise. The noise to which I refer is acoustic in origin. To obtain better results, the recordings discussed below were used with the PostFilter plugin in Wavelab to reduce the low frequency noise.

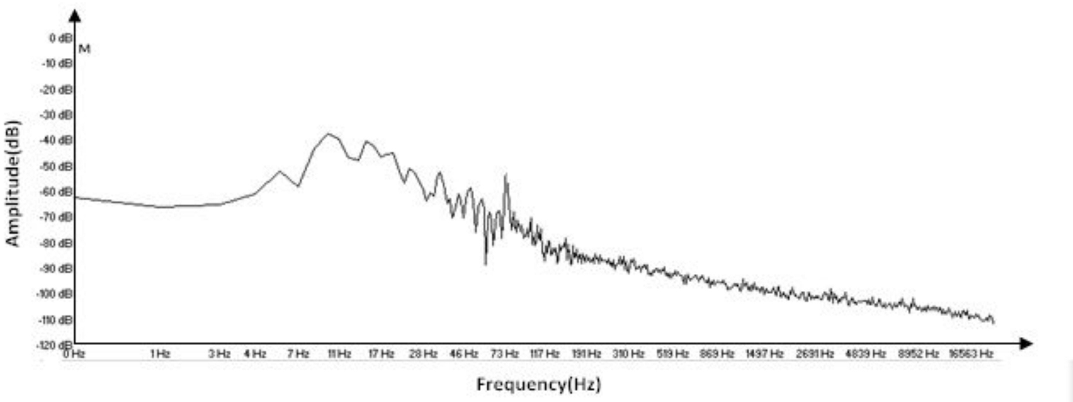
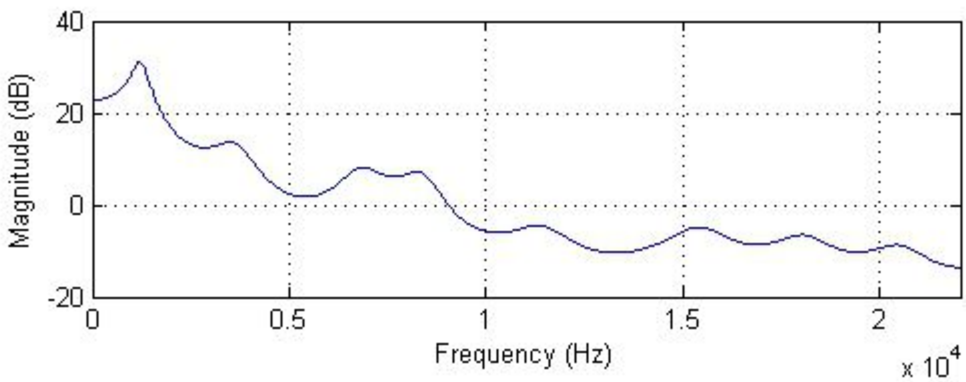
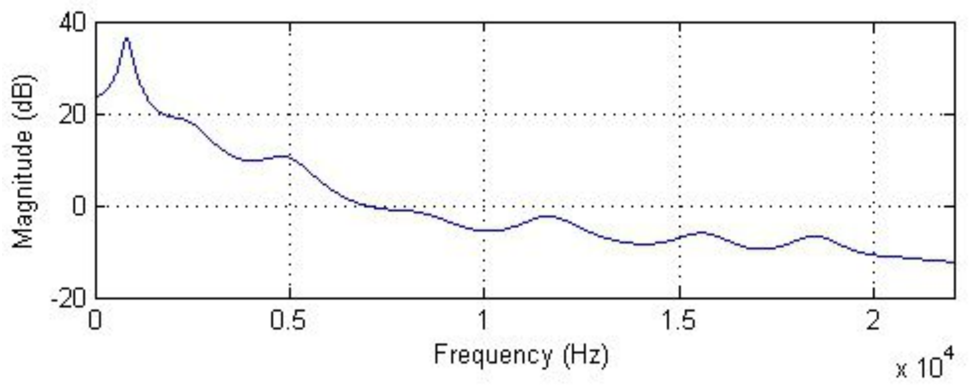


Figure 19: Spectrum of noise from anechoic chamber and recording equipment

The impulse responses of full twenty-one strings were recorded in the anechoic chamber. Figure 20 shows the spectral envelope of the recorded impulse responses of three different strings which were derived via linear predictive coding (LPC) analysis in Matlab. Linear predictive coding is a tool adopted for obtaining the spectrum envelope of a signal which is widely used in audio and speech signal processing (Deng and Shaughnessy, 2003). The previous twenty samples were used to estimate the shape of the formants (i.e. the LPC prediction order was 20). Matlab is a powerful technical computing system which integrates computation, visualization, and programming environment. The name Matlab stands for matrix laboratory and it is widely used for dealing with data and algorithms. Matlab offers a wide range of tools for importing, creating and playing audio files as well as the means for processing, measuring and displaying them (Wells, 2014).





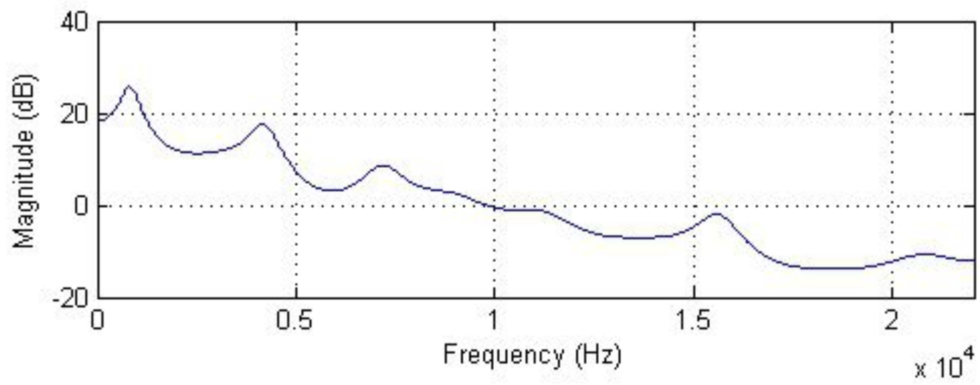


Figure 20: The spectral envelopes of recorded impulse responses of the String No. 20, 15 and 5 (prediction order 20).

The overall shape and the position of some of the peaks of the three diagrams are similar. The resonance of the body can be clearly seen from Figure 20. The first peak has the highest amplitude for all the impulse responses of three strings. The number of resonance peaks is different for different strings. There are eight, seven and six resonance peaks respectively in Figure 20. The string with higher fundamental frequency has less peaks.

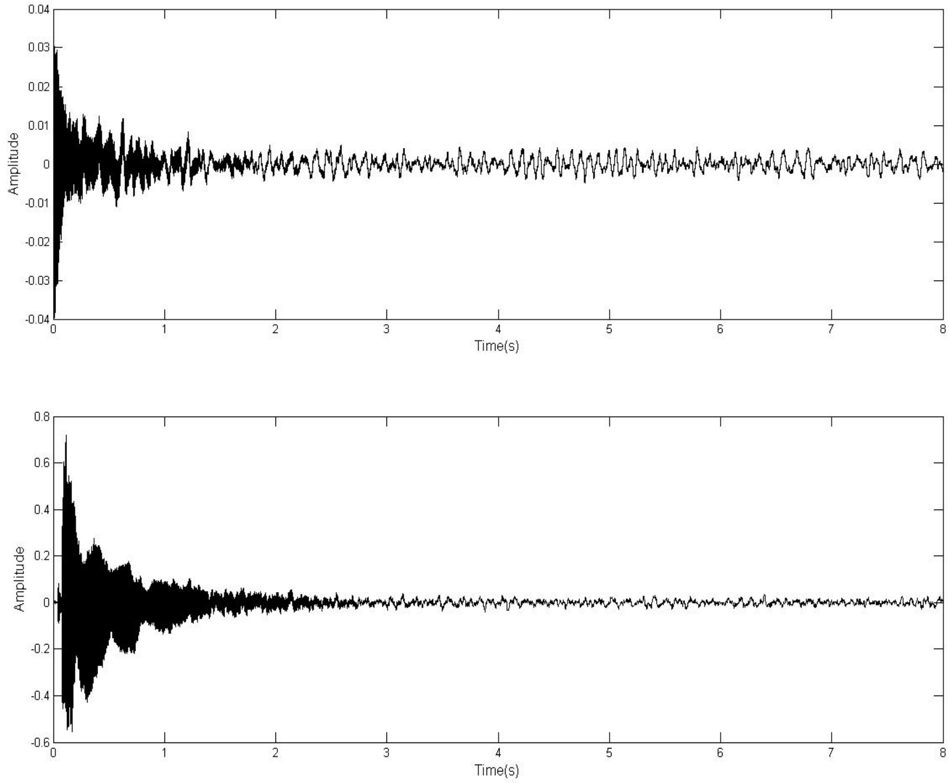
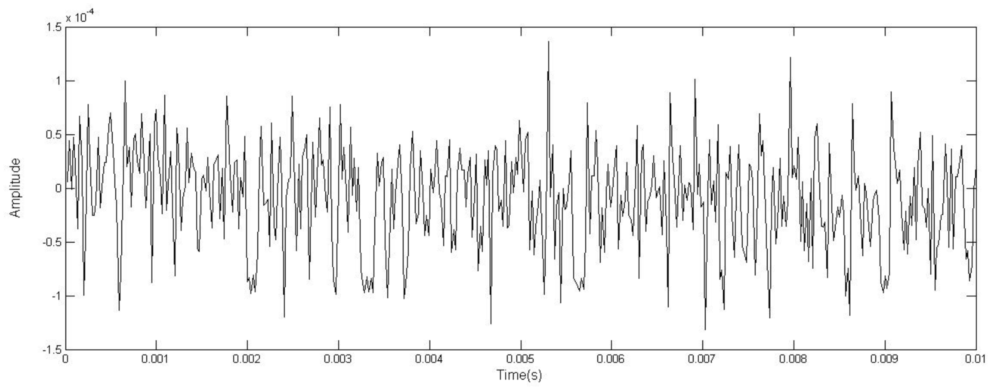


Figure 21: The waveform of plucking the String No.13 using Neumann U87 in the Trevor Jones studio and anechoic chamber.



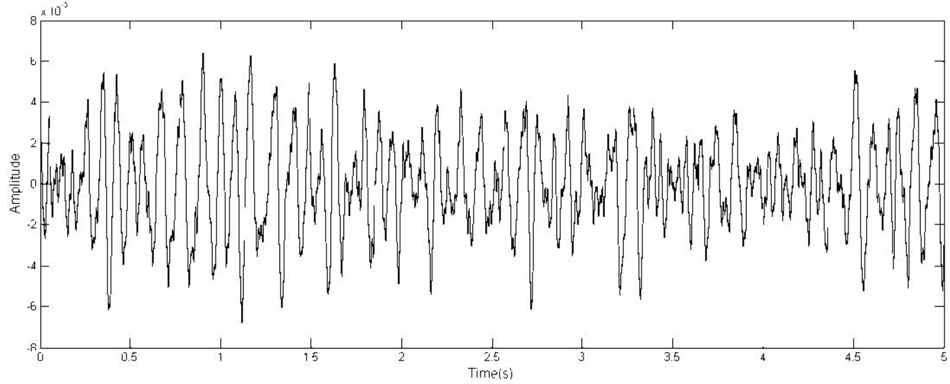


Figure 22: The waveform of a recording of silence in the Trevor Jones studio and anechoic chamber.

As can be seen from Figure 21, two waveforms have a similar shape with a rapid decay shortly after attack of the tone and then a steady, slower decay, and the decay time is almost the same (approximately 8s). Comparing the time responses shows that the plucking recorded in the anechoic chamber has a slower decay. There is some noise at the end of the waveform in Figure 21. Figure 22 demonstrates the plot of a recording of silence in the studio and anechoic chamber which shows the level of the noise from these two places (around 0.5 x 10e-3 and 2 x 10e-2 respectively).

Chapter Four – Sound synthesis of the guzheng in Max/MSP

4.1 Spectral modelling synthesis of the guzheng

As discussed in Chapter Two on page 25, a sound produced by an acoustic instrument is a set of complex oscillations and each oscillation contributes a piece of the overall timbre of the sound. The summed set of oscillations which determines the resulting waveform can be described as a group of sine waves. Under this circumstance, the sine waves are called frequency components. Each frequency component has its own frequency, amplitude and phase. There are two ways to describe a single sound: spectrum and waveform. A waveform graph is portrayed in the time domain, while the spectrum is portrayed in the frequency domain (Cipriani and Giri, 2009: 187). The individual frequency components of the spectrum are known as harmonics or partials.

Additive synthesis is the process of synthesizing a sound from its harmonics or partials. The sound can be reconstructed by adding the sine waves, each of which is one partial in the harmonic spectrum. Each partial has a different intensity or volume which composes the harmonic spectrum of the sound. The overall intensity determines the loudness of the sound. But the relative intensity of each partial determines the timbre of the sound as well. Charles (1988) states that the intensities must vary for the sound to simulate real instruments accurately which includes defining an envelope for each of the twelve to twenty-four partials used with additive synthesis (Charles, 1988: 232).

The software Max/MSP was used to model the guzheng. Max/MSP is a graphic programming language and widely used by musicians, artists, sound designers and so on. Programs are created by connecting objects with virtual cables. There are mainly two objects used for the additive synthesis model, cycle～ and line～respectively. The cycle～ object is an oscillator which produces a wave that is by default sinusoidal. The line～ object is the signal generator that generates a signal ramp or envelope (Cipriani and Giri, 2009). To create a signal segment, the object needs a beginning value plus a list containing one or more pairs of target values and times in milliseconds.

The detailed frequency, amplitude and perhaps starting phase information for each partial of the sound are the most important parameters required for additive synthesis (Russ, 2008: 310). The basic additive synthesis patch of the guzheng is shown in Figure 23 with controls over the detailed pitch (fundamental frequency) and amplitude.

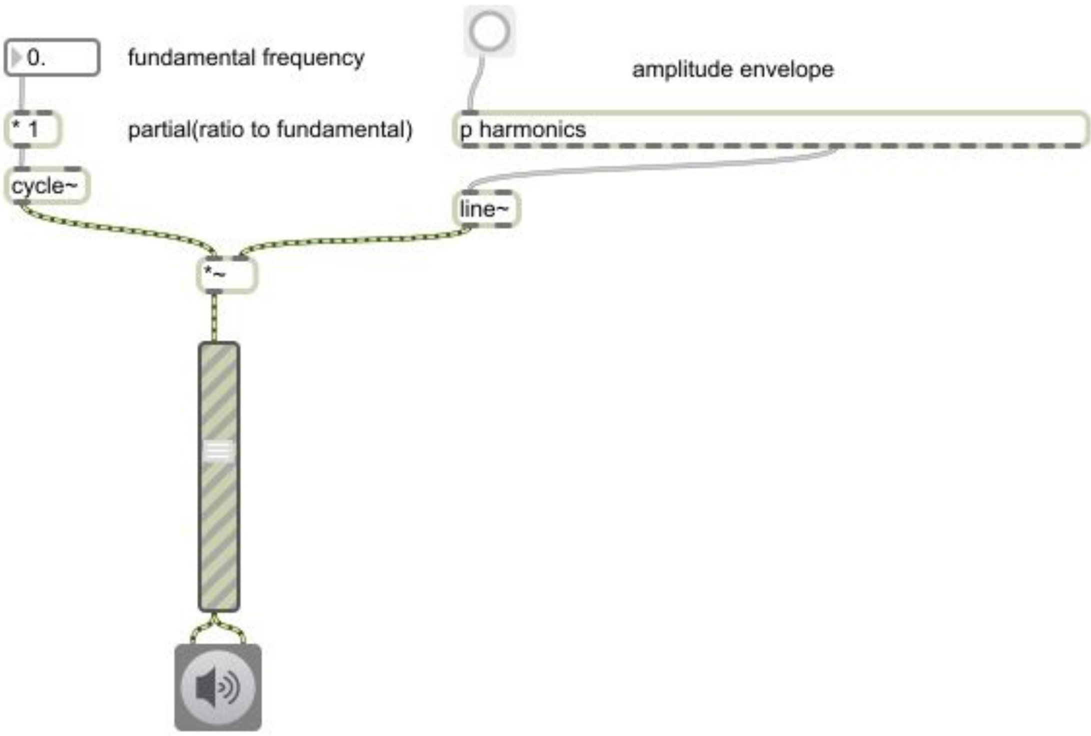


Figure 23: The basic additive synthesis model of the guzheng in Max/MSP.

A list of pairs of numbers (the first number defining a target value and the second number specifying a total amount of time (in milliseconds)) is needed to be sent to the line～ object to create the amplitude envelope.

A Matlab function called specEnv which analyses and plots the amplitude envelopes of harmonics for a single note was used. The recorded plucking of String No.13 was analysed to create the additive synthesis model. An application for viewing and analysing the contents of music audio files called Sonic Visualiser was used. The ‘Yin: Estimated f0 plugin’ in Sonic Visualiser was adopted to estimate the fundamental frequency of the recorded String No.13 (Brossier, 2006: 79).

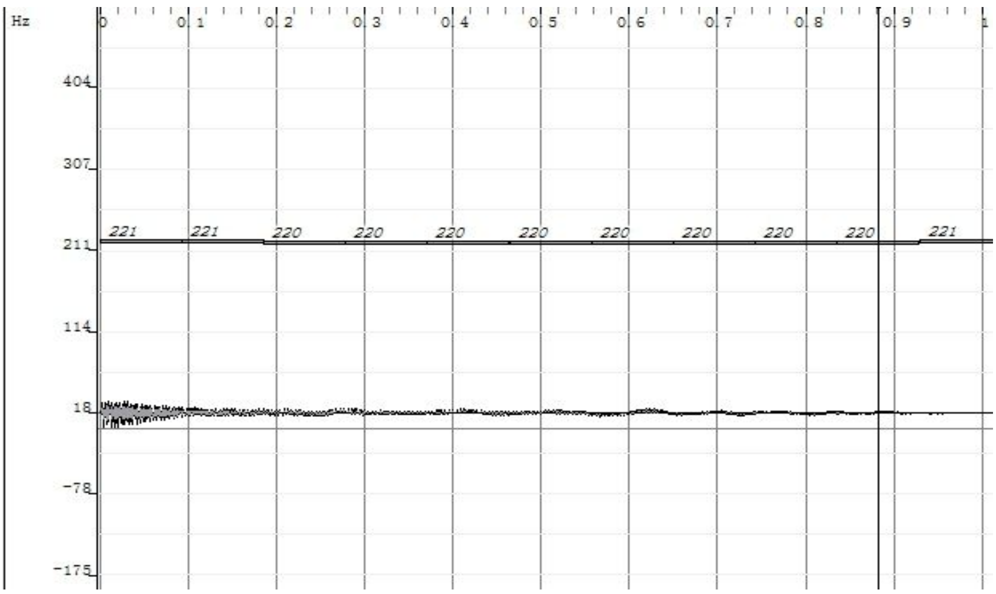


Figure 24: Fundamental frequency estimation of the String No.13.

As can be seen from Figure 24, the fundamental frequency of the recorded String No.13 is approximately 220Hz (the horizontal line above the grey waveform). Therefore, the amplitude envelope was obtained from the specEnv with the following settings: 'String No.13 plucking' is the analysed mono audio file. The fundamental frequency is 220Hz. The distance between points in the amplitude envelope that determines how many samples there are between measurements is 256. Here, higher numbers mean less data points with faster calculation. Lower numbers mean more data points with longer calculation. The sample rate of the audio file is 44100Hz. A 3D 'waterfall' plot of the amplitude envelope of the input audio was produced (Figure 25) when the function finished. This plot demonstrates how the energy in the string decays over time and the frequency.

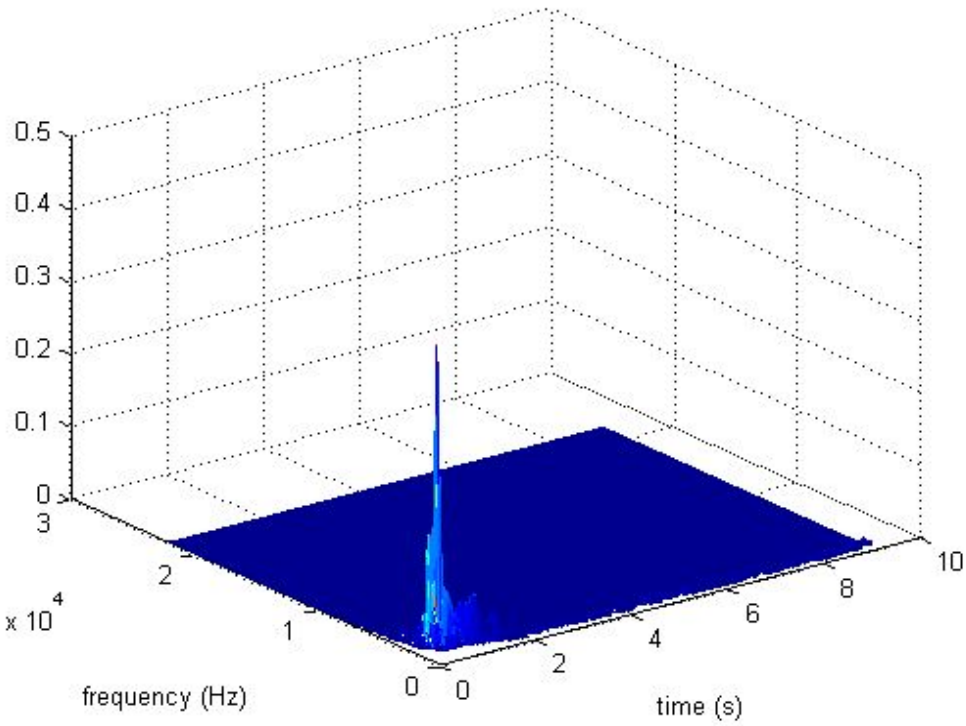


Figure 25: The 3D plot of the amplitude envelope of the recorded string No.13.

Other commands are needed to produce the 2D plot of the amplitude envelope of every harmonic afterwards. For example, the commands 'plot (t_axis,a(:,2))' can plot the amplitude envelope of the second harmonic (Figure 26) .

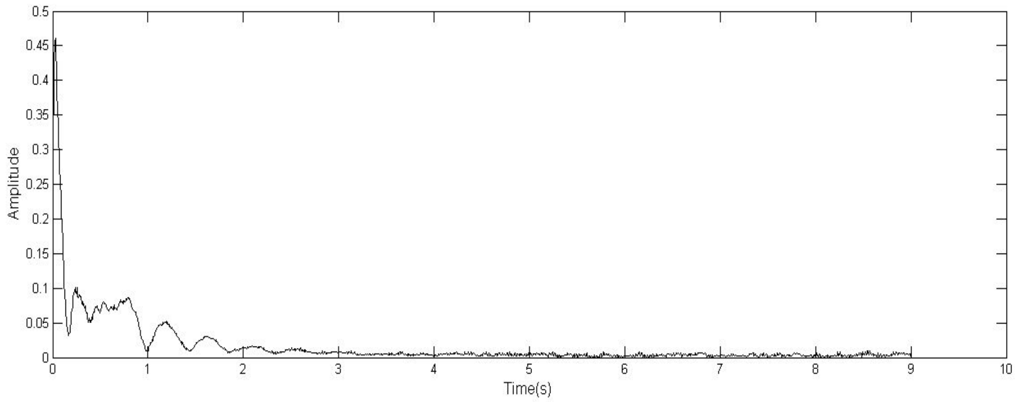


Figure 26: The amplitude envelope of the second harmonic of the recorded string No.13.

The important and typical points of the graph were chosen as a list of pairs of numbers sent to the line～ object to produce the amplitude envelope. To simulate the guzheng accurately, twenty-four harmonics of the tone were analysed to obtain amplitudes information through envelopes and then added together. The amplitude of each partial was with its own envelope generator. In other words, twenty-four line～ objects were used in the additive synthesis patch of the guzheng in Max/MSP. Twenty-four lists of pairs of numbers were used to sent to respective line～ object. Each list contains about twenty pairs of numbers and there are approximately 480 pairs of numbers in all sent to twenty-four line～ objects. The pitch of the tones can be varied by changing the fundamental frequency. Consequently, tones beyond the range of the real guzheng can be obtained. A subpatch called harmonics which contains twenty-four lists of pairs of numbers sent to the respective line～ object was designed to simplify the patch.

The output sound of the additive synthesis model contains a buzzing sound during the decay of the note. To investigate which oscillators produce the buzzing sound, output sounds with different combinations of oscillators were compared. Several oscillators rather than only one oscillator were proved to produce the buzzing sound by this comparison. The sound example 'six harmonics' is the output of six oscillators with the best sound quality. The sound example 'twelve harmonics', 'eighteen harmonics' and 'twenty-four harmonics' which are the outputs of twelve, eighteen and twenty-four oscillators respectively are also included in the database .

To solve this problem, the important points of amplitude envelopes were chosen again to smooth the envelope which may delete the buzzing sound. There is some noise during the decay time of the plucking. Therefore, most data points were chosen from the envelope of the attack part and few points were selected from the decay part. The selected data were all the highest and lowest points during a period of time. Fewer peaks were chosen to achieve the smoothing. Each list contains about ten pairs of numbers rather than twenty pairs in the original additive synthesis model. At the same time, removing clipping by controlling the gain～ object is needed, because high volume will lead to distortion in the additive synthesis patch. The additive synthesis model with simplified amplitude envelopes has the better sound quality. The samples before and after smoothing named 'The output of original additive synthesis patch' and 'The output of simplified additive synthesis patch' respectively are contained in the submitted CD.

4.2 Physical modelling synthesis of the guzheng

The physical modelling synthesis of the guzheng in Max/MSP is mainly based on the Karplus-Strong algorithm (explained in Chapter Two on page 30). The whole physical modelling synthesis patch is shown in Figure 27.

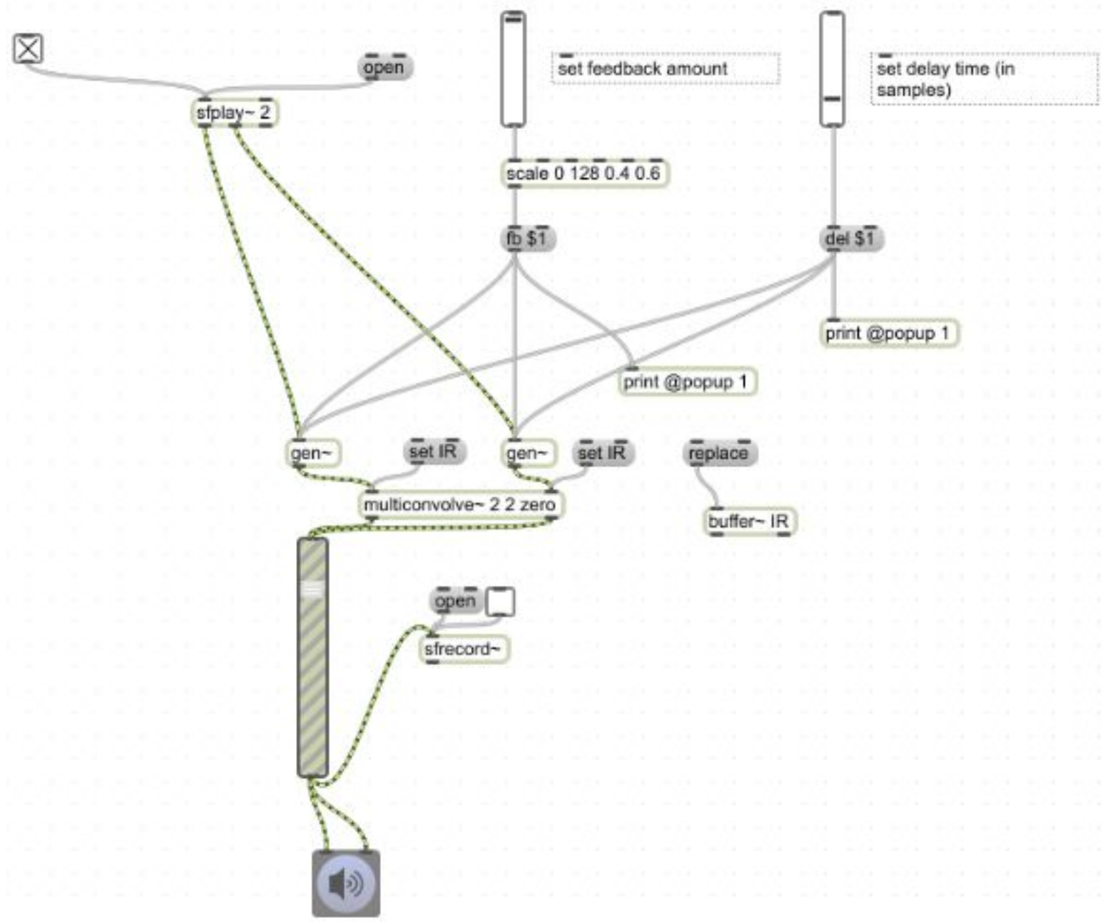


Figure 27: The whole physical modelling synthesis patch.

'The string is initially displaced from its equilibrium state when it is plucked. When released, the wave vibrates from its initial shape, to its mirror shape, and back again'

(Gulla and Katedralskole, 2011). Fifteen recorded pluck sounds of the guzheng were analysed to isolate the initial pluck shape which is made up of one pluck plus one reflection. Part of the waveform which would be the time taken for a pluck to travel up and down the string once was selected as the initial pluck shape. The initial pluck shape is a short excitation waveform as a burst noise that triggers the model. Five pluck shapes which can obtain good results in the Max patch are contained in the file named 'pluck shape' in the 'Max patches' folder in the disk.

The sound brightness can be controlled by the low pass filter. The gen～ object (Figure 28) developed by Wells works as a low pass filter. A delay with a maximum length of 44100 samples (delay time in samples) is controlled from the parameter 'del'. It is fed into the first input of the gen object from the main plucked string patch. The feedback ('fb') parameter is multiplied with the output of the delay and the previous output (history) and the results of the multiplication are then fed back into the input of the delay. The output of the delay is then sent to the output of the sub-patch (Wells, 2013).

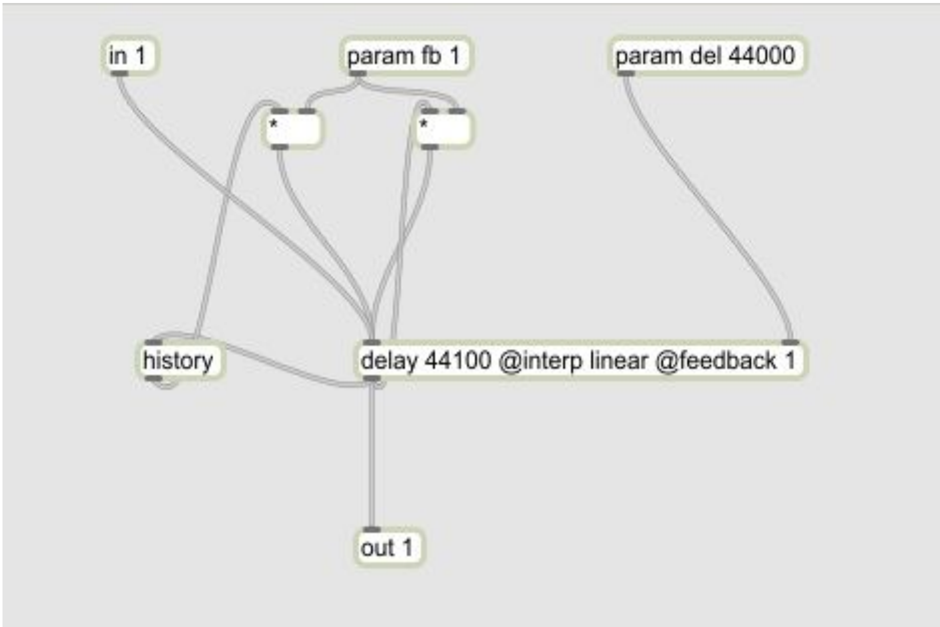


Figure 28: The inner workings of the gen～ object.

The convolution is set up by a recorded impulse response of the guzheng to model reverberant instrument body response (The specific impulse response recordings used here are listed later on). A Max external object called multiconvolve～ was used for realtime convolution. This object is from the HISSTools Impulse Response Toolbox (HIRT) released by Alex Harker and Pierre Alexandre Tremblay from Huddersfield University. The HIRT is a collection of Max objects for solving problems relating to convolution and impulse responses which allows integrating convolution reverb into Max patches quickly and easily (Harker and Tremblay, 2012: 151). The individual impulse response set from buffer～ object which can store audio samples.

The amplitude of the output sound can be controlled through the gain～ object. The delay time and feedback amount directly control the length of the waveguide. The pitch of the plucking output can be changed through changing the delay time.

Therefore, plucking sounds beyond the range of the real guzheng are able to be produced with this model which extends the capabilities of the guzheng.

4.3 The synthetic results

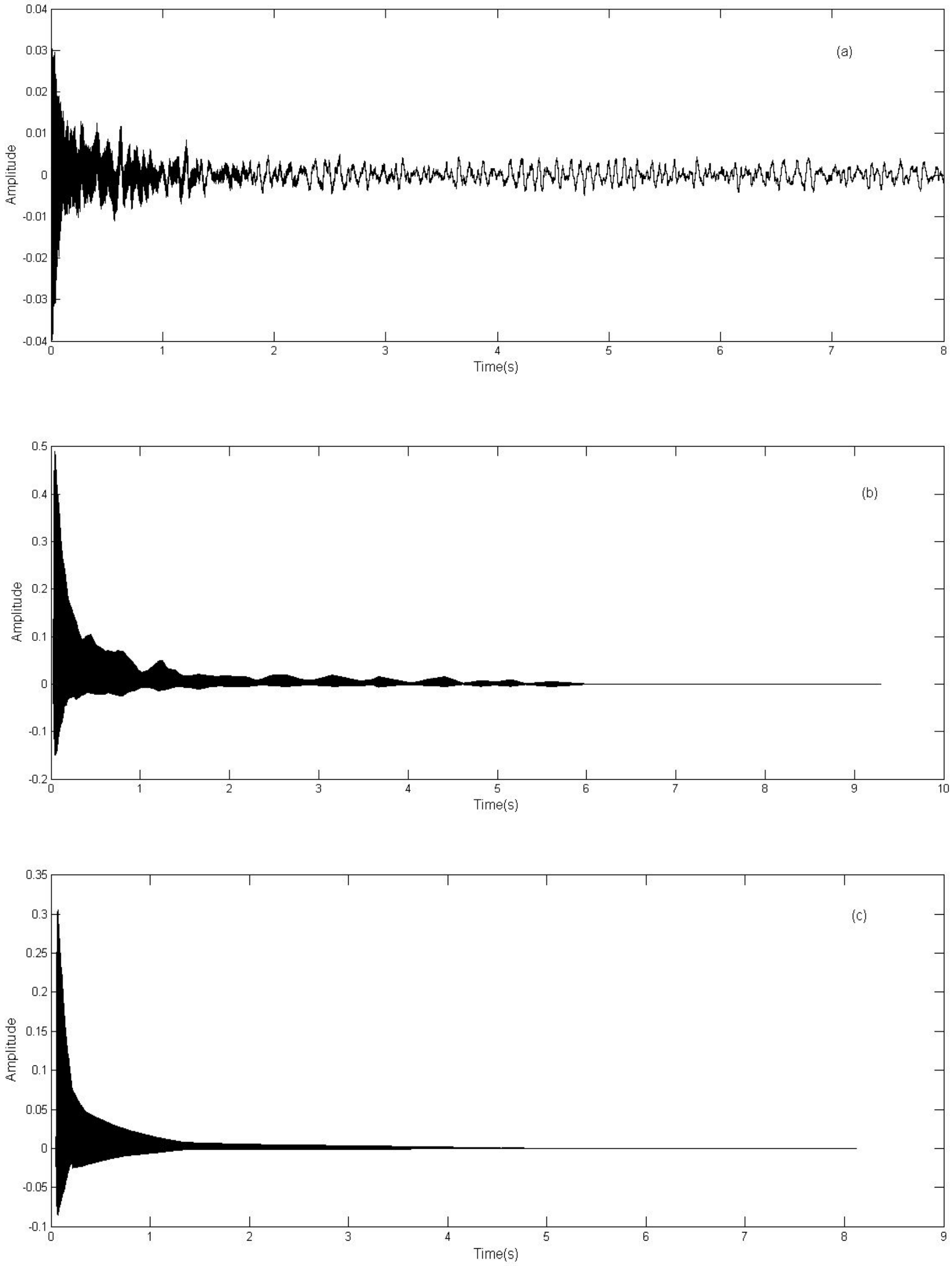
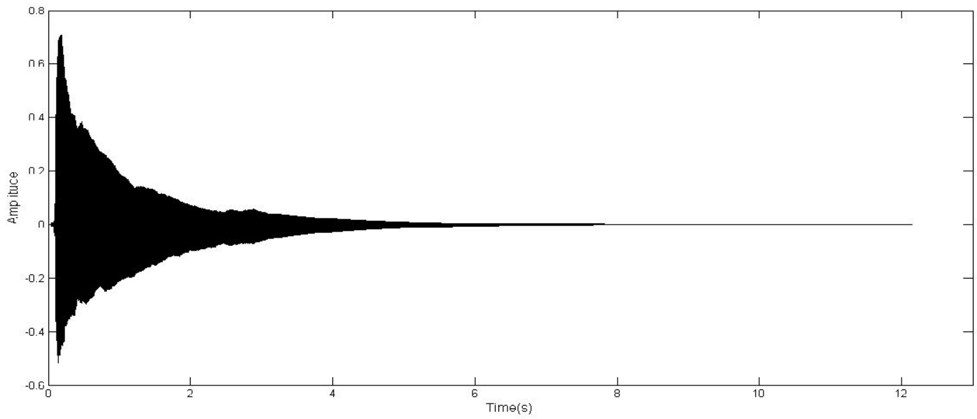


Figure 29: The waveform of the recorded tone (a), synthetic tone with additive synthesis model (b) and simplified additive synthesis model(c).

The amplitude envelope of the recorded String No.13 (220Hz) was analysed and adopted for the additive synthesis model. Therefore, the synthetic tones with fundamental frequency of 220Hz were used as the example above. As can be seen from Figure 29, the attack speed of the pluck of the three is almost the same. Although the pluck shape in Figure 29(b) is more similar to that of the recorded tone than the pluck shape in Figure 29(c), the third result with the simplified additive synthesis model has the best sound quality with the lowest amount of noise. There is some noise in the recorded tone especially during the decay. The additive synthesis model with simplified amplitude envelopes can effectively decrease the noise.



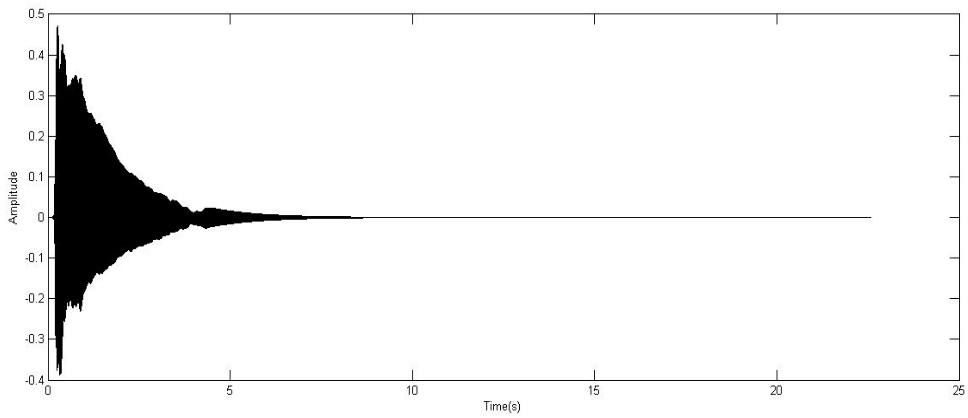
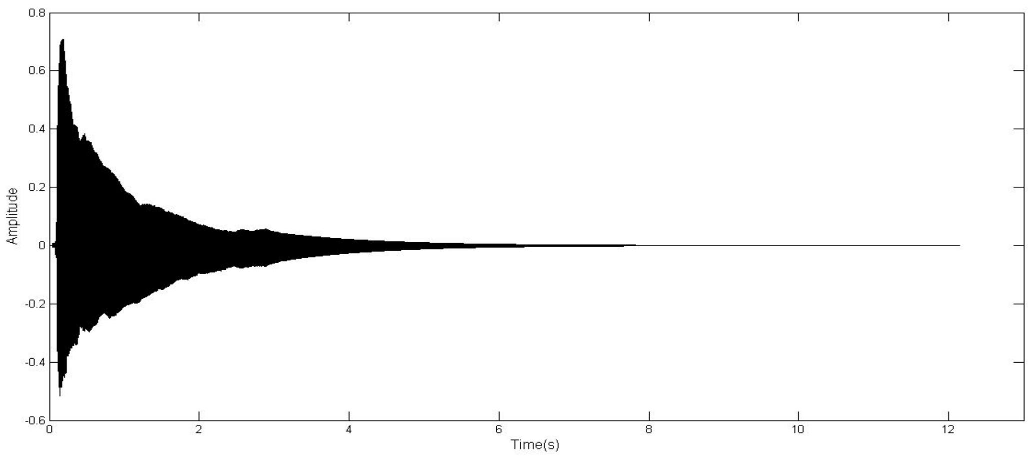


Figure 30: The sound output of the physical modelling synthesis model with initial pluck shape and the pluck waveform respectively.

Each initial pluck shape and impulse response was tried in the physical modelling synthesis model and some files were chosen which can obtain good results, including the pluck shape of String No.15, 16, 18, 19, 20 and the impulse response of String No.5, 6, 9, 10, 19. The initial pluck shape of the String No.15 and the impulse response of the String No.19 were used to achieve the best synthetic result in Figure 30.

The attack speed of the synthetic result with the initial pluck shape is faster and its decay time is shorter than the synthetic result with the pluck waveform. Compared with the result without the initial pluck shape, the sound output with the initial pluck shape is more like the real guzheng tone. Reducing the level of output with the pluck waveform by moving the fader is required to avoid the clipping at the beginning of the tone.



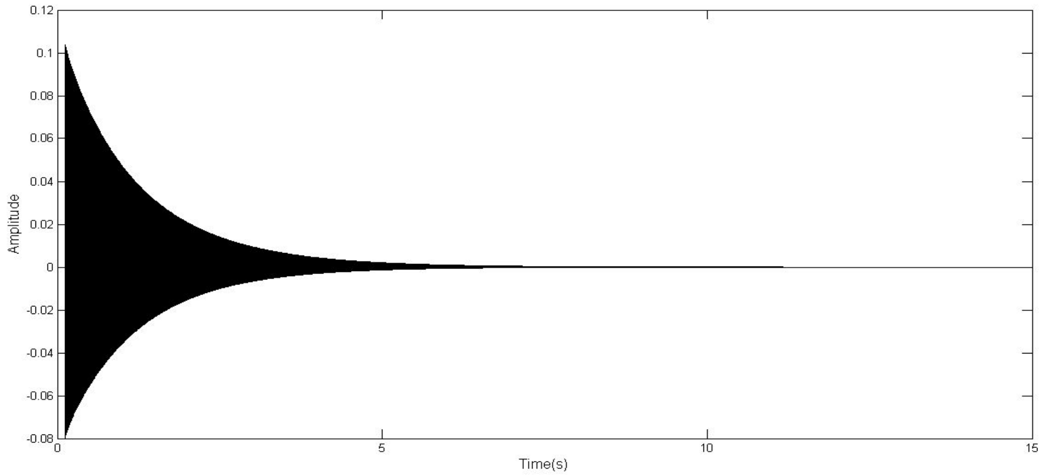
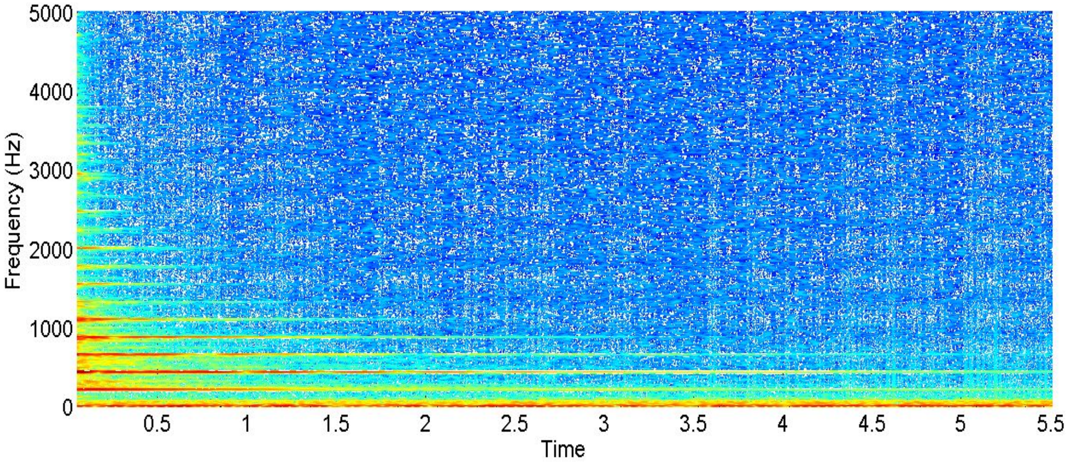
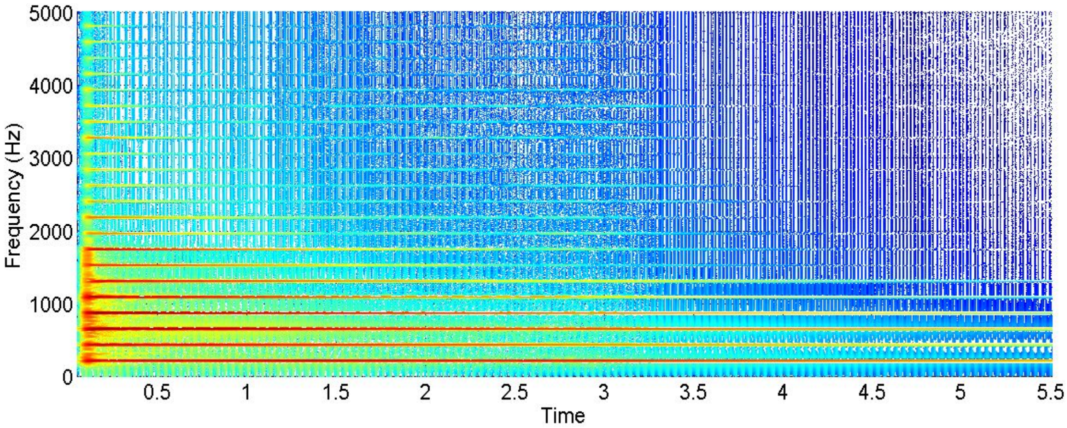


Figure 31: The waveform of the output of the physical modelling synthesis model with convolution and without convolution respectively.

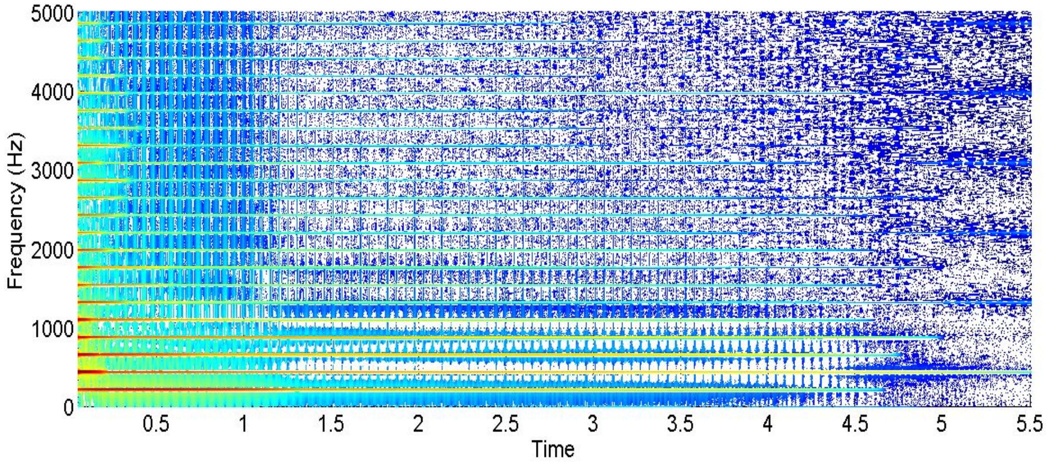
The convolution which uses the recorded impulse response simulates the body resonance. The amplitude of the output with the convolution is much higher than that of the output without the convolution which makes the sound very bright. The waveform of the result without the convolution is very simple and the waveform of the result with the convolution with more details makes the sound more realistic. Therefore, the convolution can effectively improve the sound output.



(a)



(b)



(C)

Figure 32: The spectrogram of the recorded guzheng tone, the synthetic tone of the physical modelling synthesis model and the additive synthesis model.

To compare the results properly, their fundamental frequencies should be the same. The fundamental frequency of the recorded tone is 220Hz. To get the result with 220Hz in the physical modelling synthesis patch, the delay time is about 200 samples which can be calculated. Compared with the result of the additive synthesis model, the timbre of the result of the physical modelling synthesis model sounds more like the guzheng tone by listening. This conclusion can be also drawn from observing and analysing the spectrogram. The higher harmonics decay quicker than lower harmonics in Figure 32(a) and Figure 32(b). However, the decay speeds of higher harmonics are almost the same in Figure 32(c).

Chapter Five – The use of recording＆synthesis to extend the sound of the guzheng

To extend the sound of the guzheng, the recorded and synthetic results were used for the production of the guzheng piece ‘Yu Zhou Chang Wan (The Song of Fishing Boats at Dusk)’. The production represents a radical and expressive treatment of this traditional piece through analysing its emotion and content and using studio techniques and technologies according to the emotion and content.

5.1 An overview of the guzheng musical piece ‘Yu Zhou Chang Wan’

‘Yu Zhou Chang Wan’, as a typical guzheng piece, is known as one of top ten famous musical pieces of Chinese traditional musical instruments which has a broad and deep impact since the 1930s. It is a solo guzheng piece and has been adapted into Chinese instrumental ensemble, guzheng and erhu duet, violin solo, etc. The origin of this piece is controversial. However, most related literatures adopt the statement that ‘Yu Zhou Chang Wan’ was adapted from a Shan Dong folk music ‘Gui Qu Lai (Coming Back Home)’ according to the characters of the guzheng by Lou Shuhua in 1938. The title of the piece -‘Yu Zhou Chang Wan’ is cited from the sentence from ‘Teng Wang Ge Xu’ written by Wang Bo (A.D.649-676) in the Tang Dynasty. The musical piece vividly depicts the beautiful scene of sunset in the water-side village where the fishing boats sail home and songs are heard here and there. Fishermen are happy with their harvests and boats are driving to the distance. In other words, ‘Yu Zhou Chang Wan’ describes a Chinese landscape painting consisting of the lake, boats and beautiful sunset (Chen, Ran, 1999: 42).

The whole piece is generally divided into three parts (The Staff is used to explain and analyse the song, but the Staff can not express the Jian Pu (Numbered musical notation) of the guzheng clearly and accurately). The first part is from bar 1 to bar 15 (see Appendix) and contains four phrases. The first part of the music is at a slow tempo which depicts the picture of the setting sun shining on the lake and the fishermen singing fishing songs. The second part (bar 16 - bar 40) with a faster speed describes the fishermen beginning to sail home with a livelier atmosphere. The melody is developed from the first part. The tones descend gradually and change repeatedly. The appearance of “sol” in the second phrase is the special part which breaks the tonal centre “la” and results in briefly deviating from the key (Zhang, Jingxia, 1984: 79).

The third part (bar 41 to the end) is the most distinctive part of this piece. The sequence and variation composition techniques are adopted in this part. The pitch is up and down which displays water waves and boats sailing to the distance. With increasing speed and intensity, the music shows the fishermen are excited with the harvests and fishing songs rise here and there. The exciting and jubilant atmosphere stops suddenly and the last seven bars are a coda as the quiet atmosphere reappears. The coda is played with decreasing dynamic and speed which describes the sound of splashing water gradually disappearing after the fishermen go ashore (Zhang, Jingxia, 1984: 79).

5.2 Hybridization in Matlab

Shapee is a powerful cross-synthesis algorithm devised by Christopher Penrose. The Matlab version was developed by Jez Wells (Penrose, 2001; Wells, 2004). The Shapee combines the frequency content of one sound with the spectral envelope of another sound. Different sounds and parameter settings were tried out. According to the content and theme of the piece 'Yu Zhou Chang Wan', sounds of nature like water, animals and single note of other instruments were chosen. Different frame widths were tried, e.g. 64, 128, 256, 512, 1024, 2048, etc.

Through a large number of attempts, the sound of rowing boats at the lake was regarded as the most suitable sound file for spectral cross-synthesis. The sound of rowing boats at the lake and the recorded guzheng piece were used for the hybridization to obtain innovative sounds which combine the timbre of the guzheng, rowing boats and water. The synthetic sound was obtained from the Shapee with the following settings: combine the frequency content of the guzheng sound with the spectral envelope of the sound of rowing boats. The frame size is 64 samples. The short frame size gives rise to quite wide spectral regions but good time resolution. The number of frames that overlap each other is 4. The shaping region is 4 which is a typical shaping region width.

As a result of the hybridization, the guzheng sound was extended. The synthetic result is an interesting sound which sounds like playing a Chinese drum in water. The Chinese drum is usually used for creating festive atmosphere. The synthetic sound is not only a good combination of water, rowing boats and guzheng timbres, but also conforms to the content and theme of the musical piece.

The synthetic sound was mainly used in the end of every phrase with two tones across an octave in part 1. Bar 1 – bar 3 (Figure 33) and bar 21 – bar 26 (Figure 34) are taken as examples and a circle is drawn on the musical notes which are applied the synthetic sound (the staff can not express playing techniques of the guzheng exactly and can only express the main melody).

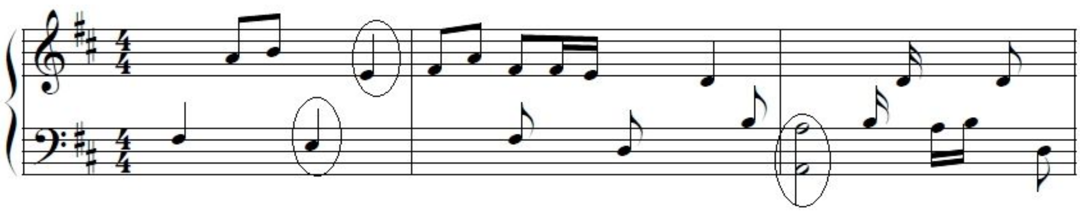


Figure 33: Bar 1 - bar 3

The simulated drum timbre always accompanies the melody of right hand in the guzheng pieces to express the festive atmosphere. The synthetic result which sounds like playing the Chinese drum in the water vividly describes the light wind that disturbs the calm surface of the water. It sounds as if it brought noise, but it is able to serve as a foil to quietness which makes people feel comfortable and cosy without nervousness and hurry.

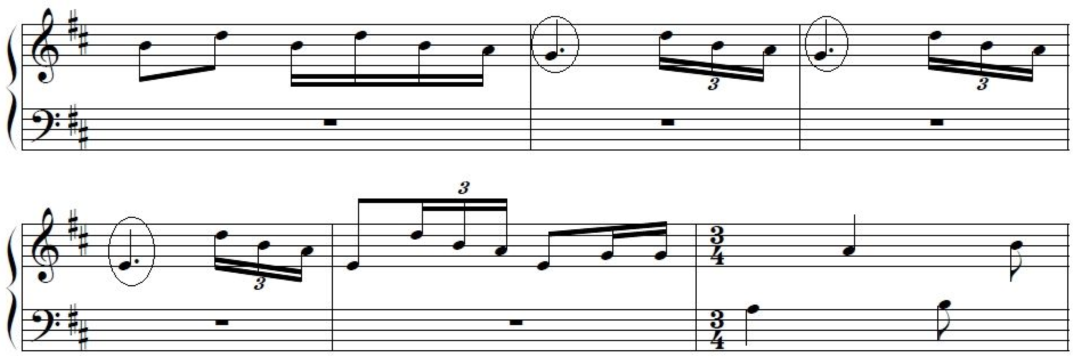


Figure 34: Bar 21-bar26

The appearance of “sol” breaks the tonal centre “la” and results in a brief deviation from the key. Compared with the previous mild part, this phrase is livelier. The synthetic timbre is beneficial to express the excitement of fishermen. Another synthetic sound I adopted was obtained from combining the frequency content of the sound of rowing boats with the spectral envelope of the guzheng sound through the Shapee. Other parameter settings are the same with the settings of the first synthetic sound mentioned above.

This synthetic sound contains a fantastic timbre with the sound of the guzheng, water and rowing boats. The sound creating an image of the water village helps the audience perceive the content of the piece and imagine the simple picture of the music. To regard it as the beginning of the whole piece, the first note of the piece was cut from the guzheng piece and synthesized with the sound of rowing boats at the lake which was beneficial to the opening changing over to the main melody naturally.

5.3 Extension of traditional playing techniques in Nuendo

'Yu Zhou Chang Wan' is a guzheng solo piece with simple and basic playing techniques. Making the full use of traditional playing techniques can help the instrument with long-lasting vitality. Numerous playing techniques of plucked-string instruments can be adopted by composers and producers to create new sounds (Yan, Fei, 2011: 29). 'Yu Zhou Chang Wan' is like a Chinese landscape painting and provides enough space for the producer to use their imagination. The characteristics and playing techniques of the guzheng should be taken into consideration for guzheng music production rather than applying electronic sound effects into the guzheng mechanically and blindly due to seeking changes and innovation. It is proposed that the guzheng with different and new expressive forces can be achieved by production which requires innovative sound effects with the lingering charm of the traditional music (Yan, Fei, 2011: 30).

More and more Chinese musicians pay attention to the acoustic of the single note. Chinese-American composer Zhou, Wenzhong said 'the Chinese regard a tone as a complete process of music with the pitch and timbre'. In other words, using a single note properly like changing the pitch, timbre and volume is able to arouse feelings the audience can identify with. Plucking including at most four octaves at the same time can be achieved by using the right and left hand together. However, plucking strings across more than four octaves with the same note simultaneously can produce acoustics with a richer timbre and more layered effects. To fully express emotions of the piece, some single notes need to be emphasized. For example, “re” is always played prominently in this piece (Figure 35).

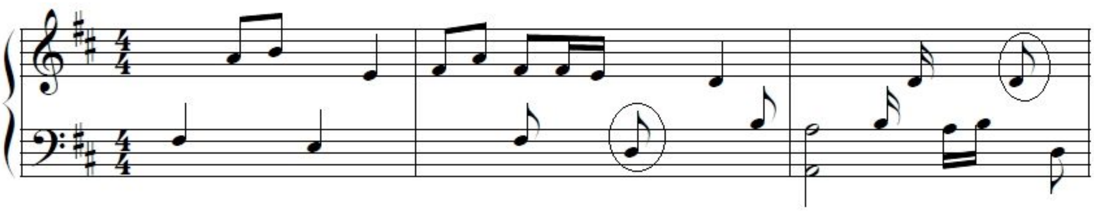


Figure 35: The emphasized tones in bar1 - bar3

Most audio files used in Nuendo were recorded at the University of York as mentioned in Chapter Three. Some synthetic results beyond the range of the real guzheng were adopted as well. The additive synthesis and physical modelling synthesis model were used to produce the plucking beyond the pitch range of the guzheng. The fundamental frequency of the central tone in this piece is about 342Hz. To create output sounds three octaves lower and two octaves higher than the central tone which do not exist in the guzheng, the input frequency is 42.7Hz and 1368Hz in the additive synthesis model respectively. The input delay time is 1026 samples and 32 samples accordingly in the physical modelling synthesis model. The synthetic results were used with the recorded plucking to emphasize the central tone.

Adding more than four audio tracks for the same single notes plucking across more than four octaves separately in Nuendo makes the horizontal melodic structure possess the vertical structure as well as stereo and abundant sound effects. The audience may feel the music linger in the air long after it is played through the processing.

Tremolo is a traditional technique of the guzheng and the sustained note can be achieved by tremolo. Traditional tremolo is only played on the single string while modern tremolo has developed into playing at most four strings within two octaves simultaneously. Tremolo played across more than two octaves can be achieved in Nuendo by adding audio tracks for recorded tremolo to produce specific acoustics. For instance, tremolo was produced to accompany plucking which originally existed in the piece in bar 5 (Figure 36).

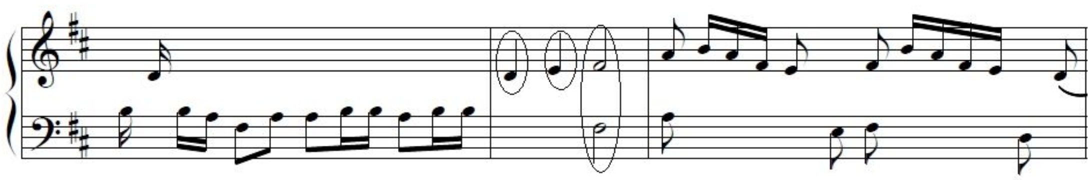


Figure 36: Bar 4 – bar 6

The notes in bar 5 have relatively long duration which sound a little stagnant and the tremolo helps to make them sound brighter and richer. The tremolo changed the melody from point to linear, from horizontal to vertical. At the same time, the tremolo with sustained tones can be regarded as the counter melody in such a phrase with relatively slow speed. The sound effect greatly enriches the expressive content of the piece and the pursuit of the artistic conception.

Figure 37: Bar 43-bar 53

The notes circled in Figure 37 were accompanied with tremolo played until the end of each bar. Combining the melody with the tremolo creates a sound with two voices where the melody (first voice) is taken as the core. Here, the tremolo was controlled with a low volume which reflected the picture of the hazy lake and boats sailing into the distance.

The guzheng, as a multi-string instrument, cannot only play monophony but also play multi-voice music using its twenty-one strings and playing techniques such as the arpeggio and the broken chord. The arpeggio is a playing technique where notes in a chord are played rapidly in sequence. The difference between the arpeggio and the broken chord technique are the speed of playing and the structure of chords. The arpeggio technique is played faster than the broken chord technique and always has fixed chord structures. The arpeggio and the broken chord are considered as auxiliary melody in most pieces and mainly used from bar 26 to bar 32 (Figure 38 shows part of them) in 'Yu Zhou Chang Wan'.

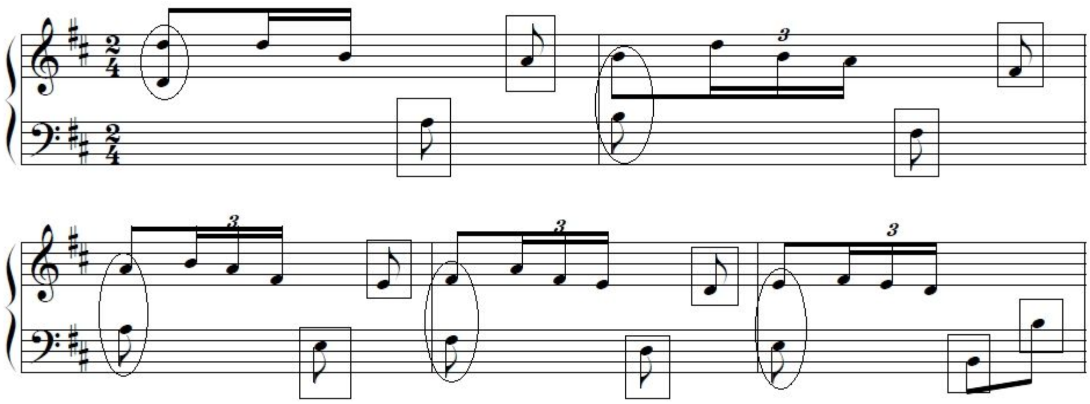


Figure 38: Bar 27 - bar 31

The notes circled are accompanied with the arpeggio and the square represents notes accompanied with the broken chord. For example,  in bar 27 was accompanied with la-do-mi-la,  in bar 29 was accompanied with mi-la-do-mi.

The arpeggio sounds bright while the broken chord sounds soft, giving both united yet different sound effects. The layer effects made the sound effects rich without messy acoustics. The arpeggio and broken chord, as the second part, were compared and combined with the first part - horizontal melody to produce two clear and definite parts. The rapid flowing arpeggio seems to describe the painting of the ripple of the stream and the happy mood of the fishermen.

The broken chord was adopted from bar 33 to bar 38 as well. Bar 33 to bar 38 is composed of broken chords and the broken chord as the second part was cut from these bars. Bar 35 to bar 38 was cut as the second part to accompany with bar 33 to bar 36 in the original piece and bar 33 to bar 35 was cut as the second part to accompany with bar 36 to bar 38 in the first part (Figure 39 and 40). The vertical melodic structure with harmonious chords sound brighter and richer than the horizontal melodic structure which is helpful to express that the fishermen are happy with their harvests.

Figure 39: Bar 33 – bar 38

Figure 40: The second voice accompanied with bar 33 – bar 38.

5.4 Delay and reverberation used in Nuendo

Appropriate reverb settings play a vital role in the recordings of Chinese traditional musical instruments (He, Mu and Meng, Zihou, 2007: 1028). Roomworks is an adjustable reverb plug-in and Roomworks SE is a simplified version of the Roomworks with better quality reverb in Nuendo (Pfeifer et al., 2007: 41). Roomworks SE was used for the whole guzheng piece and Roomworks was adopted in the beginning part of the piece.

The reverb parameters were set after a great number of trials through imagining playing the guzheng piece in a concert hall. The pre-delay value which determines the amount of time between the original dry signal and the onset of early reflections was set to 50 milliseconds. The larger value makes the space feel larger. The Reverb Time was set to 1s controlling the duration of the reverb tail to give more clarity. The Size dial is to control the size of the virtual room and was set to 20. The Width is used to expand or collapse the stereo image and was set to 100 (full stereo) (Houghton, 2007). With these settings, the guzheng piece sounds natural with good quality. Also it does not damage the clarity and rhythm of the sound. The reverberation makes the guzheng sound as if it is in a real space.

MonoDelay and ModMachine were chosen from many delay plug-ins in Nuendo for the production of the guzheng piece. MonoDelay is a simple delay plug-in with five parameters. MonoDelay was used in the beginning part of the piece (the introduction) to bring the picture of boats slowly drifting further and further away from the dock and to arouse the audience’s interests. At the same time, the delay effects help the beginning part transfer to the main melody naturally and smoothly.

The ModMachine is able to filter the feedback of the delay and is normally used for creating unusual sounds (Shepherd, 2013: 366). The part with distinctive characters (the third part of the piece without the coda) were cut from original mono files and processed with the ModMachine. The processed sounds were then exported as a stereo audio file and imported to the second audio track. The original part is played with massive glissando techniques to simulate the sound of flowing water. The processed sound with delay effects sounds like boats sailing into the distance and the lake surface gradually becoming calm which expresses well the theme of the piece. The sound cut from the original piece creates an exciting and jubilant atmosphere. In contrast, the following part depicts the quiet atmosphere. With the delay effects, the connection between the processed part and the coda is more natural and smooth than before.

Chapter Six – Conclusions and future work

Extending the capacities of the guzheng using current transformation, modelling, recording and production techniques is new and original. An additive synthesis model and physical modelling synthesis model of the guzheng are presented. These are based on measurements and analysis of the instrument made as part of this work. With the models, extended sounds and a broader pitch range of the guzheng can be obtained which is beneficial for composing innovative guzheng pieces and developing various guzheng performances.

The traditional guzheng piece and playing techniques recorded in the Trevor Jones studio have a good sound quality. The impulse responses of the guzheng were measured in the anechoic chamber and several playing techniques of the guzheng were recorded as well. The copper wire method for measuring the impulse response of stringed instruments is applied to the guzheng. The method allows for high repetition accuracy with a high-degree of reliability and validity. This is the first time that the instrument has been measured and captured in this way.

The acoustics and synthesis of the guzheng are discussed in this dissertation. The proposed synthesis models are able to reproduce the most important characteristic of the guzheng, namely plucking. Whilst interesting new sounds have been produced based on the physics and spectrum of the guzheng, their current applicability is limited until the models are further developed. The synthesis models can be improved further for timbre quality and more playing techniques should be covered. The additive synthesis model can be extended to the sinusoids plus noise model, and more partials can be included in the model. For the physical modelling synthesis model, more accurate initial shape of the string will be possible if selected from an analysis of more plucking waveforms of different strings.

The production of the traditional guzheng piece 'Yu Zhou Chang Wan' is based on the meaning of the piece and demonstrates the application of recording, synthesis, transformation and production techniques to extend the potential of the guzheng. This piece draws together the other work in this dissertation, to produce a novel combination of techniques and technologies to extend, yet also preserve, the sound of the guzheng.

Appendix

1. The Staff of the guzheng piece -‘Yu Zhou Chang Wan’

渔舟唱晚（Yu Zhou Chang Wan)


1.2.3.
4
3

2. The code of the Matlab function – SpecEnv (Wells, 2014).

```
function[f_axis,t_axis,a] = specEnv(x,f0,overlap,Fs,filterWidth)

% function[f_axis,t_axis,a,res] = specEnv(x,f0,hop,Fs,width)

%

% Function to plot the amplitude envelopes of harmonics for a single note

% It assumes constant pitch throughout the duration of the note

% x: a mono audio vector containing the note to be analysed

% f0: fundamental frequency of audio input (the filters that extract the

% envelopes will be centered on this frequency and its harmonics)

% overlap: percentage overlap between successive frames. As frames are Hann

% windowed, this defaults to 50% and should not be set any lower.

% Fs: sample rate of audio vector, default is 44.1 kHz.

% filterWidth: the width of the harmonic filters in %. At 100% means    the

% filter edges touch each other, at 50% the filters are half this width.

% The default is 100% as this preserves the energy in additive model, but

% for more stochastic or noisy sounds, a lower setting may produce better

% results

% f_axis: vector containing the frequency values (in Hz)

% of each of the harmonics

% t_axis: vector containing the time values (in seconds) of each analysis

% point
```

```
% a: a matrix containing each amplitude envelope
%
% The amplitude for each harmonic is calculated at each hop by dividing the
% spectrum into filter bands centred on harmonics of the fundamental and
% taking the square root of the summed energy in each band.
%
% October 2014, Jez Wells


if(nargin<3)
    % default to 50%
    overlap = 50;
end
if(nargin<4)
    Fs = 44100;
end
if(nargin<5)
    % default to 100%
    filterWidth = 100;
end
FFTSize = 2^17;


% first calculate frame size
```

```
% Hann window main lobe is 4 bins in width

% therefore f0 (and, therefore the distance between harmonics) should be at

% least 4 bins. Here we set it to 5 to provide a margin for error

frameSize = ceil((5*Fs)/(f0*(filterWidth/100)));

hop = floor((1-(overlap/100))*frameSize);

if(hop>ceil(frameSize*0.5))

        formatSpec = 'The hop size is %d. It should be less than half the frame size
which is %d.';

        warning(formatSpec,hop,frameSize)

end

while(frameSize>FFTSize)

        FFTSize = FFTSize*2;

end

oneSideSize = (FFTSize*0.5) + 1;

hannWindow = hann(frameSize);


% calculate lower and upper filter band indices

nHarmonics = floor(Fs*0.5/f0);    % number of harmonics before Nyquist

binWidth = FFTSize*f0/Fs;


harmonicBins = round([1:floor(nHarmonics)]*f0*FFTSize/Fs);

halfFilterWidth =    floor(min(diff(harmonicBins))*0.5*(filterWidth/100));
```

```
lower = harmonicBins - halfFilterWidth;
upper = harmonicBins + halfFilterWidth;

noBands = length(harmonicBins);

% check where upper and lower coincide
upper(find(lower-upper==0)) = upper(find(lower-upper==0))+1;

halfFrame = ceil(frameSize/2);

if(length(find(x(1:halfFrame)))>0)
    % pre-pend zeros to avoid windowing effects at very start
    if(isrow(x))
        x = [zeros(1,halfFrame),x];
    else
        x = [zeros(halfFrame,1);x];
    end
end

if(length(find(x(end-halfFrame-1:end)))>0)
    % post-pend zeros to avoid windowing effects at very start
    if(isrow(x))
```

```
            x = [x,zeros(1,halfFrame)];
        else
            x = [x;zeros(halfFrame,1)];
        end
end

N = floor(length(x)/hop); % number of fourier transforms
NN = length(x);

% create output matrix and vector
a = zeros(N,noBands);

% preserve energy, regardless of FFT size
fftMult = sqrt(2/FFTSize);    % 2 because we are only taking half of FFT

for n=1:N
        idx1 = ((n-1)*hop)+1;
        idx2 = idx1+frameSize-1;
        if(idx2>NN)
            idx2 = NN;
            frame = x(idx1:idx2).*hannWindow(1:idx2-idx1+1);
        else
```

```
        frame = x(idx1:idx2).*hannWindow;
    end
    X = fftMult*fft(x(idx1:idx2),FFTSize);
    for nn=1:noBands
        a(n,nn) =
sqrt(sum(X(lower(nn):upper(nn)).*conj(X(lower(nn):upper(nn)))));
    end
end


% produce mesh plot of output
f_axis = (upper+lower)*0.5*Fs/FFTSize; % Hz
t_axis = (((0:N-1)*hop)+1)/44100;      % seconds
mesh(t_axis,f_axis,a');xlabel('time (s)'); ylabel('frequency (Hz)')
```

3. List of accompanying material

Audio CD containing:

1. Recording of the traditional piece ‘Yu Zhou Chang Wan (The Song of Fishing Boats at Dusk)’.
2. Production based on the traditional piece ‘Yu Zhou Chang Wan’.
3. Plucking of string No.13 recorded in the anechoic chamber.
4. Plucking of string No.13 recorded in the Trevor Jones studio.
5. Impulse response of string No.5
6. Impulse response of string No.15
7. Impulse response of string No.19
8. Impulse response of string No.20
9. The output of original additive synthesis patch
10. The output of simplified additive synthesis patch
11. The output with low pitch (42.75Hz) of simplified additive synthesis patch.
12. The output with high pitch (1368Hz) of simplified additive synthesis patch.
13. The output of physical modelling synthesis patch
14. The output of physical modelling synthesis patch without convolution
15. The output of physical modelling synthesis patch without the pluck shape
16. The output with low pitch (1026 delay) of physical modelling synthesis patch.
17. The output with high pitch (32 delay) of physical modelling synthesis patch.
18. Cross-synthesized result (1).

19. Cross-synthesized result (2).

Data CD containing:

1. Impulse response measurements

    Impulse responses of some strings recorded by Neumann U87

    Impulse responses of String No.1-No.21 (recorded by Earthworks M30)

2. Impulse response measurements (High Pass Filter)

    Impulse responses of String No.1-No.21 (recorded by Earthworks M30 with high pass filter to obtain better quality)

3. Max patches

    multiconvolve~

    Pluck shape

    1% 、5%、10% and 25% filterwidth additive synthesis patch

    Original additive synthesis patch

    Physical modelling synthesis patch

    ReadMe

    Simplified additive synthesis patch

4. Outputs of max patches

    Outputs of 1%、5%、10% and 25% filterwidth additive synthesis model

    The output of the additive synthesis model (low pitch) 42.75Hz

    The output of the additive synthesis model (high pitch) 1368Hz

    The output of the additive synthesis model

The output of the physical model (low pitch) 1026delay

Physical model output without convolution

Physical model output without the pluck shape

The output of the physical model (high pitch) 32delay

The output of the physical model

The output of the simplified additive synthesis model

Outputs of six、twelve、eighteen and twenty-four harmonics in the simplified additive synthesis model

5. Recordings of playing techniques

Recordings in the anechoic chamber: Bending, Harmonics, Plucking and Vibrato.

Recordings in the Trevor Jones studio: Arpeggio, Plucking and Tremolo.

Resource List

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<u>Score</u>

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