DESIGN, CONSTRUCTION, AND THE TESTING OF AN ELECTRIC MONOCHORD WITH A TWO-DIMENSIONAL MAGNETIC PICKUP

by

Michael Dickerson

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Abstract

A single-string instrument (monochord) was carefully designed and constructed to test a new prototype of a two-dimensional magnetic pickup. The objective of the research was to design the new transducer which would depict a more meaningful signal analogous to the two-dimensional vibration of the string.

The monochord and 2D pickup were designed with much specification and detail. However, the testing of the output power spectra and frequency response functions to validate performance proved insufficient. Although the results were inconclusive, extensive progress was made toward determining the correct methods needed to test the true performance of the pickup and can be continued.

Introduction

The objective of this research was to design a monochord, a single string instrument, and determine if a two-dimensional magnetic pickup produces an analogous signal that accurately represents the actual vibration of a string than a typical one-dimensional pickup. The frequency response functions and power spectral densities of the system were compared. After all the experiments are completed, the monochord will be handed over to the BYU physics department for use as an in class demonstration.

Monochord

Since the time of Pythagoras, the monochord was used to mathematically describe musical pitch.[1] Essentially, a monochord can demonstrate several characteristics of a standing wave. To allow complete analysis of the standing wave the string on the monochord is fixed at both ends. Additionally, a moveable bridge is located on the monochord to allow change in the length of the string. Monochords allow the evaluation of several properties of a vibrating string, including wavelength, frequency, amplitude, phase, number of nodes and antinodes, speed of propagation, different modes, and string length. Knowing the specific characteristics of the string allows for more thorough easier evaluation.

Generally, the body of most plucked string instruments radiates the energy of the excited string. The monochord is no exception. While most monochords are constructed with hollow wooden bodies (allowing for sound radiation), the monochord constructed for this project has been made from solid aluminum.

Therefore, the constructed body was not designed for the purpose of resonating and radiating, but more specifically designed as an electric monochord that can withstand high amounts of tension. The aluminum construction will also tolerate extensive handling, demonstrations, and experiments by other students and professors. Furthermore, it can accommodate several different lengths of instrumental strings including guitar strings, bass guitar strings, and piano strings. In addition, it can accommodate a total of six strings simultaneously. For the purpose of this experiment, the effective length of the string is 25.5 inches, based on the length a Les Paul Gibson guitar.

The Magnetic Pickup

Since the development of the electric guitar in the 1930's, the concepts regarding magnetic guitar pickups have altered very little. The basic principle behind a magnetic pickup is the conversion of mechanical energy into electric energy.[2] A magnetic pickup measures the velocity of the vibrating steel string and is proportional to the voltage that is produced by the varying magnetic flux.[3] It consists of a magnetized iron core wrapped inside a copper coil. Magnetic field lines flow through the coil and through a small section of the steel string. When the string is at rest, the magnetic flux is constant. However, when the string is plucked, the flux changes and induces an electric voltage in the coil. This plucked string induces an alternating voltage at the fundamental frequency of the string, where the voltage is proportional to the velocity of the string's motion (not its amplitude). The voltage depends on the string's thickness and permeability, the magnetic field, and the distance between the magnetic field and the string.

2D Guitar Pickup

In recent years Freed and Isvan, were among the first to study various new multi-axes, multi-string transducers. "Using pole pieces with a laterally asymmetric geometry…[they] created a pickup where perpendicular motions produce in-phase output in each coil and lateral motions result in out-of-phase signals"[4] (see *Figure 1)* . They discovered "by summing and differencing the two pickup output signals, a good estimate of horizontal and vertical motion can be obtained."[4]

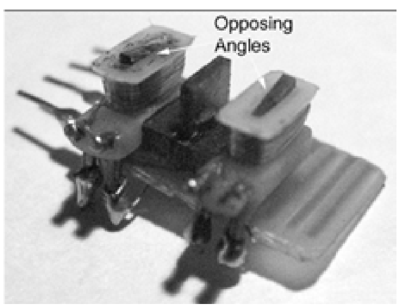

Figure 1: Freed and Isvan's designed multi-axes guitar pickup.

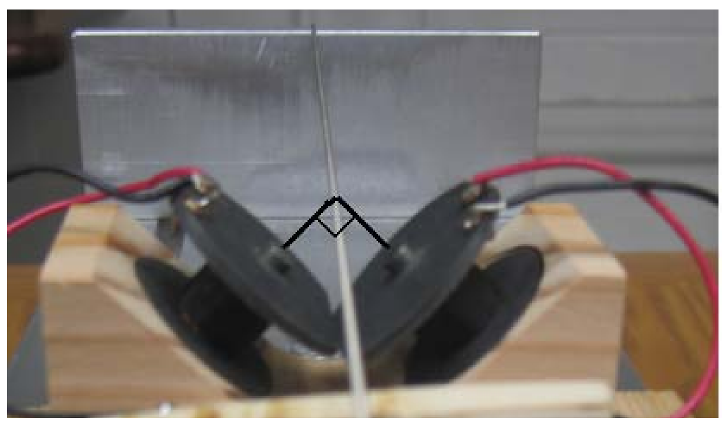
Figure 2: The two-dimensional guitar pickup designed for the experiment.

As shown in *figure 2*, a new two-dimensional magnetic guitar pickup was designed for this research project in anticipation of capturing all the transverse propagating modes of a guitar string. Orienting the magnetic pole pieces orthogonal to each other, each pickup captures the velocity of the string according to its own axis. For this experiment the x and y axes of the string were excited by the shaker and are observed by the two-dimensional pickup. The orthogonality of the pole pieces is denoted by the right angle superposed on the photograph. Using a spectrum analyzer, the power spectrum and frequency response of each individual pickup was recorded. Analyzing the graphs of retrieved data, a correlation can be noted between both pickups and the string's vibrational behavior.

Experimental Methods

Equipment

In order to obtain the anticipated results, several procedures preceded the actual experiment. First, a monochord was carefully designed and specified in SolidWorks (*Figure 3*). The file was then transferred to a Computer Numerical Control system where the body and several other components of the monochord were constructed entirely of aluminum. A tuner piece and two bridges were designed then fashioned on a machining mill. The entire design and development of the monochord (*Figure 4*) required a total of 100+ hours, making them the major components of this project.

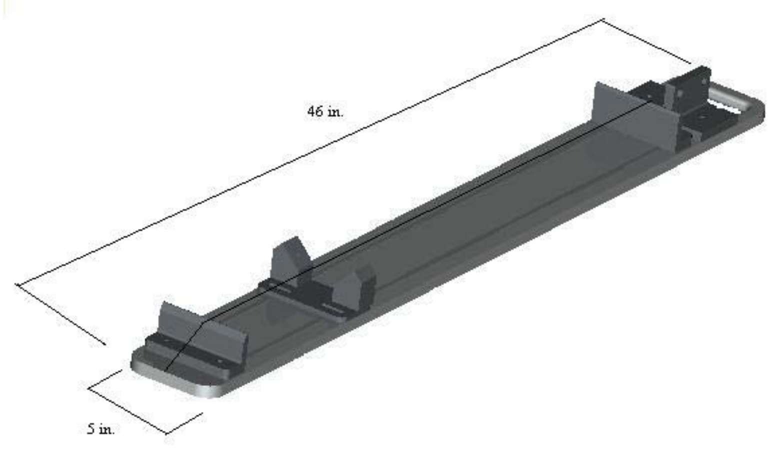

Figure 3: The SolidWorks monochord design for the experiment.

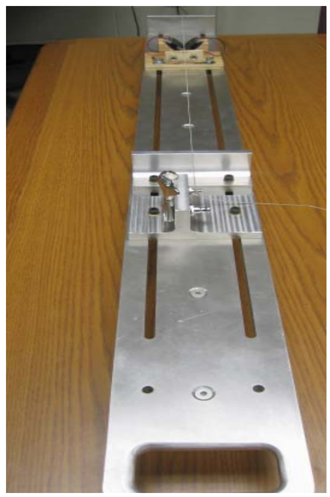

Figure 4: The final manufactured monochord.

A two-dimensional guitar pickup was designed based in part on previously designed pickups from manufactures. Most magnetic pickups are designed with an artistic point of view rather than a scientific procedure. A magnetic pickup looks like a RLC circuit. For simplistic reasons the inductance was neglected and the pickup was designed based on the resistance of previous guitar pickups. To create this pickup, two single coil Alinco V magnets were wound with 42 gauge pickup coil wire. These two magnets were labeled pickup #1 and pickup #2 for simplicity.

Next, the resistance needed to be calculated in order to determine the number of turns required for the wire to be wrapped around the magnet. Typically, magnetic pickups have six magnets wrapped together with an overall wire resistance of approximately 6kΩ. The desired resistance of this 2D pickup was around 1kΩ because of the inclusion of only one magnet. In order to determine the resistance needed for this 2D pickup, the following equation was used: $R = \rho\ell / A$, where ρ is the resistivity, ℓ is the length of the wire, and A is the cross sectional area. The resistivity of copper (ρ) was found to be 1.72×10^{-8} Ωm. The variable A was calculated to be 1.8×10^{-5} m^2. Finally the length of ℓ was calculated to be 182.7 m, which calculates to about 6000 turns at 250 revolutions per minute for 24 minutes. The actual measured resistance for pickup #1 and #2 were 0.958kΩ and 0.963kΩ respectively.

In order to create an in-phase 2D pickup, each magnetic pole piece was similarly polarized (illustrated in *Figure 5*). Each pickup's copper winding was wound in the same direction. However, once set up on the 2D pickup mount, the similar poles repel each other, thus creating an out-of-phase signal. Once the pickups were wired to the ¼ inch receptacle and positioned at a 45 degree angle to the string (or orthogonal to each other), the polarity of pickup #2's wires were reversed to produce an in-phase constructive signal. For this experiment, each pickup was connected separately to the spectrum analyzer.

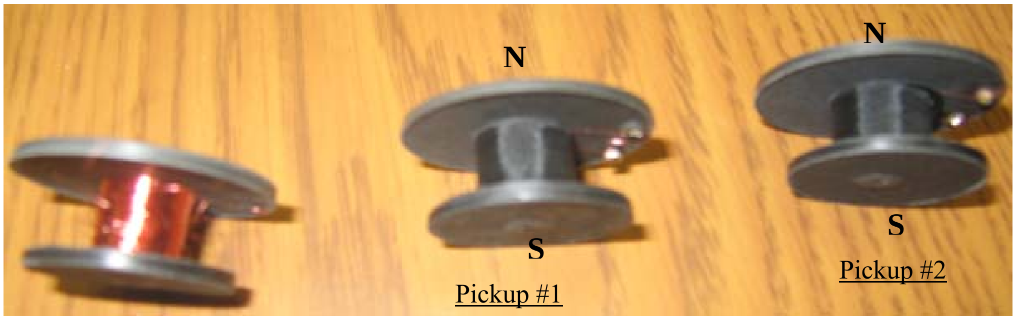

Figure 5: Uncovered magnetic pickup, magnetic polarity of Pickup's #1 and #2.

Spectrum Analyzer and MatLab

Finally, to record the power spectrum and frequency response function a Hewlett Packard Spectrum Analyzer was used. For the frequency response channel 1 analog input was designated to receive the specified 5V voltage output sent from the source output. The source was also connected in parallel to a shaker. Channels 2 and 3 inputs were consequently designated to receive the voltage outputs from each individual pickup. A simple MatLab code was created to post process the recorded information.

Procedure

The 2D magnetic pickup was placed at several different locations on the monochord ranging between 1 and 5 inches from the bridge. Each pickup was connected to a channel on a Hewlett Packard spectrum analyzer through a bnc coaxial cable. *Figure 6* shows the experimental setup. The string was tuned to 83 Hz to replicate the low E on an electric guitar. To obtain the power spectrum, the string was plucked once at a specified position. The analyzer was then started and averaged the strings vibrations linearly over fifteen seconds.

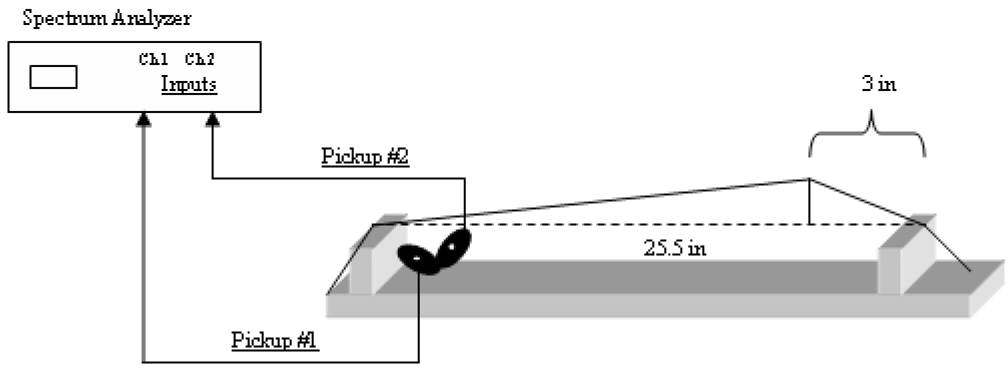

Figure 6: Experimental setup of the monochord and pickup positioning to obtain the power spectrum.

For the actual process of retrieving the frequency response of the system, a broadband random signal of 5 peak volts was sent through the output of the analyzer to a Ling Dynamic System shaker and to the input of Channel 1. Pickup #1 and pickup #2 were connected to the inputs of Channel 2 and Channel 3 respectively. (*Figure 7)*

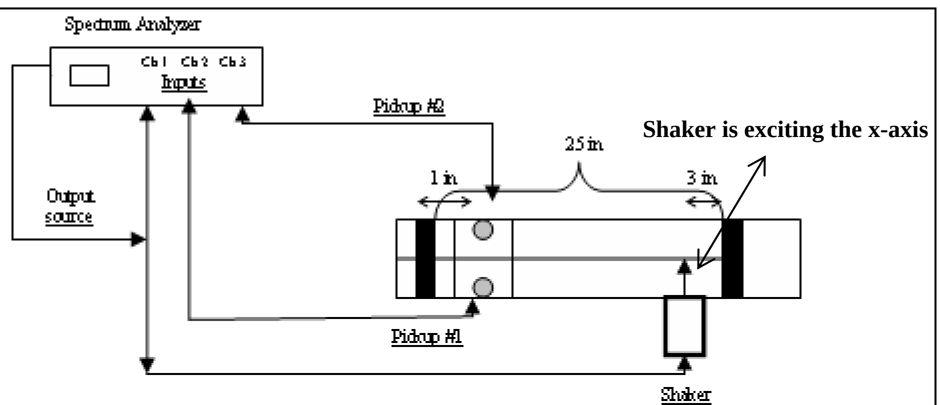

Figure 7: Experimental setup of the monochord and pickup positioning. The effective length of the string is 25.5 inches.

Both the shaker and the 2D pickup were placed at multiple positions along the monochord. The shaker was super-glued to the string in either the x or y axes (depending on the measurement) and thus excited the string in that particular axis. Looking at the monochord from a birds eye view the x-axis is going up and down, indicated in *Figure 7*. The y-axis would be going in and out of the page. *Figure 8* shows the axes relative to the string. At each position, the frequency response was recorded. Multiple measurements were taken from different positions of the shaker and the pickups.

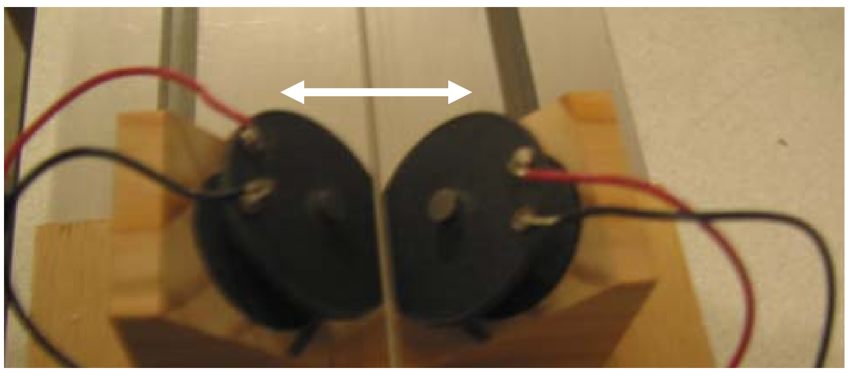

Figure 8: The x-axis of the string is perpendicular to the pickup. The y-axis is going in and out of the page.

Results

Power Spectrum of Pickup #1 and #2

The files recorded by the spectrum analyzer were loaded into MatLab, where the power spectra and frequency response functions were graphed and plotted between 0 to 1600 Hz (the frequencies of particular interest). The pickup was positioned 3 inches from the bridge and plucked 5 inches from the head (*Figure 6* shows plucking at 3 inches) of the monochord; the results are graphed in *Figure 9*. Looking at the power spectrum for Pickup #1 the fundamental frequency of 83 Hz was noted. The harmonics were excited up to 1000 Hz. The predominant peak on the graph is at 249 Hz. The first peak on the graph occurs at 71 Hz which might be linked to a distortion on the plucked string. Other harmonics can be seen after the initial 71 Hz that come from that frequency. Further investigation is required to better understand this secondary harmonic series.

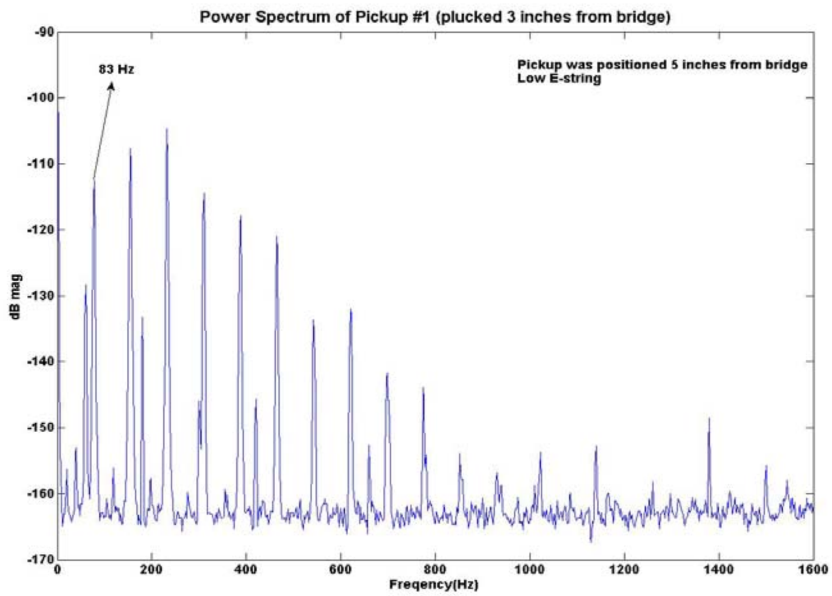

Figure 9

In *Figure* 10, Pickup #2's power spectrum shows that the fundamental frequency is again 83 Hz. The predominant frequency is the second harmonic at 166 Hz. The dominant frequency can be associated to the number of times the string passes over the magnet. The harmonics are excited in different patterns based on pickup placement and plucking position.

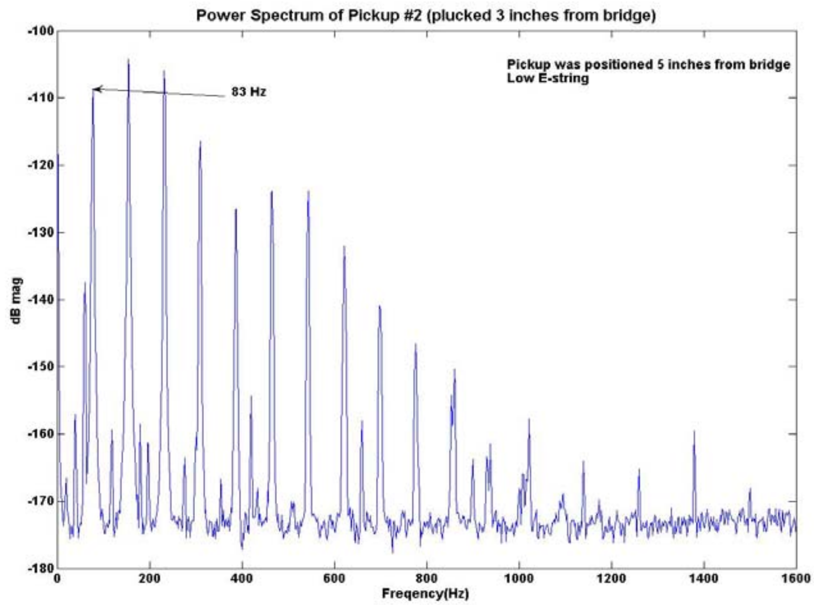

Figure 10

.<u>Frequency Responses of the system</u>

Figure 11 shows the frequency response and coherence of the system for Pickup #1 with the string excited by the shaker in the x-axis 3 inches from the head of the monochord. For this system the coherence is generally good. The frequency response shows all the harmonics excited by the broadband signal starting at 83 Hz. Around 900 Hz there is a significant drop which could be attributed to a node of the system. The pickup doesn't pick up that particular frequency as well as the lower frequencies.

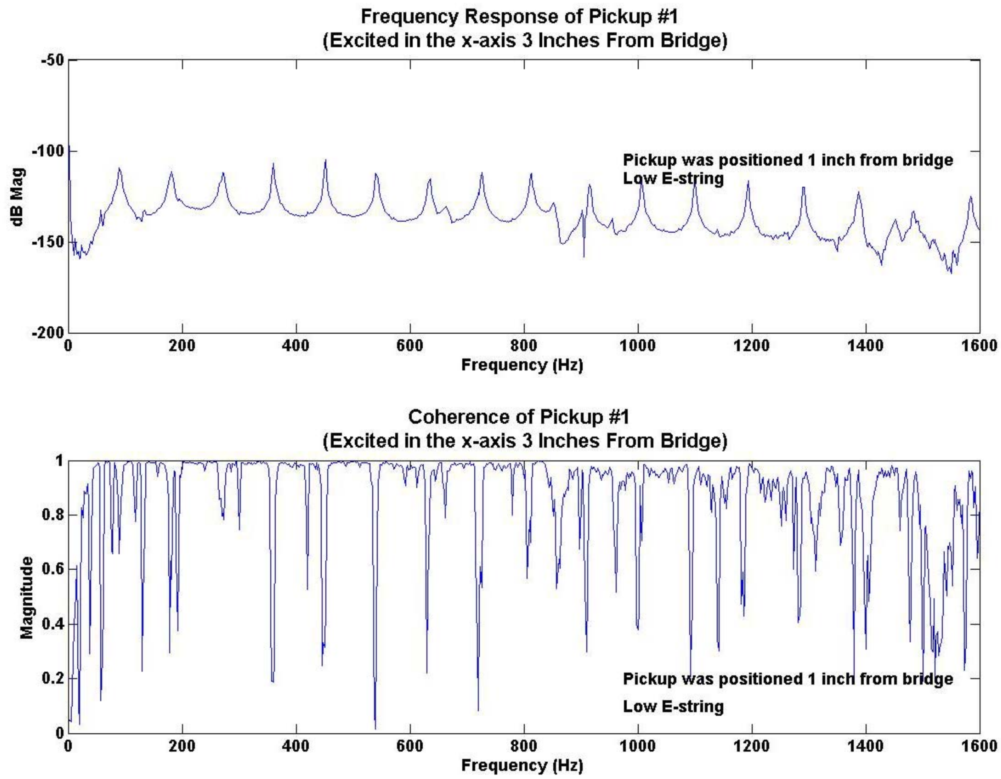

Figure 11

Figure 12 shows the frequency response and coherence of the system for Pickup #2 with the string excited by the shaker in the x-axis 3 inches from the head of the monochord. The coherence is not as good as in *Figure 11*, but the frequency response again shows the multiple resonances excited by the signal. Around 650 Hz there is a possible node of the system. In both *Figure 11* and *12*, the fifth harmonic was the predominant frequency noted in the system.

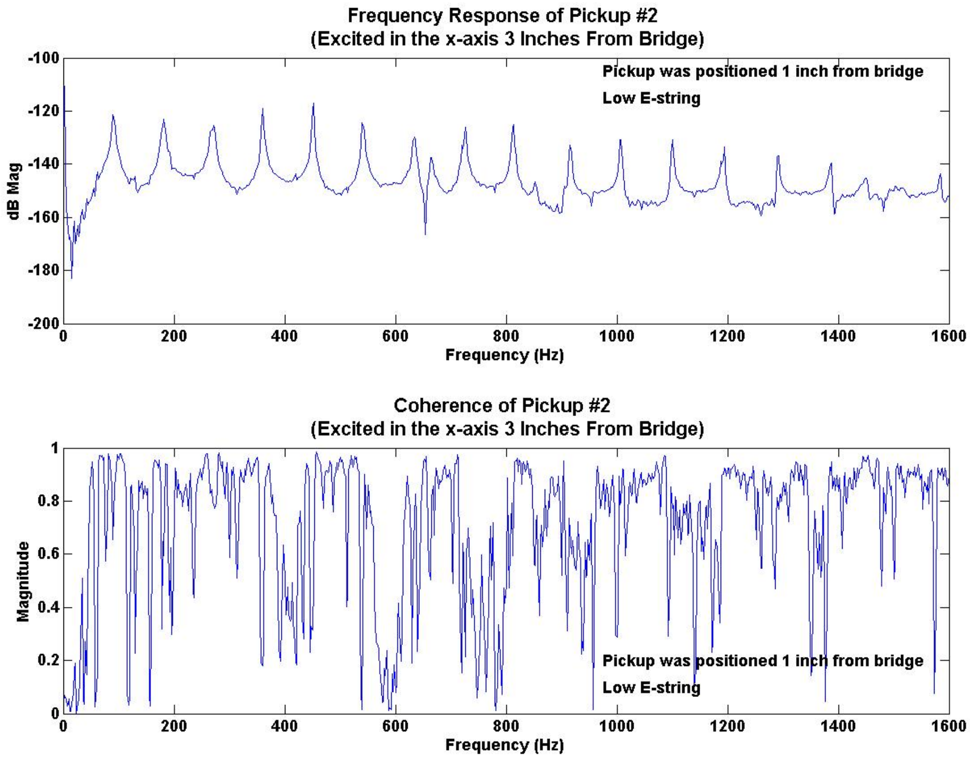

Figure 12

Figure 13 shows the frequency response and coherence of the system for Pickup #1 with the string excited by the shaker in the y-axis 3 inches from the head of the monochord.. Unfortunately, the coherence measured is the poorest out of all the measurements taken. It is believed that the signal to noise ratio was low and Pickup #1 was possibly placed at a greater distance from the string than Pickup #2. It is also possible that a cable might have hit the string during the measurement. Another possibility is that during the experimental process, the shaker could have become unglued, thus causing an invalid frequency response.

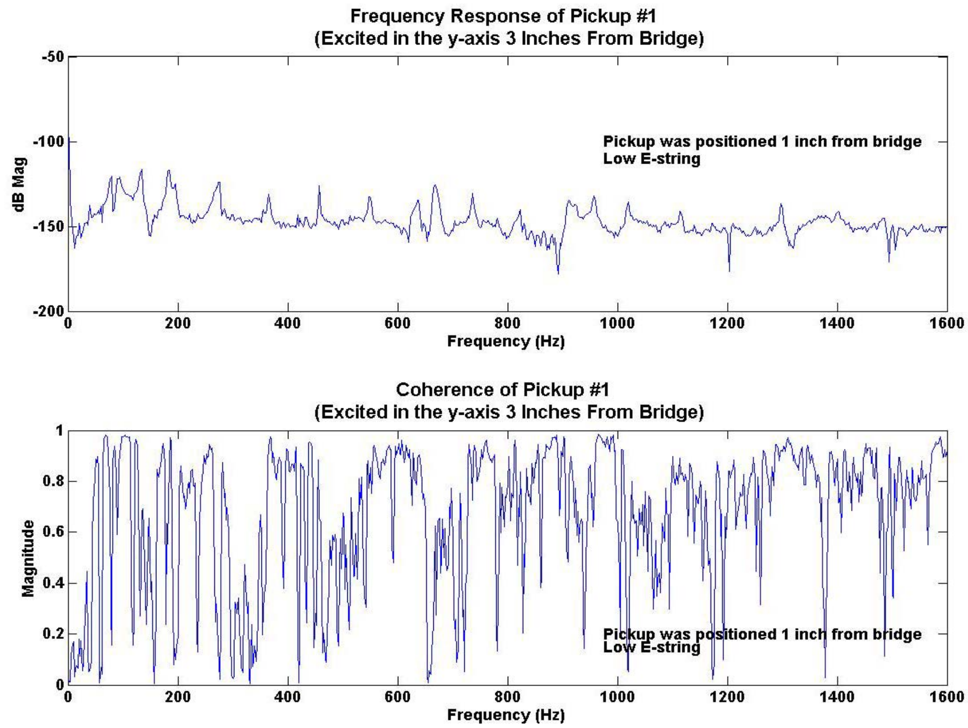

Figure 13

Figure 14 shows the frequency response and coherence of the system for pickup #2 with the string excited by the shaker in the y-axis 3 inches from the head of the monochord. The coherence is better than the coherence in *Figure 13*. The predominant frequency is the second harmonic. There are many notable troughs in the frequency response of *Figure 14*. The dashed arrows show that at those frequencies the coherence is good.

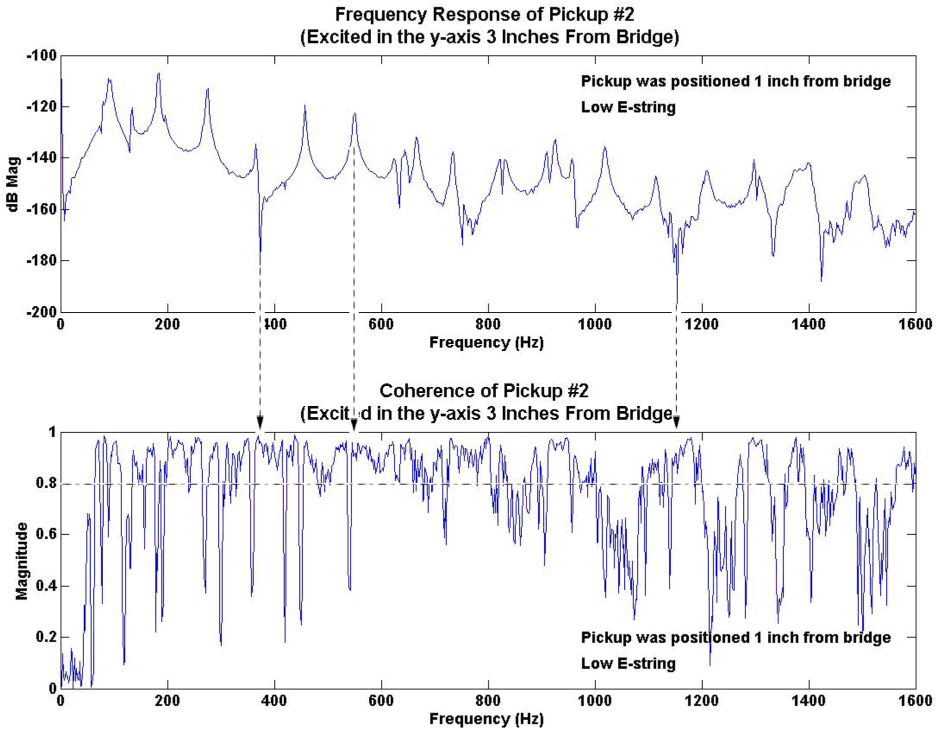

Figure 14

Discussion

The measured frequency response functions are heavily dependent upon the string. The measured frequency response functions in the x-axis fell within the expected range. There was good coherence noted where each harmonic peaked on the x-axis. In the y-axis, the measurements need to be retaken and reprocessed. *Figure 14* shows a reasonable frequency response while *Figure 13* shows a frequency response that is inconclusive. In order to have better comparative results, several measurements with different types of pickups would be needed. It is possible that different harmonics did not peak on the graph due to experimental error such as hitting the string while a measurement was being made, or the shaker becoming unglued.

For future studies, it is essential to have better laboratory control to obtain more accurate and precise results. In order to reduce errors in determining the frequency response functiond and power spectra of the pickups, a better experimental setup would be needed. The frequency response of the each pickup is dependent in part on the inductance of the RLC circuit. A more in-depth study of each pickup would be needed in order to find the resonance frequency (ω_o) of each pickup. The equation to find ω_o is $\omega_o = \frac{1}{\sqrt{LC}}$ where L is the inductance and C is the capacitance. Unfortunately, time did not permit the calculation or actual measurement of the inductance of the pickup. The equation to calculate L of a solenoid is $L = \frac{\mu N^2 A}{\ell}$, where μ is the permeability of the Alinco V magnet, N is the number of turns of wire, A is the cross sectional area of the magnet, and ℓ is the length of the magnet. . Furthermore, the known permeability (μ) of an Alinco V magnet would need to be found.

Another measurement that would aid in determining if the pickup actually represents a more accurate signal would be to measure the frequency response of each pickup individually (without a string). For future studies, the output voltage as well as the magnetic field could be measured in order to determine the sensitivity of the pickup. In order to further determine whether a 2D pickup actually receives a better or more accurate signal than a traditional pickup, a time wave signal could be recorded, compared, and analyzed.

The products of the project, the monochord and 2D pickup, were designed with much specification and detail. The magnetic pickup is believed to produce and depict a more useful analogous signal than a traditional pickup. However, the tests that were performed were insufficient to asses the true value of the design. Although the results were inconclusive, extensive progress was made toward determining a path and methods needed to better system. I encourage further research on this topic.

Appendix

MatLab code for post processing

```
close all

clear all

frequencyres=load('FS5.txt');
y=load('FS5.x');
figure
subplot(2,1,1)
plot(y,frequencyres)
s=sprintf('Frequency Response of Pickup #1 \n (Excited in the x-axis 3 Inches From
Bridge)');
title(s,'FontSize',16,'FontWeight','bold')
xlabel('Frequency (Hz)','FontSize',14,'FontWeight','bold')
ylabel('dB Mag','FontSize',14,'FontWeight','bold')
set(gca,'XLimMode','manual','YLimMode','manual','FontSize',14,'FontWeight','bold')
text(975,-105,'Pickup was positioned 1 inch from
bridge','FontSize',14,'FontWeight','bold')
text(975,-115,'Low E-string','FontSize',14,'FontWeight','bold')

coherence=load('CO23.txt');
y=load('CO23.x');
subplot(2,1,2)
plot(y,coherence)
s=sprintf('Coherence of Pickup #1 \n (Excited in the x-axis 3 Inches From Bridge)');
title(s,'FontSize',16,'FontWeight','bold')
xlabel('Frequency (Hz)','FontSize',14,'FontWeight','bold')
ylabel('Magnitude','FontSize',14,'FontWeight','bold')
set(gca,'XLimMode','manual','YLimMode','manual','FontSize',14,'FontWeight','bold')
text(975,.2,'Pickup was positioned 1 inch from
bridge','FontSize',14,'FontWeight','bold')
text(975,.1,'Low E-string','FontSize',14,'FontWeight','bold')
```

References

[1] www.wikipedia.com, 11/20/2005

[2] W. Stanton, "Present-Day Developments in Magnetic Pickups," *J. Audio Eng. Soc.*, vol. 3, pp. 70, (1955 Apr.).

[3] W. Strong and G. Plitnik, *Music Speech Audio*, pp.45, (1992).

[4] A. Freed and O. Isvan, "Musical Applications of New, Multi-axis Guitar String Sensors," *CNMAT*, www.cnmat.berkeley.edu/Research. pp.1-4, (2000).