University of Southern Queensland

School of Engineering

Synthesis and Emulation of a Musician's Signal Chain and Sound

A dissertation submitted by

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ABSTRACT

The introduction of the transistor revolutionised the music industry. Electric guitar amplifiers were redesigned, and heavy, loud, and expensive vacuum tube amplifiers were being challenged by smaller, cheaper, more diverse, lighter solid state or transistor amplifiers. Lower levels of power to reach desired tones drove the popularity of digital amplifiers as the tones were able to be reached at vastly lower volumes than traditional vacuum tube amplifiers. As digital amplifiers became more popular, more and more musicians, while enjoying the convenience and user friendliness of the new amplifiers, desired the ‘warm’ and more pleasant tones of the vacuum tube amplifiers. This presented challenges for researchers to emulate the tones and acoustic characteristics of classic amplifiers and analogue effects to provide the desirable tones in the digital modelling amplifiers. Vacuum tube amplifiers and classic guitar effects were studied and digitally emulated, able to be downloaded as digital effects or plugins. The vast range of plugins grew exponentially with all makes and models of manufacturers providing digital versions of their classic sounds and effects. The huge range of plugins available has caused frustrations with guitarists attempting to emulate their guitar heroes and their unique guitar sounds. This project aims to allow a user to, instead of building a custom guitar signal chain with digital plugins, adjusting endless parameter settings and available customisations to create an input, sample a piece of recorded electric guitar, then extract the acoustic characteristics to emulate the target tone with a single processing framework.

The nature of the saturation in vacuum tubes creating the harmonic distortion responsible for the desirable tone proved challenging with end users not being satisfied with the tones as they sounded ‘fake’ and ‘hollow’ prompting manufacturers and researchers to further research the emulation of analogue amplifiers. This project explores what the ‘warm’ sound is and why it can’t be emulated in digital amplifiers and explore opportunities to close the gap between analogue and digital amplifiers. Current emulation techniques are researched and a range of guitar samples across different genres, playing styles and timestamps are analysed to explore any visual correlations between waveforms, frequency spectrums and time frequency plots.

This project determines that current emulation techniques can emulate guitar tone from a recording in a controlled production and recording environment however challenges exist in real time applications due to the heavy computational cost and subsequent impact of latency and aliasing.

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CHAPTER 1 - INTRODUCTION

1.1 Outline of the Study

The opportunity for innovation around guitar tone emulation was identified by a combination of personal experience, curiosity, and the popularity of modelling guitar amplifiers in the marketplace (Guitar World, 2022). Guitar World states that in 2022 digital modelling amplifiers dominated sales highlighting a shift in the marketplace from classic guitar amplifiers to contemporary digital modelling amplifiers. Due to their lightweight nature, affordability, reliability and endless opportunity for DSP innovation, digital amplifiers occupy four of the top five top selling guitar amplifiers. The purpose and scope of this study is further outlined in 1.4 Research Objectives.

1.2 Introduction

Oscar Wilde said, *"Imitation is the sincerest form of flattery that mediocrity can pay to greatness"*. This quote is very relevant in the pursuit of guitar enthusiasts desire to emulate their guitar heroes. Despite classic tube amplifiers falling in sales, the specific tones their preamp circuitry produce are sought after more than ever resulting in a boom of digital amplifiers emulating the tone. The tones of these classic amplifiers are emulated using a technique called Virtual Analogue modelling (Yeh 2009). Once the tones of specific guitar amplifiers are modelled, it is up to the end user to customise their sound using guitar effects, either digital or analogue in their signal chain.

Analogue audio effects are physical circuits housed in deployable stomp boxes placed at a musician's feet where they can be activated and deactivated easily. All analogue effect pedals are customisable by the simple manipulation of knobs which define the characteristics of individual components like resistors (Holmes 2019). The limitless combination of customisable effect pedals present endless creative possibilities for the pursuit of guitar tone and the difficulty of emulation.

"How to sound like my favourite guitarist" is the next frontier of DSP innovation in this space. The fine tuning of an endless availability of guitar effects is a creative outlet of guitarists which creates a unique signature. Amateur and hobby guitarists seek inspiration by being able to sound like their favourite guitarists however struggle to get the sound just right. A simple way for enthusiasts to mimic their guitar heroes represents an opportunity for innovation.

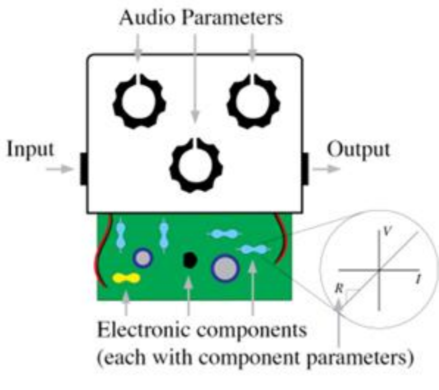


Figure 1 Cutaway diagram illustrating the internal structure of an analogue guitar pedal.(Holmes 2019)Guitar

1.3 The problem

The timbre of an electric guitar is the result of a series of elements colloquially known as a 'signal chain'. This chain consists of the physical instrument, pre amplification effects processors including distortion, chorus, reverb, delay and compression, the guitar amplifier, and speaker cabinet. The emulation and modelling of each of these individual components in the signal chain have been widely studied and are readily available commercially as digital software components or plug-ins. Each of the components can be replaced by a plug-in in a series digitally on a standard home computer and accessed with some basic hardware to interface with the analogue instrument. To successfully emulate the timbre of another guitar, the user must seek the correct effect, amplifier, and cabinet, manipulate the customisable controls on each plug-in and rely on their ear to 'dial in' or match the original timbre. Whilst this is an enjoyable process for many hobby musicians, frustrations can arise when the smallest amendment to a setting can have drastic consequences in the final audible timbre. An opportunity exists to model the signal chain by emulating all the components excluding the instrument as a single processing unit. This concept is illustrated in Figure 2.

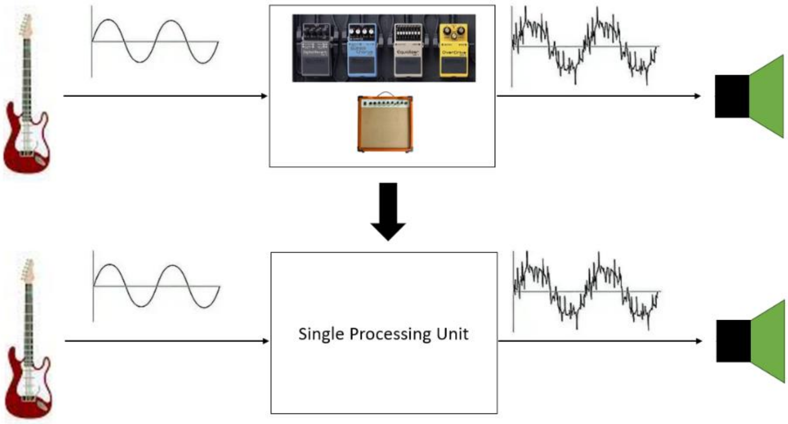


Figure 2 Signal chain of an electric guitar

1.4 Ethical Considerations

Music is an artform, therefore a piece of music can be copyrighted by the artist however there is no copyright legislation governing tone. There is a common opinion among journalists and forum bloggers that this will change due to the rise in emulation software, artificial intelligence, and modelling applications. The pursuit of copying guitar tone is a grey area and there is a feeling that the legislation simply hasn't caught up with the technology yet. As this project is focusing on the emulation of tone signatures and not sampling the recorded melodies or riffs, there are no ethical ramifications.

1.5 Research objectives

This research will use a qualitative review of literature to explore to opportunities in timbre emulation and synthesis of the electric guitar. The review will explore the digital emulation of individual components of an electric guitar signal chain and how those techniques can be used to emulate the entire signal chain.

Original Guitar timbre = Guitar input (DI) + DSP

New guitar timbre + DSP = New guitar input

The aim of this project is to answer the question: Can this process successfully mimic the original guitar tone?

New Guitar timbre = Original Guitar timbre.

The research methodology is outlined in Chapter 3 and includes the following components,

(a) Peer reviewed literature will be studied to understand the mechanics of waveform generation specific to the electric guitar, and the DSP alterations to the waveform due to the instrument, amplification stages, and any added effects processing units included between the instrument and output speaker.
(b) Peer reviewed literature will also be studied to understand the past, current, and future techniques, processes, and opportunities around the digital emulation of classical, analogue amplification and effect units.
(c) Electric guitar tracks will be recorded and sampled using music production equipment and live instruments to analyse the waveforms. DSP tools including Fourier Transform, waterfall plots and image spectrograms will visualise the waveforms and assess the nature of different music genres and styles (Country, Rock, Classical, metal etc.)
(d) The results from the waveform analysis will be collated and used in conjunction with the studied emulation techniques to investigate the feasibility of a real time emulation algorithm.

1.6 Conclusions

This dissertation aims to determine if timbre of an electric guitar can be identified, captured, and combined with a different clean guitar track to mimic the original timbre with no discernible difference to an end listener.

A review of literature will identify current techniques and technologies in developing digital amplifiers and guitar effects and how they can be combined to produce a holistic approach to developing a DSP signature of a unique guitar track.

The outcomes of this study will be used to design and develop a digital tool to analyse a guitar track, capture the unique signature and layer this signature on a clean guitar signal to emulate the original guitar tone.

CHAPTER 2 - LITERATURE REVIEW

2.1 Introduction

This chapter reviews the peer reviewed literature to establish the opportunity for a digital tool to identify and capture the signature of a guitar tone. This project aims to allow a musician to emulate the distinct sound of a guitarist of their choosing by sampling a piece of recorded music, extracting the digital signal processing signature of the sound, then synthesizing that signature onto the musician's own instrument. To design an algorithm to perform the analysis, an understanding of the nature of recorded electric guitar must be established. This literature review will research the DSP characteristics of the main types of guitar effects, how linear filtering is used to create a guitar emulation and how the signal chain can be modeled and emulated.

2.2 How harmonics determine the signature of a playing 'style'.

A guitar produces sound by sound waves resonating from a plucked string. The original note played from a single string can be referred to the 'foundation' note. When this foundation note is struck or 'plucked', a standing wave is created. This standing wave combines the foundation note frequency and the natural harmonics of that frequency which occur at N^2 of the foundation frequency.

Figure 3 illustrates this phenomenon. A ukulele string was plucked to produce a 'G' note at 391 Hz. The graph shows where the amplitude is strongest at the first peak, then smaller amplitudes occur at multiples of 391 Hz (Chen et al. 2015).

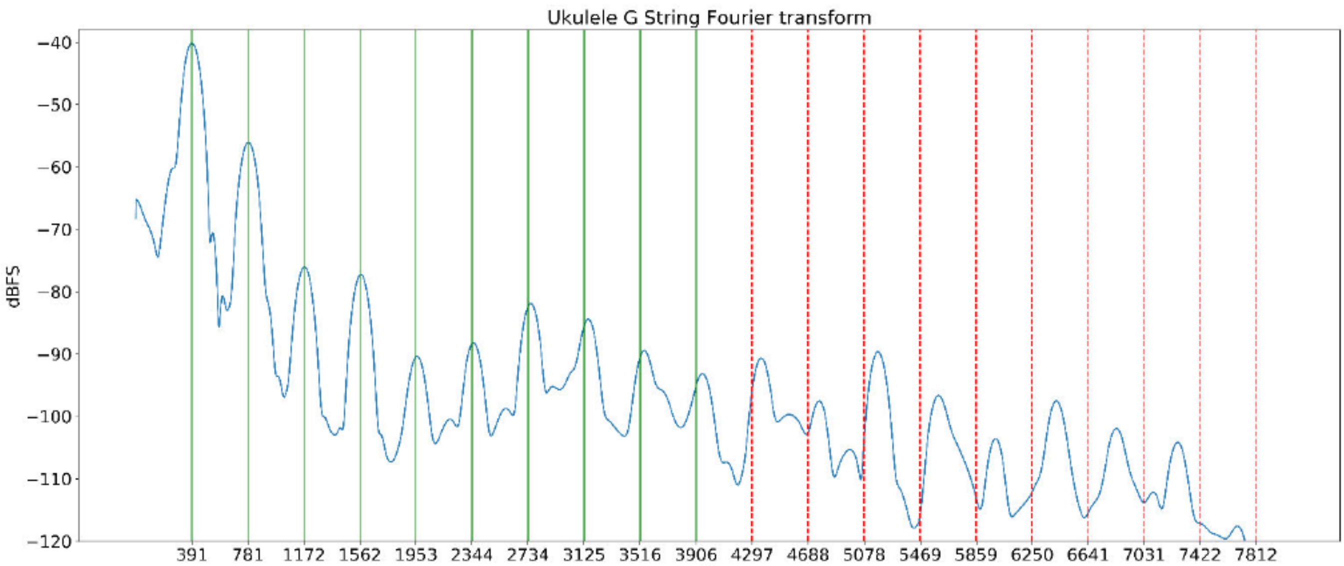


Figure 3 Fourier analysis of a Ukulele string.

All stringed instruments follow this pattern. The harmonics and their intensity are unique for each instrument, determined by their manufacturing material, size, and individual characteristics and contribute the final timbre or tone. (Clinton 2020) Illustrates this concept further in their study of vibration characteristics in the guitar itself. A resonance imaging study was performed on a guitar to see the resonance and vibration in the body of a guitar at certain frequencies.

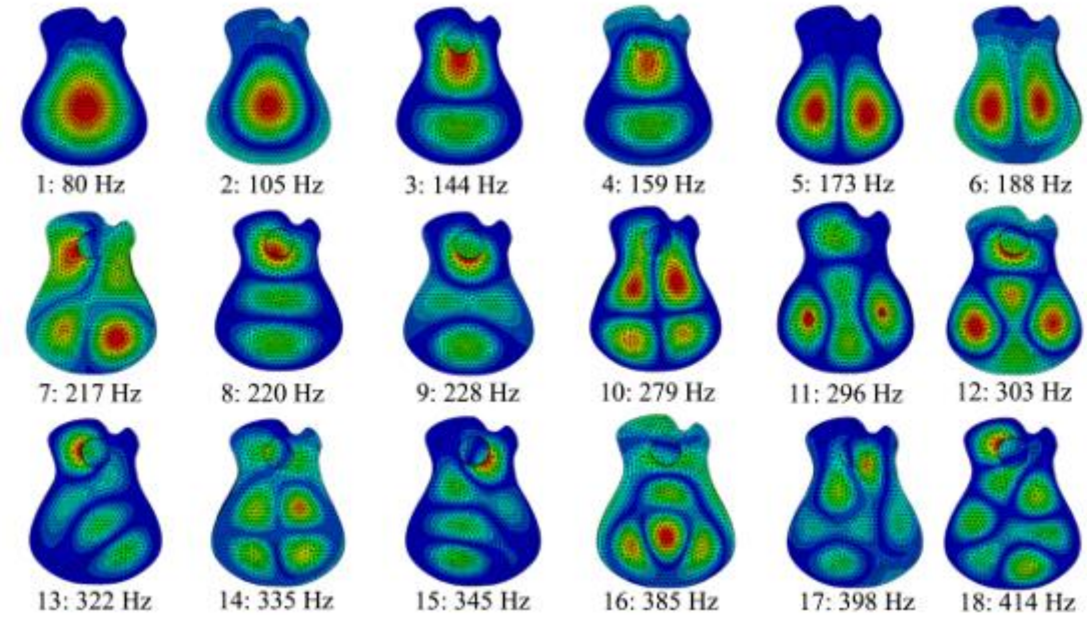


Figure 4 Resonance imaging of a guitar body at different frequencies (Clinton 2020)

Red regions illustrate the highest intensity of vibration with blue being the lowest with higher frequencies generating more complex patterns. Whilst these patterns are similar in like for like instruments, the patterns were proven to be unique, introducing different frequencies of harmonics and ultimately a unique timbre or tone.

Electronic components including amplifiers, guitar pickups and effects added by a user into the signal chain also introduce harmonics. The harmonics created by the signal chain resonate at different frequencies than the natural harmonics introducing more intervals which combine with the harmonics created by the physical instrument to produce the final timbre of the sound consumed by the listener.

The final amount of harmonics introduced to a signal can include multiple frequencies is referred to as Total Harmonic Distortion (THD). At low gain, these harmonic distortions are at a low intensity rendering them indiscernible to the human ear. When the gain is increased, ie. When the volume or gain is increased on an amplifier or effect pedal for example, these harmonics are amplified, along with the foundation standing wave, saturating the electronic components causing more harmonics as the sine wave gets compressed and clipping begins. The more the gain is increased, the more the waveform resembles a sawtooth wave which becomes more ‘gritty’ and ‘messy’ sounding producing more distortion in the final sound.

2.3 Digital Signal Processing of Digital Guitar Effects

Digital guitar effects take the incoming guitar signal, quantise the signal into audio range bins through ADC then apply the algorithm which mimics the desired effect. The signal then passes through a DAC where it continues along the analogue path to the speaker. (Blasie 2020).

2.3.1 Distortion Effects

Distortion effects can be categorised into three bins. Gain, Overdrive and Distortion. Gain is simply the increase in magnitude of the signal entering the amplifier circuit. The amount of gain will determine the amount of clipping and whether the resulting signal is overdriven or distorted. (Blasie 2020).

Overdrive is the effect of a signal being driven over a specified threshold. In a classic tube amplifier, this threshold is the tube's headroom. In a digital amplifier, this is set with an electronic limiter, which creates high frequency harmonics resulting in square wave characteristics. Driving the signal past this threshold can result in two situations, hard and soft clipping.(Blasie 2020). Soft clipping compresses the peaks of the signal which are higher than the threshold to a value lower than the threshold. Hard clipping takes any value larger than the threshold and compresses it to the threshold value.(Yeh et al. 2008). Soft clipping retains it's sinusoidal nature whereas hard clipping creates hard cutoffs and takes on a more square wave nature.(Yeh et al. 2007) This hard clipping results in a darker and harsh sound. The visual representations of hard and soft clipping are displayed in the following figure.(Blasie 2020)

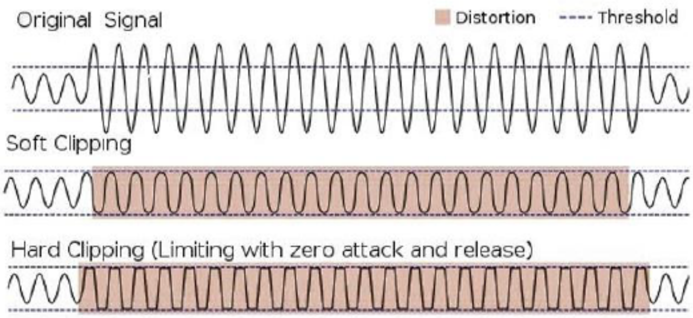


Figure 5 Hard and soft clipping of an audio signal.

2.3.2 Time Varying effects

Time varying effects samples the input signal then buffers sample to repeat after an amount of time. Time varying effects can be categorised into delay, chorus, and tremolo.

Delay takes the sampled signal then repeats it after a set constant time variable. The user can set the time and number of repetitions. Chorus is very similar to delay, the only difference is the time is varied instead of fixed resulting in a sweeping sound instead of an explicit repeat of the signal.(Nonzee & Poongbunkor 2001). Lastly the tremolo effect utilises amplitude modulation to vary the amplitude of the signal resulting in a 'wobbling' or spinning speaker effect.

Other effects like flanger and phaser are variations of chorus and tremolo and present themselves similarly in DSP analysis. (Timoney et al. 2010).

2.4 Linear Filtering to Emulate Acoustic Guitar

The study completed by (Karjalainen et al. 2000) explores how equalisation techniques can be used to make a solid bodied magnetic pickup electric guitar sound like a hollow body acoustic guitar, a process they refer to as guitar-to-guitar emulation. The process of the guitar is broken down into a model which is represented visually by Figure 4.

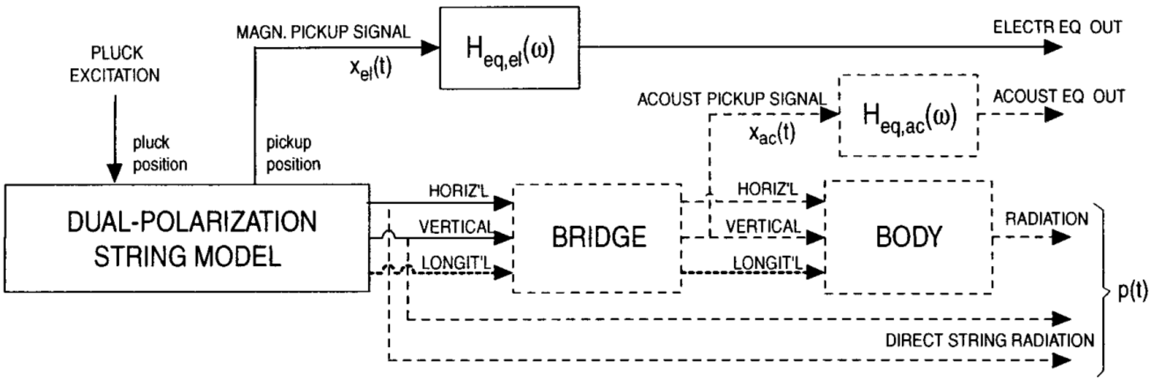


Figure 6 Generic guitar model with electric and acoustic guitar signal paths. (Karjalainen et al. 2000)

Figure 4 expresses the generic model of a guitar, with an electric guitar signal path in bold and acoustic guitar in dashed. The study discovered that in an acoustic guitar the pickup in an acoustic guitar was more dynamic than the electric guitar due to the resonance in the hollow body. This resonance is needed to be eliminated and analysed due to the solid body electric not having any of this resonance. This is achieved by performing Fast Fourier Transform (FFT) on the signal received by the pickup due to the excitation of the strings and the measured output of the acoustic guitar and dividing them to create a filter as shown in Eq.1.

$$H_{eq,acoustic}(\omega) = P(\omega)/X_{electric}(\omega) \qquad \text{Eq.1}$$

By applying this filter to the $H_{eq,electric}$ block, it was discovered the electric guitar output did in fact sound more resonant and acoustic guitar like. The study determined that although the electric guitar was able to take on characteristics of an acoustic guitar timbre, absolute emulation is difficult due to the construction and function of the two different instruments.

Results from this study highlight that any emulation of guitar timbre must be completed with at least the same style and body type of instrument as the original.

2.5 Guitar signal chain modelling

The digital modelling and emulation of signal chain components (effects, guitar amplifier, speaker cabinet) have been studied and are readily available commercially as plug-ins with varying quality and customer satisfaction. (Wright et al 2023) has declared that the techniques which emulate these components can be considered in two approaches. White box and Black box.

2.5.1 White-box emulation

White box emulation is an approach where functions describing the behaviour of the system are derived and used for emulation (Wright et al 2023). An example of this approach is illustrated in the study by (Kröning et al. 2011) where the mesh equations were derived for a MXR DynaComp Compression pedal.

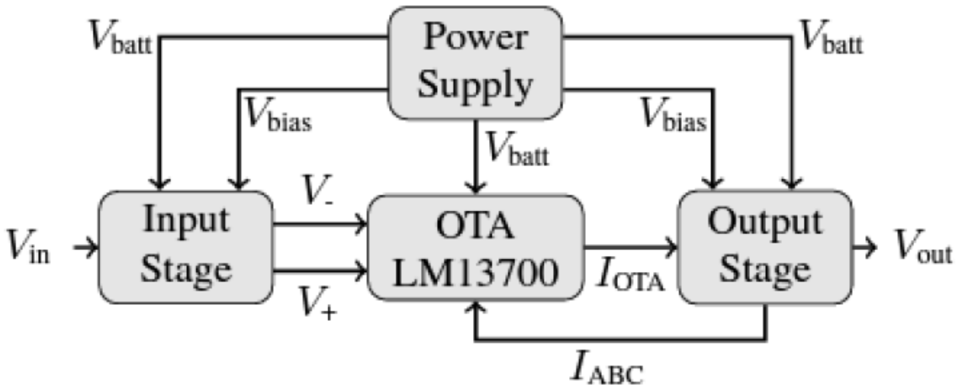
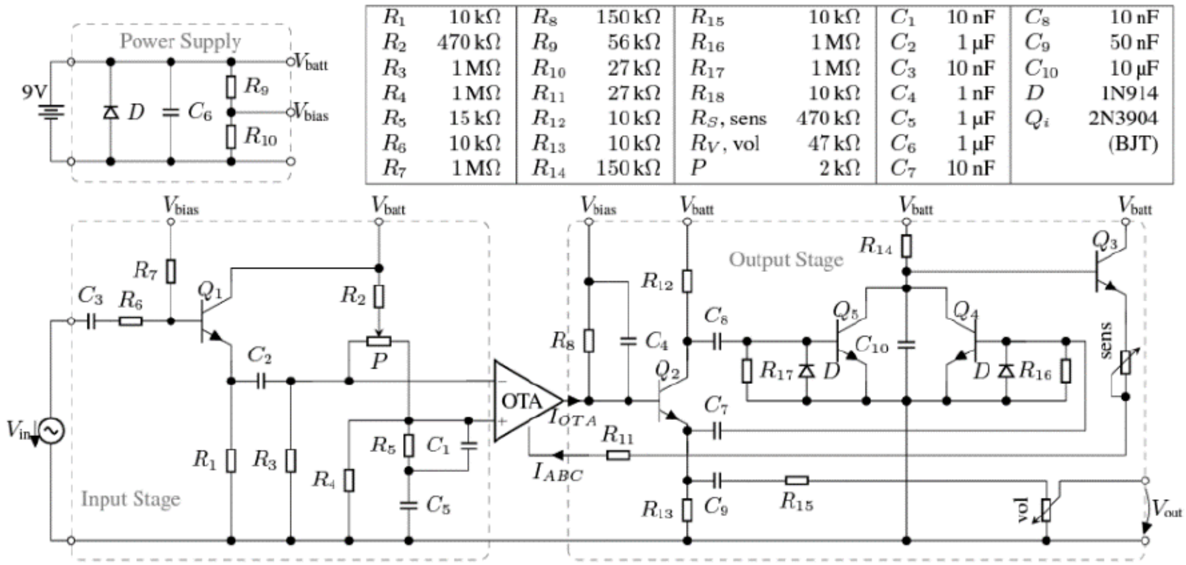


Figure 7 Block diagram of MXR DynaComp Compression pedal



R_1	10 kΩ	R_8	150 kΩ	R_{15}	10 kΩ	C_1	10 nF	C_8	10 nF
R_2	470 kΩ	R_9	56 kΩ	R_{16}	1 MΩ	C_2	1 µF	C_9	50 nF
R_3	1 MΩ	R_{10}	27 kΩ	R_{17}	1 MΩ	C_3	10 nF	C_{10}	10 µF
R_4	1 MΩ	R_{11}	27 kΩ	R_{18}	10 kΩ	C_4	1 nF	D	1N914
R_5	15 kΩ	R_{12}	10 kΩ	R_S, sens	470 kΩ	C_5	1 µF	Q_i	2N3904
R_6	10 kΩ	R_{13}	10 kΩ	R_V, vol	47 kΩ	C_6	1 µF		(BJT)
R_7	1 MΩ	R_{14}	150 kΩ	P	2 kΩ	C_7	10 nF		

Figure 8 Circuit diagram of MXR DynaComp Compression pedal

The team of researchers on this project took the circuit diagram of the pedal and was able to derive the mesh equations and subsequent state space vectors to effectively simulate the output response of the analog effect pedal.

$$
\begin{aligned}
0 &= -V_{R_{13}} + V_{C_7} + V_{BE_4} \\
0 &= -V_{Batt} + V_{R_{12}} - V_{C_8} + V_{BE_5} \\
0 &= -V_{Batt} + V_{R_{14}} + V_{C_{10}} \\
0 &= -V_{bias} + V_{C_4} + V_{BC_2} - V_{C_8} + V_{BC_5} + V_{C_{10}} \\
0 &= V_{R_8} - V_{bias} + V_{BE_2} - V_{C_9} - V_{R_{15}} + V_{R_{vol_1}} + V_{R_{vol_2}}
\end{aligned}
$$

Figure 9 Mesh equations for output response of Block diagram of MXR DynaComp Compression pedal

$$
\begin{aligned}
\dot{\boldsymbol{x}}(t) &= \left[\dot{v}_{C_4}(t)\ \dot{v}_{C_7}(t)\ \dot{v}_{C_8}(t)\ \dot{v}_{C_9}(t)\ \dot{v}_{C_{10}}(t)\right]^T, \\
\boldsymbol{u}(t) &= \left[I_{OTA}(t)\ V_{bias}(t)\ V_{Batt}(t)\right]^T, \\
\boldsymbol{i}(t) &= \left[I_{B_2}\ I_{E_2}\ I_{B_4}\ I_{E_4}\ I_{B_5}\ I_{E_5}\right]^T.
\end{aligned}
$$

Figure 10 State Space Vectors for output response of Block diagram of MXR DynaComp Compression pedal

(a) (b)

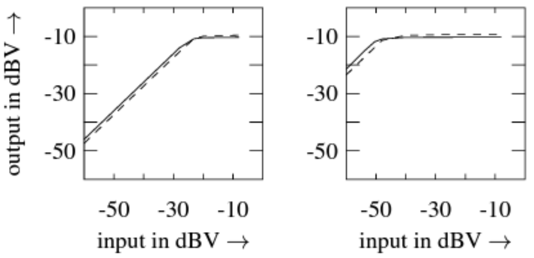


Figure 11 Plots of actual output (a) and simulated output (b) of Block diagram of MXR DynaComp Compression pedal

A similar study was completed by (Pakarinen et al 2010) to emulate a triode vacuum tube guitar amplifier. The linear and time invariant (LTI) nature of the equalizer and reverb units in most vacuum tube amplifiers means a linear digital filter approach is proven to be effective along with transistor components.

A vacuum tube amplifier circuit was used for the analysis and creation of the filter.

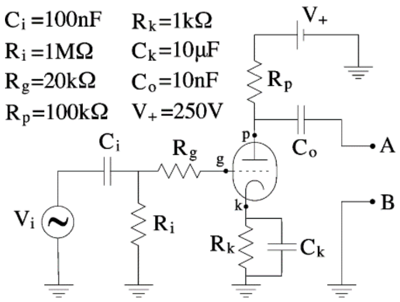


Figure 12 Circuit diagram of a vacuum tube triode guitar amplifier

This circuit was converted into a wave digital filter model. The researching team used WDF to provide a greater accuracy for the filter coefficients.

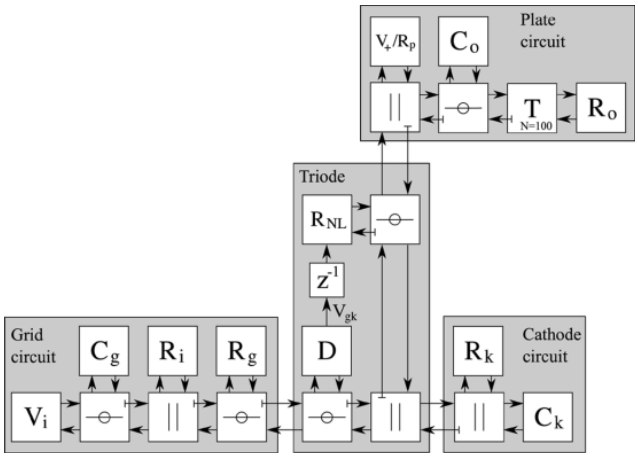


Figure 13 WDF configuration for circuit diagram in Figure 10

Using this technique, the amplifiers were able to be simulated realistically. This method was chosen due to the bidirectional nature of the WDF complimented the behaviour of the vacuum tube amplifiers.

2.5.2 Black-box emulation

Instead of modelling each component individually, Black box emulation unlike white-box emulation collects data from a system and is fit into a model to match the output of a system. It derives a function to represent the entire device with an equation uncorrelated with the individual components. (Wright et al 2023).

(Novak et al. 2010) released a research paper modelling an analogue guitar effect using a Chebyshev filter. The research team used the nonlinear convolution method to design an exponential sine excitation as an input filter. This was proven to allow the frequency responses of the high frequency harmonics to be analysed and convolved with the output signal. This allowed the team to model the linear system with a one path measurement.

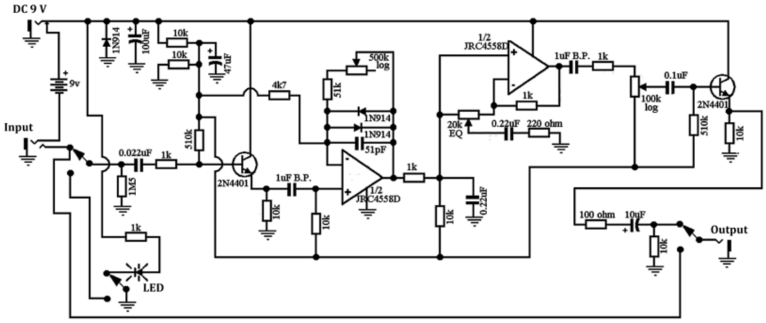


Figure 14 Circuit diagram of the modelled overdrive pedal.

From the circuit diagram in Figure 12, the team were able to develop the Chebyshev non linear model in Figure 13, then derive the orthogonal polynomials with the recurrence relationship Eq. 2, 3 and 4. The simulation results are displayed in Figure 16.

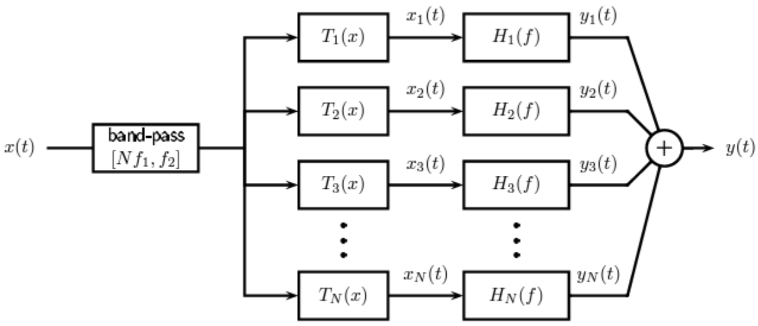


Figure 15 Chebyshev polynomials.

$$Tn(x) = \cos(n\,\theta), \text{ where } x = \cos(\theta), \qquad Eq.2$$

Orthogonal polynomials defined by,

$$Tn(x) = 2x\,T_{n-1}(x) - T_n - 2(x),\ n = 2,3,..., \qquad Eq.3$$

Initial conditions,

$$T_1(x)=1,\ T_2(x) = x. \qquad Eq.4$$

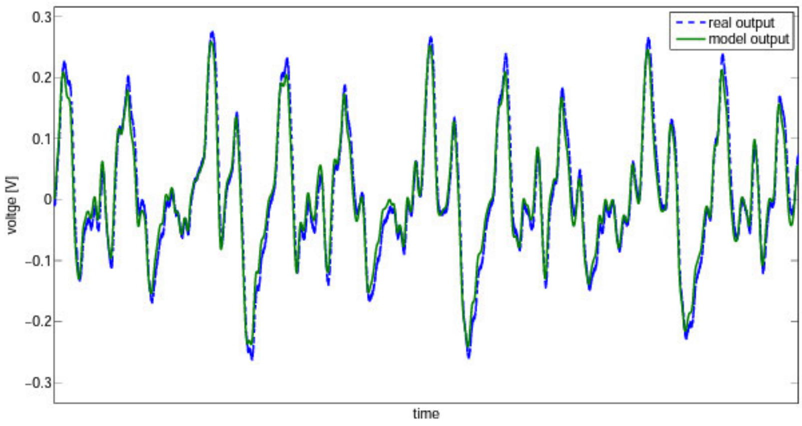


Figure 16 Actual output vs simulated output of analogue overdrive pedal (Novak 2010)

Another example of black-box emulation is the work from (Eichas & Zölzer 2016). The research team used a block orientated method with a linear filter and non linear block to combine into an extended Wiener model. A wiener model was used for the ease of mapping input to output amplitudes. The team were able to successfully emulate three analogue distortion pedals with low level of error.

Researchers have been able to successfully digitally emulate analogue effect pedals using both white and black box emulation approaches, however both approaches rely on the resolution of differential equations of component values which are discretised into lookup tables. This process is iterative and computationally expensive. This has drastic effects on the possibility of real time processing. Neural networks could overcome some of these roadblocks.

2.5.2 Deep Learning methods – Neural Networks.

The rise in machine learning has resulted in a greater presence of neural networks in everyday processing and higher study. This has provided recent innovation in audio analogue modelling. (Vanhatalo et al. 2022) has explored the use of neural networks to achieve electric guitar timbre emulation with three architectures. Convolutional (CNN) and recurrent (RNN) neural networks and a hybrid approach. The convolutional techniques used in computer vision and recurrent network approaches in speech recognition can be potentially combined to emulate sound characteristics (Goodfellow 2021). This approach requires the machine to be trained using datasets. (Damskägg et al. 2019) illustrated this concept in their study where they used a wave net architecture originally developed for speech synthesis to emulate a vacuum tube amplifier and distortion pedal. Figure 1 illustrates the approach in the study where a stack of dilated convolutional layers was used to access more past information. The information is accessed by a dataset which in this case took 4 hours to complete.

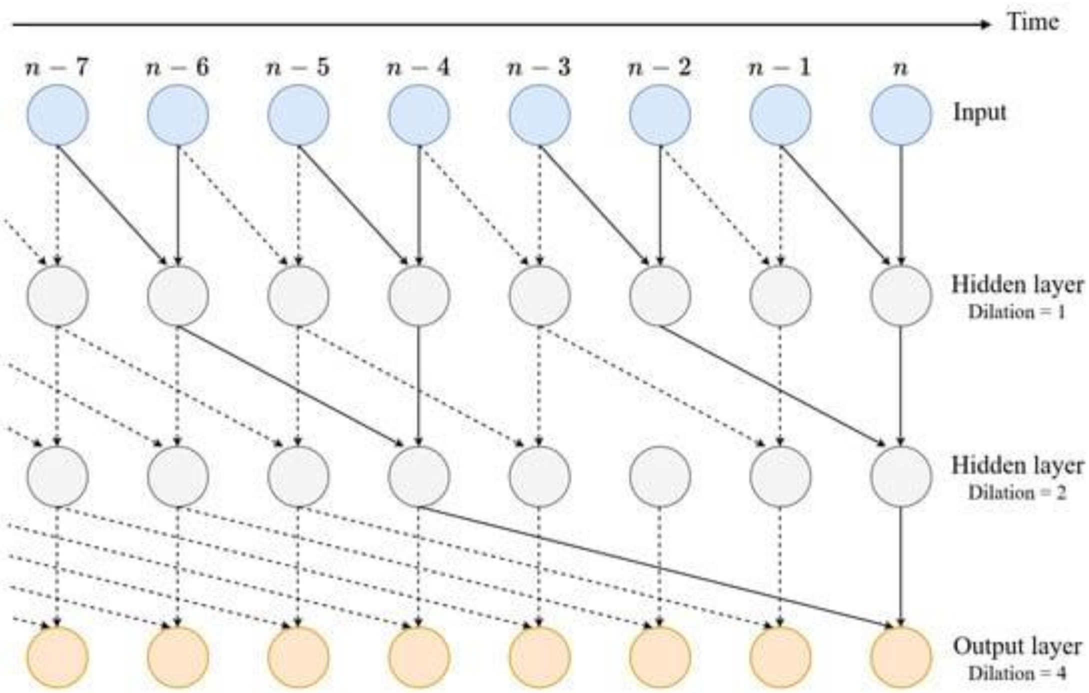


Figure 17 Feed Forward WaveNet Architecture (Damskägg et al. 2019)

It was discovered in this study that the resulting model is significantly impacted by the sampling rate and the resulting latency (Damskägg 2019). For a musician to be comfortable and not hindered by latency, the constraint is 10 ms (Schmitz & Embrechts 2018). At a sampling rate of 256 samples at 44.1 kHz, the time required to fill the buffer is 5.8 ms, leaving 4.2 ms for DSP computation meaning lower sampling rates are required. With 44.1 kHz being at the low end of the scale for high audio quality in a production or performance setting,

(Vanhatalo et al. 2022) Goes into detail how the CNN and RNN approaches can potentially provide a means to emulate analogue music equipment in a real time setting. More work in this field is required to explore the effects of aliasing. The sampling rate being limited to 44.1 kHz means that the audio quality is questionable and cannot be upsampled to allow headroom for DSP. This opens the opportunity for parametric models which are still being researched with little results to date.

The literature review has explored the mechanical characteristics of how electric guitars produce a signal and how that signal is manipulated by various elements in a signal chain. Predicting and emulating the spectrum of harmonic frequencies is crucial to achieving the aims and objectives of this project and pose significant challenge for real time applications.

CHAPTER 3 - RESEARCH DESIGN AND METHODOLOGY

This research in this project will include both quantitative and qualitative approaches. A qualitative review of literature will compliment a quantitative DSP analysis of waveforms to form conclusions and closing arguments.

1. Peer reviewed literature will be studied to the mechanical dynamics of electric guitars and the correlation between striking or 'plucking' the strings and the resulting waveform signal heard by the end listener. The path this signal takes from the instrument to the output speaker is often altered by effect processing, compression, amplification stages and external interference. A deep dive into the peer reviewed literature will study the alterations these factors have on the signal, how they are customisable and the resulting waveforms.

2. Peer reviewed literature will be studied to explore and understand the past, current, and future processes/techniques in digital emulation of classical, analogue amplification equipment to assess the feasibility of potential emulation of an entire electric guitar signal chain.

3. This project will use a combination of downloaded (freeware) electric guitar tracks sourced from online platforms and samples recorded in the home studio.

   The home studio includes,

   a. Electric guitars – Fender Stratocaster and Schecter S1 Custom 3.
   b. 'Positive Grid Spark' digital modelling and recording USB amplifier.
   c. Orange Tiny Terror Valve amplifier
   d. Studio One 5 DAW (Digital Audio Workspace) Software.
   e. Digital and Analogue guitar effects- Digital plugins and Stomp boxes
      - Boss DS-1 Distortion Pedal
      - Moor mini blues pedal
   f. Computer

All the resources for this project are my personal possessions, so I will not need to purchase anything.

Table 1 lists the test cases used in the project which were recorded in the home studio. Clean samples are zero effects applied with the amplifier gain low enough to discourage clipping, Overdrive is a boss DS-1 distortion pedal with gain setting to encourage soft clipping and distortion is the boss DS-1 pedal gain on max.

Table 1 Test cases for waveform analysis

Test Case	**Single Note / Multiple notes**	**Nature**	**Comments**
Neck Pickup	Single	Clean	Single note recorded on the neck pickup of Fender Stratocaster
Centre Pickup	Single	Clean	Single note recorded on the centre pickup of Fender Stratocaster
Bridge Pickup	Single	Clean	Single note recorded on the Bridge pickup of Fender Stratocaster
Single note Clean	Single	Clean	Single 'A' note played at 110 Hz
Single Note OD	Single	Overdrive	Single 'A' note played at 110 Hz
Single Note Distortion	Single	Distortion	Single 'A' note played at 110 Hz
2 note fifth interval	2 notes	Clean	2 notes played at 5th interval. (A 110 Hz and E 165 Hz)
2 note octave	2 notes	Clean	2 notes played at 8th interval. (A 110 Hz and A 220 Hz)
3 chord riff Clean	3 note chords	Clean	Progression of three chords including root note (tonic), major 3rd and 5th intervals. Chords – A, D and E
3 chord Overdrive	3 note chords	Overdrive	Progression of three chords including root note (tonic), major 3rd and 5th intervals. Chords – A, D and E
3 chord Distortion	3 note chords	Distortion	Progression of three chords including root note (tonic), major 3rd and 5th intervals. Chords – A, D and E

In addition to the recorded test cases, downloaded freeware guitar riffs are used for more comprehensive analysis of different guitar styles. 10 electric guitar tracks listed randomly will be analysed with waterfall plots, spectrograms, and Fourier analysis to visualise the waveforms and highlight any similarities and differences between different playing styles and typical signal chains. These samples were chosen to provide a wide variation of styles with enough similarities to analyse for correlations. For example, Sample 1 and 6 should be very different whereas Sample 1 and 2 should show similarities.

Table 2 10 electric guitar tracks for visual imaging analysis

Sample	**Nature**	**Genre**	**Style of**
1	clean	Country/Soft melody	Slow country
2	clean	Pop	80s Pop
3	Overdrive	Rock	Deep Purple
4	Overdrive	Rock	ACDC
5	Overdrive	Rock	Jimi Hendrix
6	Distortion	Metal/Hard Rock	Joe Satriani
7	Clean	Pop/Rock	Red Hot Chilli Peppers
8	Distortion	Hard Rock	Poison
9	Distortion	Hard Rock	Steve Vai
10	Distortion	Hard Rock	Black Sabbath

This project will use MATLAB to perform all DSP analysis of the audio files.

- Time response of the waveforms.
- Frequency response/ Fourier transform of the waveforms.
- Waterfall plots.
- Image spectrograms to highlight the characteristics of the waveforms.

4. The results will be summarised with critical reflections and the feasibility of real time emulation will be discussed usings findings from the literature review and DSP test cases.

This methodology is designed to provide a foundational background of the nature of the mechanics of electric guitar and the processing of the signal through the signal chain and how the final output is shaped. Once the mechanics of the guitar chain is understood, an analysis of the signals will provide a visual insight into the nature of the waveforms and how similar styles correlate and the difference in nature between different styles.

CHAPTER 4 - WAVEFORM GENERATION AND ANALYSIS

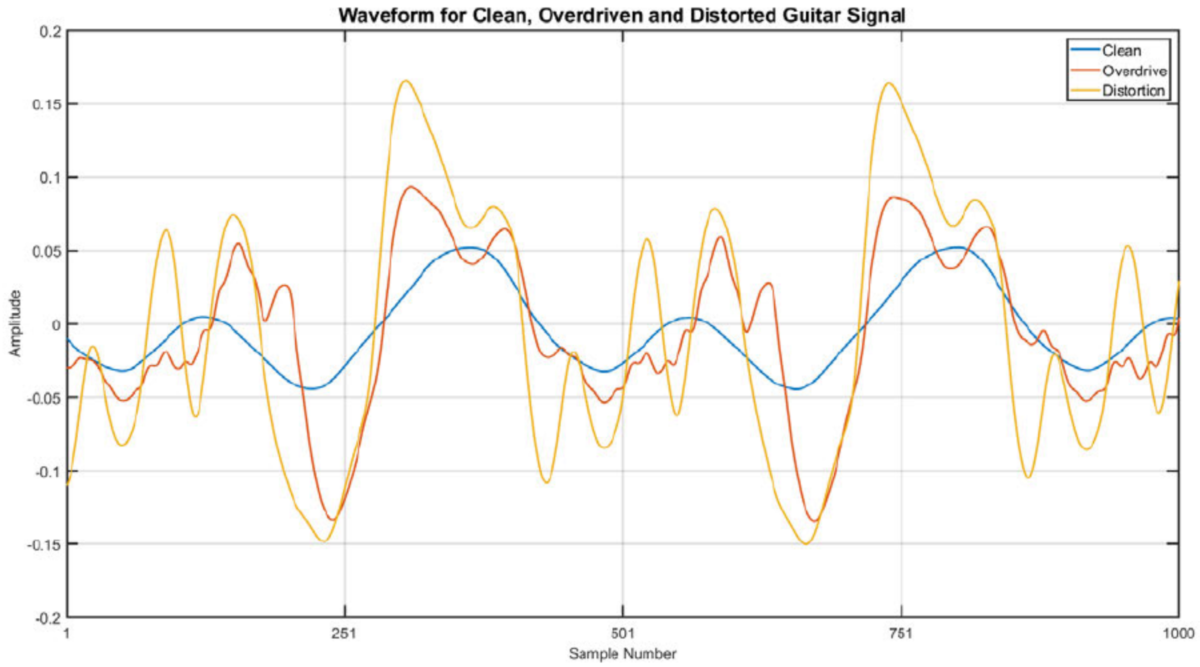


Figure 18 Plot of 'A' note (110 Hz) played on an electric guitar (same pickup) clean, mid gain (Overdrive) and high gain (Distortion) to compare waveforms.

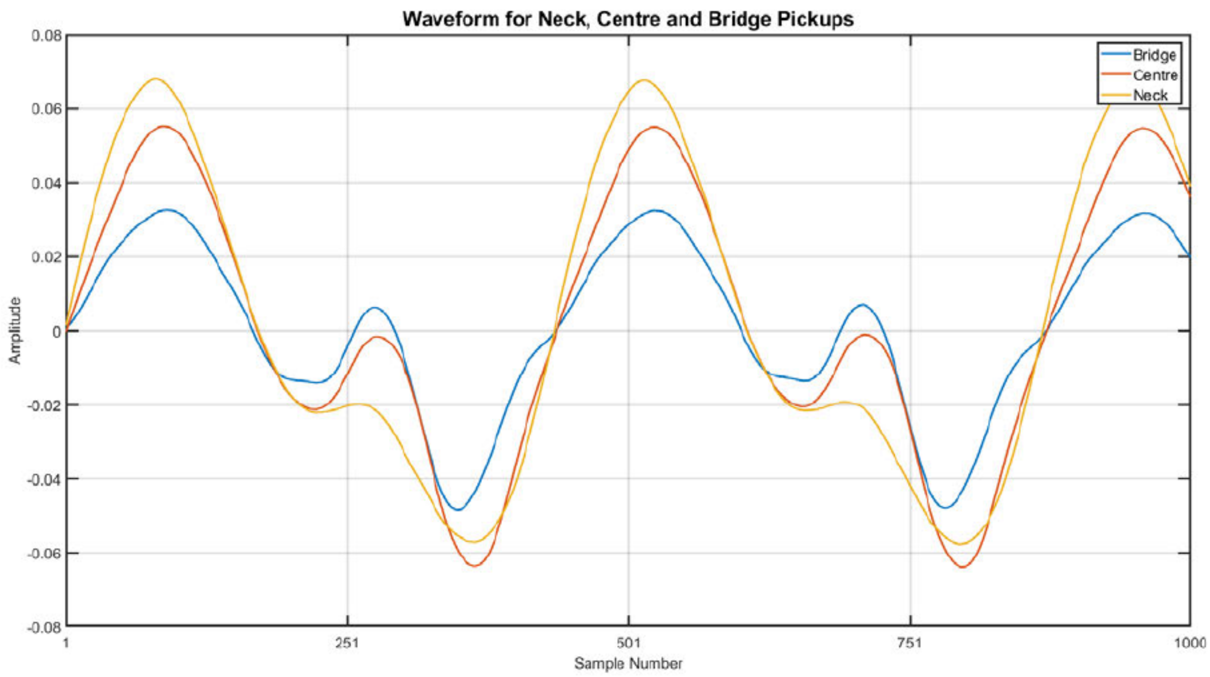


Figure 19 Plot of 'A' note (110 Hz) played on an electric guitar with no effects on three different pickups.

The first analysis of this project was conducted on a single note played on different pickups and a single note played with varying levels of distortion applied. The waveforms were superimposed over each other to visualise the relationship between them. Figure 18 illustrates the characteristic of a single guitar note explored in section 2.2 where it was discovered that a single string doesn't produce a pure sine wave. It can be clearly seen there are multiple frequencies in the waveform. The waveforms also display the increase in gain from the clean signal to the distorted signal. The harmonics are introduced, boosting frequencies and subsequent amplitude of the peaks.

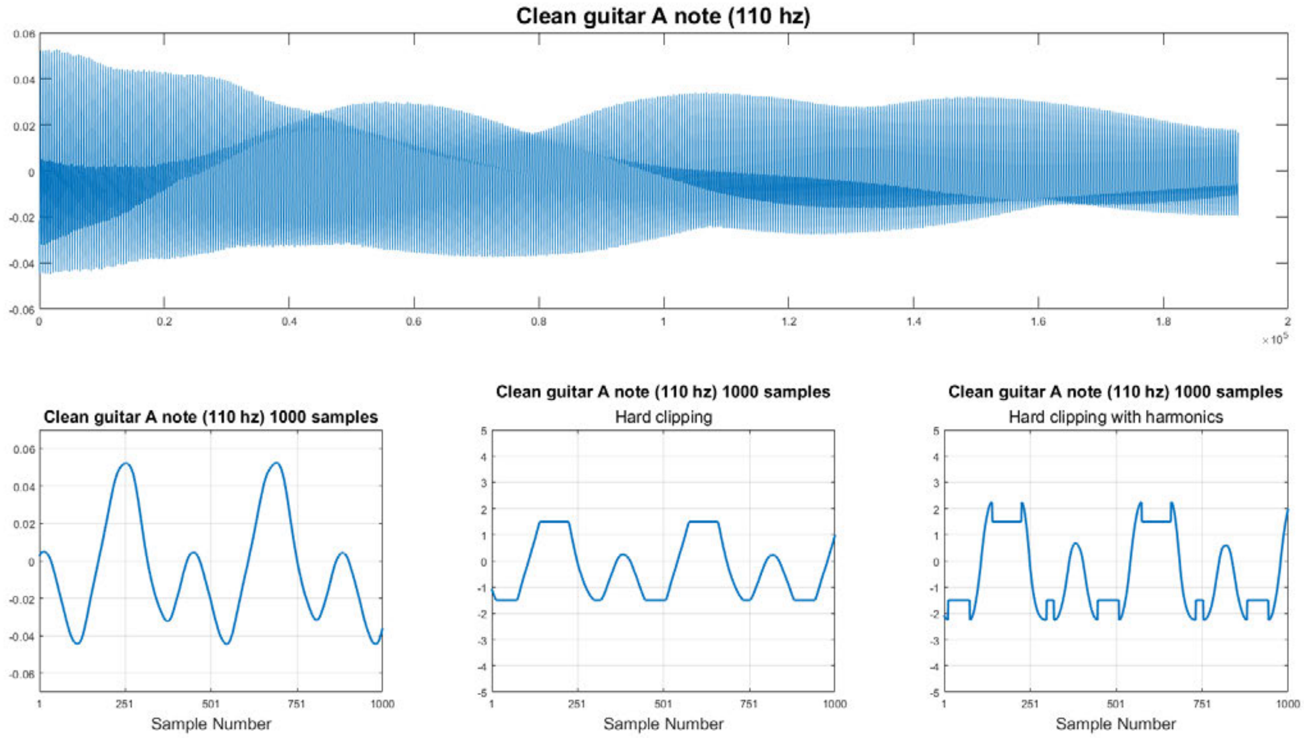


Figure 20 Clean single note with basic hard clipping and harmonics

Figure 20 shows a very crude attempt to recreate the harmonics digitally using hard clipping and simulated harmonics to compare the sound of the waveforms. The resulting waveform in figure 20 did add distortion to the clean wave, however the sound was of a very low quality sounding rough and unpleasant to the ears.

More analysis was required to get a better understanding of the waveforms. The next round of testing took the samples from table 1 and plotted the time response showing the decay envelope, the Fourier analysis to see the frequencies of harmonics and waterfall plot to visualise the flow of frequencies by time. For the waterfall plot and spectrograms, the signals were broken into frames of 256 samples for analysis. Figures 21 through 26 are the resulting plots.

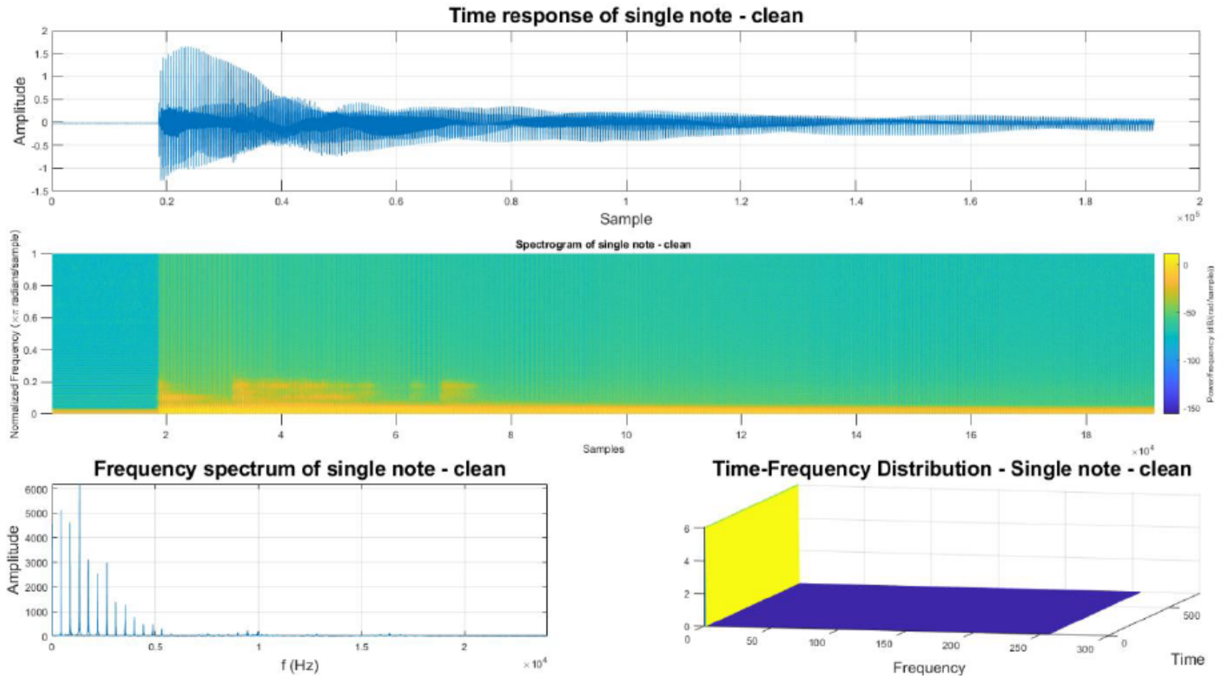


Figure 21 Signal analysis of a single note 110 Hz with no effects – Clean Guitar

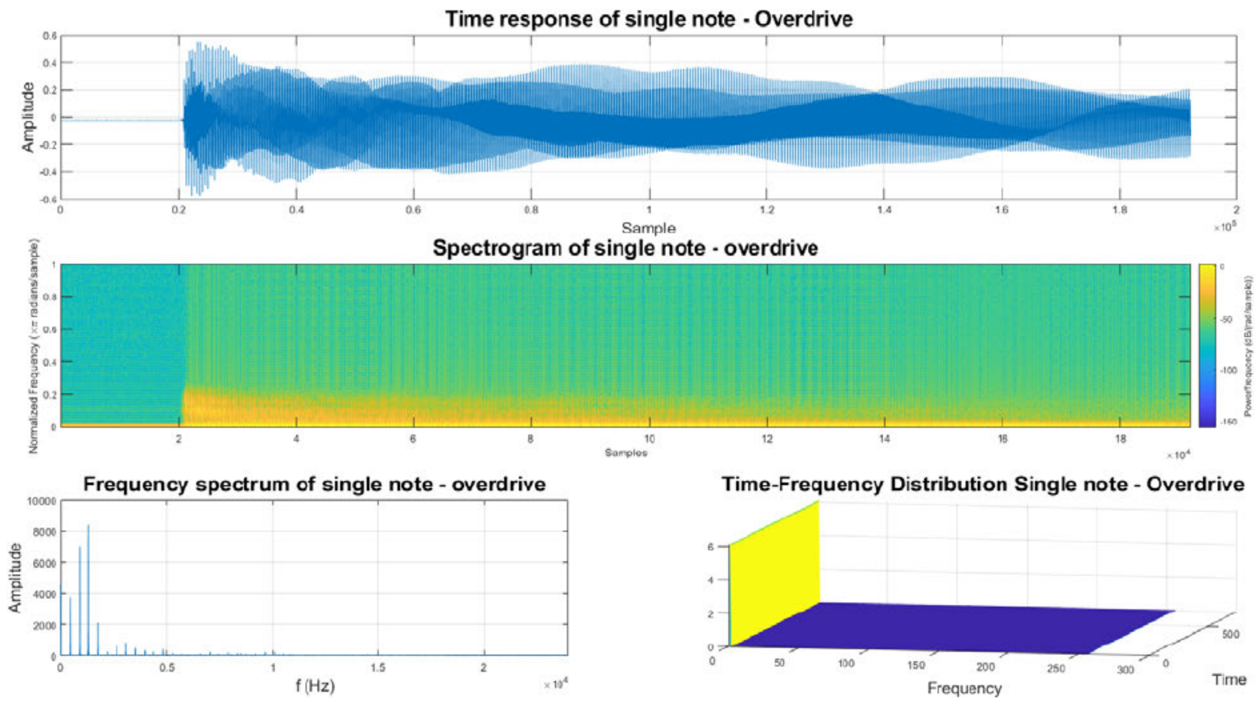


Figure 22 Signal analysis of a single note 110 Hz with moderate distortion – Overdrive Guitar

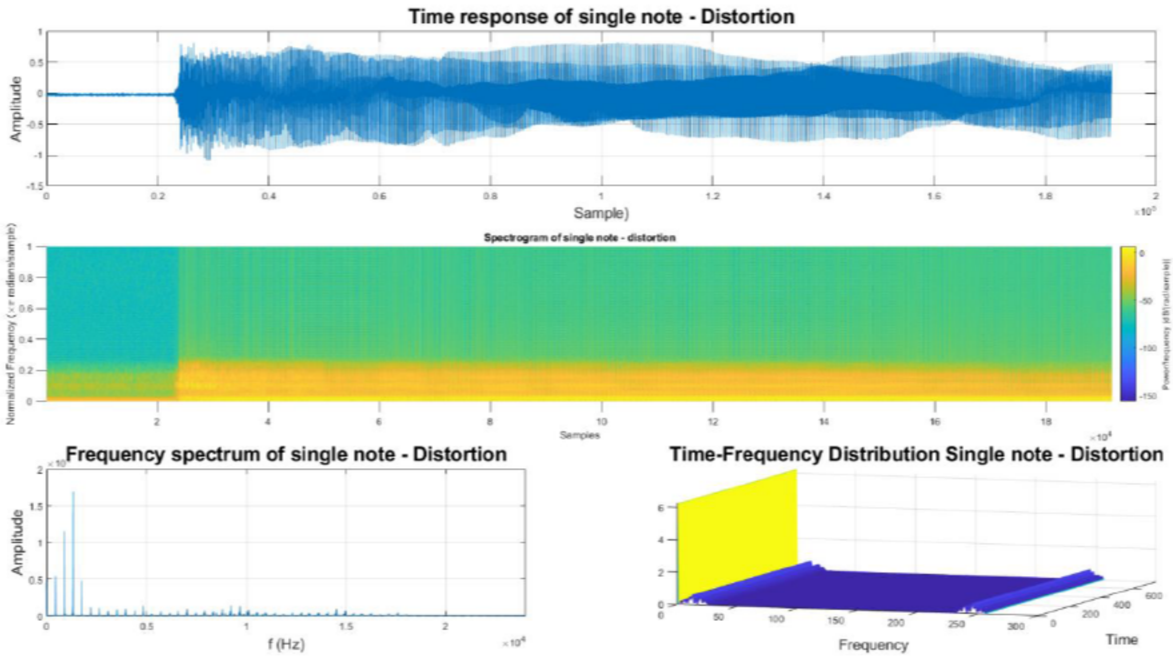


Figure 23 Signal analysis of a single note 110 Hz with Heavy distortion – Distorted Guitar

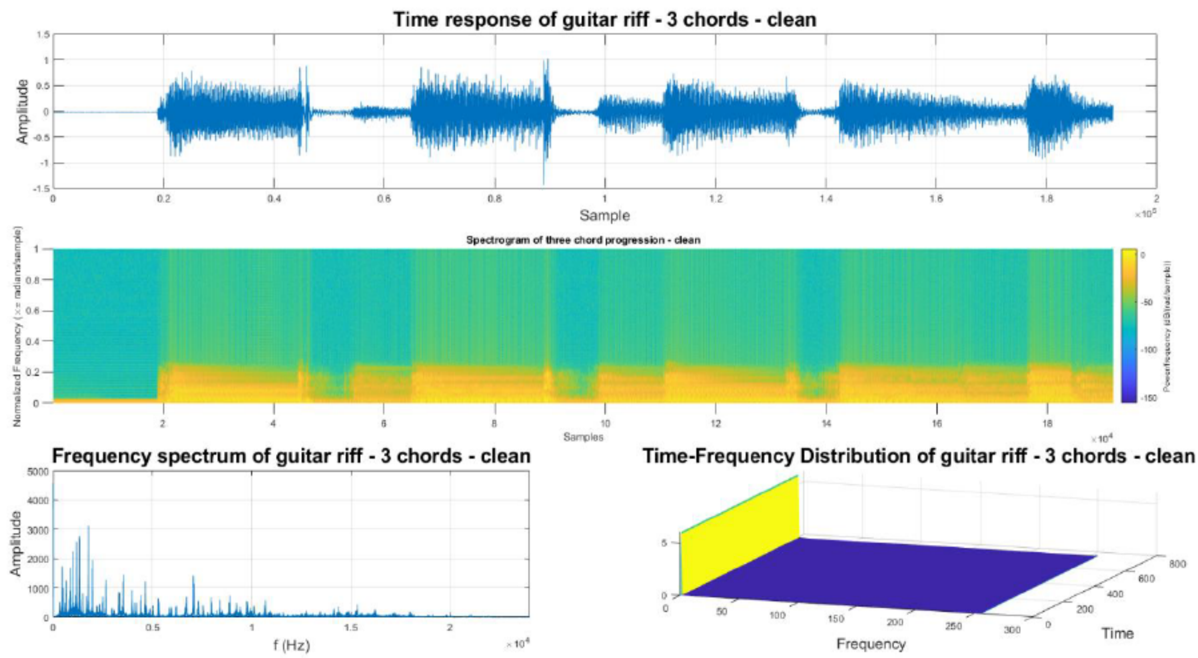


Figure 24 Signal analysis of a three chord progression – Clean Guitar

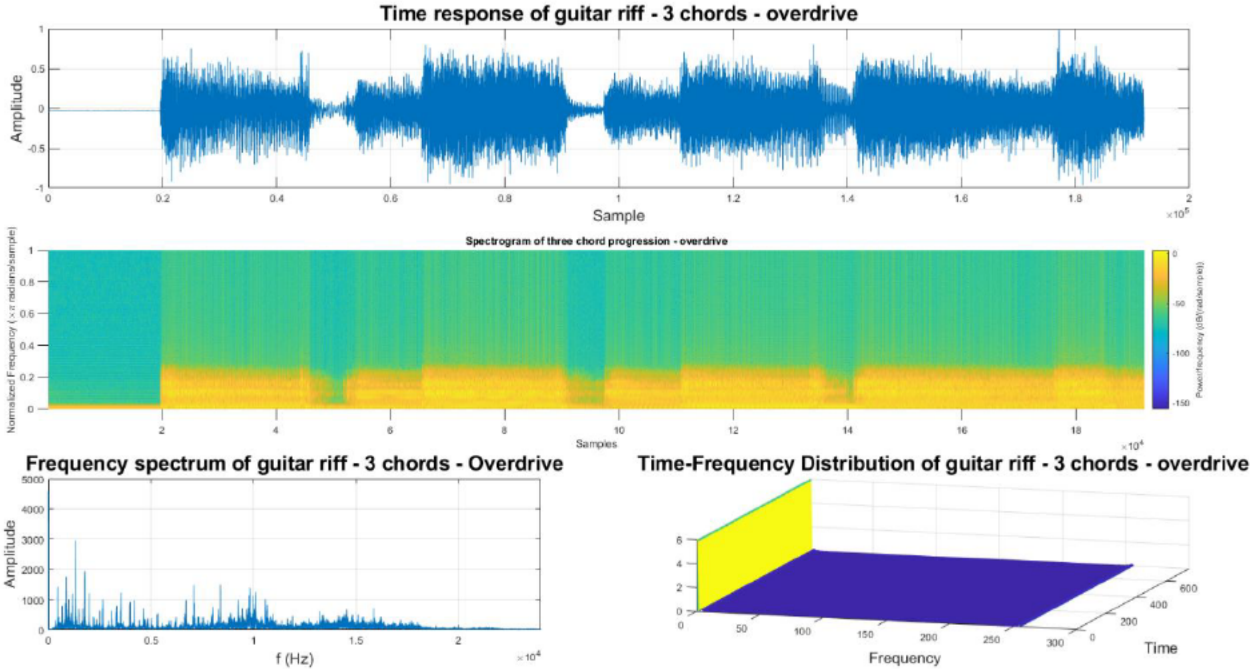


Figure 25 Signal analysis of a three chord progression – Overdrive Guitar

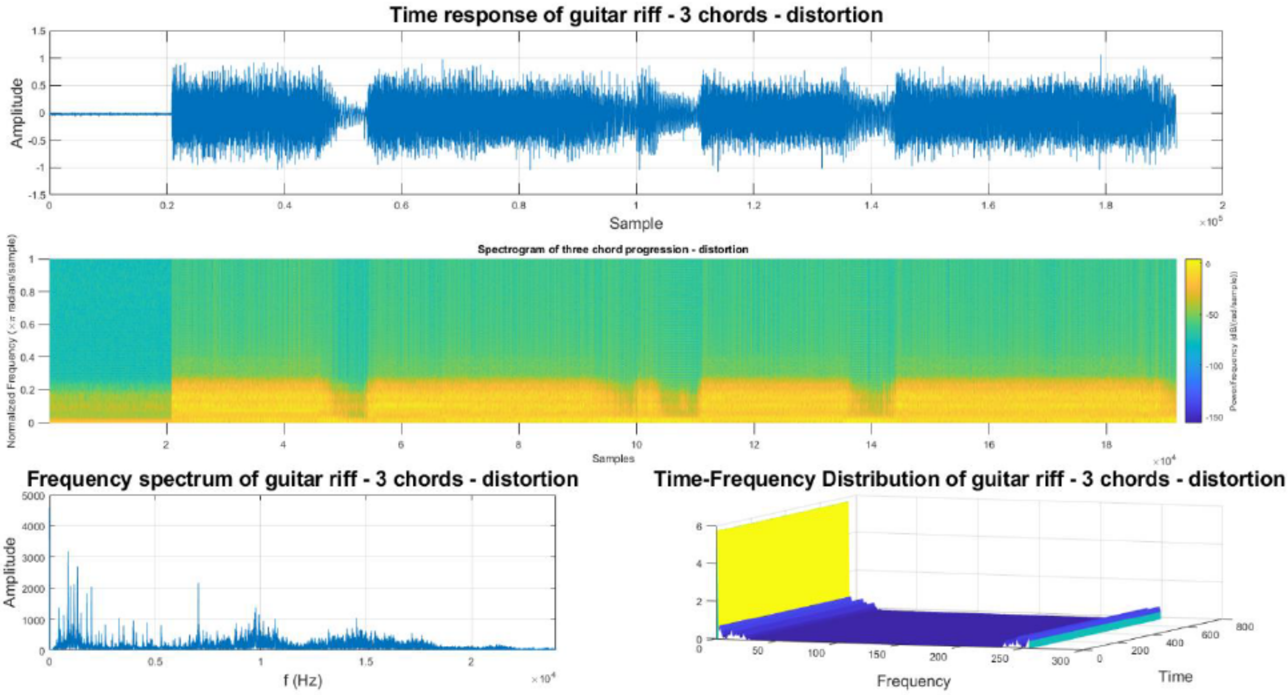


Figure 26 Signal analysis of a three chord progression – Distorted Guitar

Figures 27 through 36 show the same plots for the 10 recorded guitar tracks from Table 2

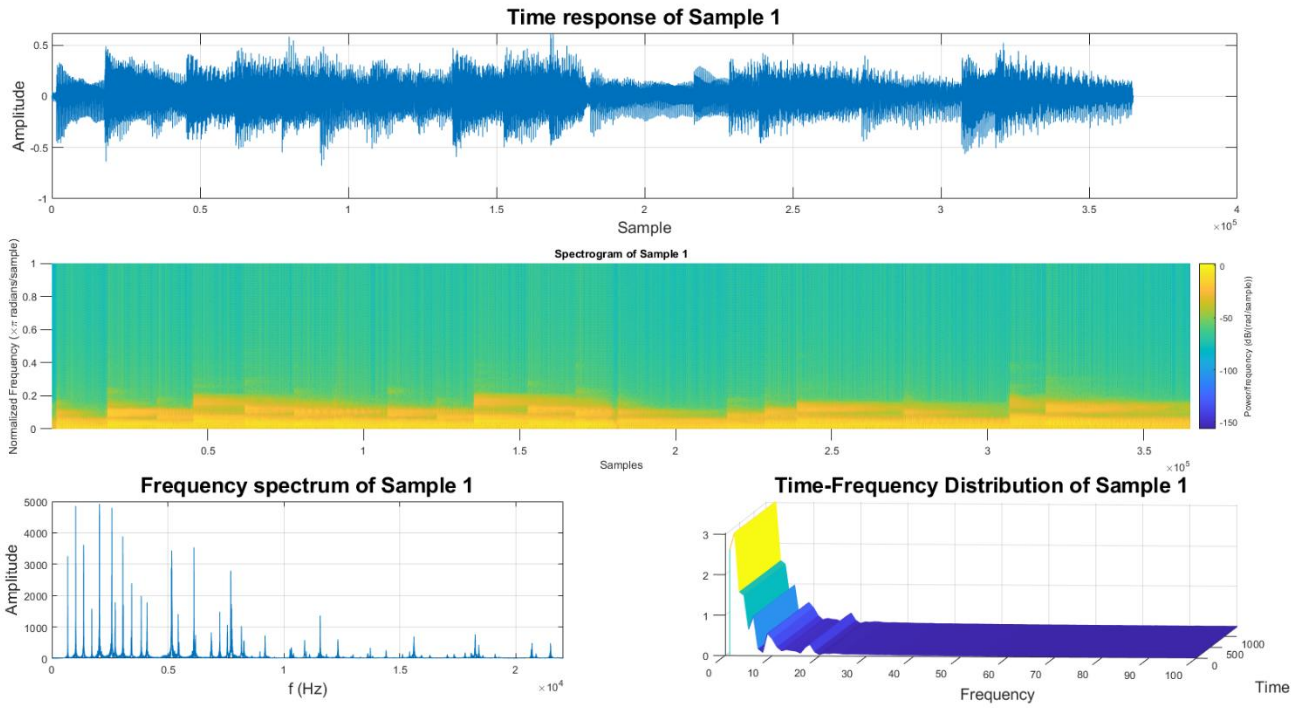


Figure 27 Signal analysis of Sample 1 (Table 2) – Slow Country style melody

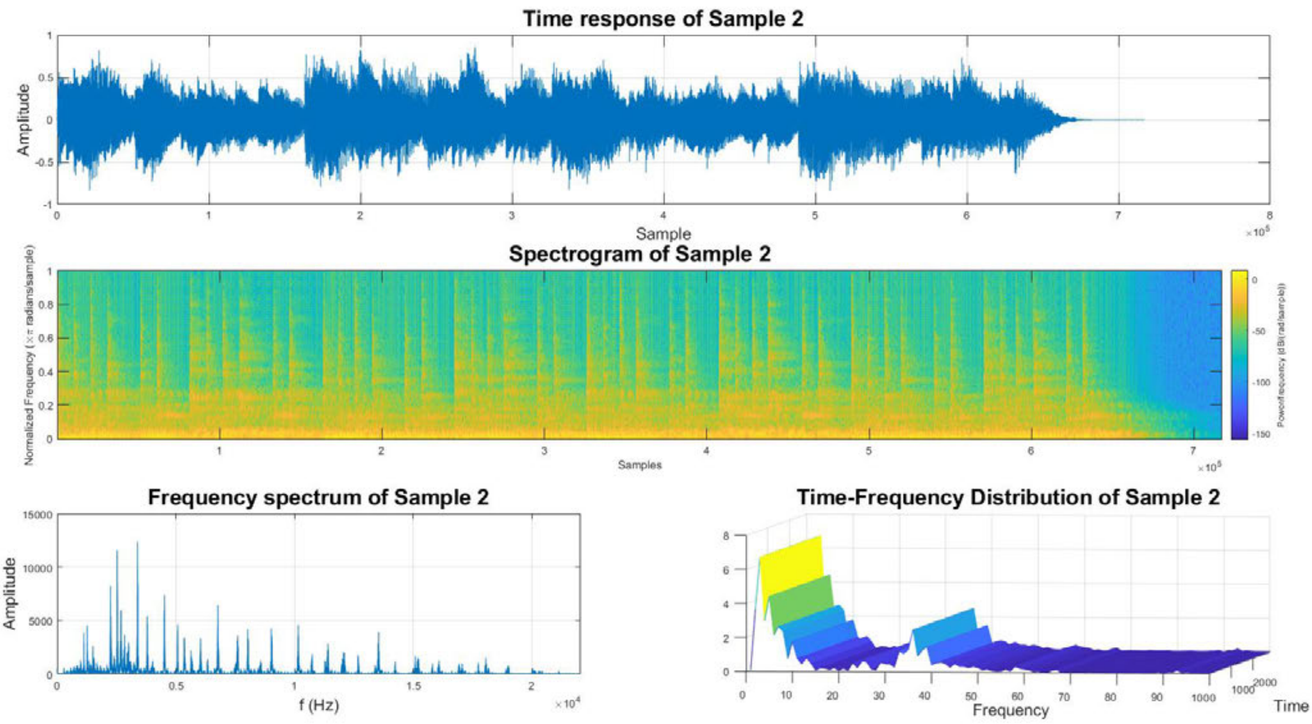


Figure 28 Signal analysis of Sample 2 (Table 2) – 80's style pop

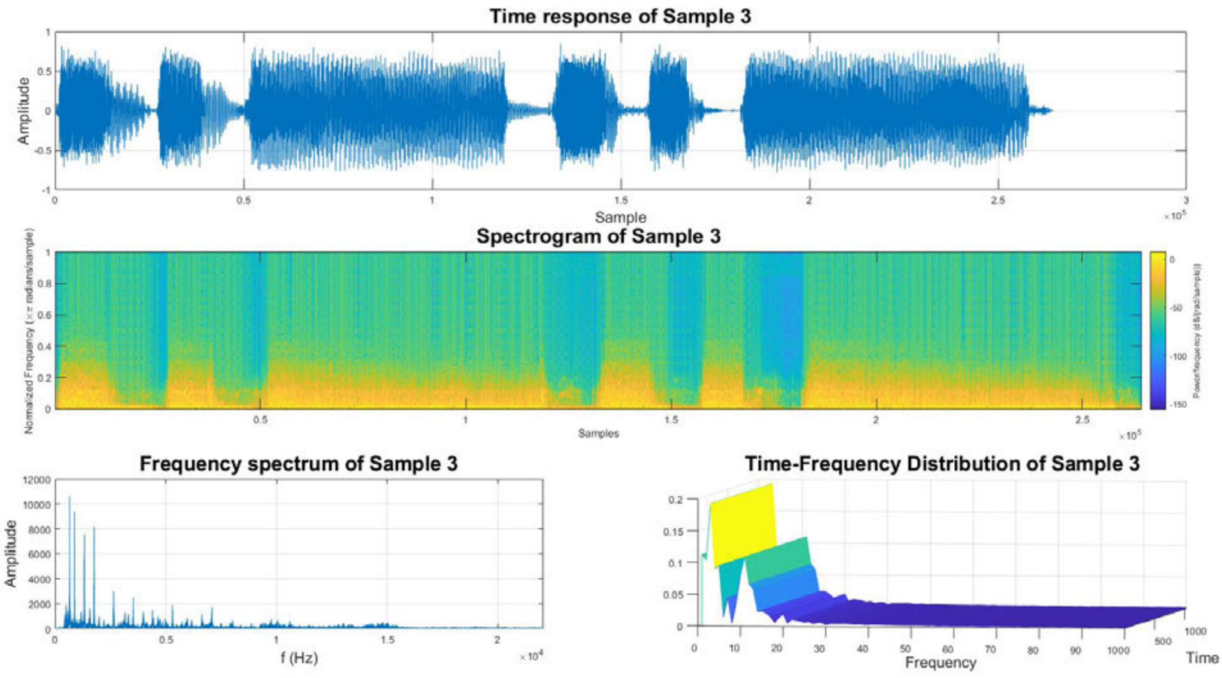


Figure 29 Signal analysis of Sample 3 (Table 2) – 70's style heavy rock

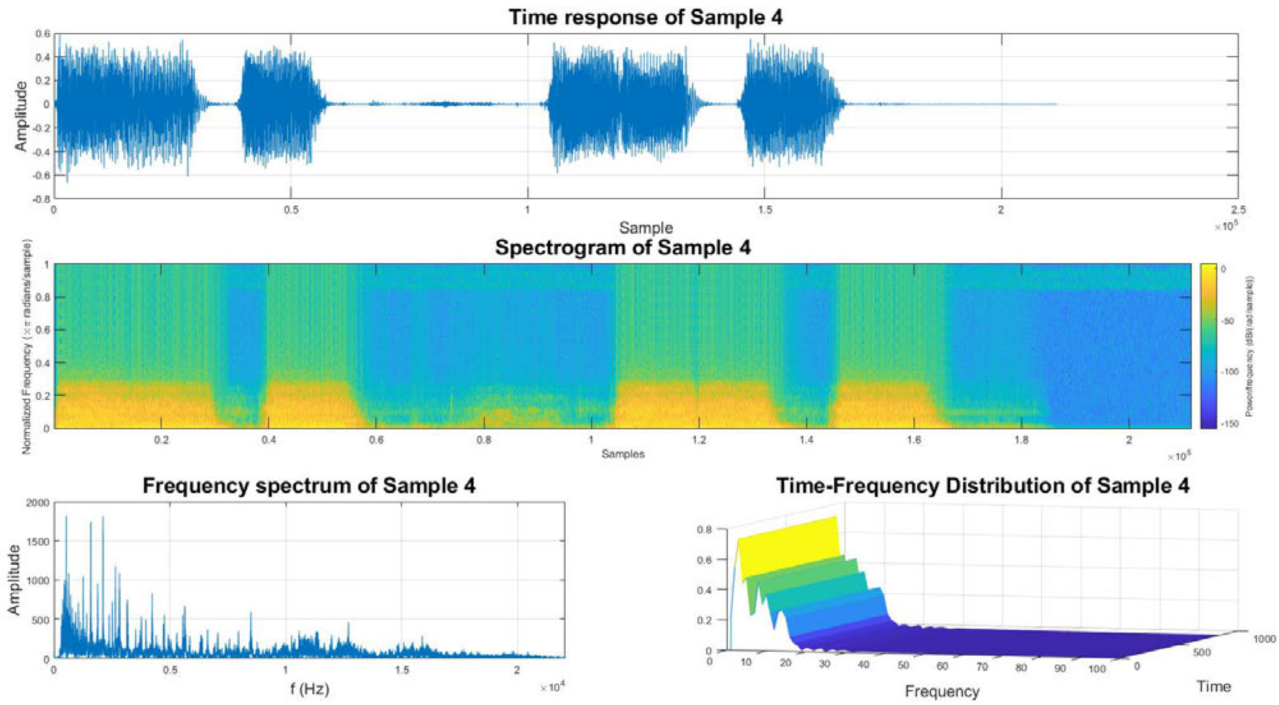
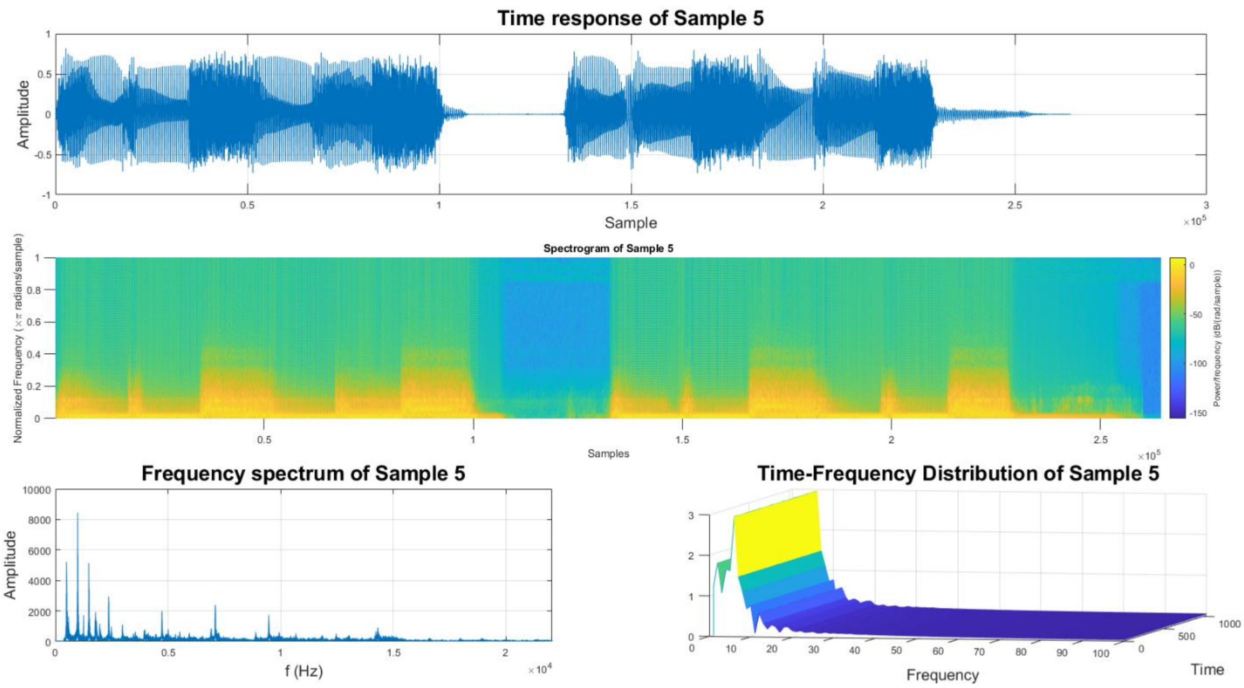
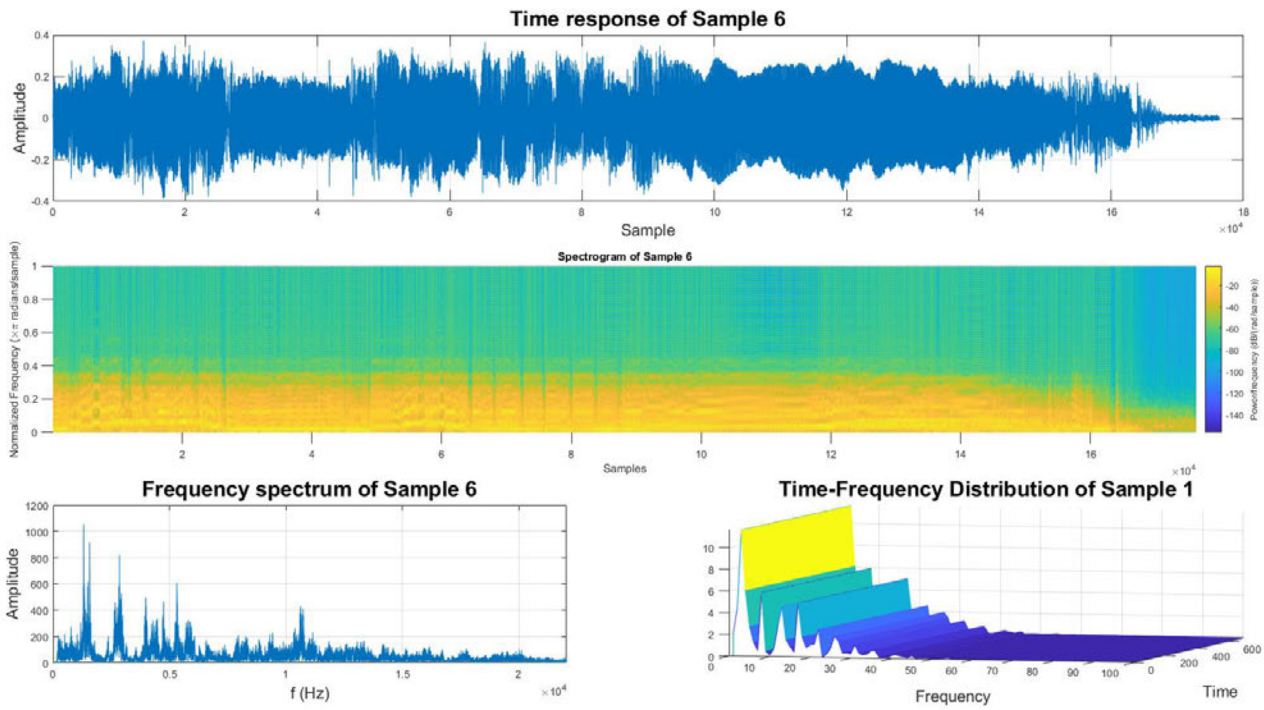
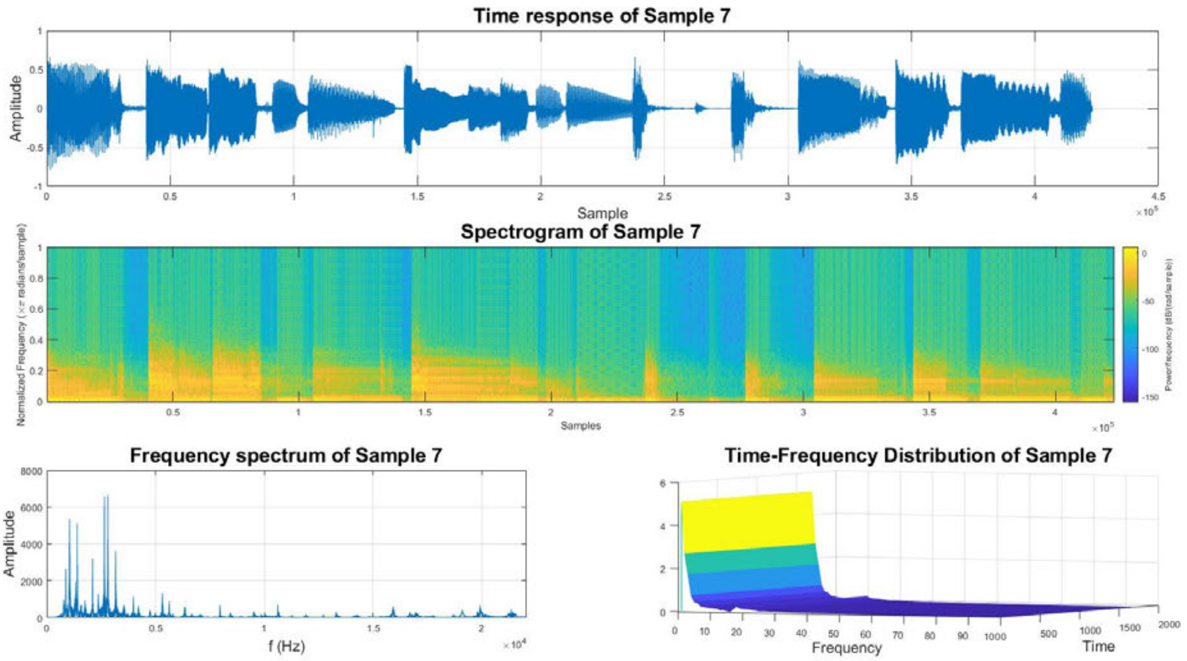
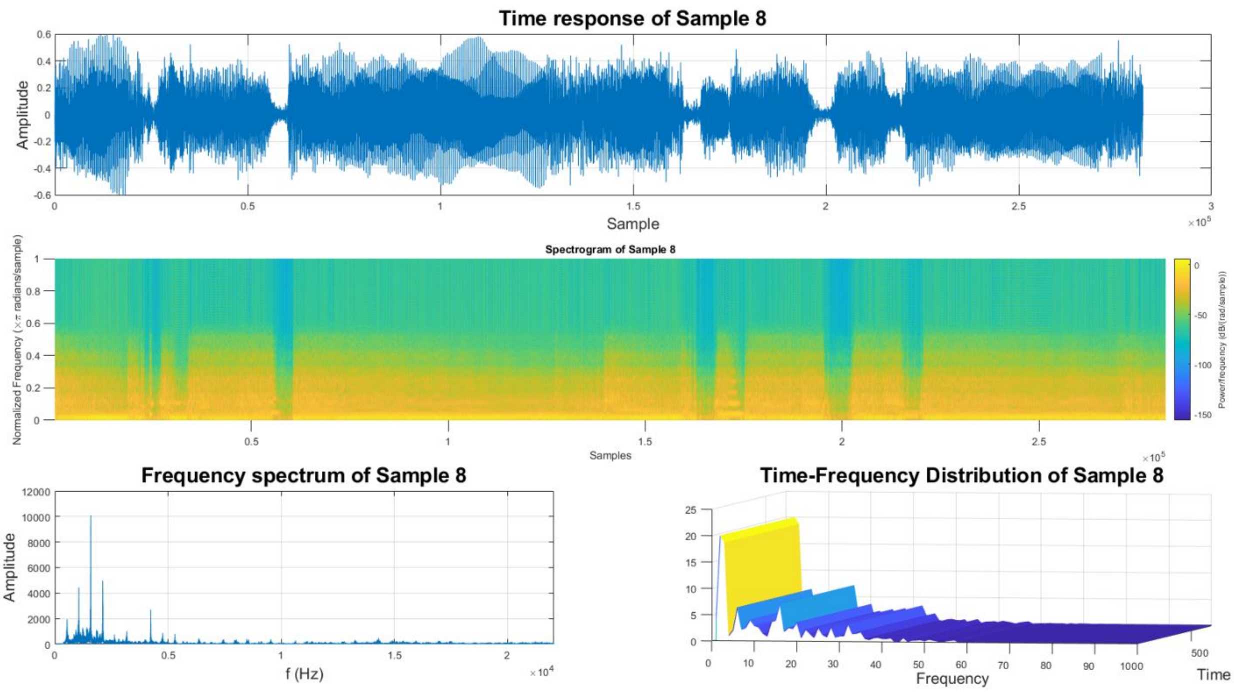


Figure 30 Signal analysis of Sample 4 (Table 2) – Australian style Hard Rock


Time response of Sample 5
Amplitude
Sample
Spectrogram of Sample 5
Normalized Frequency (×π radians/sample)
Samples
Power/frequency (dB/(rad/sample))
Frequency spectrum of Sample 5
Amplitude
f (Hz)
Time-Frequency Distribution of Sample 5
Frequency
Time


Time response of Sample 6
Amplitude
Sample
Spectrogram of Sample 6
Normalized Frequency (×π radians/sample)
Samples
Power/frequency (dB/(rad/sample))
Frequency spectrum of Sample 6
Amplitude
f (Hz)
Time-Frequency Distribution of Sample 1
Frequency
Time


Time response of Sample 7
Amplitude
Sample
Spectrogram of Sample 7
Normalized Frequency (×π radians/sample)
Samples
Power/frequency (dB/(rad/sample))
Frequency spectrum of Sample 7
Amplitude
f (Hz)
Time-Frequency Distribution of Sample 7
Frequency
Time


Time response of Sample 8
Amplitude
Sample
Spectrogram of Sample 8
Normalized Frequency (×π radians/sample)
Samples
Power/frequency (dB/(rad/sample))
Frequency spectrum of Sample 8
Amplitude
f (Hz)
Time-Frequency Distribution of Sample 8
Frequency
Time

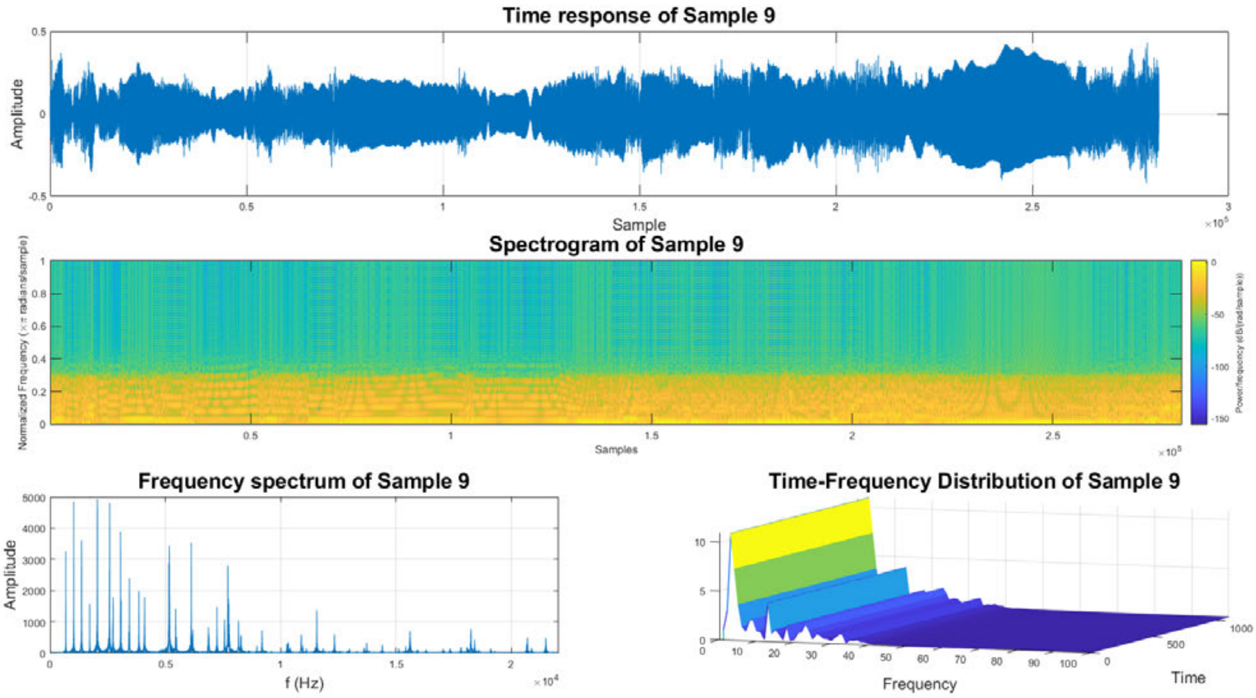


Figure 35 Signal analysis of Sample 9 (Table 2) – 80's style heavy rock

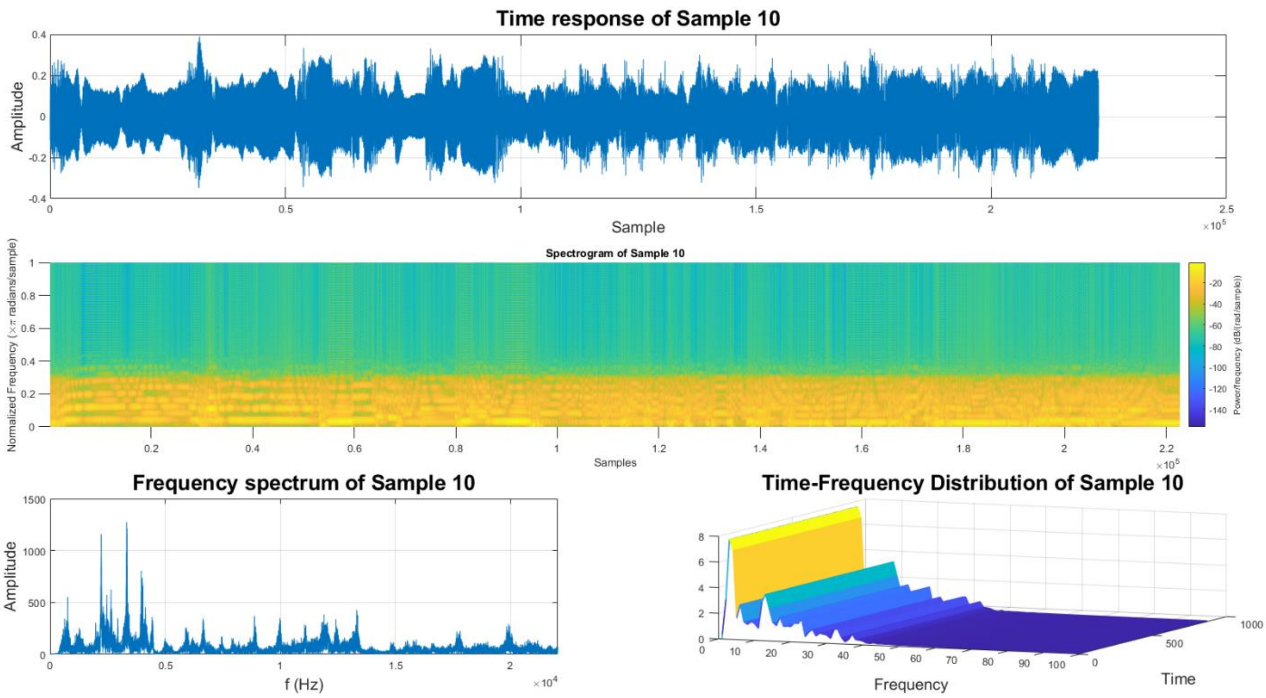


Figure 36 Signal analysis of Sample 10 (Table 2) – 70's style heavy metal

The samples were recorded on a modelling amplifier and sourced from freeware internet sites. The samples recorded were on a single guitar to gauge the impact of signal chain exclusively. More testing is required to gain a clearer picture on how different guitars, different amplifiers and playing styles differ in their characteristics. Time and equipment restraints meant the testing is quite one dimensional. A more thorough testing would include:

- More than one style of guitar – Semi hollow body, hollow body, different pickup configurations, different string gauges and tunings.
- Greater range of amplifiers – mix between digital, vacuum tube and hybrid amplifiers at varying levels.
- Same/similar progressions and notes played with same settings by three or more different players to see if playing style affects harmonics.

More testing would have provided a deeper understanding of the generation of harmonic distortion.

CHAPTER 5 - DISCUSSIONS

The analysis and experimentation of the waveforms of recorded electric guitar tracks in this project has confirmed and visualised the nonlinear nature of vacuum tube guitar amplifier distortion. The introduction of the spectrum of unpredictable frequency harmonics is evident in figures 27 through 36. The range of playing styles, genres and levels of audible distortion or fuzz each have their unique frequency spectrum and waveform envelope. If any correlation between styles or genres were to exist, it could be reasonably expected that similar sounding samples 6, 8 and 9 would share acoustic characteristics and very different sounding samples 2 and 9 to be clearly visually discernible. Both cases are unintuitive in their similarities and differences. Correlations and differences in the waveforms and acoustic characteristics are not an effective approach to successfully emulate a guitarist's timbre or sound.

The emulation of a guitarists timbre or tone must begin with the successful emulation of the unpredictable frequency spectrum generated by the guitar itself and harmonic distortion due to clipping in the vacuum tubes in the amplifier circuit. The acoustic characteristics can be captured with a black box technique called frequency response where a chirp or similar response is used to capture a snapshot of the frequency spectrum which is layered onto the unpaired guitar track being played live or recorded. This is the most common method of emulation but has limitations. Only recording a snapshot of the amplifier's sound means the dynamic harmonics caused by different levels of gain and playing styles are missed and a one dimensional linear distortion is applied to the entire signal, not capturing the actual timbre or sound of a particular guitarist.

Deep neural networks can emulate the sound of a recorded guitarist using large amounts of data and training datasets. The technique called EQ matching can take a piece of recorded guitar, then apply the neural network dataset to emulate the original sound. This approach requires expensive signal processing equipment and software, operational expertise time to train the deep neural network. The other limitation with the neural network approach is its real time ineffectiveness due to latency. Outlined in chapter 2.5.2, the 10 ms window for filling the feed forward buffer and processing before the user is affected by latency results in little to no benefits for the hobbyist or amateur guitarist. Digital quantization of analogue signals is prone to latency if sampling frequencies are not able to match the rates outlined by Nyquest theory. Formal studies of aliasing caused by neural networks and the effects on sound is lacking. (Damskägg et al. 2019) studied the effect of aliasing in a feed forward neural network prediction system. They proved that aliasing was present in the output of their system, however, was not easy to detect without sophisticated antialiasing techniques prompting more research into the effects of aliasing were required.

Current emulation techniques can be very effective however they are predominately studio based with no effective real time solutions currently available.

An observation made in this project was the testing methods for effectiveness of emulation techniques relies heavily on listening tests with real test subjects which is time consuming, and open to vast spectrums of subjectiveness. Trained ears of professional musicians differ greatly to other vocations and listeners experience a spectrum of perfect pitch leading to different interpretations (Behr et al. 2017).

CHAPTER 6 - CONCLUSIONS AND FURTHER WORK

6.1 Further research opportunities

Methods of emulating guitar tone from vacuum tube amplifiers have ranged from convolutional to recurrent structures. Researchers have attempted utilising techniques from white box to black box approaches and a combination of the two labelled grey box emulation with limited success. The architectures have been capable of real time processing and emulation, however the heavy computational cost and processing time have not been able to avoid latency issues with sampling rates higher than 44.1 kHz which is the lowest end of the spectrum regarding high quality music in recording and production applications. Low sampling rates make the analogue to digital conversion susceptible to aliasing in current emulation techniques with little to no research into the effects on the final output of the sound. This is a great opportunity for further research.

Opportunities to automate testing and error factor of emulation techniques is a great area of further study also. The vast range of subjective and critical opinion of live test subjects relying on their ears is not a thorough enough process and a more intensive method to determine error is required.

6.1.1 Psychoacoustic analysis

There is a distinct lack of non subjective evaluation techniques to compare vacuum tube amplifier outputs and the digital emulation of that output. Research into Psychoacoustic analysis can objectively compare two waveforms with a larger amount of specific sound descriptors (Düvel et al. 2020).

> Spectral Entropy – Analysis can compare the uniformity of peaks and the resulting entropy.
>
> Inharmonicity – Analysis can quantify the deviation of natural vs nonlinear harmonics between two waveforms.
>
> Roughness – Analysis determines the fluctuations of amplitudes at corresponding time or sample incidences.
>
> Loudness – Analysis can measure intensity sensations as they would be perceived by the human eardrum and how they differ between two samples.
>
> Spectral flux – This analysis will capture spectral changes over time and measure the changes or correlation in the frequency spectrum of the frame relative the following or preceding frame.
>
> Zero crossing rate – Gives information on how many times the zero threshold is crossed indicating the noisiness of a waveform compared to another. This technique is important to test the effectiveness of low pass filtering and the effects of the final output waveform.

The six sound descriptors outlined can be combined to provide a simulation of the human eardrum and how sounds are perceived before being processed by the brain. A thorough understanding of this holistic approach will allow the development of an algorithm to objectively compare two waveforms as it would be perceived by the human ear. This technique will remove the subjectivity of a listener's personal preference, bias, ideologies, experience and hearing levels providing a stronger platform for comparison and finding a balance between sampling rate and processing time (Oliveira et al. 2013).

6.2 Conclusion

The ability to sample a piece of guitar music from a recorded artist, and pair the acoustic characteristics onto an unpaired guitar signal to emulate the original tone or timbre remains an opportunity for researchers. Current techniques can emulate sound in a studio with challenges in real time applications which is where most of the opportunity lies. To achieve real time effectiveness, the effects of oversampling, aliasing and high frequency removal via filtering needs to be better understood. The limitations of the human ear is not providing enough objective data to identify where the differences in sound between the original output and emulated output lie. A more effective listening automation is required to compare different sound descriptors and provide insight on where to focus research and innovation. Effective emulation of vacuum tube amplifiers is the frontier of sound emulation.

APPENDICIES

ENG4111/4112 Research Project

Project Specification

For: Duane Griffiths

Title: Synthesis and emulation of a musician's signal chain and sound.

Major: Electrical/Electronic Engineering

Supervisors: Prof. John Leis

Enrollment: ENG4111 – EXT S1, 2023

Project Aim: This project aims to allow a musician to emulate the distinct sound of a guitarist of their choosing by sampling a piece of recorded music, extracting the digital signal processing signature of the sound, then synthesizing that signature onto the musician's own instrument.

Program: Version 1, 15th March 2023

1. Conduct initial background research on guitar effects and how they affect a clean signal from the guitar's pickups from a DSP perspective.

2. Conduct background research on how digital effect emulation software or 'plugins' are developed and applied.

3. Develop and use a signal processing algorithm in MATLAB to perform real time spectrum and wave analysis on an audio sample to identify individual guitar effects and the 'signature' of the blended effects being applied.

4. Modify the signal processing algorithm to identify, capture and store the distinct digital signature to be layered on a clean audio signal.

5. Use MATLAB to alter a clean guitar audio file with the captured signature and test for accuracy and desired sound.

6. Develop a platform to layer the signature over a live guitar/amplifier system as a digital effect.

If time and resource permit:

7. Explore and develop the implementation of the MATLAB prototype algorithm in a browser window using JavaScript.

8. Explore the computational burden of the algorithm to determine if it is suitable to use as a real time DSP application.

PROJECT PROPOSAL FORM

***1** Students who wish to undertake a project from the Faculty "Offer" of Topics, complete section A and B only.*
***2** Students who wish to undertake an "Own Project" (eg.one proposed by yourself or your employer) complete sections A and C only.*

PART A

Full Name (Please PRINT & UNDERLINE FAMILY NAME): Duane GRIFFITHS

Student Number: [redacted]

Program: (Delete as appropriate) Engineering

Proposed study mode for your project work: ONL

Major: Electrical/Electronic

PART B (FACULTY OFFER PROJECT PROPOSAL ONLY)

PROJECT PREFERENCES:

1st Preference (Project_ID & Title):
Proposed Supervisor:

2nd Preference (Project_ID & Title):
Proposed Supervisor:

3rd Preference (Project_ID & Title):
Proposed Supervisor:

For each of the above attach a one page document showing evidence of your understanding of the work you plan to do on the proposed topic.

PART C (OWN PROJECT PROPOSAL ONLY)

NOTE: refer to Sections 3.3 & 3.4 of the ENG4111/2 Project Reference Book:

Provisional Title (be brief) : Synthesis and emulation of Musician's unique signal chain and sound.

Project Origin (e.g. own idea / employer suggestion / etc.) : Own idea

Description / details – *must attach a* ***one-page*** *document containing details (title, objectives, methods, etc.) of the proposal*

Proposed Supervising Staff *: John Leis*

Upload this form to the course *StudyDesk*

(With "Own Proposal" *as the second page of this document if an "own" project)*

USQ collects personal information to assist the University in providing tertiary education and related ancillary services and to be able to contact you regarding enrolment, assessment and associated USQ services. Personal information will not be disclosed to third parties without your consent unless required by law.

ENG4111 PROJECT PROPOSAL FORM VALID AT : 27 FEBRUARY 2023 ISSUED 20/09/20

Faculty of Health, Engineering and Sciences

ENG4111 Research Project Part 1

PROJECT PROPOSAL FORM

Title: Synthesis and emulation of a musician's signal chain and sound.

Thesis: Can a musician's unique sound be synthesised and emulated by another artist?

Objectives: Musicians often use various analogue and digital effects pre and post amplification to obtain a unique sound or signature. These sounds can be recreated by tuning effects such as distortion, reverb, delay, overdrive etc. My objective is to sample a piece of recorded music, analyse the layering of effects on the clean signal and determine if that can be synthesized and used as a single digital effect to emulate that guitarist sound for a performing artist.

Methods:

- Review peer reviewed literature to determine the best method of DSP to synthesize sound.
- Research current commercial emulation/synthesisation products.
- Use digital signal processing to analyse a piece of recorded music.
- Create a digital plugin to layer the synthesised sound over a clean audio signal.
- Test the plugin over various sounds utilising human test subjects to determine accuracy of emulating the sounds.
- If time persists, develop a portable unit for live stage applications.

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LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE AND ACRONYMS

DSP – Digital Signal Processing.

DAW – Digital Audio Workspace.

DI – Direct Input, the guitar signal with no effects applied. Raw signal from the guitar.

Clean Guitar Signal – The guitar signal with no effects applied. Raw signal from the guitar.

Tone Signature – The waveform characteristics of the guitar effects without the DI.

Signal Chain – The individual preamplification components contributing to the timbre.

Plug-in / Plug-ins – A software expansion or add on. In this dissertation, plug-in will exclusively refer to a software emulation of a component of the signal chain.

Timbre – The features of sound which allow a listener to distinguish the different between two sounds of similar pitch, frequency, and loudness.

RISK ASSESSMENT

I have completed the Safetrak WHS risk Register

NUMBER	RISK DESCRIPTION	TREND	CURRENT	RESIDUAL
2484	Duane Griffiths Research project		Very Low	Very Low

DOCUMENTS REFERENCED

RISK OWNER	RISK IDENTIFIED ON	LAST REVIEWED ON	NEXT SCHEDULED REVIEW
Duane Griffiths	22/05/2023	27/05/2023	27/05/2024

RISK FACTOR(S)	EXISTING CONTROL(S)	PROPOSED CONTROL(S)	OWNER	DUE DATE
I have numerous electrical/electronic devices and appliances at my study desk.	**Control:** All the equipment and leads/plugs are in a safe working condition. Very low risk of injury.	**No Control:**		
I will be sitting for extended periods of time	**Control:** I have a very comfortable ergonomic chair. My workspace is clutter free and well ventilated with ample access to sunlight.	**No Control:**		
Risk of Malware/Spyware and other computer viruses during download and use of software packages required for the research project.	**Control:** I chose Engineering Control to represent the installation and use of Antivirus software such as Trend Micro.	**No Control:**		
Loss of work due to computer malfunction or malicious activity by third parties ie. Hacking.	**Control:** I have my work backed up to an external hard drive as well as a third party cloud storage server.	**No Control:**		