TED ANKARA COLLEGE FOUNDATION HIGH SCHOOL

THE EFFECT OF TEMPERATURE ON THE FREQUENCY OF A GUITAR STRING

Extended Essay (Physics HL)

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A. ABSTRACT

Frequency is the number of times that a periodic function or vibration repeats itself per unit time. The period is the duration of one cycle in a repeating event. The Standard International unit for frequency is the hertz (Hz). Hertz represents the number of cycles per second that an event occurs.

Frequency is the property of sound. Sound shows wave characteristics. Many systems have distinct frequencies such as musical instruments, UV radiation and radio waves. The number of waves that pass through a point in one second is the systems frequency. The more waves pass the larger the frequency, the more waves pass the waves are either faster or have smaller wavelengths. Therefore, frequency is inversely proportional to the wavelength. Several factors like temperature or pressure can affect frequency.

The guitar is the most common stringed instrument, and shares many characteristics with other stringed instruments. A guitar string is a common example of a string fixed at both ends which is elastic and can vibrate. The vibrations of such a string are called *standing waves*, and they satisfy the relationship between wavelength and frequency that comes from the definition of waves. Waves travel faster on a tighter string and the frequency is therefore higher for a given wavelength. On the other hand, waves travel slower on a more loose string and the frequency is therefore lower for a given wavelength. Multiple frequency vibration makes a guitar instrument interesting.

The aim of this study is to determine the effect of temperature on the frequency of a guitar string. A strobe tuner is used to measure the frequency of the string. A strobe tuner is a special tuner that acts as a stroboscope thus measuring the frequency of a given note. In this study, the temperatures applied on the guitar string are 11, 18, 25, 32 and 41 Celsius. In conclusion, this study demonstrates that frequency and temperature are inversely proportional: while one increases the other decreases.

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C. NOTATIONS

λ = Wavelength

f = Frequency (Hz)

v = Speed of the wave (m/s)

A = Amplitude (m)

Y_m = Amplitude of the wave (m)

ω = Angular frequency (radians per second)

k = Wave number (radians per meter)

T = Temperature ($^o C$)

L = Length (m)

α = Expansion coefficient

S.D. = Standard Deviation

1. INTRODUCTION

Music is as an art form in which sounds and tones are arranged in an orderly sequence to produce a continuous and unified composition (1). The foundation of music is the musical note. The 'note' depends on the frequency at which the string vibrates (2). The distinction between music and noise is the physical form.

Music in its simplest form is monotonic; that is, a sequence of single frequencies played one at a time. Real music is polytonic; a mixture of different frequencies played together in a manner that sounds harmonious.

You can make music with different instruments. Guitar is one of the most important musical instruments. Each of the strings of the guitar is tuned to a particular pitch or frequency of sound. Disregarding constants such as the string diameter, temperature of the instrument, etc., the pitch of each string depends on the tension on the string which is created between the two points on the instrument which support the vibration, and the length of the vibrating portion of the string (3). Frequencies give the music a sense of power even if they occur infrequently (4).

In this study, I want to determine the effect of temperature change on the frequency of a guitar string.

1.http://www.cwrl. utexas.edu/~ syverson /worldsfair

2.http://www.acoustics. salford.ac.uk/feschools/ waves/standing_ waves.php

3.http://www.classic-guitar.com/lesson5.html

4.http://www.digitalprosound.com/2002/03_mar/tutorials/mixing_excerpt1.htm

2. BACKGROUND INFORMATION

2.1 WAVES

Wave is a disturbance or oscillation that travels through space and matter. Waves will also travel along a cord if you vibrate one end back and forth (Fig.1). The waves move from left to right and then stop. Waves can move over large distances but the water or chord itself has limited movement. Waves carry energy from one place to another. The energy is transported by waves to long distances.

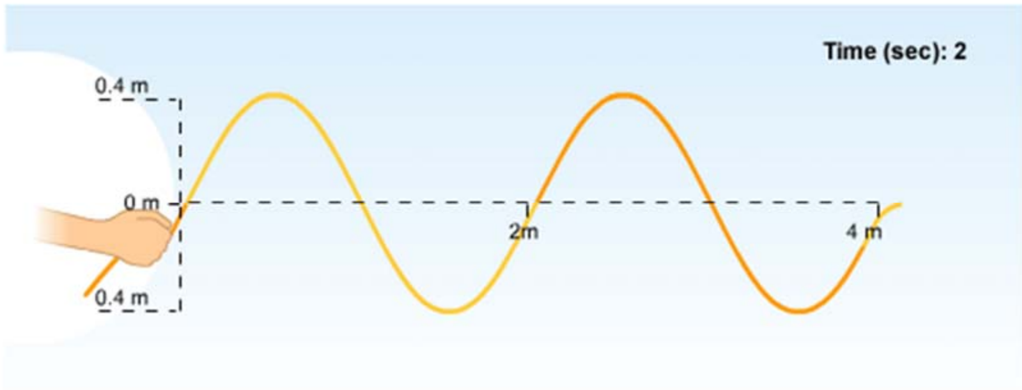

Figure 1: Wave travelling on chord (4).

There are two main types of waves:

1. Mechanical waves
2. Electromagnetic waves

Water waves and sound waves are examples of mechanical waves. Radio waves, microwaves, ultraviolet radiation, x-rays are the examples of electromagnetic waves.

4.http://www.bbc.co.uk/bitesize/standard/physics/telecommunications/communication_using_waves/revision/5/

A continuous wave can be seen in Figure 1. Frequencies can be maintained in various ways such as plucking a guitar string or moving water around. Almost any vibrating object sends out waves (5). Therefore, the source of a wave is a vibration.

The high points on a wave are called *crests* and the low points, *troughs*. The maximum height of a crest is called *amplitude* (A). The distance between two crests is called *wavelength* (λ).The *frequency* (f) is the number of crests (Figure 2).

The wave velocity (v) is the velocity at which crests move forward.

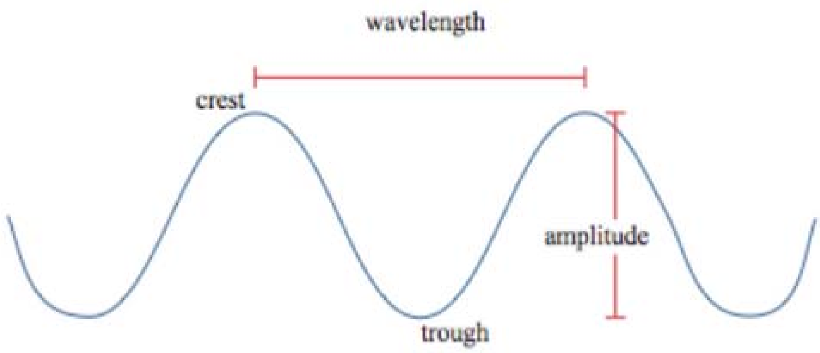

Figure2: Characteristics of single-frequency continuous wave(6).

When a wave travels from left to right as seen in Fig. 1, it is called transverse wave. If the particles of the medium are along the direction of wave's motion, it is called longitudinal wave.

5.http://commons.wikimedia.org/wiki/File:Crest_trough_wavelength_amplitude.png

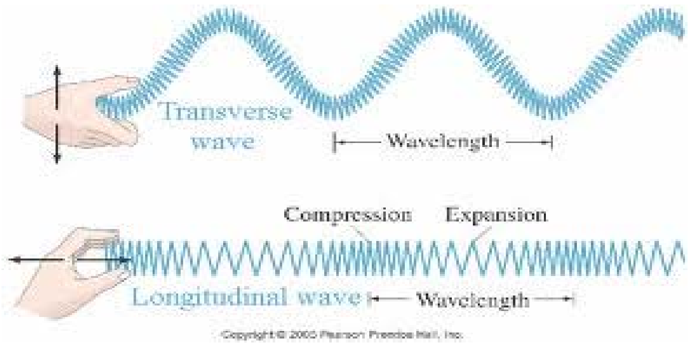

Figure 3: Transverse and longitudinal waves.

2.2 REFLECTION AND TRANSMISSION

When a wave strikes a surface, it changes direction. This is the reflection of the wave. The reflection of a wave pulse is different from when the wave reflects from a fixed end or when the wave reflects from a free end. The reflected pulse returns inverted if the end of the cord is fixed; however, it returns right side up if the end is free. The inversion of the reflected pulse can be explained by returning to our conceptions of the nature of a mechanical wave (6).

2.3 INTERFERENCE

When two waves meet and pass each other, interference occurs. Interference usually refers to the interaction of waves come from the same source or the same frequency. Interference effects can be observed with all types of waves, for example, light, radio, acoustic, and surface water waves (7).

6.http://www.physicsclassroom.com

7.Giancoli, 2008

There are 2 types of interference.

1. Constructive interference
2. Destructive interference

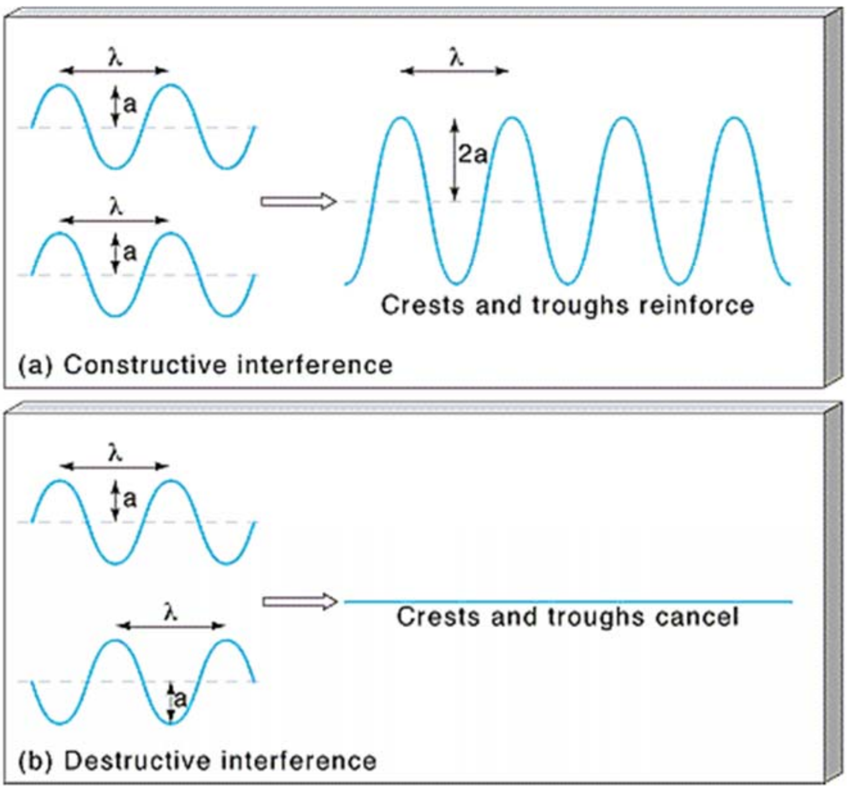

Figure 4: Constructive (a) and destructive interference (8).

Constructive interference is a type of interference that occurs at any location along the medium where the two interfering waves have a displacement in the same direction. They produce a resultant displacement greater than their separate pulse (Fig. 4a).

8.www.pas.rochester.edu

Destructive interference is a type of interference that occurs at any location along the medium where the two interfering waves have a displacement in the opposite direction. Two waves add to zero (Fig.4b).

Interference of incident and reflected waves is essential to the production of resonant standing waves. Interference has far reaching consequences in sound because of the production of "beats" between two frequencies which interfere with each other.

2.4 STANDING WAVES

A standing wave is also known as a stationary wave. Two travelling waves of the same frequency, speed and amplitude move in opposite directions along a string, the two waves will be superposed in such a manner that standing waves will result.

Two waves represented by the equations;

$y_1 = y_m \sin(kx - \omega t)$

$y_2 = y_m \sin(kx + \omega t)$

y_m = amplitude of the wave

ω = angular frequency, measured in radians per second, is 2π times the frequency (in hertz),

k = wave number and measured in radians per meter is 2π divided by the wavelength λ (in meters), and

x and t are variables for longitudinal position and time, respectively.

We can write;

$y = y_1 + y_2 = y_m \sin(kx - \omega t) + y_m \sin(kx + \omega t)$ (Equation 1)

We can show the Equation 1 by using the trigonometric equation for the sum of two sins of two angles in another way.

$\sin B + \sin C = 2 \sin 1/2\,(B+C) \cos 1/2\,(C-B)$

$\mathbf{y = 2\, y_m\ \sin kx \cos \omega t}$ (Equation2)

This is the equation of a standing wave (9).

This equation describes a wave that oscillates in time, but has a spatial dependence that is stationary: sin (kx).x executes simple harmonic motion as the time goes on, all particles have the same frequency. In standing waves different particles do not have the same amplitude but vary with the location x of the particle.

When you vibrate the cord at a specific frequency, the two travelling waves will interfere in such a wave that a large-amplitude standing wave will be produced (10,11). These are called standing waves because they are not travelling. The cord has segments which oscillate up and down in a fixed manner. The points of destructive interference are called nodes. Antinodes are the points of constructive interference where the cord oscillates with maximum amplitude (Fig 5).

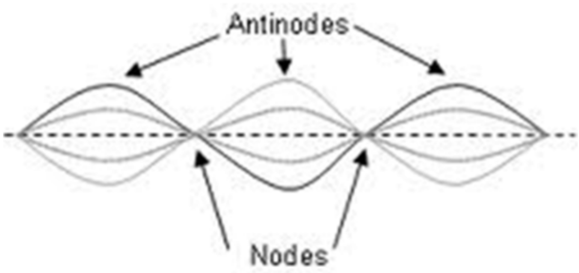

Figure 5: Antinodes and nodes of the wave (12).

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9. Halliday & Resnick, 1970

10.Giancoli, 2008

11.Mansfield,1998

12.www.kwantlen.ca

The nodes and antinodes remain particular frequency. Standing waves can occur more than one frequency.

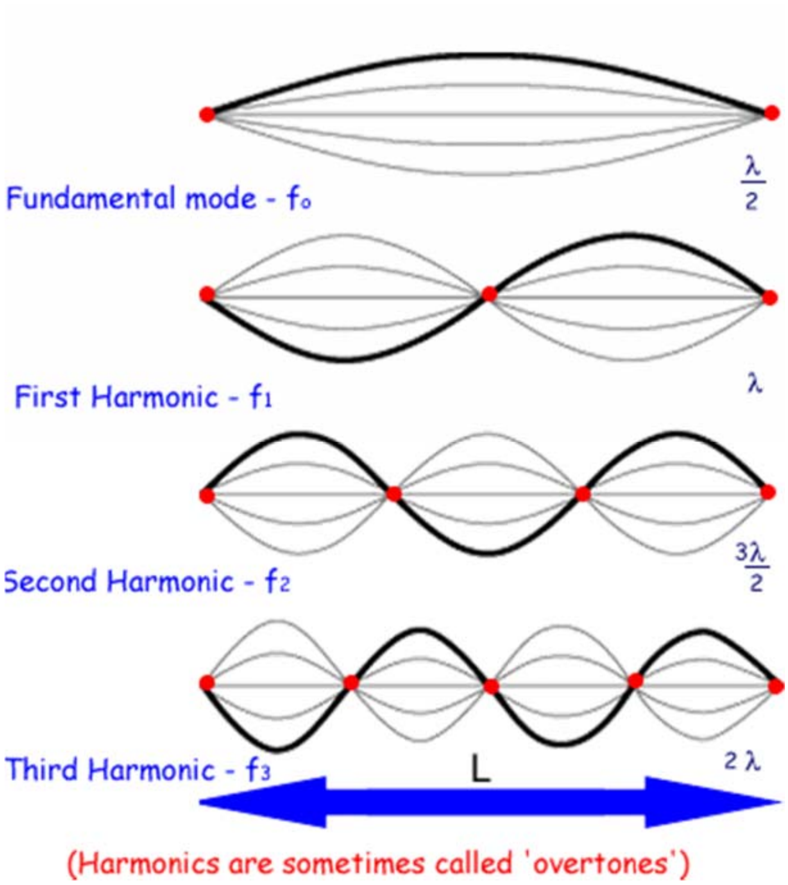

Figure 6: Standing waves corresponding to different frequencies (13).

Standing waves are produced by the natural frequencies or resonant frequencies of the cord. The lowest frequency of vibration that produces a standing wave is fundamental mode. The standing waves shown in first, second and third harmonics are produced twice, three and four times the lowest frequency, respectively (14, 15) (Fig. 6).

Standing waves are the basis of all stringed instruments.

13. www.cyberphysics.co.uk

14. Giancoli, 2008

15.Tripler,1991

1.5. STANDING WAVES ON A GUITAR

The strings on a guitar are all the same length. Each string has a different sound because the strings have different tensions (16).

Sounds are waves moving through the air. All of the standing waves are called harmonics; musical notes are standing waves of specific frequency. Actually, an instrument can play different frequencies at once. The vibrating strings of an instrument cause the air surrounding the instruments' string to vibrate with the frequency of the note played (17). When a string is plucked, a standing wave is created (Fig.8). The vibrations of such a string are called standing waves. They are in relationship with the frequency.

$$v=f\lambda$$

v=speed of the wave (m/s)

f= frequency (Hz)

λ= wavelength

16.Giancoli, 2008

17.http://newton.physics.uiowa.edu

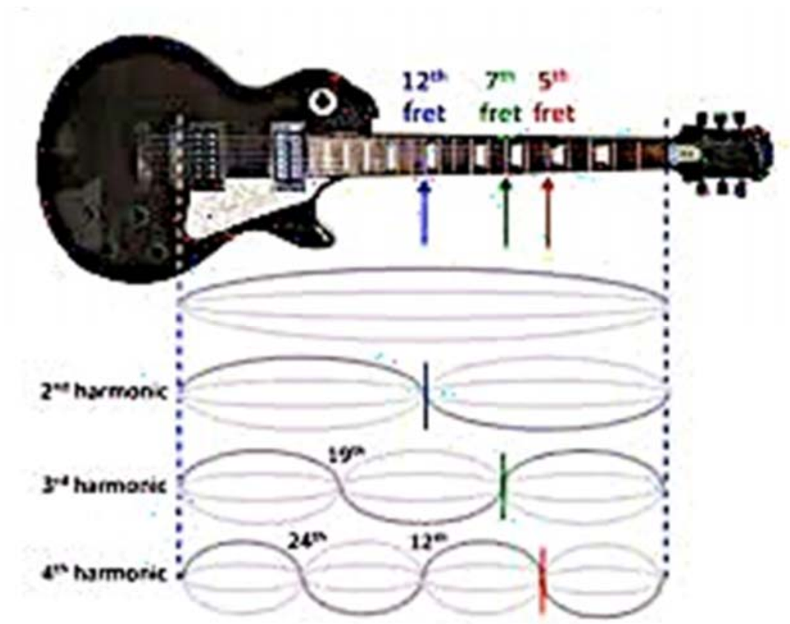

Figure 7: Standing waves on a string; only the lowest frequencies are shown.

In Fig. 7 guitar strings are shown. When a finger is placed on the string of a guitar the effective length of the string is shortened so its frequency becomes higher because the wavelength becomes shorter (18).

2.6 THE FACTORS AFFECTING THE FREQUENCY

Several factors like temperature or pressure can affect frequency. Temperature changes can affect the sound of an instrument in different ways. Warm weather changes effect of the friction between each string.

Researchers are convinced that cooling an instrument can change its tone as well. In their experiment, they freeze a trumpet and flute in -300 Fahrenheit refrigerator for a few

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18.Giancoli, 2008

days. As a result, this showed that the sound comes out lower from the instruments (19).

Other researchers have shown the effect of temperature change on string (violin, guitar), woodwind (flute) and brass (trombone, French horn) instruments. They heated the instruments to the temperature 30 ^{0} C and cooled the instruments to 13 ^{0} C. During the high temperature the stringed instruments pitch is decreased, woodwind and brass instruments pitch are increased. On the other hand, when the instruments cooled, stringed instruments showed higher pitch and woodwind and brass instruments showed lower pitch. Higher pitch is making the tune to be sharp. Therefore, for stringed instruments in high temperature musicians must press harder on the strings to make tune sharper and in low temperatures they have to press lighter to make tune flat (20). Temperature affects the pitch of organ pipes in two ways: the velocity of sound in air is temperature dependent, and the length of the pipe increases as temperature increases (21).

3. AIM

Every sound produced and heard is actually a wave travelling with a frequency. While many people and musicians only focus on the art part of music this essay does otherwise. The aim of this study is to estimate the effect of temperature on the frequency of a guitar string.

4. RESEARCH QUESTION

How temperature affects the frequency of a guitar string and why?

19.Rogers, 2004

20.Lee, 2009

21.Askill, 2007

5. HYPOTHESIS

When a player plucks a guitar string, the player makes the string vibrate hence producing a standing wave; this vibration is transported to the air molecules surrounding the guitar thus a sound is produced.

The sound of each string can be changed easily by only loosening or fastening the string. If it is fastened the sound produced has a higher pitch (higher frequency) if it is loosened the sound produced had a lower pitch (lower frequency).

When a guitar is played in different environments with distinct temperatures, the sound changes noticeably. Because the temperature affects the guitar strings directly by expanding or abbreviating the metal string; this causes the tension on the string to change, so the sound produced changes.

It can be hypothesized that when temperature increases the string increases in length thus the tension decreases so the frequency is lower and when temperature is decreased the string length is decreased thus the tension increases so the frequency is higher.

6. KEY VARIABLES

6.1. CONSTANTS

Guitar String (bronze) (type)

Temperature of Environment (°C)

Humidity of Environment

Heat Source

Distance of thermometer to the Guitar

Initial Temperature of guitar (≅ 25°C)

Atmospheric pressure (assumed to be constant ≈ 1021 mbar in Ankara)

Amount of heat energy given to string per unit time

An ordinary acoustic guitar with bronze strings

Identical Ice Capsules

Plucking distance

Initial tension of string

Distance of Blow Dryer from guitar

6.2 DEPENDENT VARIABLES

Frequency (Hz)

6.3 INDEPENDENT VARIABLES

Temperature (°C) thus Tension of Bronze String

7. MATERIALS

- An ordinary acoustic guitar with bronze strings
- Bosch PTD 1 Laser Radiation Point Thermometer
- Blow dryer
- Identical Ice Capsules
- Oven Paper
- A pick
- A Ruler: to control the plucking distance
- Strobe Tuner: for frequency measurement

8. METHOD

1. A guitar string is plucked from a stretching distance of 0.5 cm and the frequency of the string is determined with the strobe tuner.

2. In order to heat up the string; a blow dryer is gazed upon the string with a constant distance for 10 minutes.

3. The string temperature is increased to approximately 25, 32 and 41 degrees Celsius and the frequency measurements are noted to the data sheet.

4. After this process guitar string is cooled and again frequency measurements are done with the strobe tuner.

5. In order to decrease the temperature of the guitar string and the air around the string, ice capsules of identical lengths (approx. 30 cm) are put on top of the strings, 10 minutes for each trial.

6. The string temperature is decreased to approximately 18 and 11 degrees Celsius and the frequency measurements are noted to the data sheet.

7. The process is repeated 5 times to make the readings more precise and accurate.

9. DATA COLLECTION

In this study, the effect of temperature on the frequency of a guitar string is determined. To investigate the effect of temperature on frequency, guitar string is heated and cooled between the temperatures 11, 2- 41, 5 °C and frequency data were measured and noted to the data sheet.

All quantitative data are given in Table 1. The experiments were done in five different temperatures and the frequency measurements were taken in these temperatures. Values which are represented in Table 1 are 5 individual experiment's results. The last column of the table shows the Mean ± Standard Deviation (S.D.) of these experiments. Temperature 25,1 °C is room temperature. The uncertainty of the thermometer is ± 0.001°C.

During data analysis One-way analysis of variation (ANOVA) test by SPSS is used to compare the means of all groups. In Graph 1, the results of One-way ANOVA are shown only for the room temperature (25, 1 °C). It is marked with *****.

On the other hand, correlation between the temperature and frequency is also analyzed by using SPSS data analysis. The result of the correlation analysis is shown in Graph 2.

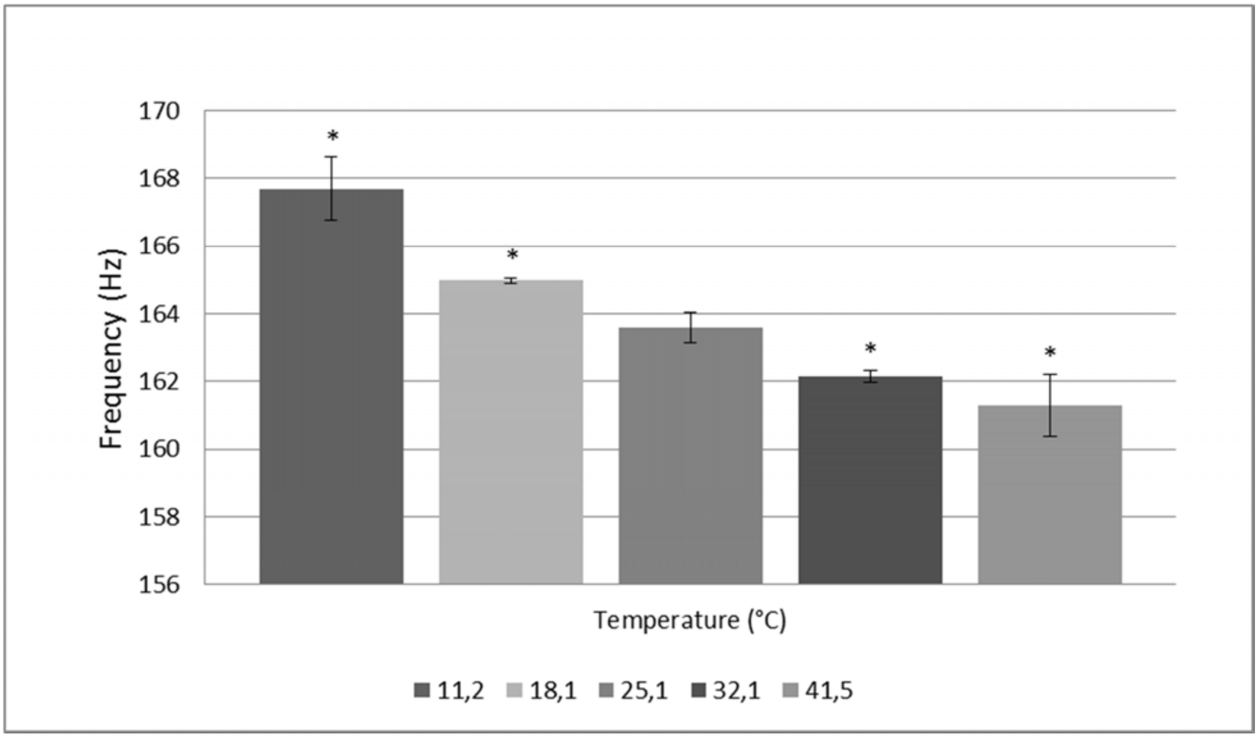
10. DATA PROCESSING AND PRESENTATION

All the data are shown in Table 1 and the results are given in Graph 1. The correlation analysis results are shown in Graph 2.

Table 1: Guitar string frequency (Hz) changes according to the temperature (°C).

	Frequency (Hz)					
Temperature ± 0.001 (°C)	**Test 1**	**Test 2**	**Test 3**	**Test 4**	**Test 5**	**Mean ± S.D**
11.200	169.11	167.82	166.98	166.74	167.86	167.70 ± 0.93
18.100	164.98	164.87	165.11	165.01	164.91	164.98 ± 0.09
25.100	163.24	163.19	164.20	163.36	163.97	163.59 ± 0.46
32.100	162.19	161.98	162.20	162.36	161.97	162.14 ± 0.17
41.500	160.28	161.38	162.76	160.98	161.12	161.30 ± 0.91

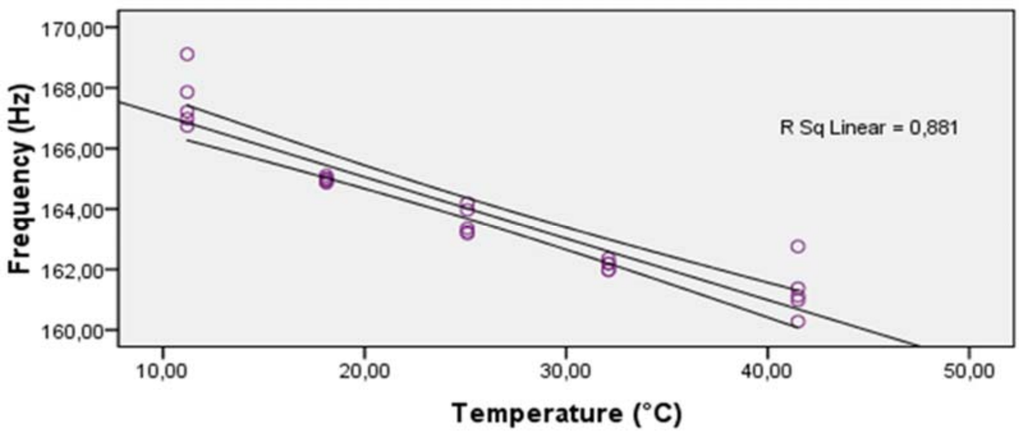
Values represented mean ± SD are 5 individual experiments.



Graph 1: Guitar string frequency (Hz) changes according to the temperature(°C).

* Significantly different according to the room temperature ($p<0.05$) .

As seen in Graph 1 the frequency of a guitar string decreases as temperature increases. By testing the data using the method of one way ANOVA the results are classified as significant and precise ($p<0.05$). In the graph the statistics of this experiment have been indicated with the symbol *. The only data that can not be classified as completely meaningful is between 41.5 and 32.1 ($p>0.05$). However every other data is completely significantly meaningful ($p<0.05$).



Graph 2: Correlation graph of the effect of temperature on frequency ($p<0.001$).

With the established correlation an inverse proportion between frequency and temperature can be established. The correlation shows that there is a meaningful proportion between these two variables ($p<0.001$). Because the R test gives a result of

0.881 we can assume that the data is almost completely linear (R Sq Linear = 1 means that the numbers are completely linear). Thus the fact that temperature increase decreases frequency is accurate information.

11. CONCLUSION

The data collected throughout the experiment concluded that the hypothesis is true. Likewise, the statement that frequency and temperature have a relationship where they are inversely proportional is true.

There is a direct correlation between the expansion of the bronze guitar string and the frequency. The expansion constant (changes due to type of material) determines how much of a change in frequency could happen when a stringed instrument is put into different environments with different temperatures. As the expansion increases Δ f (change in frequency) increases accordingly.

This is the main reason most musical instrument get old and become less useful every day. By changing the location of an instrument constantly the string undergoes expansion and abbreviation and it ware out. This is why importable instruments such as piano need less tuning (approx. 7 years at a time) while guitars need tuning approx. every other day.

During this experiment some random and systematical errors were present thus in further researches on this subject changes must be made so that the experiment is more professional.

To improve this experiment;

- A more isolated environment could be established or the experiment could be done in a laboratory in order to decrease any loss of energy and to decrease the amount of disturbance.
- A different heating technique could be used in order to homogenize the spread of heat on string thus making the results more accurate perhaps connecting the string to a electrical system and heating it up with a voltage.
- Although it is a limitation because the experiment would become expensive: different guitars of identical strings could be used in order to make the readings more precise and have more data.

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13. APPENDIX

1.1. CALCULATIONS BASED ON THE TEST RESULTS

The line in Graph 2 suggests a direct correlation between frequency and temperature. Thus a formula can be established using simple functions.

Every line has an equation of;

$F(x) = mx + n$

$F(x)$ = function itself (dependent variable y)

m = slope

x = independent variable

n = number due to the change of the function.

Slope (m) is the ratio of the change in y value to the change in x value.

In order to establish the slope shown as m in the previous equation the change in y value according to data should be divided in to corresponding change in x value.

The change in y values is calculated by having the difference between max value and min value.

167.7-161.3 = 6.4

The change in x values is:

41.5-11.2 =30.3

Thus the slope would be:

6.4/30.3= 0.21122112…

So the formula would be as follows:

f (x) = 0.x + n

And by putting in any value the number n can be found.

x=11.2

167.7=0.*(11.2) + n

n=165.3343234165.33

The final equation would be (in function form):

f(x)= 0.x + 165.33

When substituted with the actual variables:

F= 0.T + 165.33

F= the frequency of the bronze guitar string (Hz)

T= the temperature of the bronze guitar string (^{0}C)

To test the formula the data readings can be put into the equation and tested to see if the results are identical.

For example when T (x) is 11.2 the F should read approximately 167.7:

F=0.*(11.2) + 165.33

=167.69 167.7

Here the same result is approximately established thus the formula is valid.

When the formula is used for every data, nearly equal results are established. The reason that the results are not directly equal is because the data are not completely linear hence R Testing being 0.881 and not 1. However, since near results can be established by using the formula derived above the data can be seen as precise.

In addition this formula was derived according to the guitar used in the experiment thus it might not have a common use among different types of guitars but guitars and guitar strings identical to the one that was used would have similar data.