Modal Analysis of Guitar Bodies

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ABSTRACT

Resonant frequencies of guitar bodies were investigated to further the understanding of the tonal qualities of guitars. To do this a Data Acquisition (DAQ) setup using Lab Windows and an HP3562A Dynamic Signal Analyzer were used to discover resonant frequencies. Resonant frequencies of a 1968 Gibson J-45 acoustic guitar were located at 90Hz, 180Hz, and 786Hz and 3-dimensional plots were developed at each frequency. The method used does provide some insight as to the vibrations of guitar bodies.

I. Introduction

Modal analysis is an investigation into the resonant frequencies or modes of vibration of solid objects. All objects have frequencies at which they vibrate after an excitation has occurred, i.e. a piece of wood or a piece of metal. In the case of guitar bodies, the vibrations are waves creating in the body of the guitar oscillation from an equilibrium position. In acoustic guitars, the vibrating string transfers energy to the bridge, which transfers energy to the air cavity and front and back plates of the guitar, inducing vibration[1]. Anyone who plays guitar feels these vibrations all the time. The difficulty of grasping the individual modes of a guitar is due to the complexity of the modes of vibration. Each resonant frequency occupies different locations of the guitar, and each resonance characteristically has nodes (points of zero displacement) and anti-nodes (points of maximum displacement) at various locations on the body of the guitar. In addition, some modes exhibit both twisting and turning, adding to the difficulty of analyzing guitar modes. Quite simply, full understanding and knowledge of the actions of guitar bodies is not entirely feasible. Nonetheless, thorough analysis can be conducted and can be beneficial. The reason for conducting the research was to gain a better understanding of the tonal qualities of guitars, or understanding why certain guitars, such as Fender and Gibson guitars, sound the way they do. In addition, by gaining a feel for vibration modes, one could theoretically shape the tonal qualities of a guitar according to his or her personal preference. Both acoustic and electric guitars can be studied, but more action will be seen in the bodies (neglecting the neck) of acoustic guitars than solid body electrics.

II. Background

Previous Research

Research of modal analysis of guitars has been done in the past. Dr. Dan Russell and Paul Pedersen of Kettering University investigated modes of vibration of various guitars[2]. To do this, they made a grid out of the body of the guitar and excited it by hitting each

location with a force hammer that had a transducer located on the tip. An accelerometer located on the wing of the guitar converted the guitar's acceleration into voltage. The accelerometer and force transducer were fed into an FFT (Fast Fourier Transform) Analyzer and the peak frequencies corresponding to resonant frequencies were determined. Animated movies displaying the modes were made using modal analysis software STAR Modal from Spectral Dynamics.

Piezoelectric Transducer

The heart of our method is the piezoelectric transducer, a ceramic crystalline structure. It can convert electrical energy into mechanical energy, and it can convert mechanical energy into electrical energy. When a voltage is applied to the transducer, the crystalline structure expands and compresses proportionally to the applied voltage. Conversely, when mechanical pressure is applied, a voltage is induced across the transducer proportional to the pressure so as to oppose the change in mechanical structure. A large mechanical pressure induces a large voltage. This two-way flexibility of the transducer makes it very valuable to us. In our experimental setup, we used two identical transducers on the surface of the guitar- one to excite the guitar into vibration (transmit transducer) where mechanical compression is induced via a voltage, and one to pick up the vibration (receive transducer) where a voltage is induced via mechanical compression. The pure sine wave signal from a function generator applied to the transmit transducer on the body of the guitar will excite the guitar at the same frequency as the input sine wave. A

resonance can thus be located by viewing the output voltage peaks of the receive transducer. A peak voltage should correspond to a resonant frequency. If the receive is at a node of a particular resonance, then very little voltage will be induced. Conversely, if the receive is at an anti-node of a resonance, a large voltage will be induced. Transducers were used to both determine the resonant frequencies and to develop the 3-dimensional plots of the guitar at resonant frequencies, with the technicalities still to come.

Lock-In Amplifier

A lock-in amplifier is a device that is used to detect and measure small AC signals, and it does this by "locking in" to signals of a specific frequency. The frequency it locks in to is the reference signal from a power supply (in our case a pure sine wave from a function generator). The lock-in we use is a dual-phase lock-in. It displays the magnitude of the real voltage (Vreal) and the imaginary voltage (Vimag), in addition to the frequency. Vreal is the voltage that is in phase with the reference signal, and Vimag in the voltage that is 90° out of phase with the reference signal. In the complex plane, Vimag (being that it is an imaginary number) represents the complex axis and Vreal represents the real axis. The total voltage (Vtotal) can thus be determined by the following equation:

$$Vtotal = \sqrt{(Vreal)^2 + (Vimag)^2}$$

The phase angle, θ, is calculated as follows:

$$q = \tan^{-1}(Vimag/Vreal)$$

It is easily seen that $Vreal = Vtotl \cos q$ and $Vimag = Vtotl \sin q$.

The lock-in amplifier is extremely valuable to us because it can read the voltage out of the transducer at a specific frequency, blocking out noise or other frequencies we are not interested in.

HP3562A Dynamic Signal Analyzer

The HP3562A Dynamic Signal Analyzer is a device that, among many other things, produces frequency spectrum plots. In our case, the signal analyzer sources random noise, a signal consisting of an extremely large bandwidth of frequencies, allowing us to excite the guitar at each of its resonance frequencies simultaneously. The graph we look at is a cross spectrum, which plots magnitude vs. frequency. The cross spectrum plot is determined as follows, where x(t) is the random noise into channel 1 and y(t) is the signal from the receive transducer into channel 2:

$$spectrum = \int_{-\infty}^{\infty} x(t)y(t)e^{-iwt}dt$$

This is the Fourier transform of channel one multiplied by channel 2, where t is time and *w* is angular frequency. The peaks determined are the resonant frequencies.

III. Experimental Method

The data collecting process was two-fold. First, the resonant frequencies were located using two methods: a Data Acquisition Setup (DAQ) and a white noise method using an HP3562A Spectrum Analyzer. Once found, another DAQ setup was used to examine the behavior of the guitar at a particular resonance.

DAQ Setup

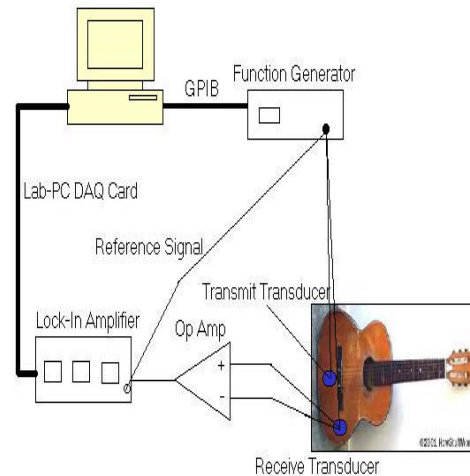Figure 1 shows the DAQ setup used for developing plots to locate resonant frequencies.

Fig. 1 DAQ Schematic

A C++ program written in Lab Windows controls the system and produces the plots. The program controls the function generator via a General Purpose Interface Bus (GPIB). In the program, we set the frequency range from 10 to 1010 Hz. The computer tells the function generator to scan this span of frequencies. The function generator sends a pure sine wave into the transmit transducer, exciting the guitar into vibration. The amplitude of the sine wave was set at .5V because it was determined that this input voltage resulted in clearly locatable peaks without exceeding output voltage limitations of the computer program. The vibration is picked up by the receive transducer. To allow free vibration, the guitar was suspended by rubber bands: one around

the nut, one at the beginning of the neck, and one around the end strap holder. To improve coupling, 50g were placed on the transmit transducer, and 60g were placed on the receive transducer. The transducers used were from Radio Shack.

The induced signal is sent through an INA121 Operational Amplifier. This is a differential amplifier that reduces noise (undesired signal), especially 60Hz electromagnetic radiation, by amplifying the difference between the two input signals. Figure 2 shows the circuit schematic.
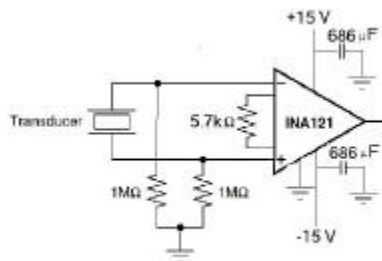
Fig. 2 INA121 Circuit schematic

The 5.7kΩ resistor sets the gain at approximately 9. The 1MΩ resistors in parallel with the inputs provide a path for the input bias current of both inputs[3]. The 686μF capacitors reduce the ripple of the power of the power supplies holding the DC voltage more constant.

The lock-in amplifier records the voltages at the specific frequency, and the computer program takes in the data and plots of Vreal, Vimag, Vtotal, and Vphase all plotted vs. frequency are developed, as well as a plot of Vimag vs. Vreal. Each graph was developed for each frequency span.

To be thorough and to get a firm understanding of the behavior of the guitar, the receive transducer was placed at many different locations on the guitar and frequency spans were run. The transmit transducer was placed and kept

just in front of the bridge. All five graphs were developed at each location.

White Noise Method

Random noise with a peak amplitude of 1V using the HP3562 Dynamic Signal Analyzer was applied to the transmit transducer located in front of the bridge with the guitar suspended with rubber bands. The random noise source output was sent into channel 1 and the output from the receive transducer was sent into channel 2. The cross spectrum was looked at to determine natural modes. The final display of the cross spectrum included 150 averages over time, which was programmed into the analyzer. It was determined that 150 averages produced high resolution plots. The signal analyzer was also programmed to plot voltage as the amplitude rather than decibels. Linear plots made it easier to locate resonant peaks. Once again, the receive transducer was moved around to various locations.

DAQ for 3-D Contours

Using the same DAQ setup as before, the C++ program in Lab Windows was modified to enable us to sit at a particular resonance and move the receive transducer around a coordinate grid assigned to the guitar and measure Vreal, Vimag, Vtotal, and Vphase at each location.

Figure 3 is the setup used to map the guitar. The pegboard placed above the guitar has holes which were assigned a specific (x,y) coordinate. The holes were all spaced two inches apart from each other. A laser was shined down through each hole, illuminating the location on the guitar to place the receive transducer. This enabled us to

coordinately grid the guitar without having to place anything on the surface of it. The computer program allowed us to set the particular frequency and amplitude of the sine wave and to enter the coordinate locations of both the transmit (which remained stationary) and receive transducers. For the Gibson J-45, 90Hz, 180Hz, and 786Hz were mapped out, and the sine wave amplitude was set at .1V, which was found to not overload the appropriate bounds of the computer program.

Fig. 3 Mapping Setup

Once the data was collected (each location at a resonance had a Vreal, Vimag, Vtotal, and Vphase, the data was fed into Lab View, which we used to develop the 3-dimensional plots of Vreal, Vimag, and Vphase. To do this, the hard data of the voltages at each (x,y) location was organized in a Microsoft Excel spreadsheet such that all points sharing the same x value were in the same row and all and all points sharing the same y value were put in the same column, essentially re-creating on a spreadsheet the spatial orientation of the guitar. The file would then be uploaded directly into Lab View, which would develop the plots.

IV. Results

Figure 4 is a cross spectrum plot with of the Gibson J-45 with the receive transducer placed just below the transmit transducer.

Fig. 4 Cross spectrum plot of Gibson J-45 with receive below transmit

The largest peaks are located at 90Hz, 145Hz, 208Hz, and 368Hz, and smaller ones are present as well.

Using the DAQ setup and keeping the transducers in the same place, a plot of Vtotal vs. frequency shows large resonances at 90Hz, 140Hz, 185Hz, 211Hz, 250Hz, 363Hz, and 427Hz. This graph is Figure 7 located at the end. Also included are Figures 8 and 9-graphs of Vreal and Vimag plotted vs. frequency from the same run.

At various locations on the guitar, resonances at 90Hz, 180Hz, and 786Hz were seen quite frequently using both methods. We felt confident in believing these to be resonant frequencies.

Figures 5, 6, and 7 are 3-D plots of the Gibson J-45 at 90Hz, 180Hz, and 786Hz, respectively. The neck of the guitar (not shown), which was not

measured in these graphs because these graphs show the front of the guitar, is parallel to the x-axis in the middle of the body.
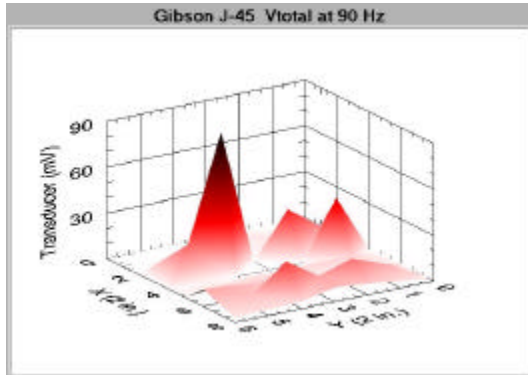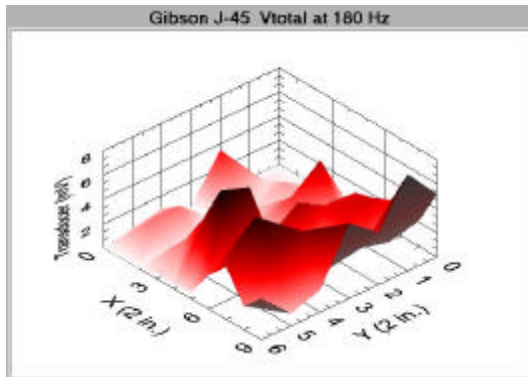

Fig. 5 3-D plot of Gibson J-45 Vtotal at 90Hz
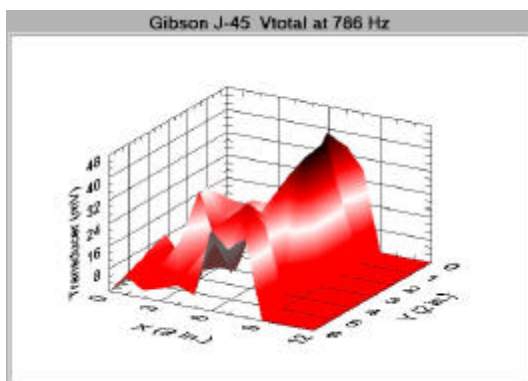

Fig. 5 3-D plot of Gibson J-45 Vtotal at 180Hz

Fig. 6 3-D plot of Gibson J-45 Vtotal at 786Hz

Plots of Vreal, Vimag, and Vtotal were developed at each frequency. Figure 10 located at the end shows a plot of Vreal at 786Hz. Also, an Ibanez RG570 electric guitar was studied less extensively, but a resonance was located at 325Hz. Figure 11 at the end shows a plot of the Ibanez at 325Hz.

V. Discussion

The data obtained using the random noise method and DAQ setup are compatible, although they are not 100% compatible. The reproducibility of the random noise method is better than the reproducibility of the DAQ system. However, the DAQ system gives more information, being that it produces plots of Vreal, Vimag, Vtotal, and Vphase vs. frequency. Unfortunately, these graphs are extremely complicated and difficult to understand, but all contain relevant information as far as locating resonances is concerned. A certain development in the method would be to understand completely the DAQ graphs, understanding for instance why in the Vreal vs. frequency graphs often peaks are negative or why at some peaks Vphase is not 0°, since theoretically all of the voltage should be in phase and real. In careful investigation into each graph, one could locate the true resonances and exclude peaks that really are not.

We are confident in saying that 90Hz, 180Hz, and 786Hz are resonant frequencies of the Gibson. However, we understand there are more resonances (like possibly 208Hz). The plots appear to have legitimacy to them due to the fact that more of the action is occurring near the middle of the guitar rather than the edges, which one would expect. The 90Hz and the 786Hz resonances have higher amplitudes than the 180Hz resonance.

One problem with the 3-D mapping is that the transducers are 3.7cm in diameter, which is very large. Therefore, they cover a large area on the guitar each time a measurement is taken, so to say that we are measuring an exact, finite point is incorrect. Also, possible development of the method could include taking more points for each mapping, even though this greatly increases both time and effort. In addition, the transmit transducer can be moved around and placed at anti-nodes of various resonances, resulting in extremely high amplitudes. The amount of work that could be put in is endless!

A definite improvement that could be made is determining a relationship between space and voltage. A 3-D plot consisting of space on the vertical axis rather than voltage would provide a more accurate portrayal of the vibration of the guitar. To do this, a calibration of the transducers is needed, explicitly a relationship between displacement and voltage.

VI. Conclusions

The methods we have used do indeed provide insight into the guitar. Resonant frequencies can be located and plotted. However, guitar vibration is very intricate, and the amount of time and effort required to gain full understanding of it is limitless. Nonetheless, the techniques we used can be enhanced and developed to provide useful information about inherent modes of guitar bodies.

VII. Acknowledgments

I would like to thank my partner Eric Moon, Dr. Steve Errede for the guidance and opportunity, Jack Boparai for his help in obtaining equipment, Dr. Lee Holloway for his help in the development of the random noise method, and Nicole Drummer for making this an extremely beneficial and fun 10 weeks.

VIII. References

[1]Fletcher, Neville H and Thomas D. Rossing. The Physics of Musical Instruments 2nd Edition. Springer Verlag, August 1998.

[2]Russell, Dan and Paul Pedersen. "Modal Analysis of an Electric Guitar." http://www.kettering.edu/~drussell/guitars/coronet.html, January 29, 1999.

[3]Texas Instruments, Inc. "FET Input Low Power Instrumentation Amplifier." http://www-s.ti.com/sc/ds/ina121.pdf, 2002.
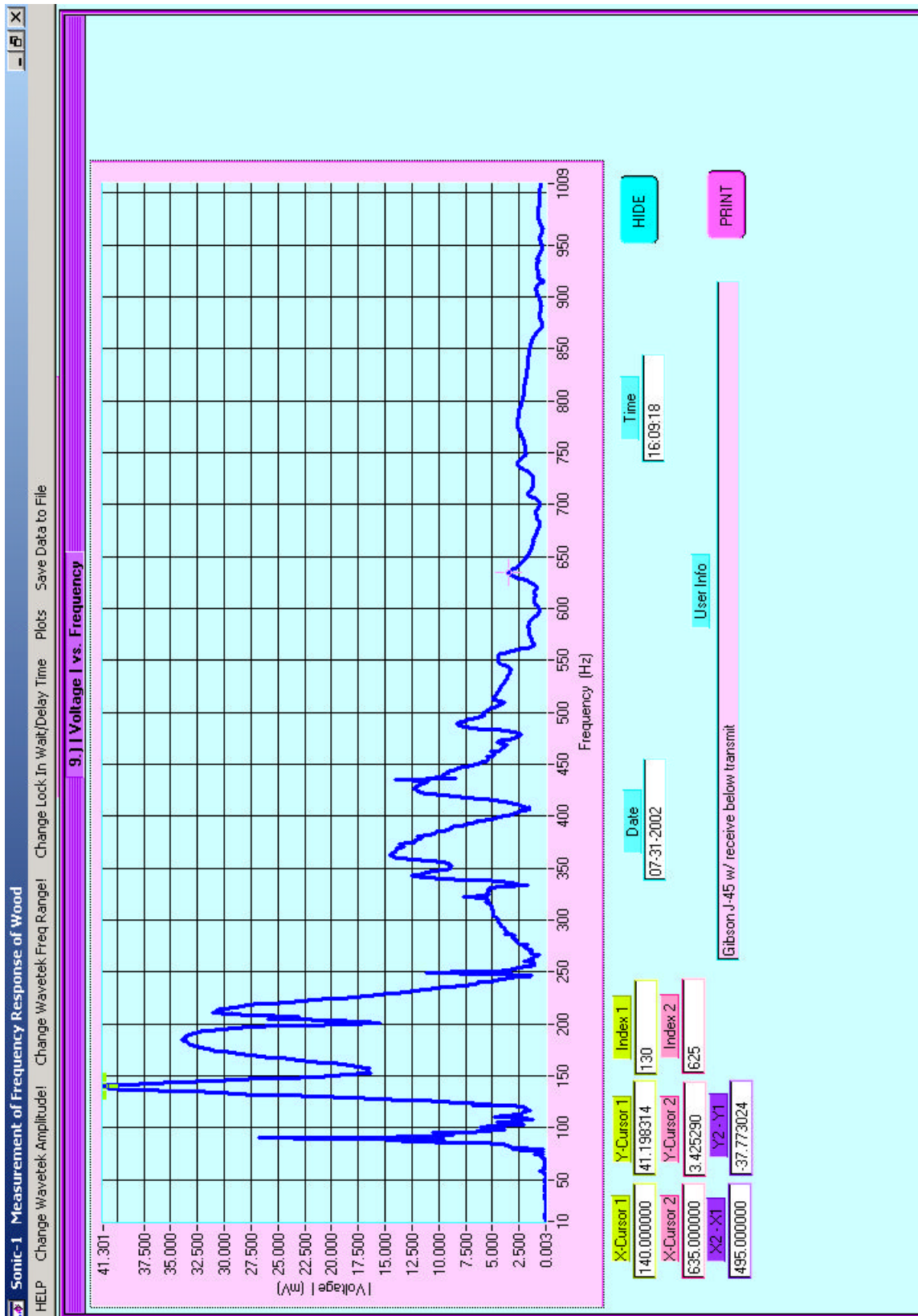
Fig. 7 Vtotal vs. Frequency for Gibson J- 45 with receive transducer placed below transmit transducer
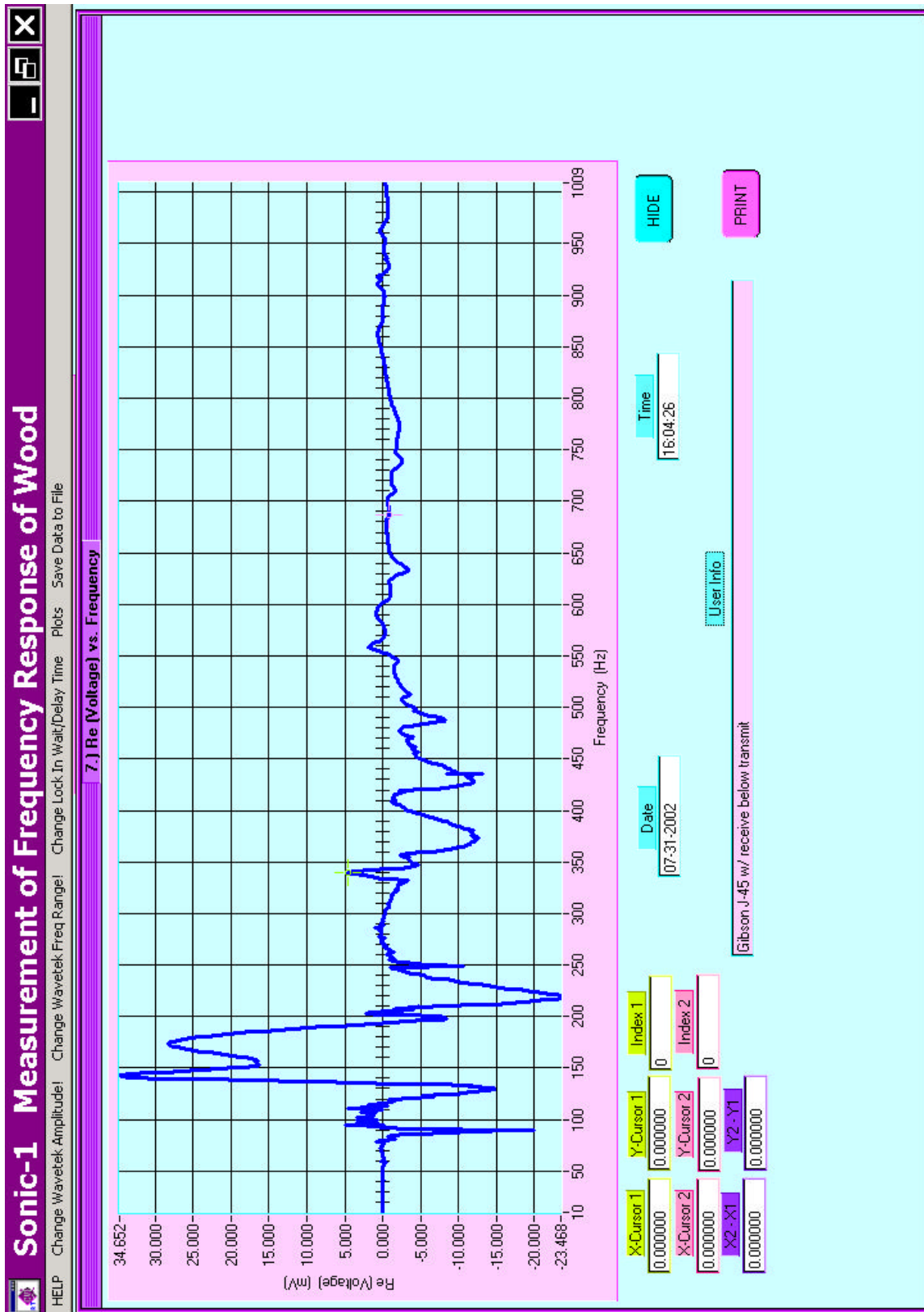
Fig. 8 Vreal vs. Frequency
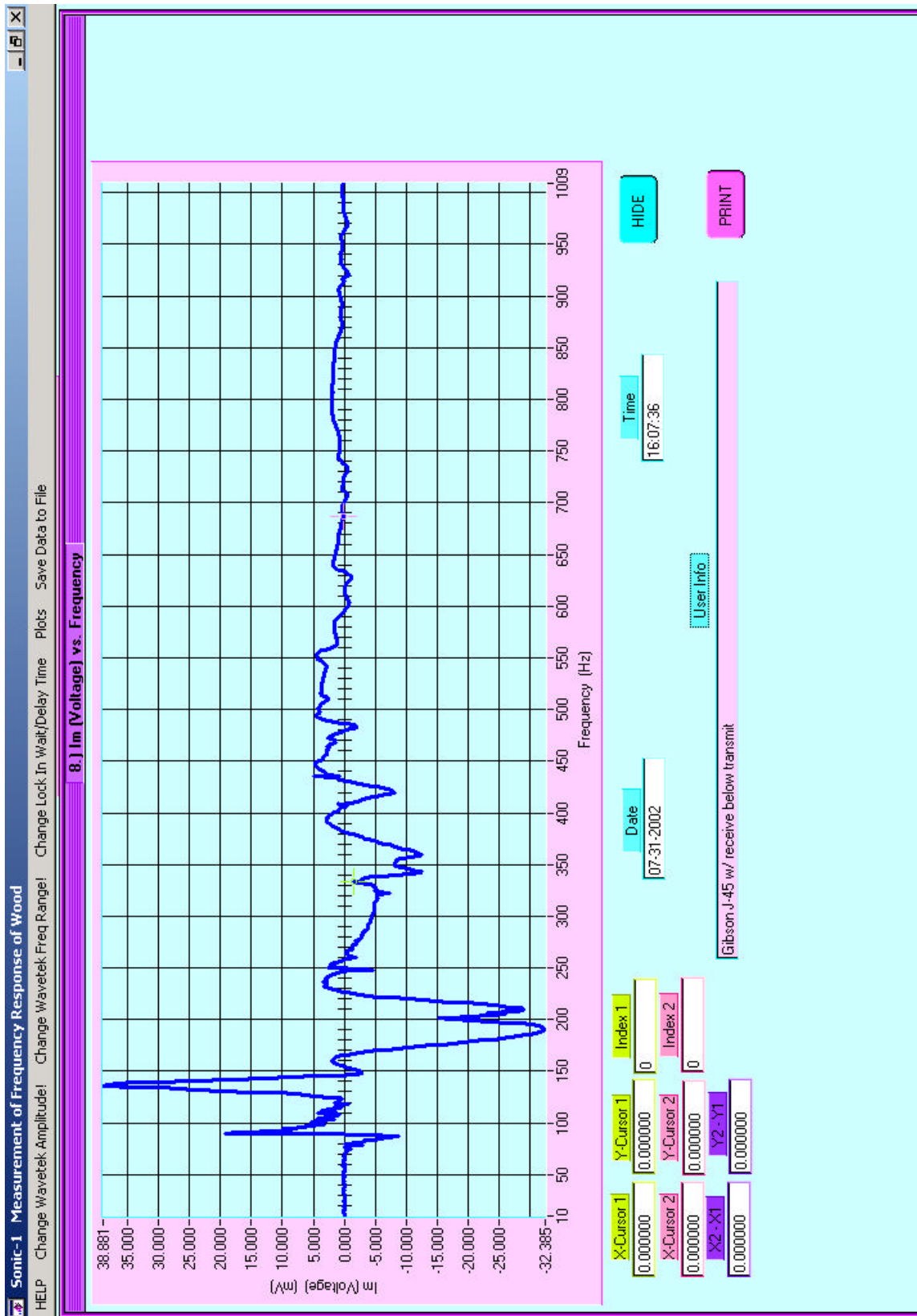
Fig. 9 Vimag vs. Frequency
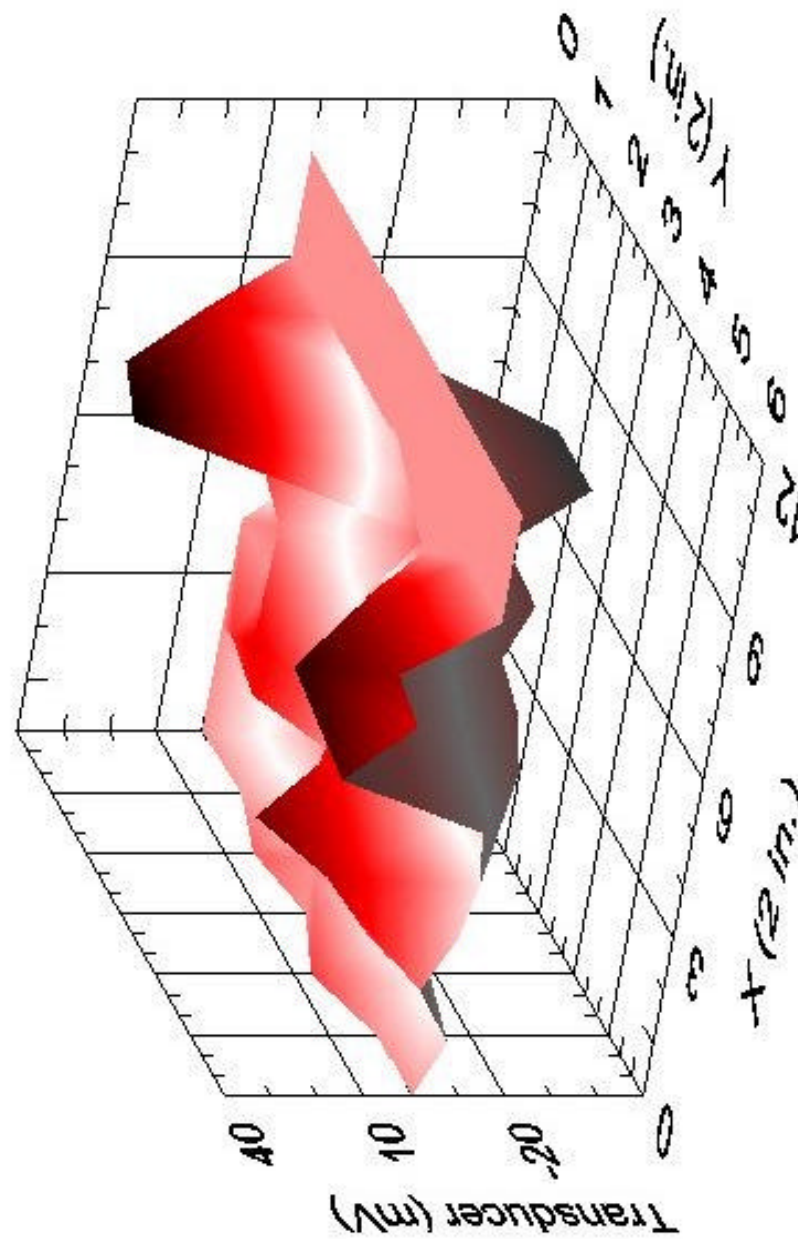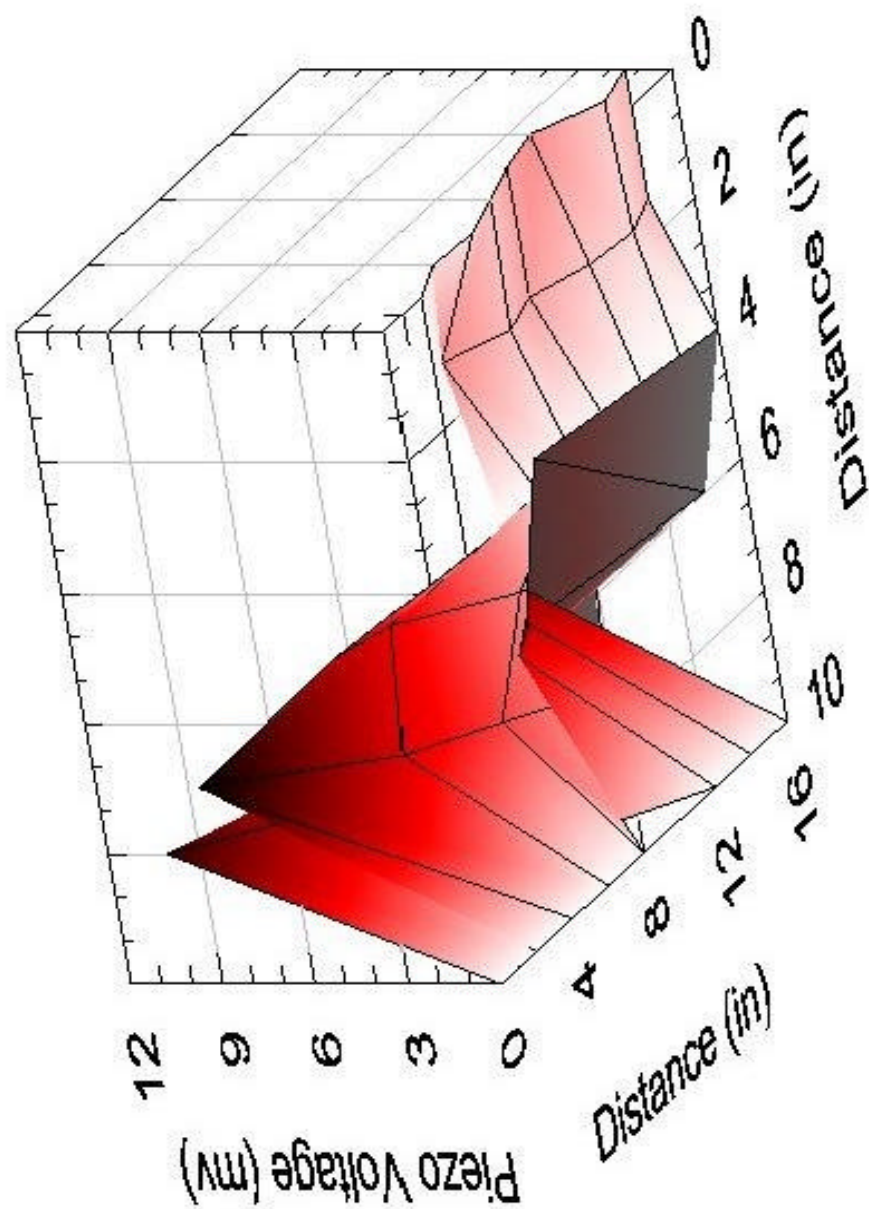
Fig. 10 Gibson J-45 Vreal at 786 Hz

Fig. 11 Vtotal of Ibanez RG570 electric guitar at 325 Hz