Vibrational Analysis of Guitar Bodies

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ABSTRACT

Understanding how a guitar vibrates could aid manufacturers in shaping the tonal characteristics of their instruments. In this paper, a method for investigating the resonant frequencies of guitar bodies is detailed. This method uses piezoelectronic transducers to convert vibrations on the surface of a guitar into an electrical signal that can be analyzed by a PC-based DAQ system. Resonances at 90 Hz, 180 Hz, and 786 Hz were discovered on the body of a 1968 Gibson J-45 Acoustic. Also, a resonance was discovered at 325 Hz on an Ibanez RG570 solid-body electric guitar. The results suggest that electric guitars do not vibrate in the same way as acoustic guitars. In addition, no harmonic relationships were found among resonance frequencies.

I. Background and Introduction

Understanding how a guitar vibrates is a very complex problem. A number of factors affect vibrations within the guitar. For example, the finish, bridge placement, and type of wood are just a few of the parameters, affecting vibrations. In this summer project, an analysis was attempted on finding resonant frequencies on two guitars: a 1968 Gibson J-45 acoustic and an Ibanez RG570 solid-body electric.

Studies have been attempted over the years in modal analysis, the study of modes of vibration. Recently, a group at Kettering University, under the leadership of Dr. Dan Russell, studied the vibrations of several Gibson electric guitars. Their method required striking the guitar with a specially tuned force hammer and picking up the vibrations with an accelerometer. This data was then analyzed with a sophisticated software package. Their work inspired our group to pursue this same analysis, but with a different approach. The method used at Kettering did not provide vibrational phase information. The method used in our project does provide such information along with amplitude of vibration.

In this paper, the experimental setup and method are detailed. Also, results and conclusions from the research are discussed.

II. Experimental Setup and Method

Three experimental methods were used to investigate the vibrational properties of guitar bodies. Specifically, analyses were performed using a frequency spanning method, a one frequency mapping method, and a white noise method. The three procedures were used together to obtain the resonance frequencies of each guitar studied. Further explanation will

provide insight into the details of our methodology.

A. DAQ Setup

The setup for obtaining data on the vibrations of guitar bodies included a computer, function generator, power supply, lock-in amplifier, and piezoelectronic transducers. Refer to figure 1 for a diagram of the DAQ setup.

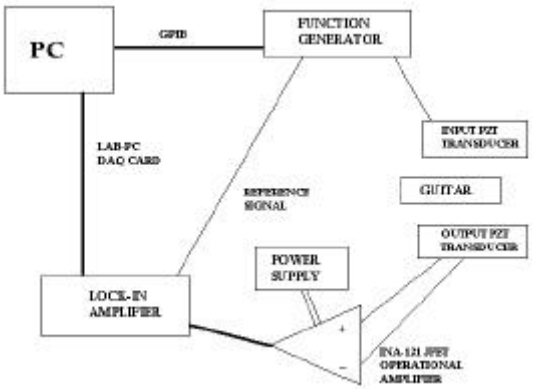

Figure 1: DAQ Setup

i. PC

The main component of the DAQ setup was the PC. The PC enabled data collection, equipment control via GPIB (General Purpose Interface Bus), and data analysis. Two data acquisition programs written in *Lab Windows/CVI* by Dr. Steve Errede enabled this experiment to proceed. The programs were called *Sonic1* and *Resonant1*. The software instructed the function generator via GPIB to send out a sine wave of a certain frequency and amplitude into the transmit PZT. Once the signal had passed through the setup, it returned to the PC via a Lab PC-DAQ card. The program recorded all data received, and provided a user interface for creating plots of Vtot, Vreal, Vimag, and Vphase. Both *Sonic1* and *Resonant1* used this method of data acquisition; however, *Sonic1* recorded a frequency span in one position on the guitar whereas *Resonant1* recorded data at one frequency and several locations on the guitar.

ii. Piezoelectronic Transducers (PZT)

A piezoelectronic transducer, a ceramic crystal, creates a voltage when stressed. A stress can be any force applied to the piezo, e.g. compression, elongation, vibration. Also, a piezo can change dimensions when a voltage is applied. Therefore, the piezo transducers proved to be extremely valuable in analyzing the vibrations of the guitar. For this experiment, one piezo was used as a transmit transducer. As a transmitter, the PZT received a voltage from the function generator, which caused the PZT to change dimensions, i.e. induce a vibration in the guitar. The other piezo was used as a pickup. Thus, it functioned opposite that of the transmit. This PZT converted the mechanical vibration into a voltage.

iii. Function Generator and GPIB

A *Wavetek Function Generator* was used to induce vibrations in the guitars under study. Basically, the generator is device capable of producing different electrical waveforms. Depending on the circumstances, different aspects of the waveforms can be modified. In this experiment, amplitude and frequency were the only important parameters to modify. The computer controlled the function generator via GPIB during the experiment.

iv. INA-121 JFET Operational Amplifier

The purpose of the operational amplifier was to reduce 60 Hz RF noise originating from the lights and equipment in the room. Refer to figure 2 for a schematic of the amplifier.

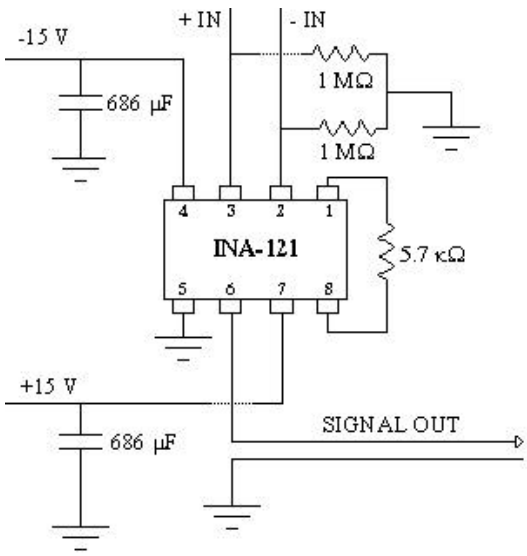

Figure 2: INA-121 JFET Operational Amplifier Schematic

The amplifier is equipped with a 5.7kΩ resistor providing a gain of 9. Two 686µF capacitors are connected to the leads from the power supply to reduce ripple voltage. The amplifier reduces noise by amplifying the difference between the input signals.

v. Lock-In Amplifier

Once the signal from the piezo pickup passed through the op-amp, it reached the lock-in amplifier. The lock-in amplifier is a device for amplifying weak AC (alternating current) signals. The details of its operation are too lengthy to discuss here; however, refer to the operating manual for further enlightenment. Basically, the lock-in amplifies a signal at a certain frequency and reads out the real voltage (Vreal) and imaginary voltage (Vimag). The real voltage is in phase with the reference signal. The imaginary voltage is 90 degrees out of phase with the reference signal. With knowledge of Vreal and Vimag, the magnitude of the voltage can be calculated by using the equation: $\sqrt{Vreal^2 + Vimag^2}$. In addition, phase information can be obtained by this equation: $\tan f = \frac{Vreal}{Vimag}$. Thus, the lock-in sends the signal information from the piezo to the computer via a LAB-PC DAQ card.

B. hp-3562A Dynamic Signal Analyzer

The next method used in the experiment involved exciting the guitar with a broad spectrum of frequencies. The spectrum was provided by the hp-3562A Dynamic Signal Analyzer. This device provided a white noise source with voltage attenuation adjustable to the experiment. In order to obtain data from guitar vibrations, the cross spectrum function of the analyzer was used in conjunction with its FFT (Fast Fourier Transform) abilities. The cross spectrum is obtained by multiplying the input spectrum on Channel 2 by the complex conjugate of the spectrum received by channel 1. In mathematical form, this operation is represented by:

$$G_{xy} = (F_y)(F_x^*)$$

where F_y is the spectrum of Channel 2 and F_x^* is the complex conjugate of the spectrum of Channel 1. Refer to the hp-3562A Dynamic Signal Analyzer operating manual for further information.

Basically, the cross spectrum and FFT of the waveforms allowed frequency peaks to be located and analyzed for study. The details of the experimental method will make the function of the Dynamic Signal Analyzer more apparent.

C. Experimental Method

Obtaining resonance frequencies from the guitar required three different approaches. The philosophy for this approach was to ensure agreement among the various pieces of equipment. For example, if a resonance peak was found by using the DAQ setup and confirmed by the signal analyzer, then the results were trusted. This redundant form of data acquisition was important since resonances of the guitar are hard to pin down accurately. The first step in our vibrational analysis required using the DAQ setup in concert with the *Sonic1* program. Each guitar studied was hung by rubber bands in order to allow it to vibrate with minimal dampening. The transmit transducer was placed slightly behind the bridge. The pickup transducer was placed at one location on the guitar. To facilitate coupling to the guitar surface, a 50g weight was placed on the transmit transducer and a 60g weight was placed on the pickup transducer. This allowed the piezos to be firmly coupled to the guitar surface without over damping their vibration. Using *Sonic1* and the GPIB, a frequency span of 10 to 1010 Hz was sent by the *Wavetek Function Generator* through the transmit transducer. Each waveform had an amplitude of 0.1 Volts to avoid overloading the lock-in amplifier. The pickup transducer detected any resultant vibrations in the guitar and sent a voltage through the op-amp and into the lock-in amplifier. At this point, the resultant voltage data entered the PC and was averaged over a short period of time to account for minor defects in the setup. This process was repeated until the entire frequency range had been analyzed. Using the collected data, plots of Vtotal, Vreal, Vimag, and Vphase could all be plotted versus frequency.

As was mentioned earlier, the need to verify any possible resonance frequencies picked up the DAQ system required a second method. Using the dynamic signal analyzer, white noise was entered into the guitar via the transmit transducer. The pickup transducer detected any resultant vibrations and sent a voltage through an op-amp (to reduce noise) and back into the signal analyzer. The FFT and cross-spectrum of the resulting data was read-out on the screen. To account for any defects in the setup and to sharpen the frequency peaks, the data was averaged 150 times. Resonance peaks discovered through this method were compared to those indicated by the DAQ setup.

Any resonances appearing in both the DAQ setup and dynamic signal analyzer data were passed on to the final step of the method. In this procedure, understanding how the resonance varied with position over the body of the guitar was analyzed. This goal was accomplished by using *Resonant1* with the DAQ setup. *Resonant1* was used to set the function generator at one frequency. This frequency was then sent to the transmit transducer placed at the origin of a coordinate grid associated with the body of the guitar. The coordinate grid consisted of pegboard placed about a foot above the body of the guitar. A diode laser was shone through each hole and indicated the

position on the guitar to place the pickup transducer. The transducer was moved around the coordinate grid until the body of the guitar had been fully studied. The vibrational data (Vtotal, Vreal, Vimag, Vphase) then returned to the PC.
Each point on the guitar had four measurements. Using Microsoft Excel, an average was obtained for each point. Importing the averaged Excel data into LabView provided 3-D plots of the voltage obtained by the piezo vs. position on the guitar.

III. Results and Discussion

A large amount of data was collected on a 1968 Gibson J-45 acoustic guitar. This guitar was examined extensively and several graphs were obtained showing the position of the resonances on both the front plate and back plate. Investigations on an Ibanez RG-570 were also completed; however, the amount of data collected is limited to one resonance frequency.

One definite resonance frequency was discovered on the Ibanez electric guitar. This occurred at 325 Hz and was prominent at several locations on the guitar. Figure 3 shows a graph of Vtotal vs. position on the guitar.

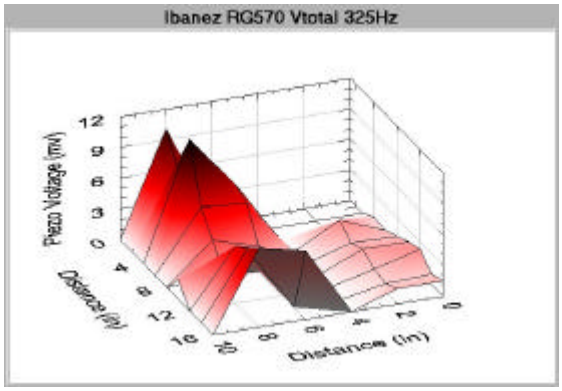

Figure 3: Graph of Vtotal vs. Position for the Ibanez RG570

The graph shows large amplitudes of vibration occurring on the left side of the guitar. In the graph, the neck of the guitar runs parallel to the x-axis. However, no measurements were taken of the neck or headstock.

Alternately, three definite resonance frequencies at 90 Hz, 180 Hz, and 786 Hz were discovered on the Gibson acoustic guitar. Figures 4 through 6 show graphs of Vtotal versus position on the front plate of the Gibson acoustic at these resonant frequencies.

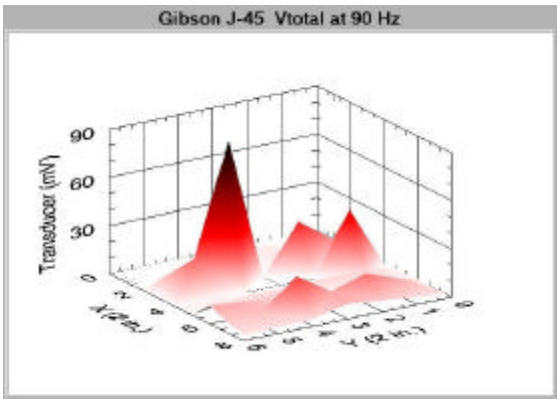

Figure 4: Graph of Vtotal vs. Position at 90 Hz for the Gibson Acoustic

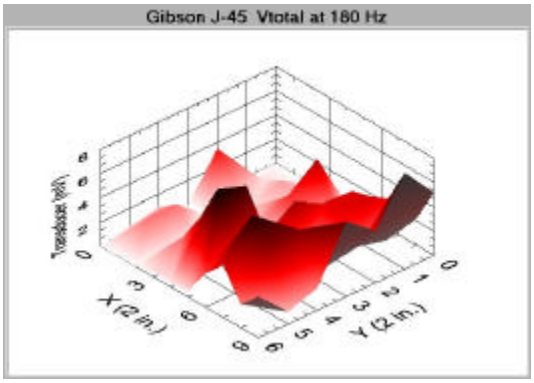

Figure 5: Graph of Vtotal vs. Position at 180 Hz for the Gibson Acoustic

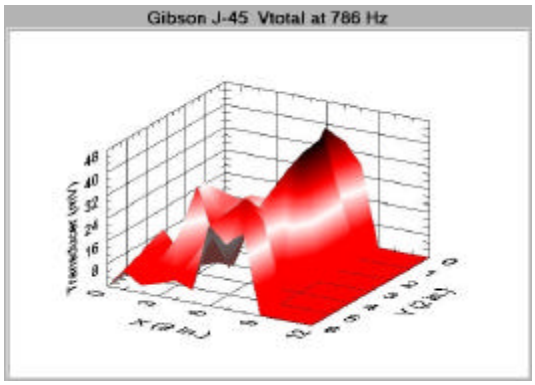

Figure 6: Graph of Vtotal vs. Position at 786 Hz for the Gibson Acoustic

The graphs show the resonant frequency at 90 Hz to be the most prominent vibration on the top plate of the Gibson acoustic. The amplitudes of vibration occurring at 180 Hz and 786 Hz are small relative to vibrations at 90 Hz. Refer to the appendix for graphs of Vreal and Vimag at these resonant frequencies.

No harmonic relationships were found between 90 Hz and 180 Hz. This is not surprising since the guitar has complex modes of vibration. However, when the amplitudes of vibration of the acoustic are compared to those of the solid-body electric, a large difference is seen in the amount the electric is vibrating as opposed to the acoustic. According to the results, resonant frequencies on the solid-body electric are not as prominent as those on the acoustic. This conclusion agrees with previous work done in the field of modal analysis. Electric guitars transmit their sound through magnetic pickups. Vibrations are not the most important aspect of an electric guitar's sound. Actually, large modes of vibration would draw energy from the strings and impede the sustain of notes played on the guitar. In contrast, acoustic guitars are designed to be played without amplification. Vibrations of the guitar are the way the sound is transmitted.

Definite limitations do exist in this experimental setup. First, an object placed on a vibrating surface, e.g. piezo on a guitar, would dampen the vibrations and possibly change their distribution. Second, each guitar had to be suspended from the rubber bands in a way that would accommodate the guitar. Specifically, the guitar had to hang level in order for the piezos to stay on the surface without slipping. Possibly, changing the way each guitar was hung from the rubber bands could have caused changes in the vibrations.

IV. Conclusions

This project was pretty successful. After much work, troubleshooting, and frustration, the experimental setup and method were developed. The DAQ, signal analyzer, and piezo transducers allowed us to explore the vibrational characteristics of two guitars to a high degree of satisfaction. Resonant frequencies were discovered on a solid-body electric and on an acoustic guitar. A large amount of data was collected on each resonant frequency.

An extension of this study could be a quantitative analysis of the data. A great deal of information is contained in the graphs of Vtotal, Vreal, Vimag, and Vphase. The ten weeks available to our group this summer did not allow an in-depth examination of the data. Hopefully, someone could perform such a detailed analysis.

Another possibility would be to develop an alternative method for investigating guitar vibrations. Then, a comparison could be made to the method presented in this paper. More insight could be provided and results verified.

Finally, a method for calibrating the piezo transducers would extend the capabilities of this experimental method. We have made the assumption that the voltage from the piezo is roughly proportional to the amplitude of vibration of the guitar. This needs verified. Insight into the actual mechanics of the piezo could yield more accurate results.

V. Acknowledgements

I would like to acknowledge Adam Kempton for being an insightful lab partner and for being very careful with the soldering iron. Also, I would like to thank Ted Argo for help in using LabView, Jack Boparai for help in obtaining equipment, and Lee Holloway for instruction in the use of the signal analyzer.

Finally, I would like to give a big thanks to Dr. Steve Errede for his vision in creating this research project.

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VI. References

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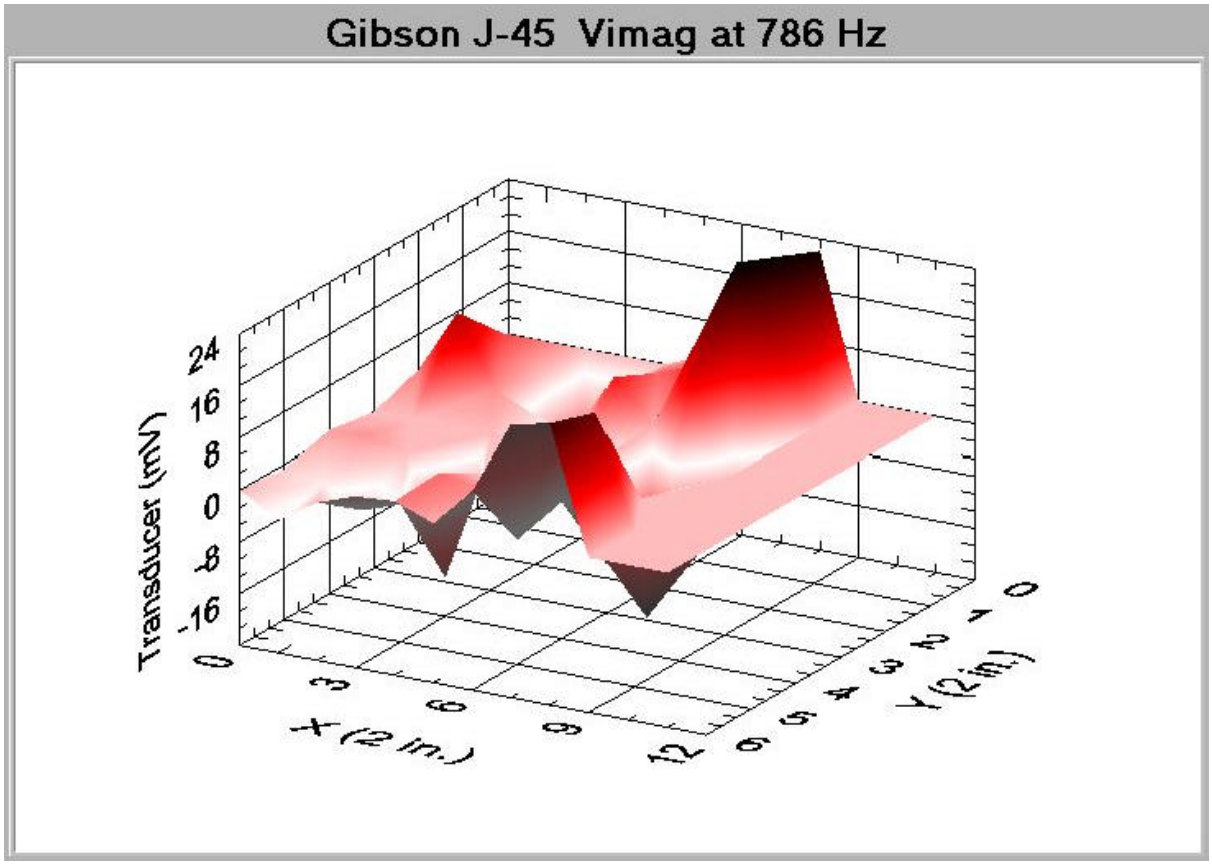
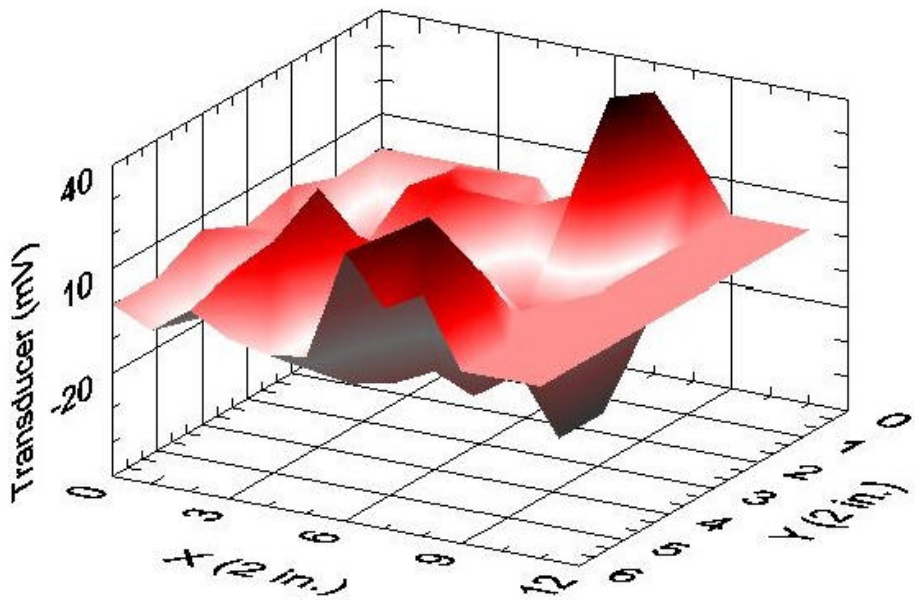
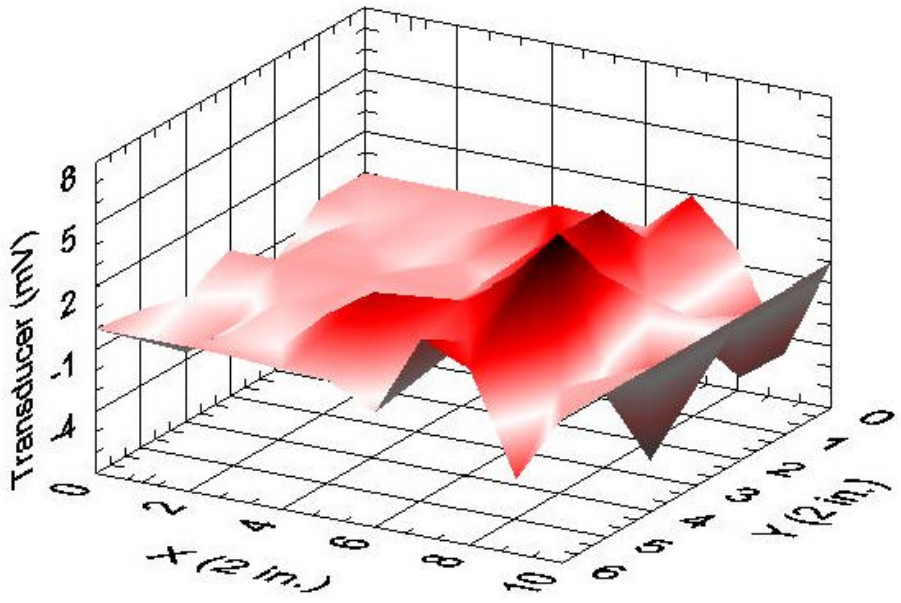
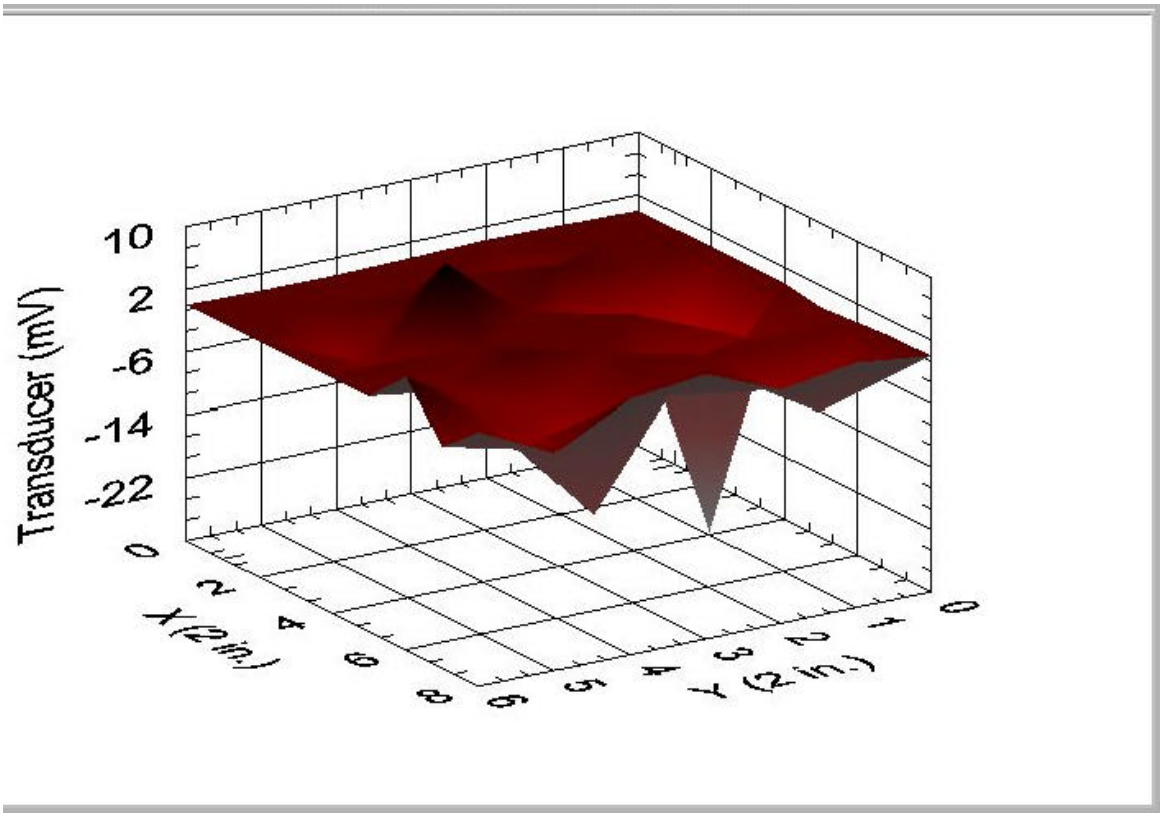
APPENDIX: GRAPHS



Gibson J-45 Vreal at 786 Hz




Transducer (mV)
8
5
2
-1
-4
0
2
4
6
8
10
X (2 in.)
0
1
2
3
4
5
6
Y (2 in.)


Transducer (mV)
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2
-6
-14
-22
0
X (2 in.)
2
4
6
8
Y (2 in.)
0
1
2
3
4
5
6