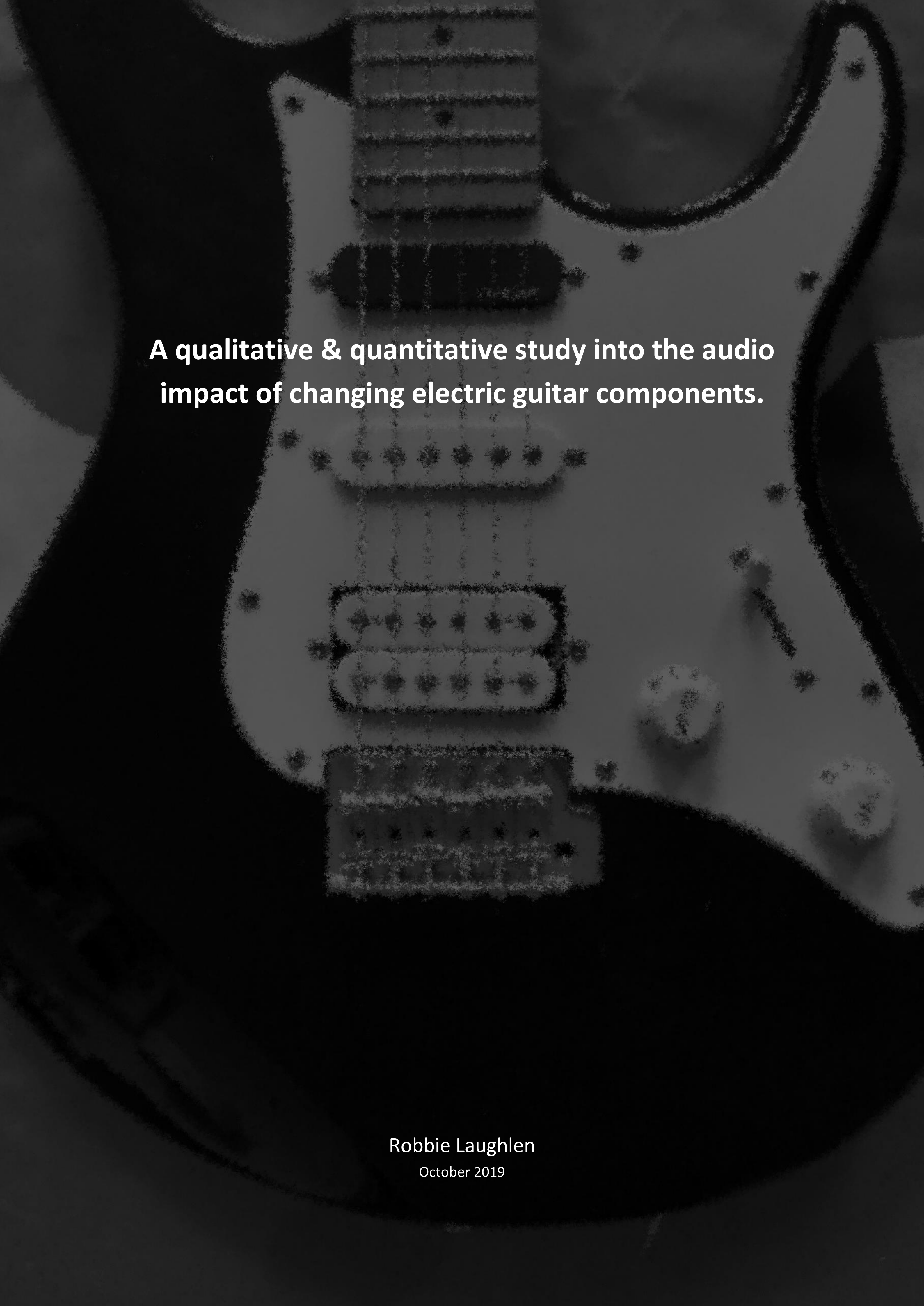

A qualitative & quantitative study into the audio impact of changing electric guitar components.

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Abstract

A study of the electric guitar, the components within the guitar, and the effect these components have on the sound produced.

Sound quality can be measured both qualitatively and quantitatively, however, the majority of guitar components are measured qualitatively to appeal to the guitarist community. The aim for the paper is to highlight the quantitative data produced when changing electric guitar components. Using the data, spectra are then produced using both audio and visual editing tools.

The spectra are the primary source of quantitative comparison which can then be used to draw conclusions. The conclusions point to the fact that a component change does affect the guitar as an increase in harmonics and sound consistency can be seen. This leads to the conclusion that the guitar audio output is affected positively both qualitatively and quantitively.

Contents

Introduction

Summary of project

This project is an observation of the changes to sound produced on an electric guitar as selected components are changed. Both quantitative and qualitative measures are observed.
I analysed multiple different guitar components by recording sound samples directly from the guitar to my PC via an analogue to digital converter.

The quantitative data used comes from the capture and analysis of sound samples, while the qualitative observations reflect whether the sound is more pleasing to the ear (*naturally highly subjective*). Scientific analysis is primarily accomplished using a method known as Fast Fourier Transforms (FFT). (3Blue1Brown, 2018) Output from the FFT tools was then fed through visualisation tools for comparison purposes.

Why this topic?

I chose this particular topic because it is at the crossroads of two of my personal interests, physics and guitars. The guitar has been a passion of mine since I was 9, particularly electric guitar in recent years. Physics has always interested me and this interest has grown stronger as I've learnt more.

There is always talk between guitarists about how some pickups are better than others; how spending £80 on vintage capacitors can be justified as they 'improve the sound of the guitar.' etc. I was convinced that this preconceived notion of 'better sound' was primarily mental and that it might be proved or disproved using analysis.
Conversely, I know that people have different preferences when it comes to sound, and that could be contributing to the praise. (For example, punk players may want a more dirty/scratchy tone, leading to them disliking clearer, 'higher quality' pickups.)
The effort and research put into this paper will also help me in improving my own guitar skills/knowledge.
The science behind frequency and harmonics is essential in many aspects of physics from a humble string to proving relativity from the ringing of a new-born black hole.

Methodology

How an electric guitar works

In simple terms, an electric guitar works by picking up the vibrations of the metal strings. This is done using magnets in the pickups (highlighted in green) to partially magnetise a section of the string. The pickups are coils that transform these vibrations into electricity through induced current. This electricity flows through the electronic components within it and is then output through a lead and into an amplifier, producing sound.

Figure 1 - Guitar Basics

Initially I chose to change 3 components; pickups, capacitors & strings. I believed that these components would produce the biggest change in sound. These products are most commonly advertised as making the biggest positive difference in sound and are therefore the natural ones to test.
However, after some analysis I found that there was something called a 'No Load Tone Potentiometer[1].' In simple terms this means that the capacitor (which alters tone by changing the relative amount of higher frequencies) can be temporarily removed from the output circuit, effectively rendering the capacitor useless. I opted to use this approach as it would mean that higher frequencies were not cut off thus providing a more accurate view of what the other components were capable of producing. The measurements would be more direct and "pure" also. After some thought I decided to remove the analysis of the capacitors from the experiment. (But I was hopeful that it would be part of a future experiment).

On an electric guitar there are usually a minimum of 2 knobs as shown here:
As you can see in ***Error! Reference source not found.***, I have highlighted 4 crucial parts of the guitar on the body of the guitar.
The tone knob *(highlighted in red circle)*, via the potentiometer it turns, dictates whether the capacitor soldered to the tone pot will be used. A potentiometer is a resistor which can be varied. They are usually either

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[1] A Potentiometer is just a resistor which can be adjusted.

250kΩ[2] (kilo Ohm) or 500kΩ. In this instance it is 250kΩ. When the knob is at 10 (fully clockwise) the resistance of the potentiometer is at its maximum. The high resistance limits current flow and thus fewer high frequencies are lost resulting in more “highs” (retaining higher frequencies in the audio output). When the tone knob is at 0 (fully anticlockwise) the resistance is at 0Ω and the capacitor is being used to its fullest; earthing the higher frequencies so the sound is more mellow due to the “loss” if those high frequencies. Changing the value of the capacitor itself primarily determines at what frequency the signals begin to be cut off.

The volume knob (orange circle) controls another potentiometer. The volume pot in a guitar is wired so that it controls the overall output signal by varying its resistance.
The pickups are highlighted in green. The top one looks different from the rest as it is a different brand of pickup.

There are 2 main types of pickups, humbucker and single-coil. In this experiment I am focusing on single coil pickups, however both work in a similar manner. A pickup is a receiver of the magnetic flux that is being emanated from the guitar string. There is a strong permanent magnet in the pickup, which creates a magnetic field in the portion of the string over the pickup. This is because the string itself is made of ferrous material. When the string is plucked the field is disrupted and magnetic flux passes through the pickup generating an electrical signal directly proportional to the vibration of the string.

As you can see in Figure 2, there are 6 magnet pole pieces at the top of the pickup (one for each string), with a coil of wire wrapped around the centre. Overall, the motion of the strings is transformed into energy, which is then passed along a circuit within the guitar until it leaves the guitar and is passed to an amplifier to be converted into sound waves.

Figure 2 - Single Pickup

The pickup switch, highlighted in the blue, selects which pickup is in use. This switch in particular is a 5-way switch; meaning it has 5 different options in terms of pickup usage. You’ll notice there are only 3 pickups (Single at the neck, single middle and then a Humbucker at the bridge position). This is because 2 of the positions utilise 2 of the pickups simultaneously as the mix of two creates its own unique sound (the science of which is interesting and important from an audio output perspective but beyond the scope of this paper). Since I had a ‘no load tone pot’, that meant that the modified guitar could output an unaltered sound compared to having a default tone pot that is marginally affected by the capacitor. This meant that for all my experiments it would be optimal to use this pot.

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[2] Ohm’s is the universal scientific symbol for resistance.

Acquiring Components

Initially I planned to purchase the various components I needed. While this was certainly viable, it wasn't cost efficient, especially for a student. As an alternative I decided to contact various guitar component companies to see if they might support my research by helping with some loaned or donated parts.

Communicating with companies

The two main components I decided to focus on were the strings and the pickups.

For the strings I had decided to purchase strings similar to the control strings on my guitar *(D'addario EXL125 XL strings 9-46.)* These are D'addario's standard strings that I regularly use. The 9-46 represents the gauge of the strings. I also wanted strings that were similar but of higher quality, so I decided to contact D'addario customer service directly.
I explained my situation to D'addario and they kindly sent me some D'addario NYXL 10-46 strings. The NYXLs have received great reviews, including receiving praise for both tone and build quality. (Tonereport.com, 2014)

I read several articles to find the best pickup companies. (FloSon, 2014) After sending multiple companies emails explaining my situation I got a reply from one company; EMG. They were kind enough to answer my emails and went above and beyond to support me. EMG were happy to answer any questions I had that were related to guitar technology. Furthermore they sent 3 pickups all the way from California. (one passive pickup and 2 active pickups).
In this paper I am focusing on passive pickups however I will discuss active pickups in a more limited manner.

I purchased the Bourns No Load 250K Pot which completed the list of components I needed to put inside my guitar.

There was one additional key piece of technology that was necessary for me to analyse the sound the guitar produced; an audio interface.
I purchased a Behringer U-PHORIA UMC202HD 24 Bit/192 kHz USB Audio Interface. The audio interface was necessary, as it meant that I could directly connect my guitar to the computer for recording.

The sample rate is the number of samples of a sound that are taken per second to represent the event digitally. The UMC202HD can record 192,000 24-bit samples per second.
Theoretically, the more samples taken per second, the more accurate the digital representation of the sound will be. (What is sample rate? - Definition from WhatIs.com, 2019)
24-bit represents bit depth. Bit depth is the number of bits of information in each sample (Wikipedia Contributors, 2019). Together these two figures define the amount of data collected and thus the resolution or fidelity of the recording.

According to the Nyquist Sampling[3] theorem the sampling frequency to exactly reproduce the original waveform should be double the original frequency of the signal (Micropyramid, 2011). Fundamental guitar frequencies usually range from 80Hz to 1200Hz with harmonics being higher. In my analysis the maximum frequency my guitar could reach was approximately 8kHz, meaning that realistically 16kHz sampling was the maximum needed. However, I opted to use 44.1kHz as this is a common sampling frequency that was originally

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[3] Nyquist Sampling: The Nyquist Theorem states that in order to adequately reproduce a signal it should be periodically sampled at a rate that is 2X the highest frequency you wish to record. (Berkeley.edu, 2019)

used in CD’s as it effectively covers the entire spectrum audible to human ears. Doing so would mean I would likely capture any harmonics produced by any string within the human audible range.

Changing Components

Before I could change any components within the guitar, I had to remove the strings that were directly over the scratchplate[4] which covers the electronics. Normally people remove strings by cutting them and disposing of them, however to make the experiment a fair test it was necessary to reuse strings throughout the experiment. This meant that I had to manually remove the strings.

Figure 3 - string removal

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[4] The scratchplate is a plastic covering common on the bodies of many guitars. It holds the electronics of the guitar within the instrument.

Removing the scratchplate (White layer in Figure 4) was done using a Phillips screwdriver.

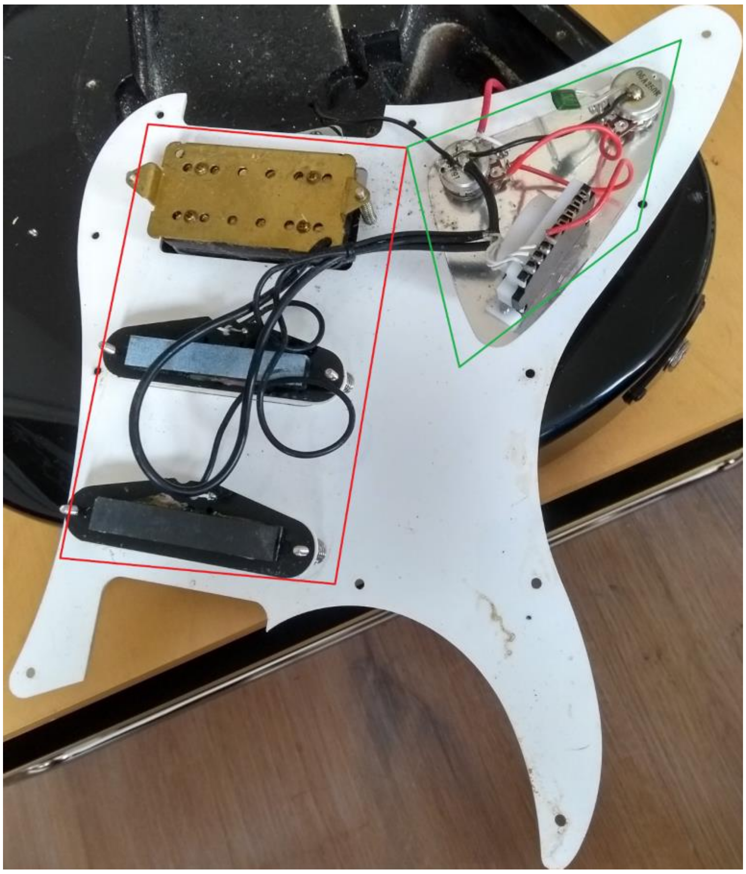

Figure 4 - Electronics

You can see in Figure 4 what it looks like underneath the scratchplate. Very simple wiring that has hardly changed since the 1940s!

Beneath the scratchplate I have highlighted 2 areas. The red area shows the pickups, while the green area shows the tone & volume potentiometers. As well as this, there is wiring that is connecting each pickup to the pickup switch, and then outputting that into the tone and volume pots.

Tone Potentiometer

The no load tone pot meant that when the guitar samples were recorded the sound would be unaltered by capacitance in the system. This made the tone pot crucial for the experiment. This change was probably the most important as it was required for every sample taken.

To remove the old tone pot and replace it with the no load one, the original component had to be desoldered and dismounted the new tone pot was them simply installed as a direct replacement. With the original wires in the same place.

The object in Figure 5 is the new tone pot. Most potentiometers look like this. The knob in the centre is used to vary the resistance, while the text at the top indicates the maximum resistance of the potentiometer.

Figure 5 -No Load Potentiometer

To check that both potentiometers were working correctly, I used a multimeter[5] to measure their resistance. In Figure 6 the old tone pot is being shown when it is at the positions 1 (Minimum) & 10 (Maximum).

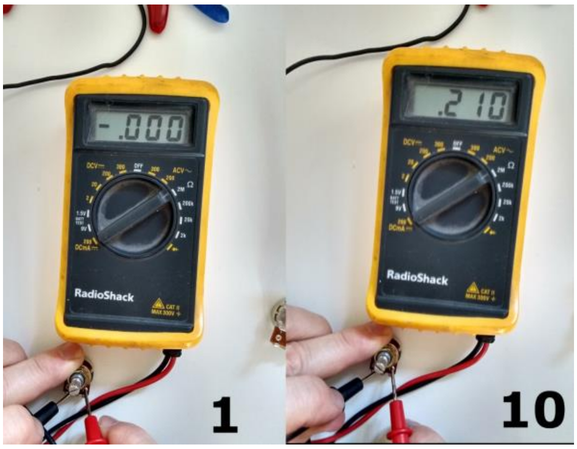

Figure 6 - Measuring old pot resistance

The maximum resistance for this tone pot is 210kΩ, not perfect but fairly close to the factory mark of 250kΩ.

However, if we compare this to the no load tone pot, there are some interesting results.

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[5] A multimeter, also known as a volt-ohm meter, is a handheld tester used to measure electrical voltage, current (amperage), resistance, and other values. [(Rodriguez, 2012)](#)

In Figure 7 the resistance for the no load tone pot is 253kΩ when at 9.9. This is important because 9.9 is technically the maximum for the no load tone pot. When the pot is at 10 the circuit us effectively opened which results in an infinite resistance.
From this we can conclude that the no load tone pot is closer to factory standard considering it is almost exactly 250kΩ at maximum.

Figure 7 - new pot resistance

Neck Pickup

I wanted to measure the difference between my default pickup and a new higher quality one. This meant that only one pickup was necessary to analyse the quality difference. The original pickup I had was a passive pickup, while of the 3 pickups that were sent by EMG only one was passive.
I decided to use the EMG passive pickup in my main experiment, as an active pickup has many different variables which could affect the sound produced.

The pickup was the most difficult component to change.
Unfortunately, EMG use a solderless connector to connect pickups (easier in most situations especially when all the other components are EMG.) This solderless method would mean that I would have to replace the potentiometers, which would compromise the control recordings.
Highlighted in red in Figure 8 is a connector which contains all the wires from the pickup. This connector was removed to show the wires underneath, shown in Figure 9.
The 2 wires poking out in Figure 9 each have an important purpose. The green & silver is the earth wire that earths the circuit (connects to volume pot), while the red wire connects to the pickup switch and carries the audio signal.
I wanted to retain the connectors that were on the end of the green & red wires (grey in Figure 9), so the soldering was an excellent alternative. I then wrapped both wires in electrical tape to insulate. You can see the 'finished product' in Figure 10

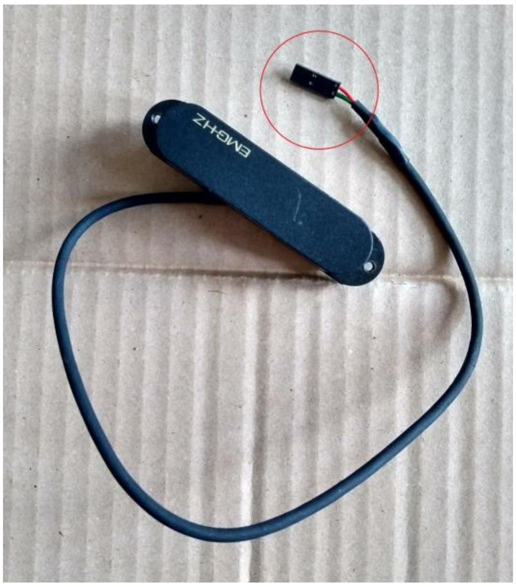

Figure 8

Figure 9

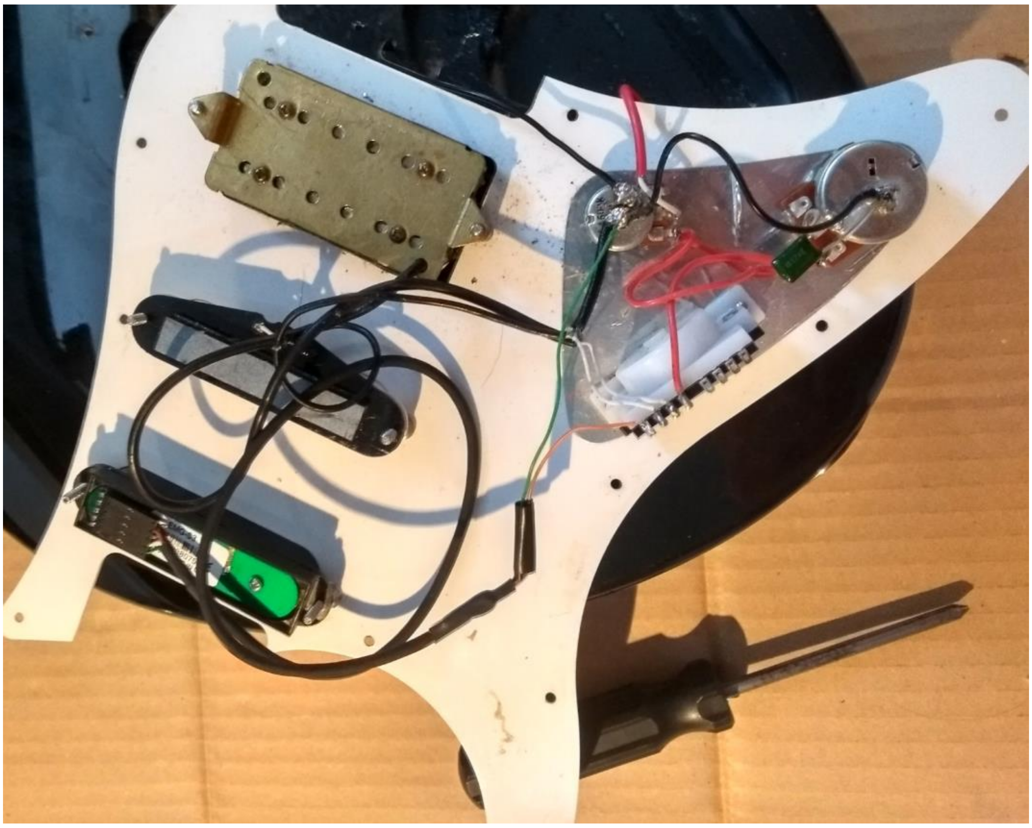

Figure 10 - Completed Wiring

Strings

In Figure 1 there are six strings with a range of thicknesses. The thinnest string is known as the high E string. This order continues in the descending note order EBGDAE. You can also get guitars with more than 6 strings and in alternative tunings, but they are not relevant to this paper.

The strings were the easiest component to change, as it is common for guitar players to change strings regularly. It’s important to note that this component change was done last as I didn’t want to negatively impact the performance of the strings by taking them off & on repeatedly.

The control strings and the new NYXL strings had the gauges of 9 & 10 respectively. There are 3 common string gauges: 9, 10 & 11. This measure is the diameter. The high E string are measured in 1/1000th of an inch. Thus, the high E string in the control group was 0.009 inches thick while the NYXL high E was 0.010 inches thick. While this sounds like a miniscule number, it can drastically affect how playing the guitar feels. To add to this, string gauge can affect tone. This needs to be considered when analysing the results, as a difference in sound could be caused by two factors rather than one.

Issues from Changing Components

Although changing the components went relatively smoothly, there were some issues that should be considered to keep the test fair. The primary issue was the quality of the soldering. Since it was something I had never done before you could argue that the soldering was not up to factory standard, meaning the sound quality may have inadvertently been altered due to poor solder joints.

There is some evidence to support this, as when the new EMG pickup was finally put in and was tested, I noticed that the overall volume from the EMG pickup was significantly less than the control pickup. However, it is more likely that this is just the design of the pickup as there is some evidence online of EMG pickups having lower output, and the soldering was fine.

Measuring the Change

Recording Results

The process for recording results was difficult & monotonous, but it provided a great insight into scientific technique, which can be less than glamorous.
I used an audio recording and analysis program called Audacity (Audacityteam.org, 2019) to record the sound files.

Before recording, it was important that the guitar was tuned as accurately as possible. This was important as an out of tune string vibrates at a slightly different frequencies compared to an in tune one, affecting the comparison. The program used to tune the guitar was ModTuner. Figure 11 is a photo of me during the tuning process.

Figure 11 - Tuning

I used a guitar lead plugged into the audio interface to get a clean recording, rather than using a microphone that could be affected by background noise. It is important to note the settings I used on my audio interface also.

Figure 12 - Computer Interface

My guitar was plugged into input 1, meaning only the nearest gain knob and settings above it need to be considered. All settings remained fixed during the entirety of the recording process and for all samples. The line-instrument[6] button was pressed in, meaning it was using the instrument input. This instrument input is necessary to get the impedance correct.

All volume knobs and tone knobs had to be static during the experiment, unless a tone/volume knob was being compared at different values. To make this easy to control I had both tone & volume at the maximum.

Visualisation & Comparison Tools

Audacity provides a spectrum analysis using Fast Fourier Transforms for any sound file opened by the program. To ensure the sound quality was as clear and unaltered as possible, I used an uncompressed lossless file type. The file type used was a .wav 24-bit signed PCM (Pulse Control Modulation).
WAV files are uncompressed, meaning the audio is not reduced in quality to lower file size. Lossless means that no compression is used and all the original data is retained.
The difference between a 16-bit audio file and a 24-bit audio file is essentially the number of ‘slices’ of audio we take at any given moment. This is represented well in Figure 13. (Tested, 2016)

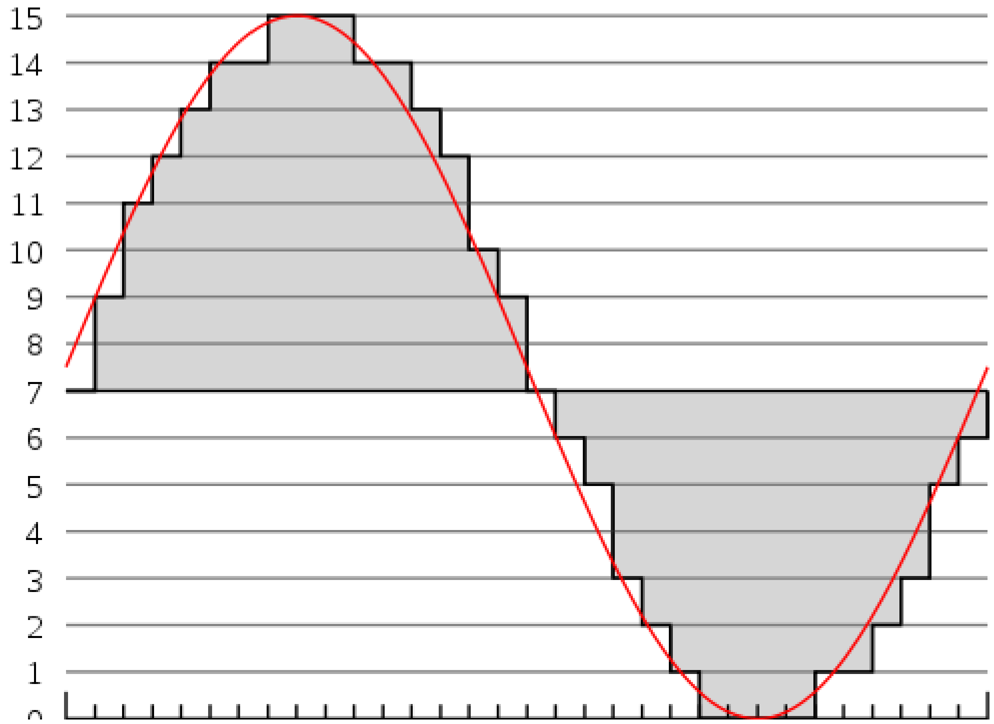

Figure 13 - waveform quantisation

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[6] A line input is designed to accept a "hi power" signal from a piece of powered equipment, CD player, synth, etc. Anything that has its own power source and provides an "amplified" signal (at line level) as compared to a microphone output.

An instrument input is designed for passive guitar pickups and other similar transducers that produce voltage levels of the same order as line level, but at very low power. (Cakewalk.com, 2019)

A 16-bit audio sample breaks the signal into 2^{16} possible measurements at a given time, while a 24-bit audio file is much more detailed and can capture 2^{24} different levels of measurement. (65,536 & 16,777,216 samples respectively making 24 bit sampling 256 times more "accurate").

The spectrum ended up being particularly useful as it meant that every sound file used could be compared using the same program and with a consistent axis.

Using the visualisations from Audacity I was able to take the average spectrum provided from 3 recordings of the string. This meant that I could compare abnormalities as well as see trends. To combine these spectrums, I used a photo editing tool known as GIMP (GIMP - GNU Image Manipulation Program, 2019)
I then worked my way up to larger visualisations using a multitude of strings, while some of these weren't what I was looking for, they still provided an insight into the way waves produced by a guitar string work and how they relate to each other.
For some of the less important results I am only comparing the high E string for the sake of simplicity. I have taken 3 recordings of every string for every component, but the time taken to make a comparison of every result would be very large with diminishing returns.

I also used a program called Sonic Visualiser to get some animated analysis. (Sonicvisualiser.org, 2019) Unfortunately this cannot be easily represented in a paper, but I will share links to the videos stored online as well as static images.

Results

Visual Presentation of Results

Static Analysis (Photos)

High E String (In Depth)

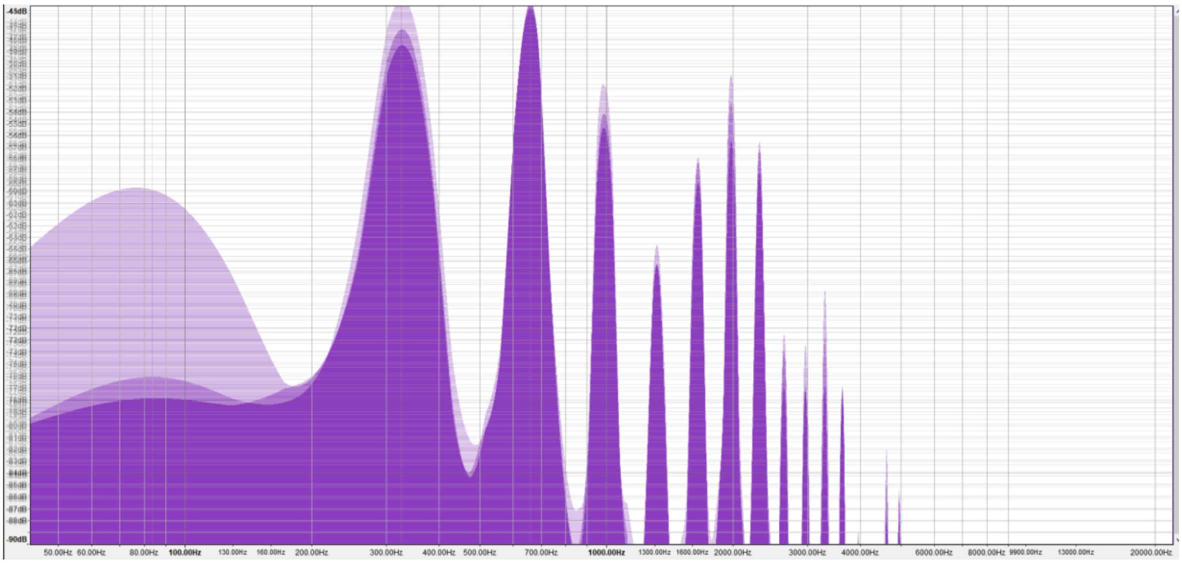

Figure 14 - High E FFT samples

Figure 14 shows the average spectrum plotted from 3 samples of the high E string. This was taken when all the components on the guitar were the factory parts, meaning it is the control. I will be using a table of note frequencies to help with my analysis (Seventhstring.com, 2019).

The first noticeable piece of information that jumps at us is that transparent lump in the lower frequencies (0-160Hz). This is interesting as the transparency means that it was not consistent throughout the tests. I consider this an anomaly. My current explanation for this is that there was human error when plucking the string, leading to there being some percussion from the string. String percussion can occur when the string hits the neck of the guitar after it has been played. This leads to a spike in noise and occasionally a buzzing sound being produced. This could have caused the rather low frequencies commonly seen in lower notes.

The initial peak is ~330Hz. Using the note frequencies table we can easily see that this is an E4. This makes perfect sense as the high E string is meant to be an E4 when properly tuned. The peak after E4 is actually more prominent. I find this interesting because the frequency at this second peak is around 660Hz. The frequency of an E5 is 659.3Hz so this is clearly the first harmonic of the root note; i.e. double the frequency. From this we can deduce that after playing the E4 (High E), the most prominent tone is an octave[7] higher. To explain this phenomenon, harmonics & the fundamental frequency must first be explained.

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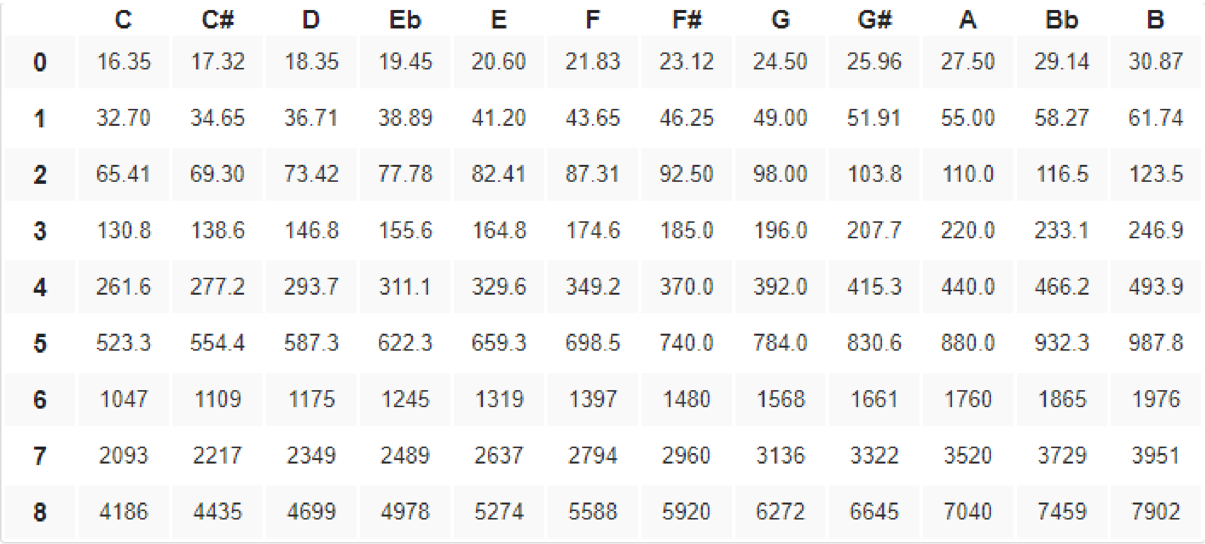
[7] In music, an octave is the interval between one musical pitch and another with double its frequency. (Wikipedia Contributors, 2019)

In this table B5 is in fact higher than E5, but this still doesn't explain why an E string being plucked is playing a B. This is due to the harmonics of the fundamental frequency (In this case 329.6 Hz) resonating when playing the E4. All the harmonics produced have frequencies that are multiples of the fundamental frequency (f_1). When a wave is created (e.g. Plucking a guitar string} many different frequencies naturally occur on the same string. These are whole number multiples of the fundamental frequency. These shorter wavelength waves are called harmonics .

The next peak seems to be at the 1000Hz mark. 1000Hz is nowhere near an E6, meaning this peak must be a harmonic that is not the same as the root note. The nearest frequency to 1000Hz in the repository is 987.8Hz. This note is a B5. This is three times the fundamental frequency so it too is a harmonic (f_3).

In music, the first and lowest note (the C0) is 16.35Hz. From there you build up your range of notes, as can be seen on the frequency table below.

Table 1 - note to frequency conversion



	C	C#	D	Eb	E	F	F#	G	G#	A	Bb	B
0	16.35	17.32	18.35	19.45	20.60	21.83	23.12	24.50	25.96	27.50	29.14	30.87
1	32.70	34.65	36.71	38.89	41.20	43.65	46.25	49.00	51.91	55.00	58.27	61.74
2	65.41	69.30	73.42	77.78	82.41	87.31	92.50	98.00	103.8	110.0	116.5	123.5
3	130.8	138.6	146.8	155.6	164.8	174.6	185.0	196.0	207.7	220.0	233.1	246.9
4	261.6	277.2	293.7	311.1	329.6	349.2	370.0	392.0	415.3	440.0	466.2	493.9
5	523.3	554.4	587.3	622.3	659.3	698.5	740.0	784.0	830.6	880.0	932.3	987.8
6	1047	1109	1175	1245	1319	1397	1480	1568	1661	1760	1865	1976
7	2093	2217	2349	2489	2637	2794	2960	3136	3322	3520	3729	3951
8	4186	4435	4699	4978	5274	5588	5920	6272	6645	7040	7459	7902

Full string set comparison

The image shown in Figure 15 is a plot of the FFT for all strings. This comparison isn't very useful in this form, as it's rather difficult to glean any data from the graph but is instructive nevertheless.

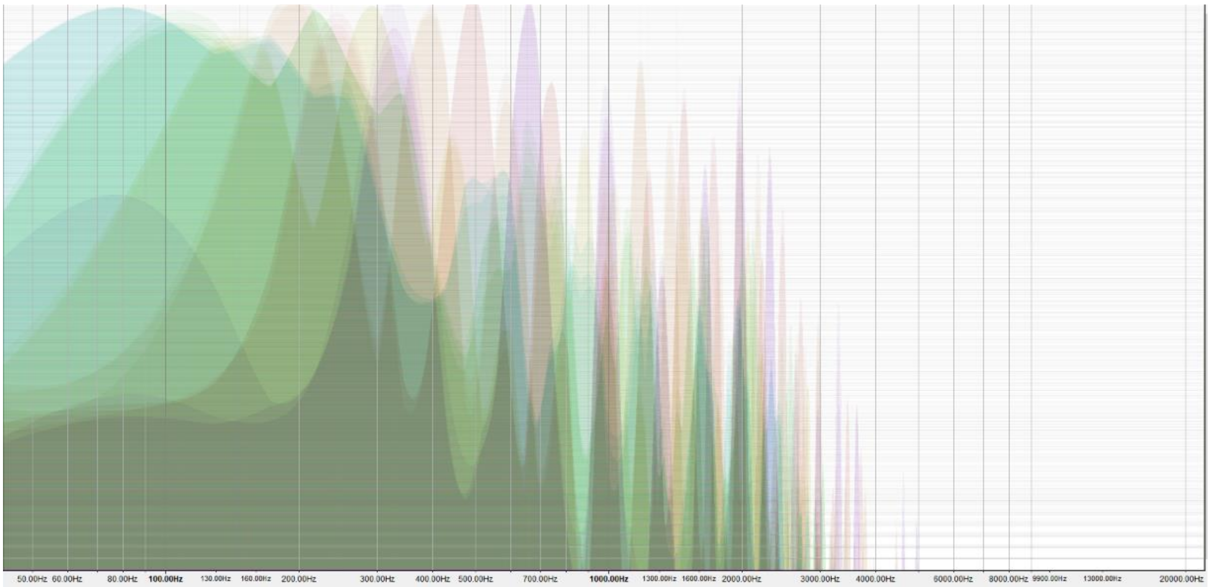


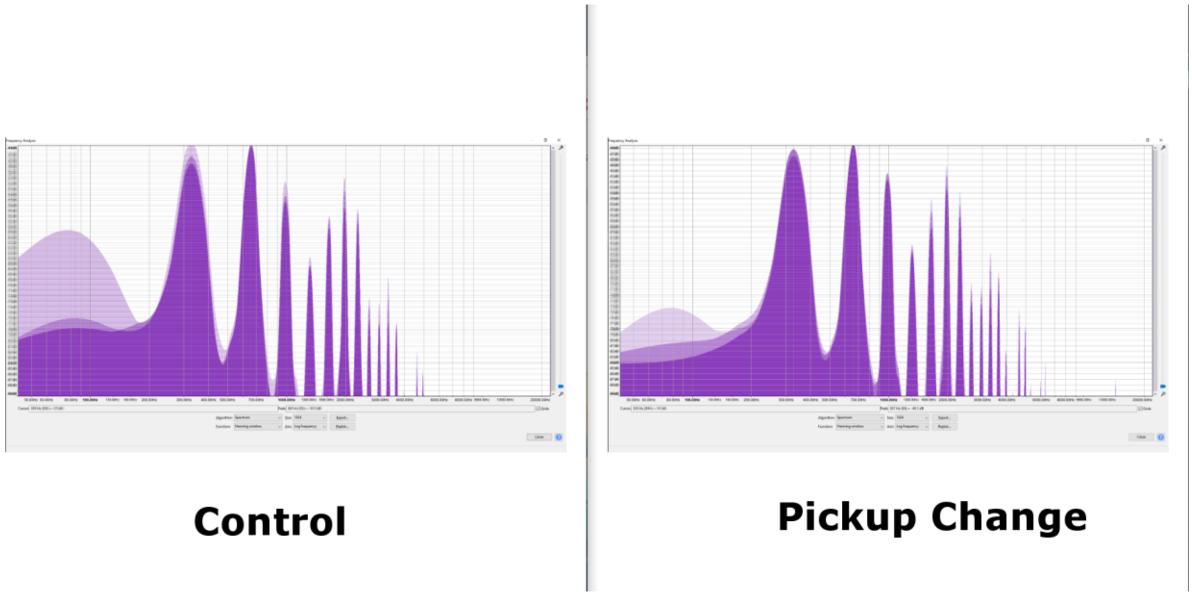
Figure 15 - All Strings FFT

The lower strings are producing lower frequencies when played, meaning there is an even spread that can be seen on the frequency domain.

In the lower frequencies the peaks are far wider, this is due to the x-axis being logarithmic.

The main observation from the full string set comparison is perhaps evident in the dark forest green. These are the main consistent frequencies. Some of these are simply overlaps from peaks and can be ignored. However, in the sub-200Hz zone, many strings share the same low frequencies. Currently I am attributing this to low percussive frequencies, but there is also the possibility that the energy of the E string being played vibrated other strings at their fundamental frequencies. There may also be other explanations related to noise in the recording etc. This helps to show that analysis of electric guitars or indeed any stringed instrument is not simple as the vibrations of the strings and the even the instrument itself are all interconnected.

Pickup Change


Control

Pickup Change

Figure 16 - Control vs New Pickup

Qualitatively, the pickups didn’t seem make a huge amount of difference, except perhaps for one key thing. The EMG pickups were noticeably quieter. This will not be seen in the spectrum analysis, as the audio has been normalized, making the recordings a similar decibel level.

There is far more information when looking at the quantitative side of things.
The switch from the control pickup (stock Yamaha) to the EMG pickup produced many interesting changes. Some of this may be hard to discern from Figure 16 in printed form, as I was able to zoom in on the spectra using Audacity.
The most obvious initial change is the lack of the large bump in the sub-200 Hz frequency range. I believe there are 2 possibilities for this occurrence. The likelihood is that the large lump was caused by an accidental percussive noise to me picking the strings. The 2 possibilities are that there was just less human error, and I created less of a percussive noise when recording with the EMG pickups. The other possibility is more interesting. It may be that the ‘higher quality’ EMG pickups are better at filtering out the more intrusive noises that most guitarists do not seek. This difference between the pickups could be used as evidence to support the idea that more ‘higher quality’ pickups do make a difference.

Visually, the spectra look very similar. The main differences between the control pickup and the EMG pickup occur at the higher frequencies. Between the 3-4 kHz range the control pickups have a far lower output sound. The notes F#7, G#7 & A#7 are ~13 dB higher when using the EMG pickup.
Furthermore, the EMG pickup has a higher frequency response. Its highest frequency was a G8 at ~6270 Hz. In comparison, the highest peak from the control pickup was ~1300 Hz less at 4942 Hz. This is strong evidence to support the fact that the EMG pickups do make a difference. However, there is always the possibility that these higher frequency peaks are anomalies. There is some evidence to support this, as the EMG pickup also has a single peak at 14279 Hz. This peak is completely alone and doesn’t occur regularly in the recordings, meaning it is likely an anomaly. It is also outside the normal range of an electric guitar and would likely be filtered out by the tone capacitor on most guitars without the no load tone pot.

Overall, the main evidence to support the EMG pickups being better is the fact that they have a higher frequency response, as well as the possibility that they filter out the lower more disruptive frequencies. This evidence is also countered by the possibility of anomalies occurring, or not wiring the pickup correctly.

String Change

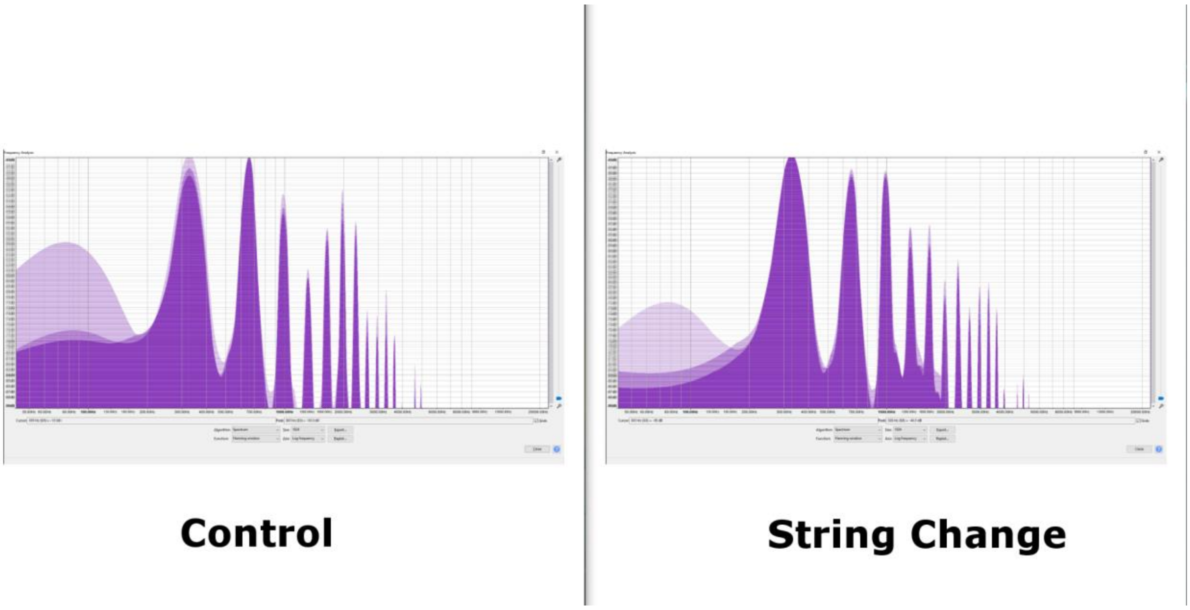


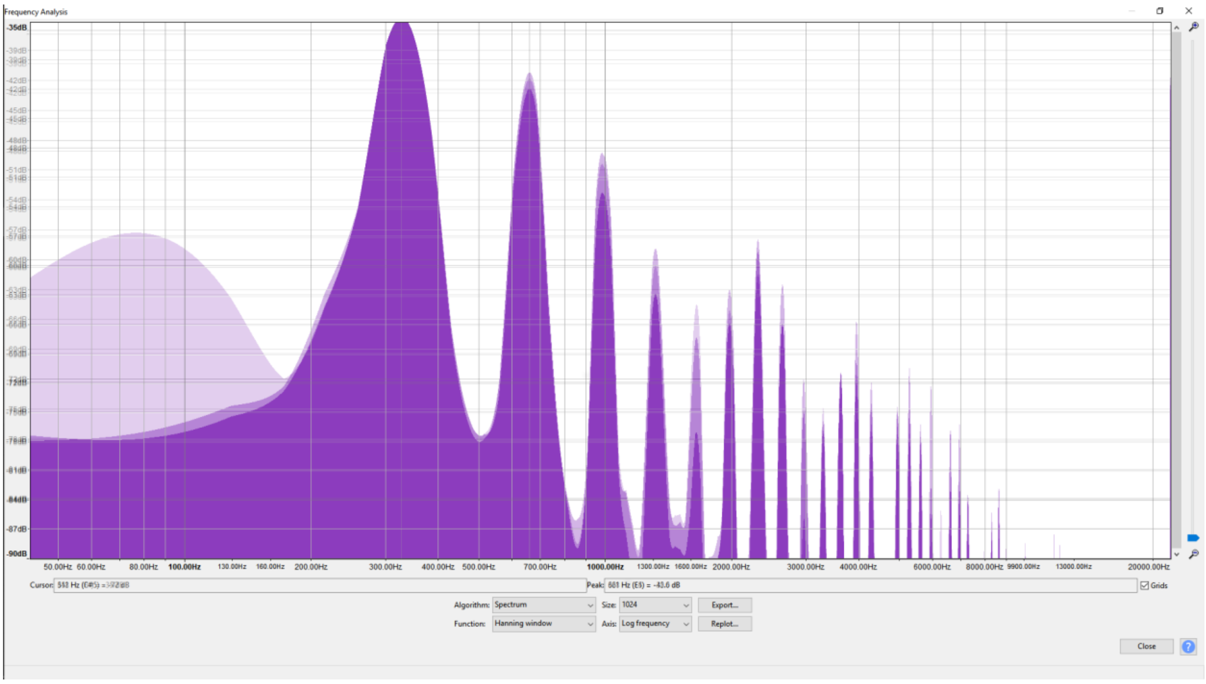
Figure 17 - Control vs New Strings

Aurally, the change of strings didn’t seem to make much difference despite the substantial marketing hype.
There was a large impact on the ‘feel’ of the strings though, at least for the author.
It is important to consider that this physical change could be caused by the change of string gauge.
Visually, the strings made a large impact on the spectrum, specifically in the higher frequencies (>2000 Hz).
The higher frequencies were less prominent using the new strings. (Difference of ~10 dB)
Another difference was the substantial decrease in output (measured in decibels) in the sub-200 Hz region.
This difference could be a major supporter of the fact that ‘higher quality’ strings are substantial improvements. Compared to the control strings, the new D’addario strings seem more consistent, and this is supported by the lack of lower frequencies.

The new strings also seem to have a more consistent gradient downwards compared to the control. The initial E4 (328 Hz) peak on the string change spectra is at -44.6 dB, while the E4 (327 Hz) peak on the control spectra is at a lower -46.9 dB. What makes this even more interesting is the fact that the second harmonic peak (E5 660 Hz) is ~2 dB higher compared to the original note on the control spectra. This isn’t the only occurrence where there are unexpected peaks. Further along the control spectra, there is a quick rise from the 1.5-2.5 kHz range. There are further anomalies such as odd spikes & drops in the control spectra, particularly occurring at the B5 & E6 notes (989 Hz and 1315 Hz respectively). From the data gathered, it seems that the older control strings are not as consistent in terms of harmonics compared to the more expensive D’addario strings. There is the possibility that the slightly older control strings had variations in harmonics due to the build-up of skin, dust & grease on the strings. This build up can cause a decrease in vibration energy from that string, as the extra build up absorbs some of it. There are other factors that can contribute to the decrease in string quality. For example, a less consistent string diameter or corrosion of the string. (Zollner, 2018)

Overall, we have 2 possiblities. Either the control strings were affected by corrosion, diameter or build-up affecting the comparison & consistency of harmonics (The likelihood of the string being affected by corrosion or build-up is low. This is due to the strings being fairly new when tested). If this is not the case, then we have evidence in favour of more expensive, higher quality, components.

Acoustic Guitar as Comparison



Peak: 661 Hz (E5) = -43.0 dB

☑ Grids

Algorithm: Spectrum

Size: 1024

Function: Hanning window

Axis: Log frequency

Figure 18 - Acoustic Comparison

I also recorded some samples from an electro-acoustic guitar. This is a traditional acoustic guitar with an integrated piezo-electric pickup (microphone) connected directly to an output jack. This allows me to connect it to the same input/recording hardware using the same cables etc.

There was a very significant difference between the control electric guitar & the electro-acoustic. Immediately there are some clear differences between the control and the acoustic. (Note: I am only comparing the high E4 string here). Firstly, the initial peak on the acoustic spectrum is clearly the highest compared to the harmonics.

Additionally, the acoustic had a frequency response far higher than any other component change. This is likely due to the piezo pickup, as a wider range of audio signals would be converted into electric signals. The highest clear peak is at 8610 Hz, but the spectrum reaches into the 20 kHz range.

Another interesting detail is the steady decrease of dB as the frequency increases. Compared to the control samples of the electric guitar, the acoustic guitar seems to give off a more 'consistent' sound in terms of harmonics. This is possibly due to the piezo pickup within the acoustic guitar or it could be because the guitar is an open body instrument with a resonant chamber.

Observations from Results

Predictions & expectations

A few predictions were made regarding some of the changes seen when changing components or when playing a different string.

One of the more obvious predictions was that bass notes (E.g. Low E compared to high E) would have a higher dB level in the lower frequencies compared to the higher frequencies.
Another prediction made was that the acoustic guitar would reach higher frequencies, as it wasn't constrained by the magnets of the pickup or the electric guitar electronics. These were both confirmed in the results.

I expected the change of guitar (Electric to acoustic) to produce a large change, as it is a completely different instrument. This prediction was opposed by the fact that the acoustic guitar had its own built-in electronics, which meant frequencies could still be cut off. I failed to take this fact into account during my predictions, meaning the spectrum did not differ as drastically as I expected. However, the maximum frequency observed from the high E recording on the acoustic instrument was at 8610 Hz, well above the maximum on the electric guitar for the same string. (4942 Hz).

I believed that the pickup change would make a bigger impact on the spectrum compared to the string change. However, at first glance the change was not as large as I expected, both strings and pickups made a relatively small change, especially in the lower frequencies. A more in depth look at the spectra in the higher frequencies was needed to observe changes.

For the strings specifically, I expected the spectrum to change drastically. This was due to the strings being a higher gauge and higher tension. Furthermore, the strings used different materials. This presumption was incorrect, as the strings didn't make as large as change as I expected.

Outliers/Abnormalities

Inevitably, some abnormalities occurred in the results & throughout the test.
It seemed like there were some harmonics missing which should have been there (Figure 16 and Figure 17). When looking at the pickup spectra, the 13th harmonic (f_{13}) of the E4 is not present for both the control pickup and the EMG pickup. This could be due to the electronics of the pickup, or something in the guitar dampening the frequency. (13th harmonic is 4286 Hz).

Other than missing harmonics, 2 key issues were the loud bursts of low frequency noise on the spectrum, and the fundamental frequency being quieter than its harmonics. There is the possibility that this is not an outlier, but there is evidence to support it being so. The evidence is covered in the cable capacitance section of the paper. Essentially, the abnormalities only occurred when using a longer cable, meaning the results may have been affected by cable capacitance.

Further Research

There are a few areas that I couldn't look into in this paper but would like to investigate in the future. The main reason these topics were not covered was either due to time constraints or deviation from the main question of the project.

Active Pickups

There are a few key differences between passive and active pickups. Firstly, active pickups incorporate an active preamp which boosts the signal level. This means they require battery power, so they are a completely closed circuit. (Dawsons Music, 2019)
This means that they are not affected by a number of factors that commonly affect passive pickups. Two important factors are cable capacitance[8] & bridge grounding[9].
The closed circuit is the cause of the pickups not being affected by these issues. When a passive pickup is being used, it is being powered by the connection between the amp, cable & pickups. Therefore, it is affected by the length of cable and other factors. Active pickups are not affected by this due to closed circuit.

One of the issues with including active pickups in my experiment was the difficulty of putting them in my guitar while maintaining the control variables. To put the active pickups in I would need to remove the strings multiple times, as well as create and build a much more complex wiring scheme. That being said, active pickups have piqued my interest, so I will continue researching them and most likely install them in my guitar at a later date.

Cable capacitance

When discussing pickups with EMG, they mentioned that cable capacitance was an important issue that wasn't as prevalent within active pickups.

To understand cable capacitance, we must first understand capacitors. A capacitor is essentially an electrical component that stores charge. You can see this occur in daily life too, dragging your feet on the carpet can lead to you giving an electric shock to someone. You are storing charge. The amount of charge your body stored was dependent on your mass, shape & composition: your capacitance. (Zerocapcable.com, 2015)

A guitar cable stores electric charge, leading to it working as a weak capacitor. When the cable is used, a current flows through the capacitor. When a higher frequency note is being played, the current is higher. Higher notes have a higher frequency (For example E4 is ~330 Hz while E3 is ~165 Hz). This means that when is a higher note is played, it is more affected by the current.

Most guitar cables have a capacitance approximately 9.1 picofarads per meter, meaning a longer cable has a higher cable capacitance. To investigate this, I recorded the same sample using a shorter cable.
The shorter cable produced some interesting results. Firstly, the shorter cable was quieter in the 0-200Hz section. Additionally, the slope of the harmonics along the frequency axis was more consistent for the shorter cable. The initial E4 note was the highest in terms of dB. This information is valuable, as it can be used as evidence to consider the percussive low Hz bumps and the loud harmonics anomalies.
Cable capacitance can be explored further in Chapter 9.4 of Electroacoustics for stage and studio.

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[8] Cable capacitance is defined as the measurement of the electrical charges stored within it. The capacitor in the cable is constructed by two conductive material which is separated by an insulator or dielectric. (Circuit Globe, 2016)

[9] Bridge grounding is a low frequency hum caused by a disconnected ground wire within the guitar.

Conclusion

Overall conclusions

Quantitative

There was evidence to support the claim that more expensive guitar components improve the ‘quality’ of sound produced.

For the pickups, the change in pickup seemed to improve the spectral response generally. This was primarily due to the increase in frequency response, as well as the possibility of a low-pass filter filtering out the percussive frequencies.

The strings also made an improvement on the guitars output. The harmonics produced by the D’addario strings had a more consistent decrease in decibels. In comparison, the control strings had harmonics that were above the fundamental frequency in decibels. The evidence against this is the fact that there may have been a skin build-up or corrosion. Furthermore, the string diameter was different. This could have all contributed to the change in spectrum, as it is possible evidence against the hypothesis that new strings improved the sound produced.

Another key detail is the cable used. The cable used to record the results was long, meaning that there was a likelihood that the results were affected by cable capacitance. This is further supported by the fact that using a shorter cable yielded less variation in results.

Overall, I can conclude that quantitatively better components provided better results when looking at the spectrum and that there is evidence to support ‘higher-quality’ components making a positive impact on the guitar sound generally.

All these changes remain both deeply complex and often subjective as what is an improvement in sound to one person may be the opposite to another. That is just the nature of this field, but it is also what helps keep it exciting and interesting.

Qualitative

This section is going to be opinion based, as a qualitative measurement of sound by definition means that I will simply decide whether the sound is ‘pleasing’ or not.

For the pickups, I felt the sound being produced was smooth, but also significantly quieter compared to the control pickup. I had no real personal preference over the passive pickup, making it difficult to say if one was better over another. They were, however ‘different’.

I preferred the new D’addario strings compared to the control ones. This was partially due to the ‘feel’ of the strings, but there was also the possibility that they sounded better due to them having less skin build-up and less corrosion.

Overall, I had a difficulty deciding between both the pickups & the strings. Conclusions from that could be that there was little difference, that I do not have the ear or experience to discern the nuanced differences or that I just had no strong preference with the range of change made.

Further Questions

While my EPQ is now finished, this does not mean that all questions have been answered. From this investigation comes a whole new host of questions that I would like to investigate later.

This is included but not limited to:

- How different cables (Such as XLR cables) would affect the sound.
- The visual difference when using active pickups or when using a shorter cable.
- The effect of pickup height on sound both qualitatively and quantitatively.
- How changing treble, middle & bass would affect sound analysis.
- The difference produced when using an active switch.
- How does normalisation of the recordings affect the dB level of harmonics?

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Gitec
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