INTERNATIONAL BACCALAUREATE

PHYSICS EXTENDED ESSAY

Investigation of sounds produced by stringed instruments

Word count: 2922

Abstract

This extended essay is about sound produced by stringed instruments, specifically guitar. There will be 2 different parts which are about two different characteristics of sound. One is pitch and second is timbre (quality and characteristics of sound). Pitch will be examined by changing length and timbre by changing thickness of string.

I chose this experiment because I am interested in both sound and physics. I wanted know more about sound and audio. In this experiment, I learnt a lot about sound, especially guitar sound. On the other hand, I did not know how to analyze sound and this essay gave me a chance to learn it. At very first times of this experiment it was very hard to analyze because, I did not know what to look at.

The procedure and most of the measurements are done by same steps only, because of independent variables, the data collected is different. Also uncertainties for length, diameter of string; frequency and hold time are same for both part 1 and part 2. This is why some of the uncertainties are not mentioned in part 2.

Finally yet importantly, the instruments are same for part 1 and part 2. Because of this while collecting different data, the instruments are resettled for avoiding errors and measurements are done in same conditions.

Word count: 218

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Introduction

The Experiment

Surely you listened a lot of guitar sounds and songs by artist. I also listened it however I sometimes wondered why artist use the string above or below. When I first started playing guitar I was not understanding it still. After a time passed away, I understood that ever string had a different sound for same note. Furthermore, this curiosity became an obsession for me. In addition, one other obsession was knowing the ratio of string length and pitch.

This experiment asks the question why two different strings sounds different for same fundamental wave and what the ratio between length and pitch is. As the notes are played or in other words, strings start to vibrate the sound waves will be produced. At the time of first travel of wave on the string, only sound will be produced is fundamental overtone further in the second travel first harmonic would be produced. The second, third even more harmonics will follow the travels of waves. These tones would be seeable on spectrum analyzer as crests.

Because this experiment is about both timbre and pitch, there is two different independent variables. These variables will be observed in two parts. First part will be about the relationship between length and pitch.

Background Information

As the guitar is one of the most known stringed instruments, it evolved so much because of its popularity in the history. Like other stringed instruments, it has a similar shape. A big body which has acoustic functions, fretboard for setting string length and a headstock for tuning. This shape is also can be seen on other stringed instruments like violin or cello. All of them has similar characteristics and same basics to produce sound, why they sound different? Simply the answer is that the violin has a thinner and cello has a deeper sound but this would be a wrong answer. It is because you can produce a sound with same fundamental harmonic which means that it is the same note. Actually there is a lot of factors changing sound. In this experiment, I will try to understand how thickness is changing timbre and if there is a ratio between string length and pitch.

To make analyzes accurate, I will use a microphone with less noise and equalization band as flat as possible. The guitar is tuned with two high accurate tuners one is physical and connected to guitar body and the other one was a plugin on digital audio workstation checking tuning with digital signals collected by microphone. Also for rewinding, all sounds are recorded on computer with narrative speech.

Standing waves

A standing wave forms in a situation when reflected waves and initial wave interfere with each other. Constructive interference is the main reason. However this interference must be resonant to form a standing wave. So standing waves forms in special frequencies which are the frequencies of notes. These frequencies have a wavelength that fits between nodes of string. The interfering waves can cause a superposition or a big wave with maximum amplitude which is two times bigger of original wave's amplitude. On the figure 1, 1^{st} drawings shows 2 waves, pink one is original wave and purple one is reflected wave. 2^{nd} drawing shows superposition of these waves and 3^{rd} one shows the interference after a little time and 4 and 5 follows it but 5^{th} one is important because it shows the maximum amplitude of the standing waves.

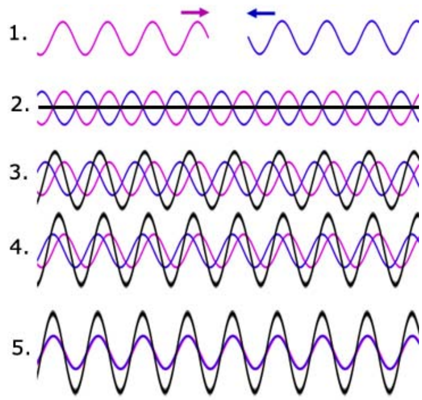


Figure 1: Standing wave formation.

Harmonics

Harmonics are resonant frequencies of fundamental frequency. These waves have frequencies above fundamental frequency. Harmonics and overtones are different from each other. Harmonics must be resonant with the frequency below however overtones mean that the new frequency is above fundamental and overtones can be both harmonic or not.

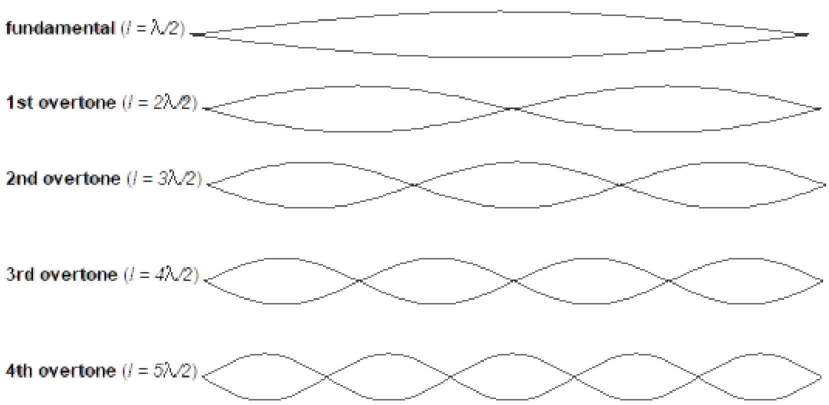


Figure 2: first for five harmonics and relationship between them.

There is a ratio between harmonics. Figure 2 shows this ratio. If the fundamental wave has a wavelength of λ then the first harmonic would have a wavelength of 2λ. By using this ratio, since both wavelength and frequency are known the speed of wave on string could be found. Since there is a friction on string all harmonics would have less amplitudes.

The speed of a wave traveling along tensioned string

$$v_w = \sqrt{\frac{Tension \times Length}{Mass}}$$

The formula is about velocity of wave on string. The tensioner and lighter string provides faster velocity. The tensioner string means that mass per unit length would be less and lighter string means that the material would be less which takes energy to move. Tension is in N, length is in meters and mass is in kg.

Experimental Design and General Description of Equipment

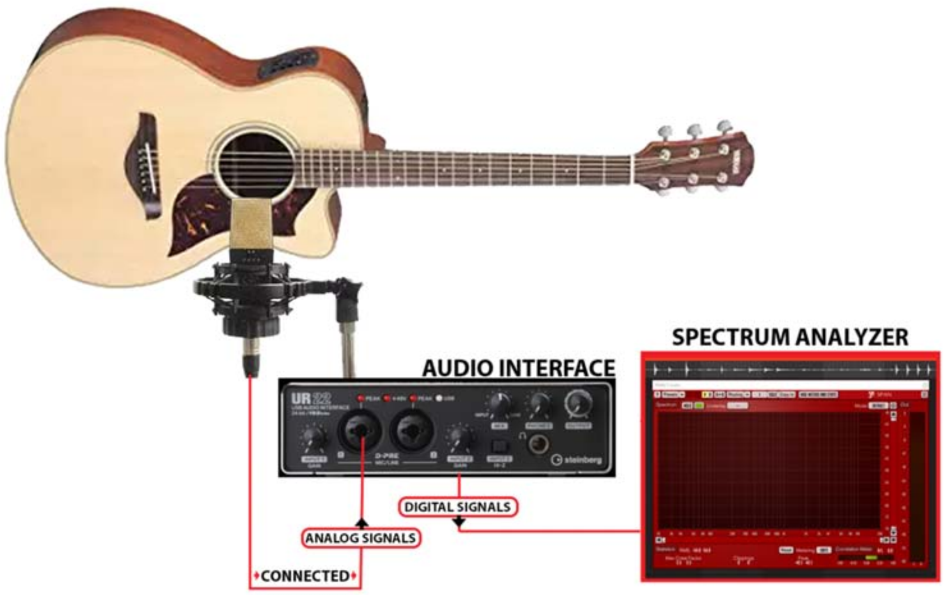


Figure 3: Experimental setup

These experiment uses hardware to collect mechanical waves as analog signals then turn it into digital signals. Later, these signals are processed and collected as wave images and spectrums. Hardware used is listed below.

- Spectrum analyzer: Because this is an experiment about timbre, a spectrum analyzer will be needed. I will use a program called SPAN as spectrum analyzer and I will use it to make graphs for frequencies. Then use that graph to compare timbres of different strings.
- Studio level microphone: For less systematic errors, I will use a studio level microphone. Also, I have access to microphone's frequency response curve so I have a base data to see if there is an increase or decrease on some specific frequencies. For example; the microphone gets more intense information between 6 – 15 KHz so I know that the recordings have more information between these frequencies and I need to decrease information between these frequencies with equalizer.

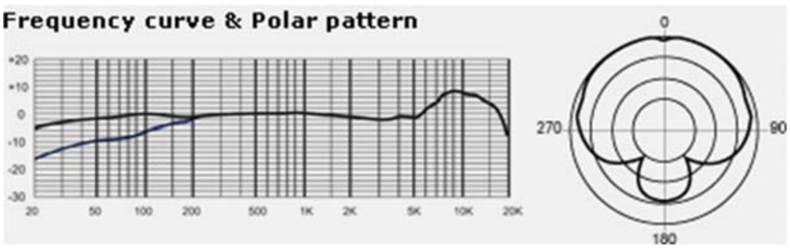


Figure 3: Frequency curve and Polar pattern of MXL 770 microphone

- Audio interface for recording: The microphone which I will use needs phantom power for working and the audio interface has this option. Also, an audio interface has better inputs for recording than computer's soundcard.

The setup is simple to set however the difficult part is isolating. After connecting the audio interface, some isolation pads could be used. If there is no isolation pads, pillows can be used to. For more isolation, heavy and denser pillows or pads is better because both block sound better and absorb noise better. Last but not least curtains or blankets are also could be used.

Part 1

Research question: How does the length of string affect the pitch of the sound produced?

Hypothesis: Changing the length of string will cause a change on pitch. If the length is shortened, the sound would be higher. It will happen because the wave will travel less on short string and this would cause more frequent vibrations.

Experimental Process

Variables

a) *Independent Variables*

- **Length of string:** The length of string affects pitch however producing the same note or tone is possible by tensioning or changing length. On guitar frets are used for changing length and this is why notes sounds different on same string. Since the frets are separated equally or in an order, possibly there is a relationship between length and pitch.

b) *Dependent Variables*

- **Pitch:** Frequency of vibrations.

c) *Controlled Variables*

- **Tuning:** Tuning is the most important variable because it's also have an effect on both pitch and timbre. So, guitar is tuned for standard tuning.
- **Distance between the mic and guitar:** For accurate results and reducing background noise's effects on recording, the microphone will be placed with 10 ± .1 cm.
- **Room temperature:** Temperature of the room that we are recording is important because, in higher temperatures, sound waves move faster. This can cause a random error. The room temperature will hold stable on 26° ± .3° C. Room temperature will be controlled with electric heater.

- **Microphone settings:** These settings are on microphone and they have directly effect on recordings. One setting is for gain which is a voltage controller and this affects the level. The other setting is for equalization and this affects the information, one of the choices is flat and other is low cut. I want more information on lower frequencies so equalization will be flat and gain will be 0dB to get more information.
- **Background Noise:** Background noise is important for this experiment. It's because something like car horn can change the information with mixing with string sound and this causes an error on analyzing process. Because of this, an insulation pad will be used to reduce this noise.
- **Thickness and material of String:** Thickness can change wave speed and amplitude because of this it's important to work on one specific string with same thickness. In the experiment, 1.19 mm diameter string is used. Also, material is another factor which can change sound. The string used in this experiment is 80/20 bronze. 80/20 means that the alloy has %80 copper and %20 zinc. This string is chosen because it's the most common and chosen string type because of its "true brass" tone.

Procedure

First set the recording system. Set microphone to 0dB and flat eq. After this is done, set isolation. While setting isolation, try to get reverberation as low as possible. This can be done by using thicker pads and put them close to the microphone. The only direction where sound can get in must be the front. This part is also valid for the second part's procedure. After opening the record program, choose your input to record. The inputs will be microphone and magnetic pickups. Turn the volume knob on guitar to its max and gain on recording software should be around 0 to -10 dB and this must be stable for all recording. Place guitar against microphone. The gap between microphone and guitar should be 10 cm. Record the sound and change length by pressing the notes. Before changing note, measure length of string. After recording is done, analyze every sound and note frequencies with the lengths pressed.

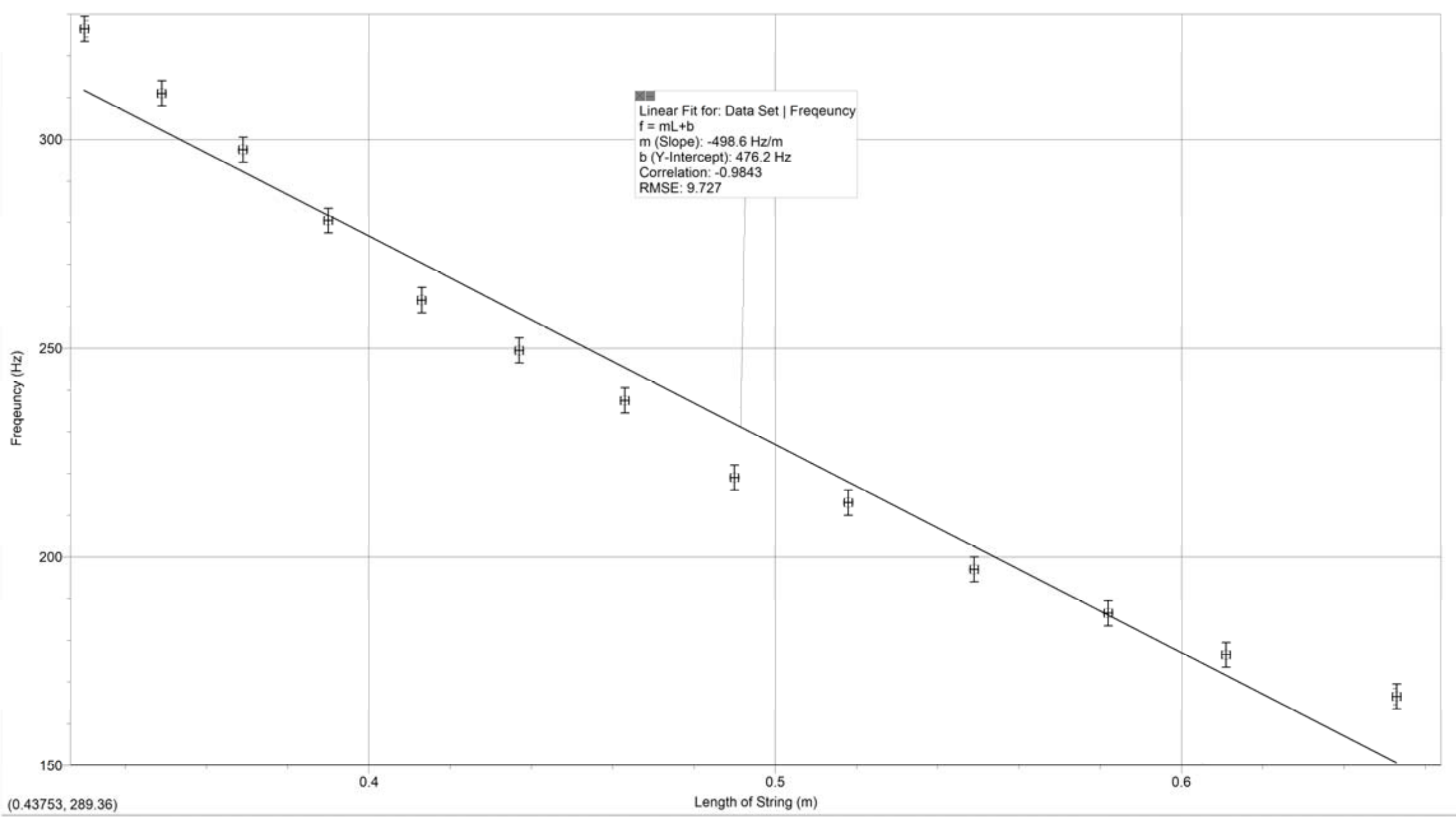
Data Collecting and Processing

String's Length (±0.1)(cm)	Data of Magnetic Pickup Records (±1)(Hz)	Data of Microphone Records (±5) (Hz) (with +2.0 Static Error)	Music tone of frequency
65.3	165	168	E3
61.1	174	179	F3
58.2	186	187	F#3/Gb3
54.9	196	198	G3
51.8	213	213	G#3/Ab3
49.0	221	217	A3
46.3	235	240	A#3/Bb3
43.7	247	252	B3
41.3	261	262	C4
39.0	280	281	C#4/Db4
36.9	296	299	D4
34.9	309	313	D#4/Eb4
33.0	327	326	E4

Table 1.1: Length of string and fundamental frequency of sound with the musical notes equal to that fundamental frequency

String's Length (±0.1)(m)	Average Frequency (Hz)(±3)	Music tone of frequency
.653	166.5	E3
.611	176.5	F3
.582	186.5	F#3/Gb3
.549	197.0	G3
.518	213.0	G#3/Ab3
.490	219.0	A3
.463	237.5	A#3/Bb3
.437	249.5	B3
.413	261.5	C4
.390	280.5	C#4/Db4
.369	297.5	D4
.349	311.0	D#4/Eb4
.330	326.5	E4

Table 1.2: Average frequencies with cm converted to meters for length.



Graph 1.1: Hz over length of string.

Uncertainty of lie of best fit: -.9843

Function of line of best fit: $f(L) = (-4.986)L + 476.2 = Frequency$

On graph 1.1 the best fit line shows a relationship between length and frequency. The function given above is the function of relationship between frequency and length. This equation is probably only for the string used. It's because the thickness and material can change the pitch. By using the equation, the table below is constituted.

Length(m)	Expected Value (Hz)	Record (Hz)
.20	376.48	372
.25	351.55	349
.30	326.62	329
.35	301.69	295
.40	276.76	277
.45	251.83	247

Table 3: Expected frequency from function and recorded frequency for same length.

Uncertainties and errors:

- **Length uncertainty:** Length uncertainty is ± 0.1 cm because while measuring the perspective could mislead measurements. Since the gaps between each line on meter is 0.1 cm, the uncertainty is ± 0.1 cm.
- **Magnetic pickup uncertainty:** Magnetic pickup has an uncertainty of ± 1 Hz because it's very accurate. It's very accurate because the principal that magnetics used to pick sounds is different from microphones. They collect specific data on each string and they collect vibrations not sound waves.
- **Microphone uncertainty and error:** The recording microphone has an uncertainty of ± 3 Hz and +2 Hz static error. These numbers are found with an oscillator and accurate speakers. A sine wave with specific frequency is played at the same time it is recorded with microphone. The sine wave frequency and microphone's input was slightly different. Also at the end of the long play of sine wave the uncertainty is found as ± 3 Hz.
- **Hold time:** Hold is the name of freezing spectrum. The hold time uncertainty is accepted as ± 50 ms because there is no exact point where guitar sound is recorded. It can be either before or after 50 ms of the point where is chosen as

start of sound. Because of this start and hold position will move with respect to this.

- **Diameter of string:** The diameters of strings are found at the back of the package which strings are sold with. These numbers were measured by company produced strings. Because of this the numbers are accurate however there is an uncertainty of ± 0.05cm.

Part 2

Research question: How does the thickness of the string affect the timbre of the sound?

Hypothesis: Changing the thickness of string but not the note played will cause a difference on sound timbre. If the string is thickened, the sound would have a timbre more dense between 100-500 Hz which is the range that involve bass sounds. I assume this because all waves transfers energy. Kinetic energy is $2^{-1}mv^2$ and with respect to the background information, thicker strings transfer waves slower.

Experimental Process

Variables

a) *Independent Variable:*

- **Thickness of string:** Thickness affects both harmonics and pitch. Thickness changes the friction and speed of wave moving on string because of this fundamental frequency can be same however, because the harmonics' amplitudes changed over different friction, the guitar probably produce different colored sounds

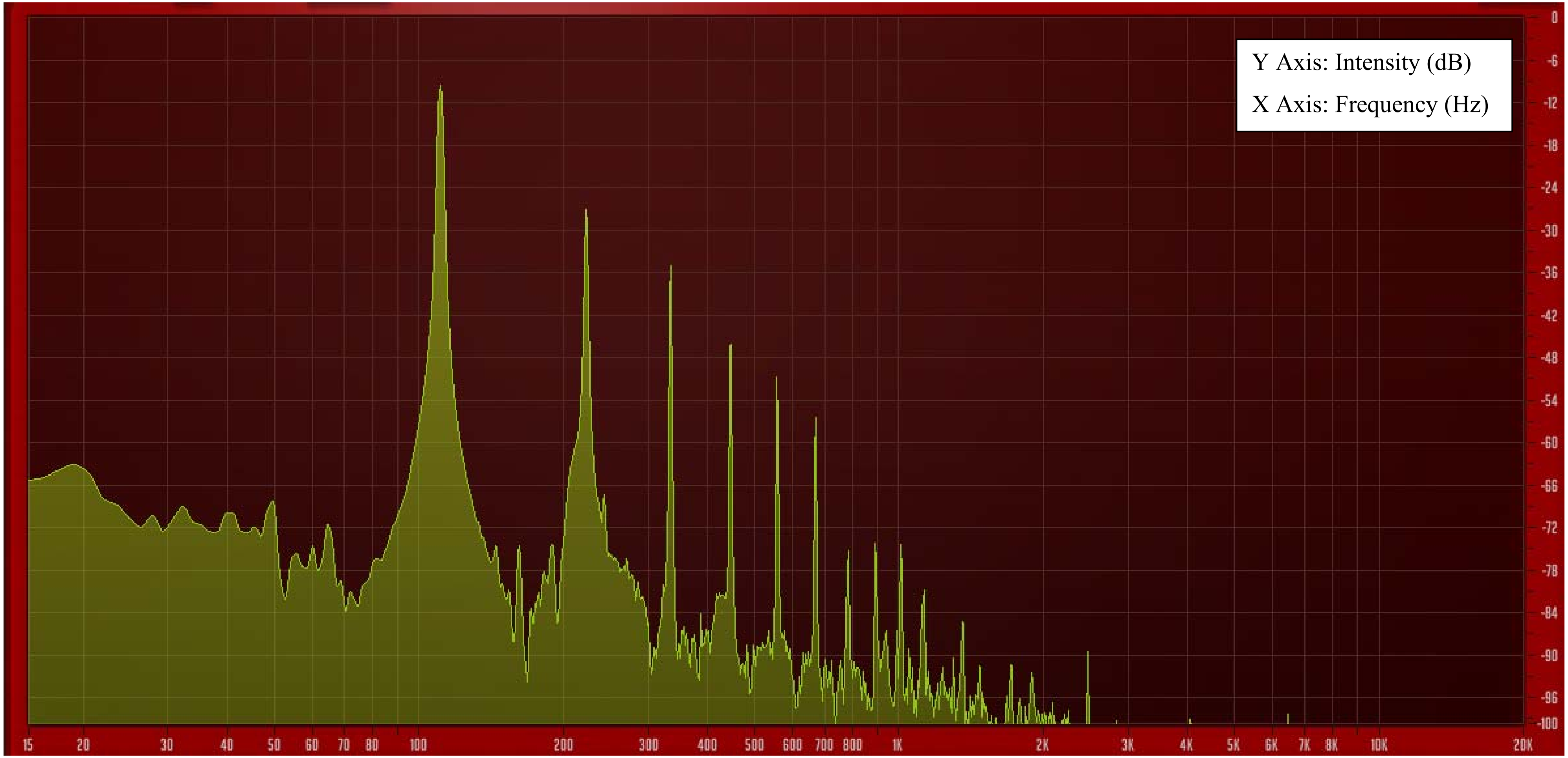
b) *Dependent Variables*

- **Timbre:** The quality and characteristics of sound. The change will be on spread of harmonics, separation of specific frequencies and intensity of these frequencies.

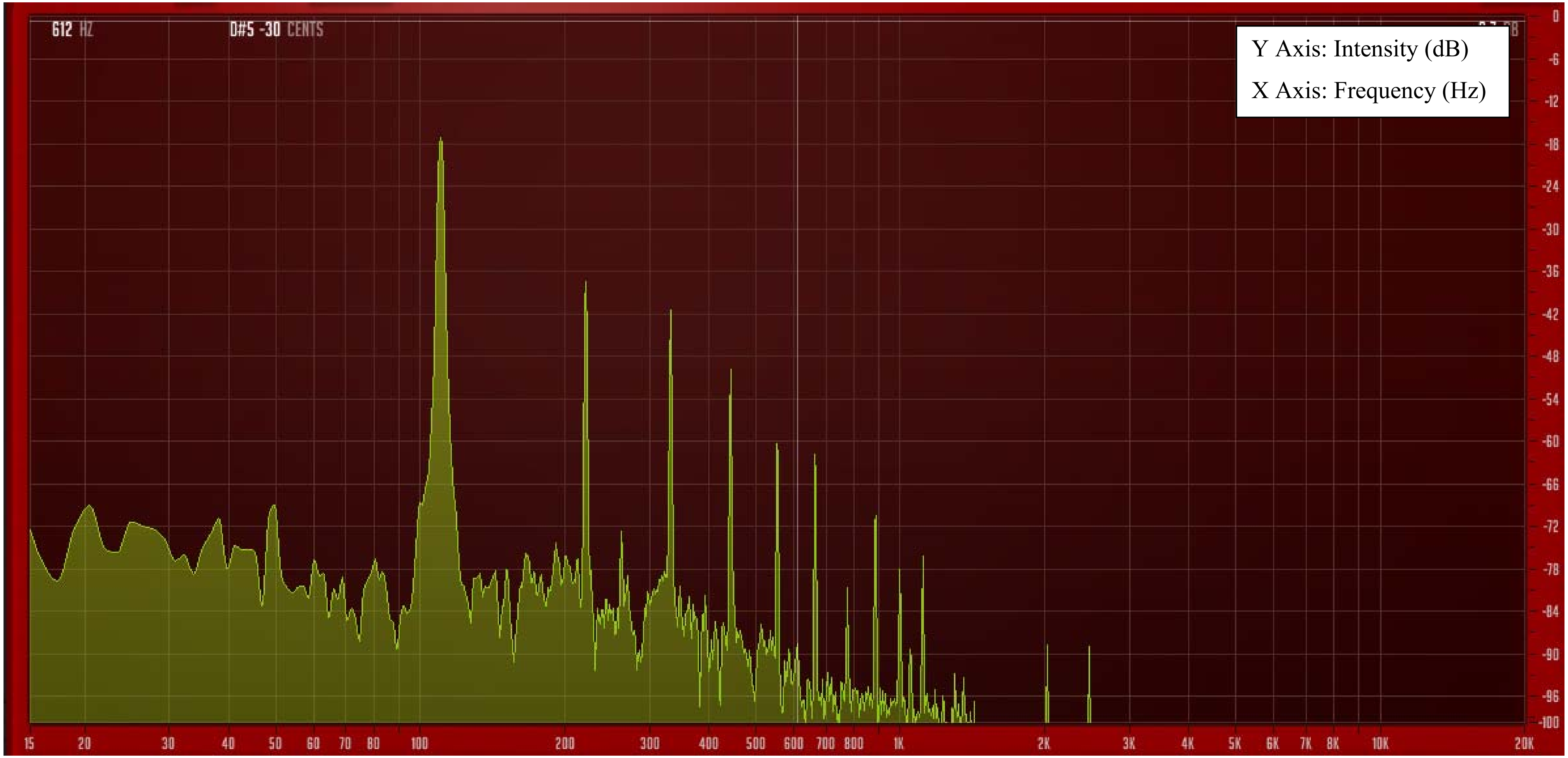
c) *Controlled Variables*

- **Tuning:** Tuning is the most important variable because it's also have an effect on both pitch and timbre. So, guitar is tuned for standard tuning.

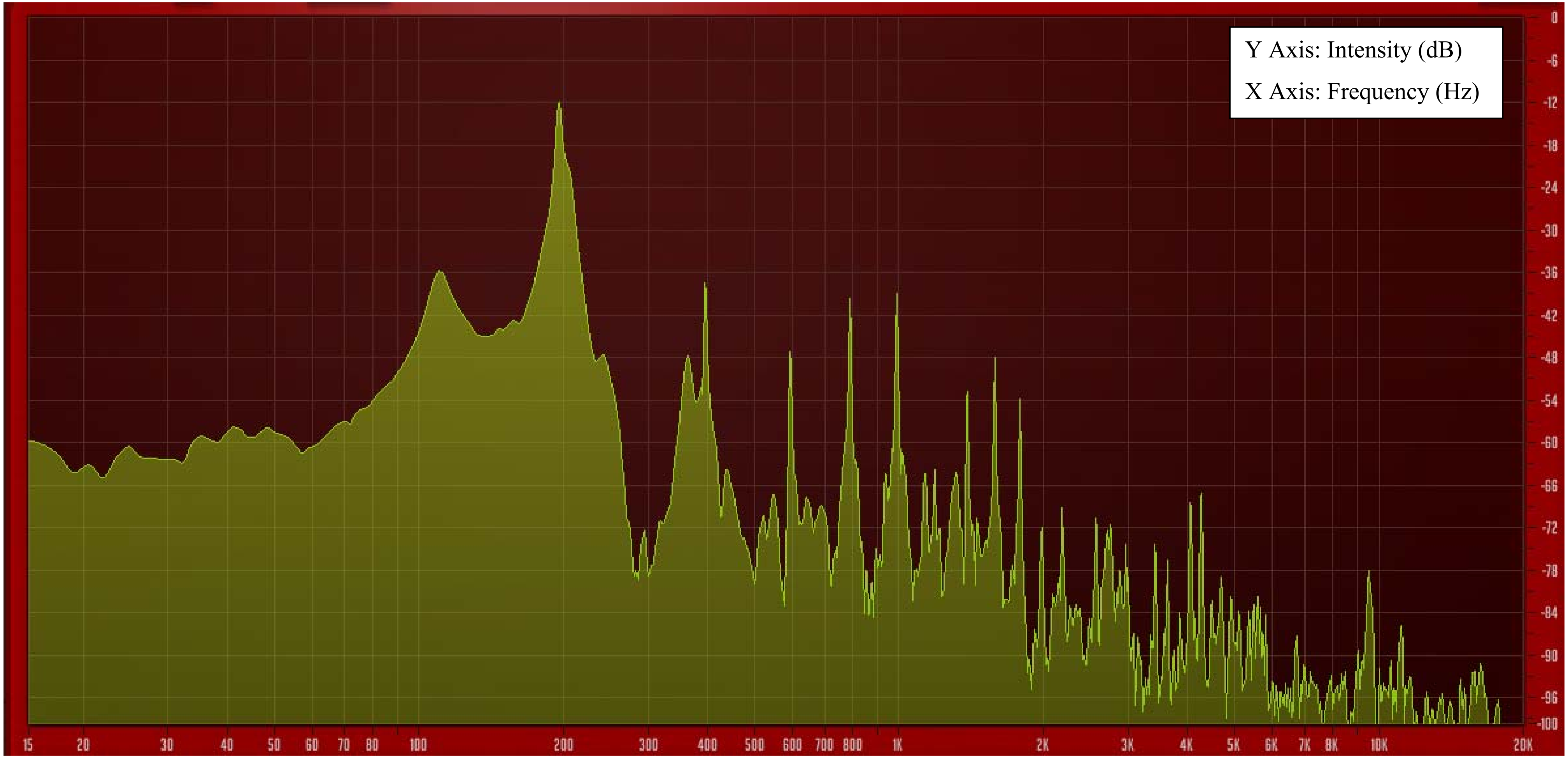
- **Distance between the mic and guitar:** For accurate results and reducing background noise's effects on recording, the microphone will be placed with 10 ± .1 cm.
- **Room temperature:** Temperature of the room that we are recording is important because, in higher temperatures, sound waves move faster. This can cause a random error. The room temperature will hold stable on 26° ± .3° C. Room temperature will be controlled with electric heater.
- **Microphone settings:** These settings are on microphone and they have directly effect on recordings. One setting is for gain which is a voltage controller and this affects the level. The other setting is for equalization and this affects the information, one of the choices is flat and other is low cut. I want more information on lower frequencies so equalization will be flat and gain will be 0dB to get more information.
- **Background Noise:** Background noise is important for this experiment. It's because something like car horn can change the information with mixing with string sound and this causes an error on analyzing process. Because of this, an insulation pad will be used to reduce this noise.
- **Note played and recorded:** Saying tension and length was a controlled variable would be wrong. It's because playing same note, frequency, on different strings that have different thickness is not possible with same length and tension however by changing them the played note is made steady.



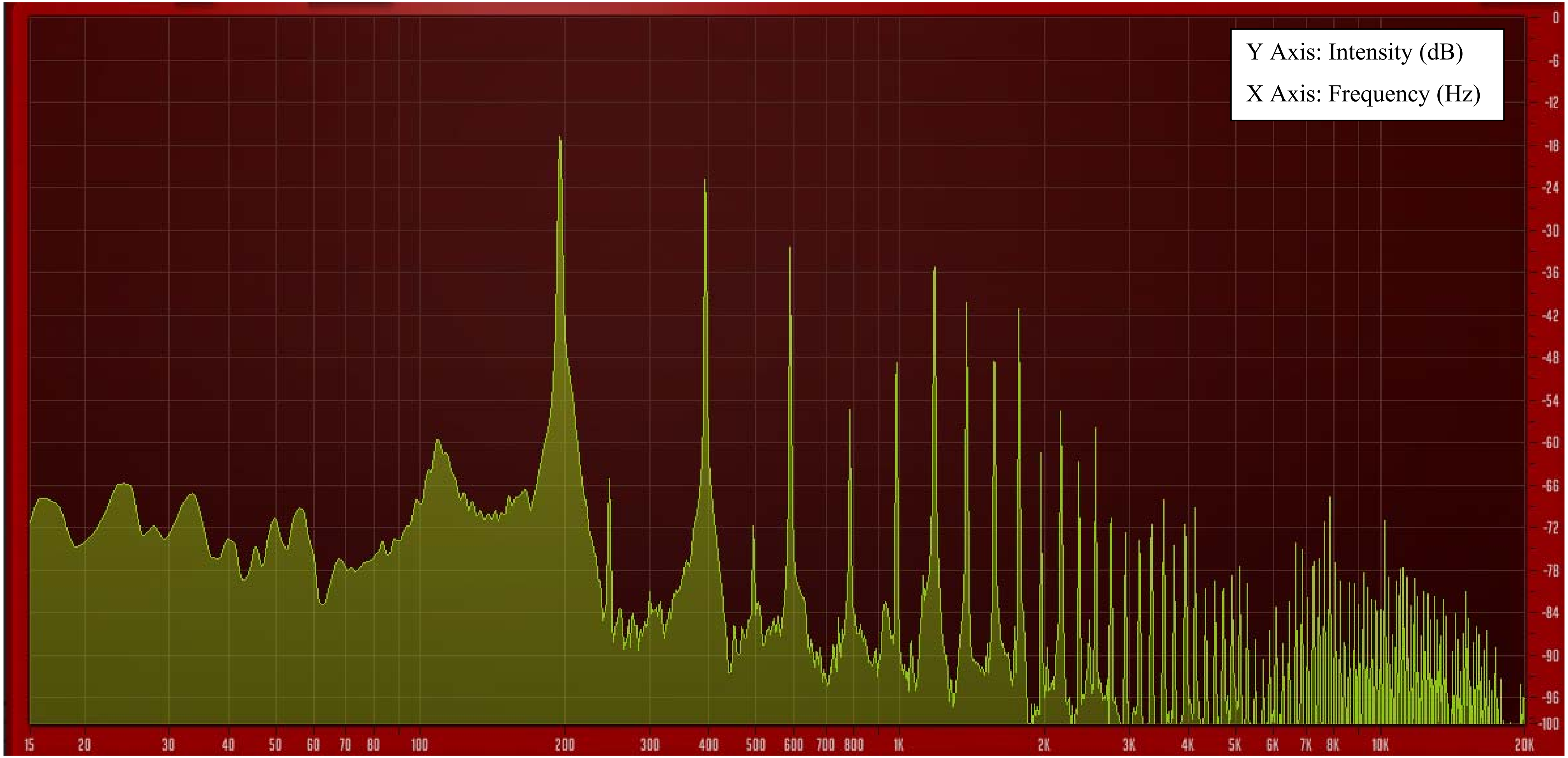
Graph 2.1: Spectrum analyzer screen on hold position after note A2 is played on <u>sixth string (R: 1.19 ± 0.05 mm Length: 0.490 ± 0.001 m) fifth fret</u>. (Holded at 122 ± 50 ms)



Graph 2.2: Spectrum analyzer screen on hold position after note A2 is played on <u>fifth string (R: 0.99 ± 0.05 mm Length: 0.649 ± 0.001 m) open</u>. (Holded at 134 ± 50 ms)



Graph 2.3: Spectrum analyzer screen on hold position after note G3 is played on *<u>fourth string (R: 0.76 ± 0.05 mm Length: 0.490 ± 0.001 m) fifth fret</u>*. *(Holded at 101 ± 50 ms)*



Graph 2.4: Spectrum analyzer screen on hold position after note G3 is played on <u>third string (R: 0.58 ± 0.05 mm Length: 0.648 ± 0.001 m) open</u>. (Holded at 150 ± 50 ms)

	Played							
	Length (m)	Diameter (mm)	Length(m)	Diameter (mm)	Length(m)	Diameter (mm)	Length(m)	Diameter (mm)
	0.490	1.19	0.649	0.99	0.490	0.76	0.648	0.58
Harmonics	Hz	dB	Hz	dB	Hz	dB	Hz	dB
Fundamental	110	-9.5	110	-18.6	195	-12.6	197	-17.7
First	226	-26.9	222	-36.7	364·	-48.2	393	-29.4
Second	330	-35.3	334	-42.5	395	-38.5	558·	-33.4
Third	442	-46.5	445	-48.9	597·	-47.6	784	-54.8
Fourth	559·	-48.9	553·	-60.5	793	-40.1	985·	-49.0
Fifth	673·	-54.9	666·	-60.9	991·	-41.1	1190·	-35.4
Sixth	793·	-79.6	776·	-63.4	1390·	-59.4	1370·	-41.7
Seventh	898	-80.1	1010·	-71.3	1570	-48.6	1570	-48.2
Hold Time(ms)	122		134		101		180	

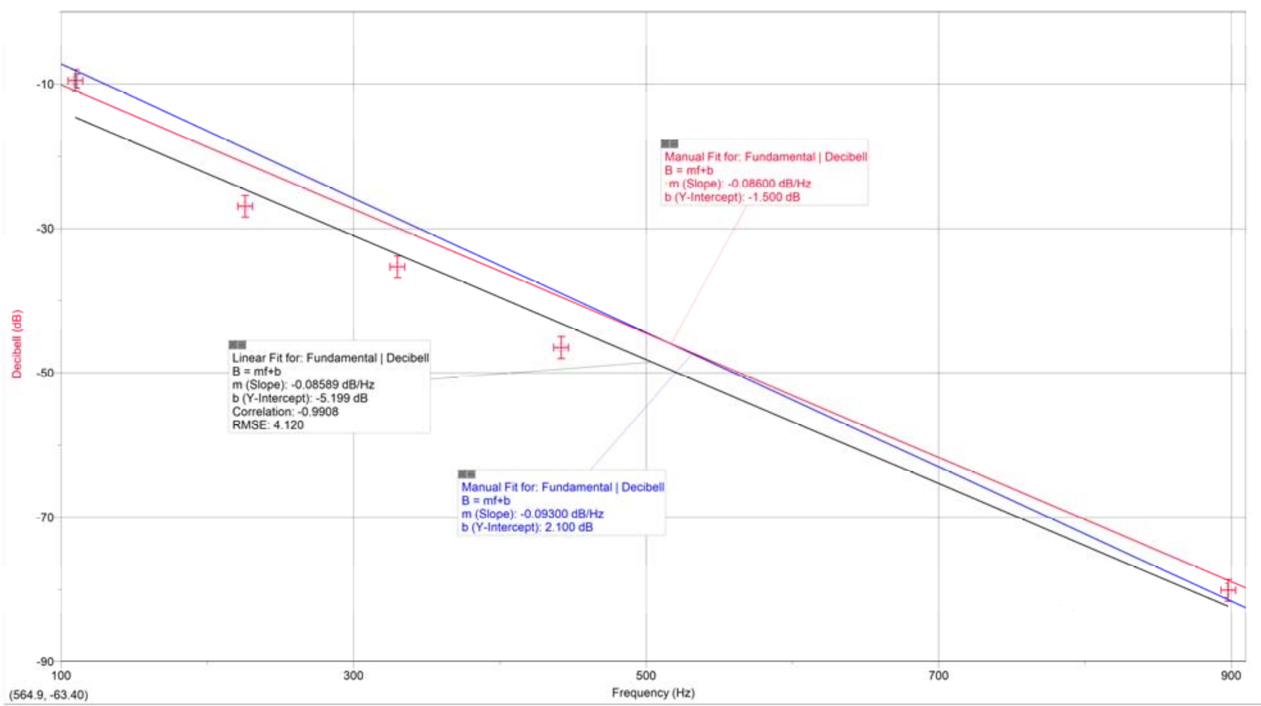
Table 2.1: 8 harmonics of each record of same note on two different strings with power (dB) and hold time.

About Table 2.1:

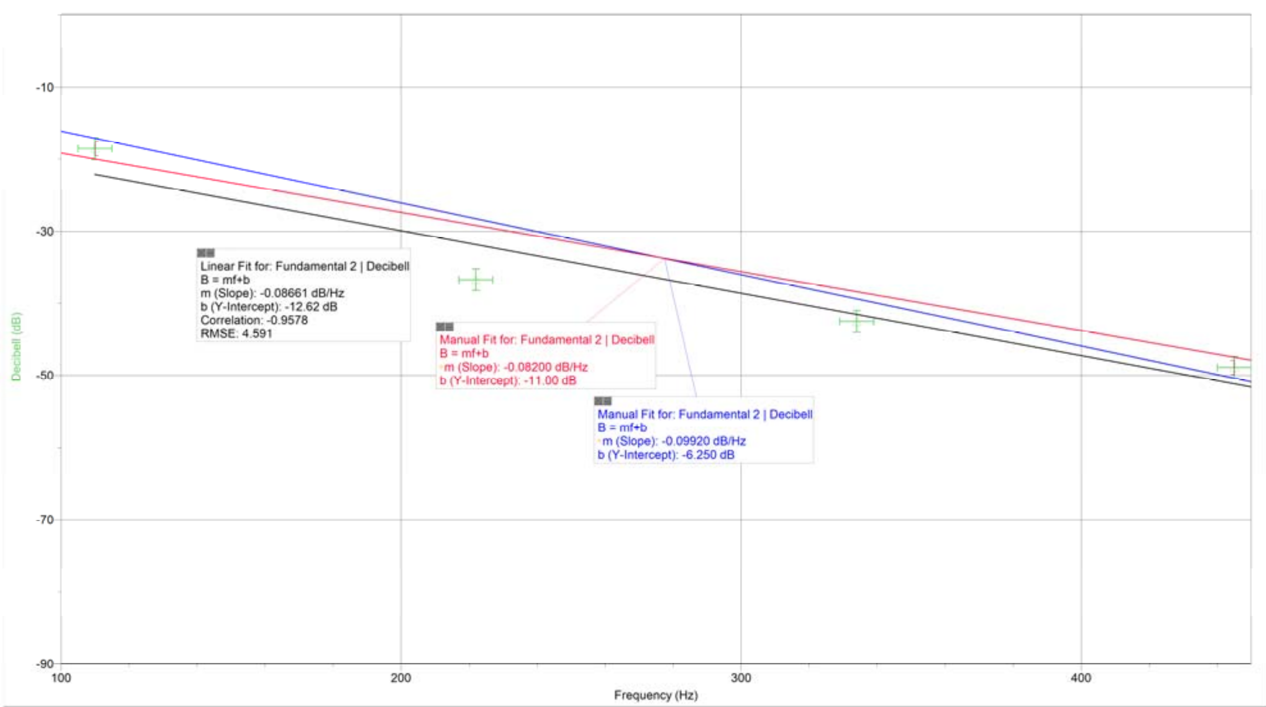
·: The values marked with this dot are the frequencies which are not same note with fundamental wave. These frequencies are not added to graphs constructed from these values.

O: Open string, not pressed on frets.

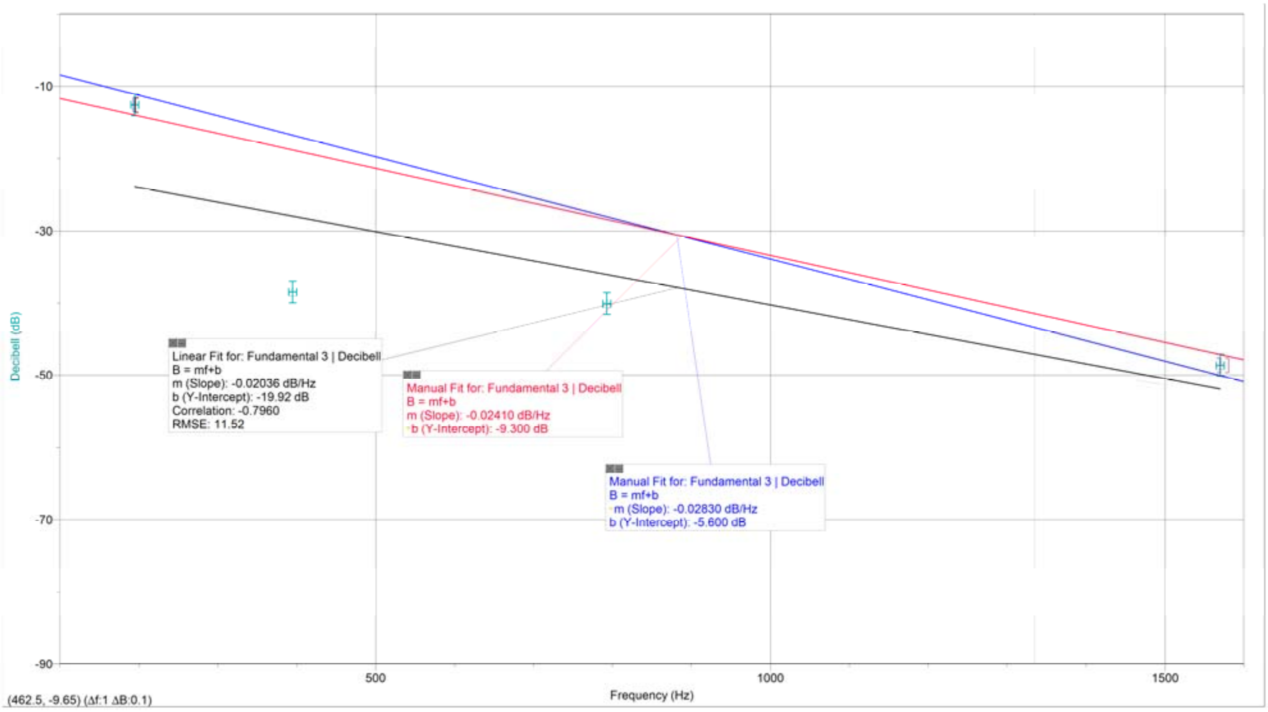
Harmonics are chosen by decibels. Overtones of fundamental frequency are chosen only. Below that frequency doesn't have chance to be produced by fundamental wave. It's because fundamental wave has the longest wavelength and the harmonics need to have shorter waves than fundamental.



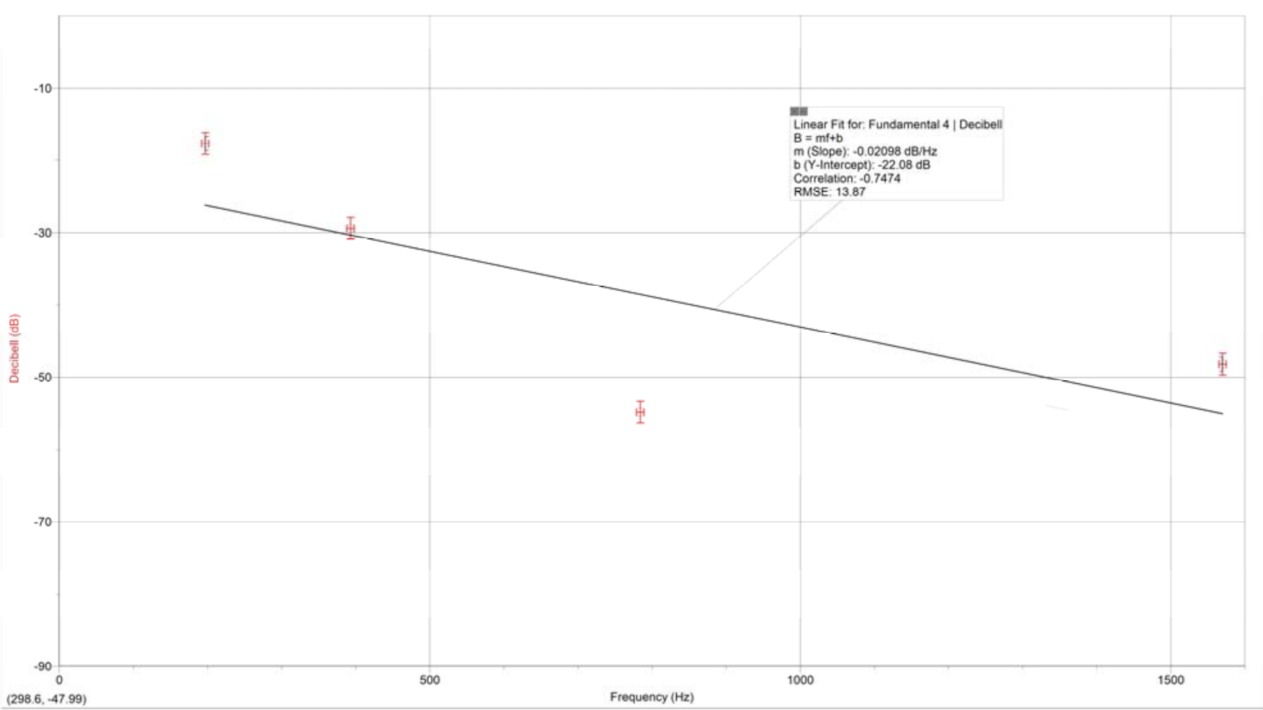
Graph 2.5: Graph of decibels over frequencies for note A2 is played on 6th string 5th fret.



Graph 2.6: Graph of decibels over frequencies for note A2 is played on 5th string open.



Graph 2.7: Graph of decibels over frequencies for note G3 is played on 4th string 5th fret.



Graph 2.8: Graph of decibels over frequencies for note G3 is played on 3rd string open.

In graph 2.8, the min and max lines didn't fit because of this there is only line of best fit. This means that there is not a linear equation between values and it's not possible to make a best fit. This is also valid for other graphs whereas the min and max could be set but error is so high that the formulas couldn't be used.

<u>Using the velocity formula</u>

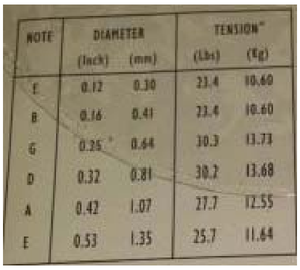
$$v_w = \sqrt{\frac{Tension \times Length}{Mass}}$$

The formula given above was mentioned on introduction. By using this formula, the calculation of velocity on different strings is done.

Example:

Velocity on fifth string with length of 648 mm.

The figure 2.1 below is from the pack of strings, it shows both diameter and tension. The tension is converted to newton from Kg.



NOTE	DIAMETER (Inch)	DIAMETER (mm)	TENSION* (Lbs)	TENSION* (Kg)
E	0.12	0.30	23.4	10.60
B	0.16	0.41	23.4	10.60
G	0.25	0.64	30.3	13.73
D	0.32	0.81	30.2	13.68
A	0.42	1.07	27.7	12.55
E	0.53	1.35	25.7	11.64

Figure 2.1: Back cover of Yamaha Super Light 80/20 Bronze string pack.

$$115.34 = \sqrt{\frac{123 \times 0.649}{0.006}}$$

String/Fret	Tension(±0.1 N)	Mass(±0.0001 Kg)	Length(±0.01 m)	Velocity(m/s)
Sixth/5	114.14	0.007	0.490	89.38
Fifth/O	123.00	0.006	0.649	115.34
Fourth/5	134.15	0.005	0.490	114.65
Third/O	134.64	0.005	0.648	132.09

Table 2.2: Velocity on strings with the length, mass and tension.

Uncertainties and errors:

- **Tension uncertainty:** Tension uncertainty is ± 0.1 newton because the manufacturer of strings have not given the uncertainty for tensions and I assume that as ± 0.1N.
- **Mass uncertainty:** Mass uncertainty is very important because the weighting device was showing grams without decimal places. The uncertainty is determined as ± 0.1 grams or ± 0.0001 kg.

Conclusion

On the Table 1, the collected data is one all octave, and the first thing that can be seen is that from E3 to E4 (one octave higher of E3) the string length is divided by two.

This is also seen on the harmonics. The first harmonic has half-length of fundamental wave. Some frequencies were not producing the same note as expected with respect to harmonic series rule. However, there is a possibility of reverberation and this can cause a wave which is not a harmonic wave of fundamental. When these notes were evicted, the harmonics had a relationship. Every harmonic frequency had a lower dB when the sound became thinner. I assume that these happened because the traveling wave lost its initial energy with friction in every revolution of travel. And as the waves transporting energy, its amplitude was becoming less. This caused a difference between the sounds produced from different strings for same note. This difference formed because of variation on friction. Because the thicker string has more friction, the sound produced is less dense over high frequencies. Also one other difference I spotted was that thinner strings had sharper sounds. By sharper I mean that the sound produced was not spread out on other frequencies, on the spectrum analyzer this could be seen.

On the other hand, the function found by changing length and pitch is the equation of frequency related to the length. Table 4 is constructed by this function and it proves the hypothesis of pitch – length relationship.

Evaluation

This experiment was hard at the points of analysis because the data was so complicated and there were two different independent variables. The first problem was the data collected as spectrum. That data couldn't be seen easily because the gap between 20 to 20000 Hz was big. However, by using Spans' point finder, every 8 crests of overtones have been recorded by hand. Table 3 contains these values. Second problem about timbers was these 8 crests have some tones which are not harmonics of fundamental wave in principle. So they made it hard to comment. Because of this, in the table, these tones are pointed out. While building the relationship between string thickness and timbre, these tones was not included the best fit line calculation.

I assume that these tones have been formed after reverberation or because of acoustic body of guitar. Rather than directly using a guitar for experiment, an apparatus to hold string could be used. This could resolve reverberation problem and reduce effects of acoustic body on sound.

The error was high on the 2nd part that the formulas couldn't be used. I assume that this is because of different characteristics of string. The thickness maybe changed the vibration and amplitude of standing wave. This is the reason of the error and uncertainty of the graphs.

One other problem was frets; they make a fixed end on the strings at the exact point of a note. If there were no frets, it would be easy to collects more accurate data because if length were changed by same periods, the equation of Hz over length would easily found. Like solution of reverberation and acoustic body problem, this can be resolved by using an apparatus to hang strings.

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