Investigating Electromagnetic and Acoustic Properties of Loudspeakers Using Phase Sensitive Equipment

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ABSTRACT

The goal of this project was to extract detailed information on the electromagnetic and acoustic properties of loudspeakers. Often when speakers are analyzed only the electrical components are considered without taking into account how this effects the mechanical operation of the loudspeaker, which in turn directly relates to the acoustic output. Examining the effect of mounting the speaker on a baffle or in an enclosure is also crucial to determining the speaker's sound. All electrical and acoustic measurements are done using phase sensitive lock in amplifiers. By analyzing the speaker in such a detailed manner, we can ultimately determine which properties really affect the overall tonal qualities of that speaker.

I. Background and Introduction

The loudspeaker is the most important link in any audio chain. It is the last piece of equipment the audio signal passes through before we hear anything. You may have the best amplifier money can buy, but that means nothing without quality speakers. In the audio chain speakers are composed of some of the simplest electric circuits; it is the quality of manufacturing and physical design that is most important in speaker quality.

Loudspeakers convert electrical energy into acoustic energy. The most common type of loudspeaker is a moving coil loudspeaker. A coil of thin wire, the voice coil, is positioned in a permanent magnetic field and attached to the speaker cone. The audio signal, in the form of electrical current, runs through the voice coil wire changing the polarity and amplitude of the magnetic field of the voice coil. This magnetic field causes the voice coil to either be attracted to or repelled by the permanent magnetic field. The moving parts of the speaker, the driver, can then turn electrical energy into acoustic energy. The electrical components of the speaker have a certain resonance when the electrical impedance is greatest. The air surrounding the speaker and propagating the sound also has its own resistance to motion, radiation impedance.

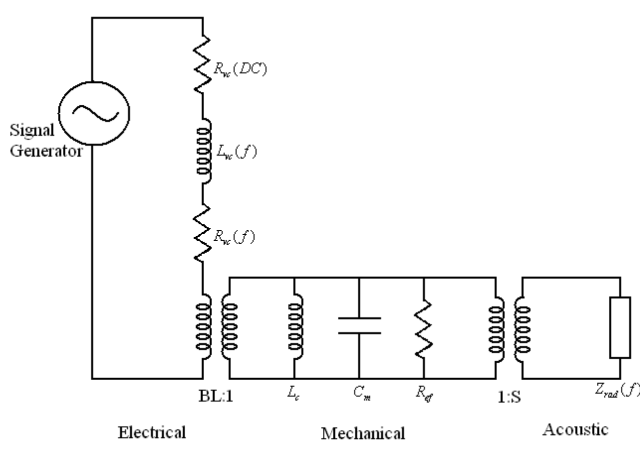

Figure 1: Electrical lumped model of a typical moving coil loudspeaker.

The frequency response, efficiency, and overall quality of a loudspeaker depend on many parameters, physical and electrical. These parameters can be represented using an electrical lumped model as illustrated in Figure 1. The electrical inductance and resistances, L_{vc} and R_{vc}, are those of the voice coil. The effective inductance, L_c, is due to the driver compliance. The effective capacitance, C_m, is due to the driver mass. The effective electrical resistance, R_{ef}, is due to the driver suspension losses. The radiation impedance, Z_{rad}, is related to the properties of the air (Pratt).

The sound of the speaker also depends strongly on how it is mounted. A speaker in free air behaves very differently than a speaker in an enclosed box. A speaker in an enclosed box is affected by the back radiation of the speaker reflecting inside that box. For a speaker to be practical in everyday use it is put in an enclosure. The speaker enclosure is designed using the loudspeaker's Thiele-Small parameters. These parameters can be measured and are often given on the data sheet of a commercial speaker.

II. Method

The loudspeaker was driven using the internal sine-wave function generator of one of the lock-in amplifiers. The lock-in amplifiers used in our DAQ setup are the Stanford Research System's SR-830 Dual-Channel DSP lock-in amplifiers. The lock-in amplifier's function generator drives the speaker and uses that reference frequency to measure the in-phase/real part and the out-of-phase/imaginary part of the signal being measured. However, the power output of the lock-in amplifiers function generator is quite low.

In order to produce enough power to properly drive the loudspeakers a high quality, low distortion audio amplifier must be utilized. In order to amplify the signal from the function generator into the type of audio signal needed for this experiment a power amplifier was custom built, using a commonly found LM3875 IC power amp. The design for the audio power amplifier was based on a Gaincard amplifier made by 47 Labs (Daniel). With an eight ohm load this chip-amp has an average 56 watt power output. For the near field acoustic measurements the power needed to be attenuated because of the sensitivity of the microphones, so an attenuating resistor-divider network was added to the input of the LM3875 power amp circuit.

A total of four lock-in amplifiers are used for both loudspeaker measurement procedures. The first procedure is a frequency sweep to determine resonances; the second procedure is an *x-y* surface scan of the loudspeaker's complex sound field at a set frequency. The first two lock-in amplifiers measure the complex pressure $\tilde{p}(x,y,z)$ and longitudinal (*z*-) component of the particle velocity $\tilde{u}_z(x,y,z)$ of the sound waves radiating from the speaker. The other two lock-in amplifiers take measurements of the loudspeaker's complex voltage $\tilde{V}$ and current $\tilde{I}$. The voltage is measured directly across the positive and negative leads of the loudspeaker and the current is measured as the voltage drop across a precision one ohm resistor in series with the speaker.

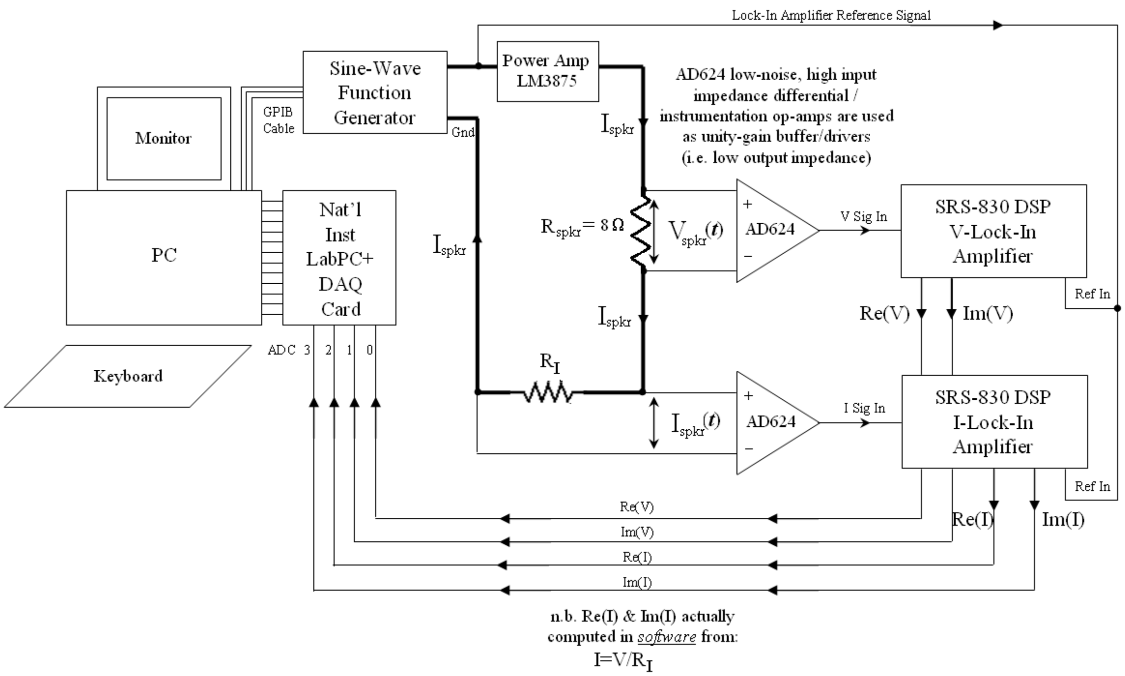

Figure 2: Data acquisition setup for measuring electronic properties

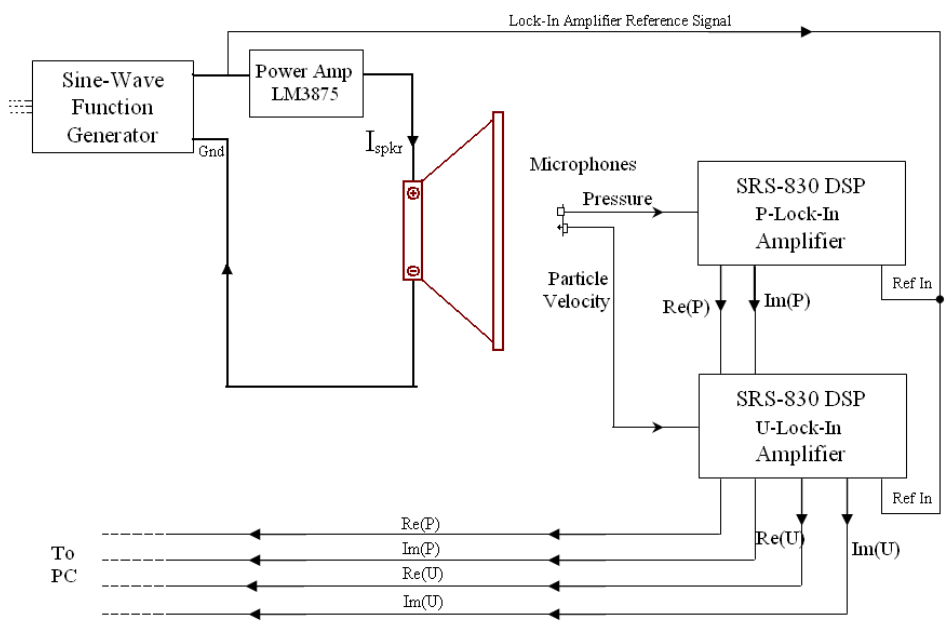

Figure 3: Data acquisition setup for measure acoustic properties

Figure 2 is a diagram of the data acquisition setup for the electrical portion of the measurements. Figure 3 is a diagram of the pressure and particle velocity measurement setup for the acoustic properties. Electrical and acoustic data acquisitions take place at the same time. Figure 4 is an example of the data acquisition setup with the speaker on the baffle board. The particle velocity and pressure microphones are above the speaker on a moving arm that is controlled by the computer. The voltage and current cables are connected below the speaker. Foam sound absorbers are used to prevent sound from reflecting off the floor and affecting what is measured and the speaker's behavior. For all measurements, the particle velocity and pressure microphones were 0.4 centimeters from the surface of the speaker.

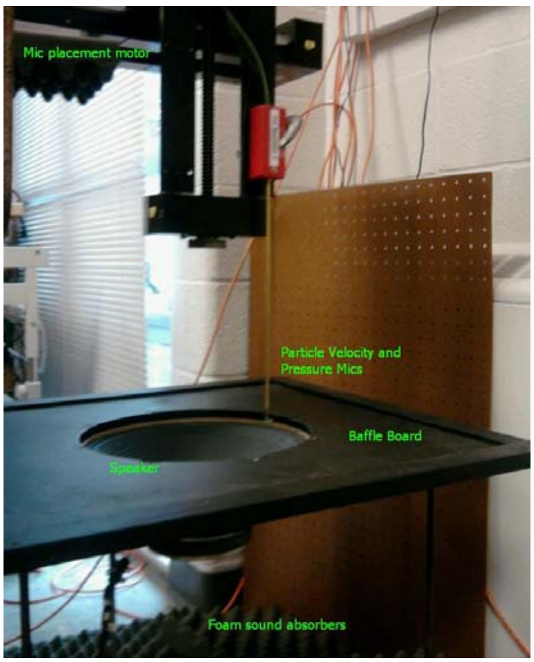

Figure 4: Speaker analysis set up with speaker on baffle board

Two of the most significant parameters being measured are the electrical impedance and the acoustic impedance. The complex electrical impedance $\tilde{Z}_{em}(f)$ is calculated in the MatLab code using the complex voltage $\tilde{V}(f)$ and complex current $\tilde{I}(f)$ flowing through the voice coil of the loudspeaker:

$$\tilde{Z}_{em}(f) = \frac{\tilde{V}(f)}{\tilde{I}(f)} \qquad \text{(Equation 1)}$$

The complex longitudinal specific acoustic impedance $\tilde{z}_{ac}(\vec{r}, f)$ is calculated similarly using the complex pressure $\tilde{p}(\vec{r}, f)$ and complex particle velocity $\tilde{u}(\vec{r}, f)$ of the air surrounding the speaker at a certain point $\vec{r}$ away from the speaker:

$$\tilde{z}_{ac}(\vec{r}, f) = \frac{\tilde{p}(\vec{r}, f)}{\tilde{u}(\vec{r}, f)} \qquad \text{(Equation 2)}$$

The pressure is a scalar quantity and has no direction. However, the particle velocity is a vector and in this experiment the particle velocity component being measured is the *z*-component, the *u*-microphone was facing directly towards the surface of the speaker.

The complex electric power $\tilde{P}_{em}(f)$ and complex longitudinal acoustic intensity $\tilde{I}_{ac}(\vec{r}, f)$ at a certain distance are calculated similarly to each other:

$$\tilde{P}_{em}(f) = \tilde{V}(f) \cdot \tilde{I}^*(f) \qquad \text{(Equation 3)}$$

$$\tilde{I}_{ac}(\vec{r}, f) = \tilde{p}(\vec{r}, f) \cdot \tilde{u}^*(\vec{r}, f) \qquad \text{(Equation 4)}$$

All of these parameters are frequency dependent. The electromagnetic resonance occurs when the loudspeaker impedance is greatest due to the effective resistance, capacitance, and inductance of both electrical and mechanical properties of the specific speaker. All parameters are measured with the phase sensitive devices, so each measurement has a real and an imaginary part. The phase shifts, which correlate to the ratio of the real to imaginary parts, are related to the resonances. All magnitudes are calculated using the root mean square of the amplitudes of the signals; this is standard for measuring the magnitude of sinusoidal signals.

The loudspeaker tested was an Italian Jensen twelve inch 8 Ohm ceramic speaker, C12N. The ceramic magnet is a ferrite magnet, the cone is made of paper, and its power rating is 50 watts. The speaker has a 12" diameter and is considered a woofer. The speaker was first suspended in free air by resting it on 3 posts to decrease any possible physical restrictions on the speaker. It was then mounted onto a 24" by 24" baffle board, as seen in Figure 4; this is to reduce radiation emanating from the rear of the speaker from disrupting the radiation from the front of the speaker. The loudspeaker was then placed in a speaker cabinet. The speaker enclosure's design is based on that of a Marshall 1965B 4×10 straight-front speaker cabinet.

III. Results and Discussion

Since a loudspeaker has resistance, inductance, and capacitance it has a predictable frequency response and there is a certain electromagnetic resonance. The speaker being investigated here has a low resonant frequency since it is a twelve inch diameter speaker. As mentioned earlier, the first measurements were done with the speaker suspended in free air, without any sort of baffling. The voltage and current measured using two separate lock-in amplifiers is used to calculate the *EM* impedance and power, as described in Equations 1 and 2.

Figure 5 is the plot of the magnitude of the complex electrical impedance versus

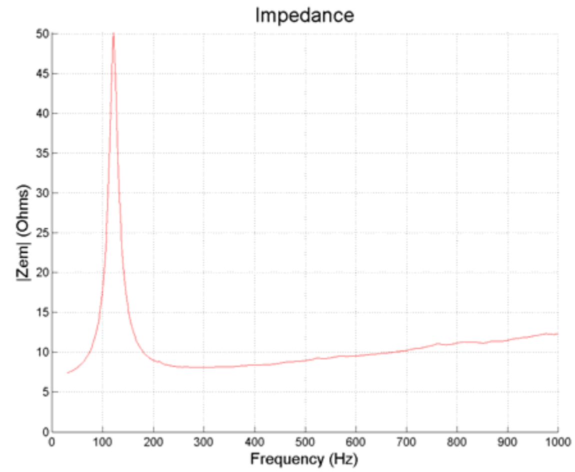

Figure 5: Magnitude of complex electrical impedance versus frequency for speaker in free air

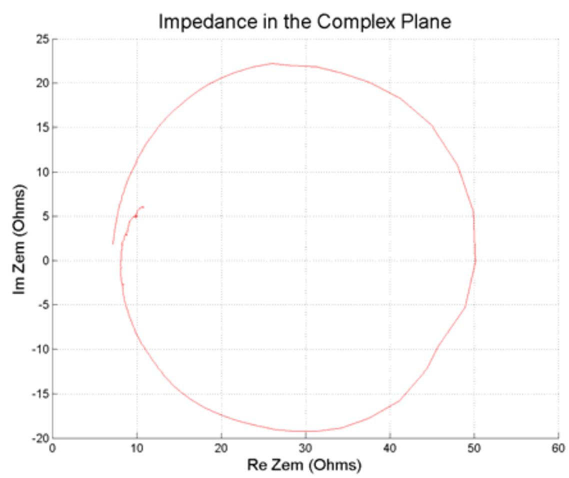

Figure 6: Electromagnetic impedance in the complex plane for a speaker in free air

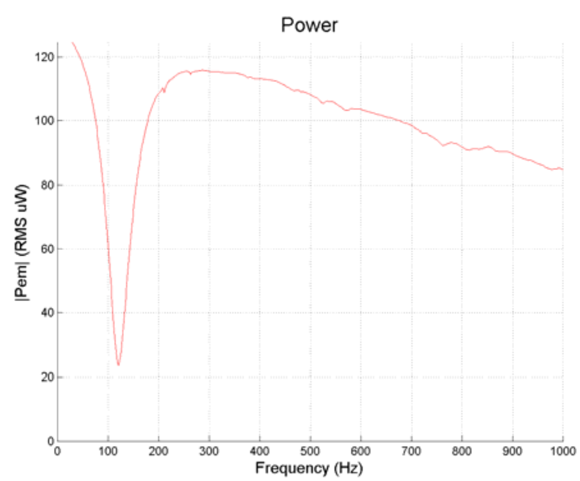

Figure 7: Magnitude of complex electrical power versus frequency for speaker in free air

the driving frequency from 29.5 to 1030.5 Hz, taken in one Hz steps. The electromagnetic resonance is at 120.5 Hz. Figure 6 is a plot of the impedance in the complex plane. That is the imaginary part of impedance versus the real part of impedance: reactance versus resistance. This plot is another way of showing what type of resonance is at 120.5 Hz. Figure 7 is the plot of the magnitude of electrical power required to drive the speaker versus the driving frequency for the speaker in free air. The resonance of 120.5 Hz correlates with the minimum in power required to drive the speaker. This can then be compared with the pressure and particle velocity directly above the center of the speaker.

Figure 8 is a plot of the magnitude of the complex pressure of the air versus the driving frequency of the speaker. The most defined maximum seen in pressure is at 761.5 Hz; this is mostly due to the properties of the air. Figure 9 is a plot of the complex plane for the pressure; it shows the imaginary versus real parts of pressure. Several small loops represent the small resonances in free air (i.e. standing waves in the room), and hence correlates more with the properties of the air than it does with the actual properties of the speaker.

Figure 10 is a plot of the magnitude of particle velocity versus driving frequency for a speaker in free air. The resonant peak in particle velocity is 123.5 Hz which is close to that of the electromagnetic components of those in the speaker. At the electromagnetic resonance of the speaker the mechanical components in the speaker are able to move more freely which in turn causes the cone to move faster.

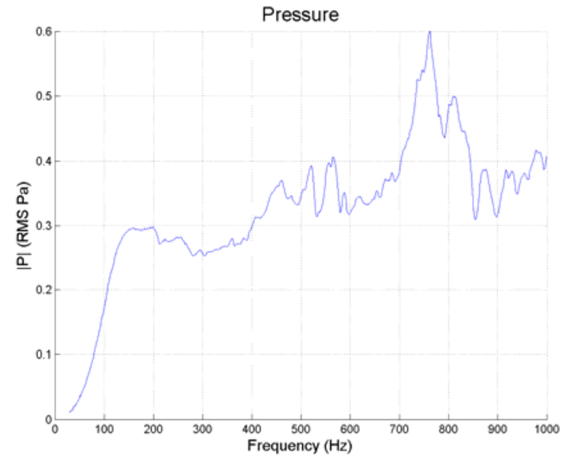

Figure 8: Magnitude of complex pressure versus frequency for speaker in free air

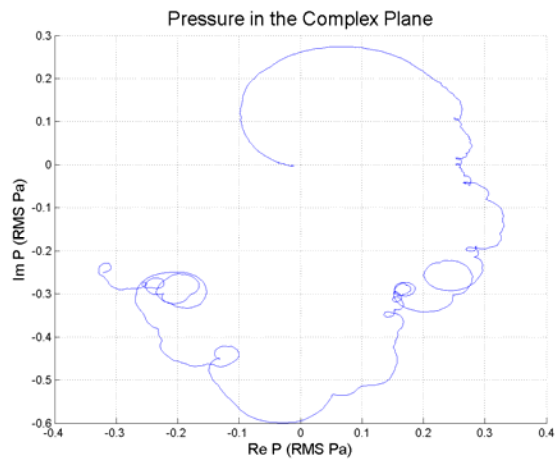

Figure 9: Pressure in the complex plane for a speaker in free air

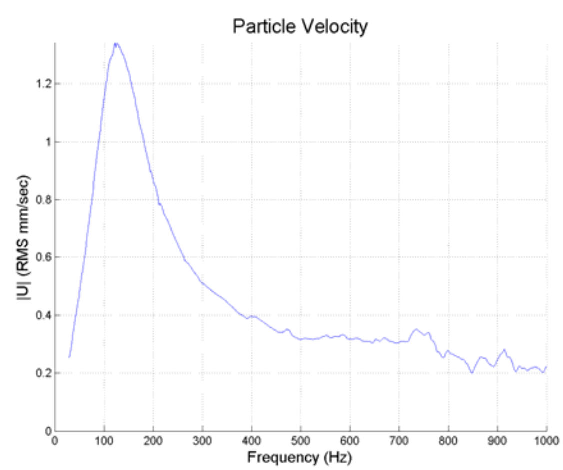

Figure 10: Magnitude of complex particle velocity versus frequency for speaker in free air

An *x*-*y* surface scan is carried out to determine the acoustic properties across the surface of the speaker when driven at the resonance frequency. Figure 11 is the magnitude of the complex pressure radiating from the speaker over the surface of the speaker driven at 120.5 Hz. Since the frequency is fairly low, the wavelength of that frequency is much greater than the diameter of the speaker. This causes the speaker to behave nearly as a flat cylindrical piston propagating air in the form of a plane wave.

Figure 12 is the magnitude of the pressure of across the surface of the speaker mounted on a 24”×24” baffle board. In typical applications speakers are always mounted on some sort of baffle board. Here it should be noted that the maximum magnitude of complex pressure is higher for the speaker mounted on the baffle board. Note also that outside the perimeter of the speaker the pressure does not go to zero like it does for the speaker in free air. So there must be some radial components to the sound field.

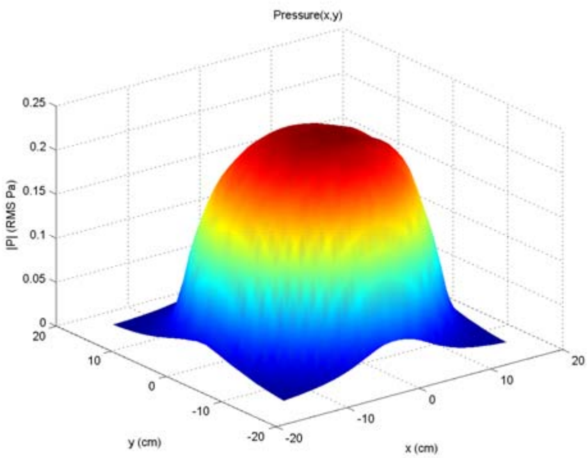

Figure 11: Magnitude of complex pressure across surface of speaker in free air being driven at 120.5 Hz

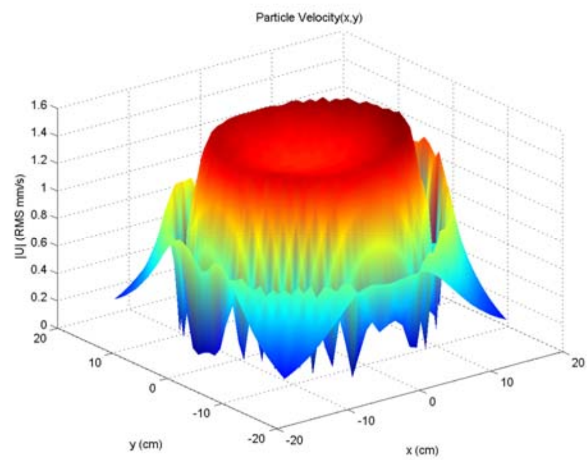

Figure 13: Magnitude of particle velocity across surface of speaker in free air being driven at 120.5 Hz

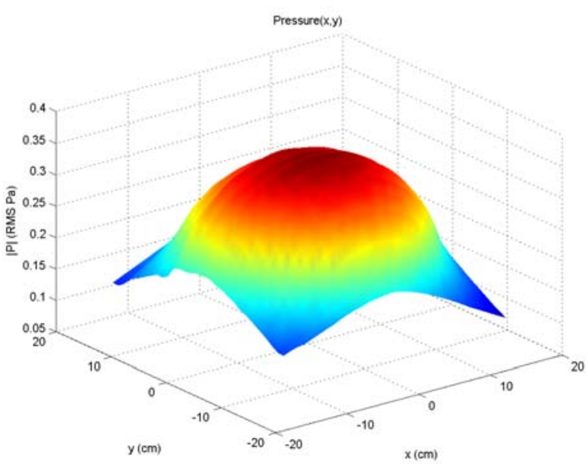

Figure 12: Magnitude of complex pressure of speaker on baffle board being driven at 115.5 Hz

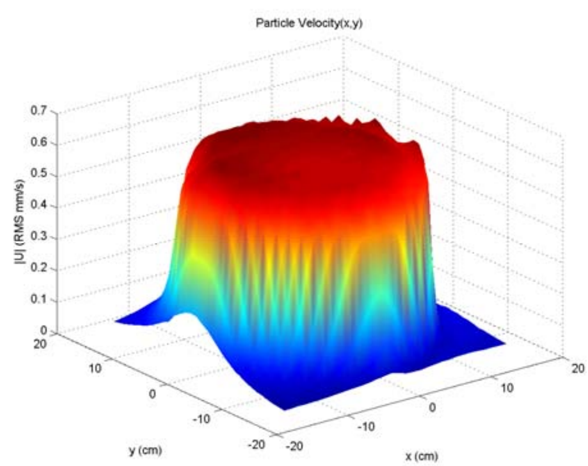

Figure 14: Magnitude of particle velocity across the surface of a speaker mounted on a baffle board being driven at 115.5 Hz

Figure 13 is the magnitude of the complex particle velocity across the surface of the speaker in free being driven at 120.5 Hz, the electromagnetic resonance. The particle velocity plot clearly shows the back radiation of the speaker. Along the perimeter of the speaker the particle velocity goes to zero, but just outside the perimeter of the speaker the sound radiating off the back of the speaker cone is detected at the front. In order to counteract this, the speaker is put on a baffle board.

Figure 14 is a plot of the magnitude of the complex particle velocity across the surface of a speaker mounted on the baffle board being driven at 115.5 Hz. The speaker is driven at 115.5 Hz because that is the electromagnetic resonance for this speaker mounted on a baffle board. Figure 14 shows a drastic difference from Figure 13 in that there is no back radiation from the speaker around the outside perimeter. Since there is no back radiation contributing the particle velocity the maximum magnitude is less in Figure 14, even though the pressure was higher for the speaker on the baffle board.

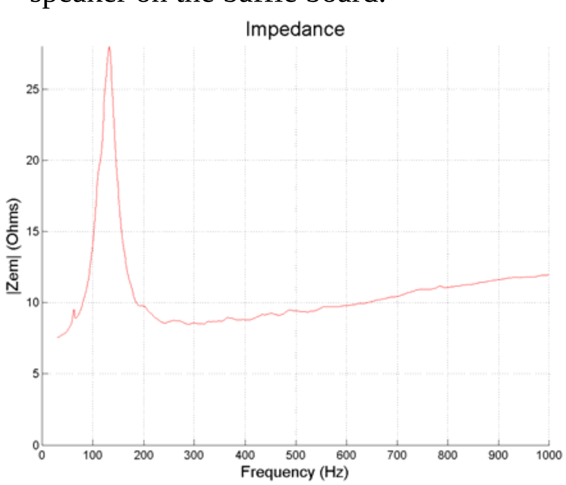

Figure 15: Magnitude of complex electromagnetic impedance versus frequency for a speaker in an enclosed box

The sound field of a speaker in an enclosure behaves similarly to that of a speaker in a baffle, except now the speaker now has a solid surface for the back radiation to bounce back off of and contributes to the speaker behavior. Different speaker enclosures have different frequency responses. Figure 15 is a plot of the magnitude of the electromagnetic impedance versus frequency for the speaker in an enclosed box. The resonance is at 130.5 Hz, slightly higher than in free air or on a baffle board. There is a small resonance at 61.5 Hz that did not appear on the speaker in free air or the speaker mounted on a baffle board. This is due to the frequency response of the absorptive material filling the enclosure or the physical dimensions of the enclosure itself.

Figure 16 is a plot of the magnitude of the sound intensity across the surface of the speaker on a baffle board being driven at 130.5 Hz. Due to the wavelength size being greater than the diameter of the speaker it looks like the sound intensity of a plane wave that would be the result of an oscillating cylindrical piston. In order to see more detailed information about the speaker cone the speaker must be driven at a higher frequency.

The speaker being driven at 3458.0 Hz will show more detail on the shape of the speaker cone. The speed of sound in free air was measured in the room where the experiment was carried out is 345.8 meters per second; this would make the 3458.0 Hz sound wave have a wavelength of 0.10 meters, compared to about 3 meters for the 130.5 Hz. This wavelength correlates with what sort of

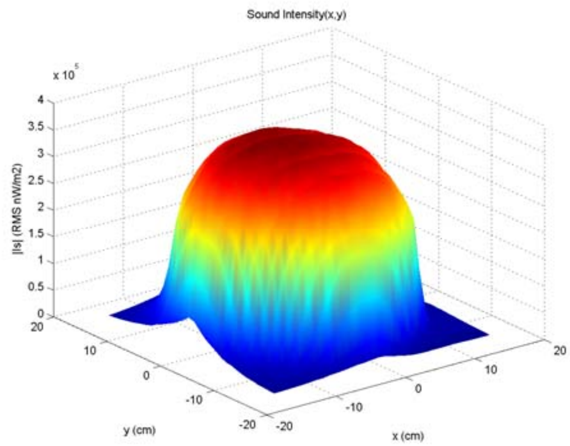

Figure 16: Magnitude of sound intensity across the surface of a speaker in an enclosed box being driven at 130.5 Hz

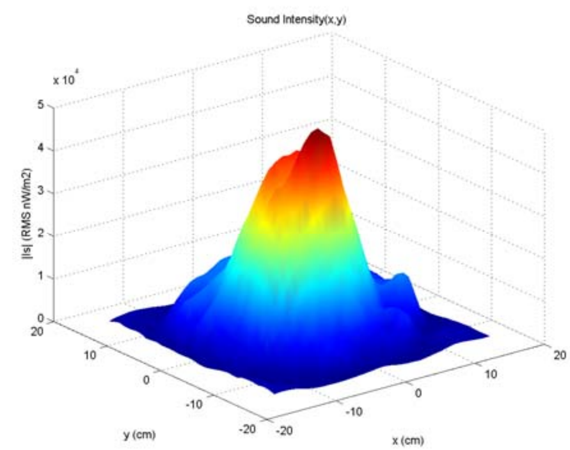

Figure 17: Magnitude of sound intensity across the surface of a speaker in an enclosed box being driven at 3458.0 Hz

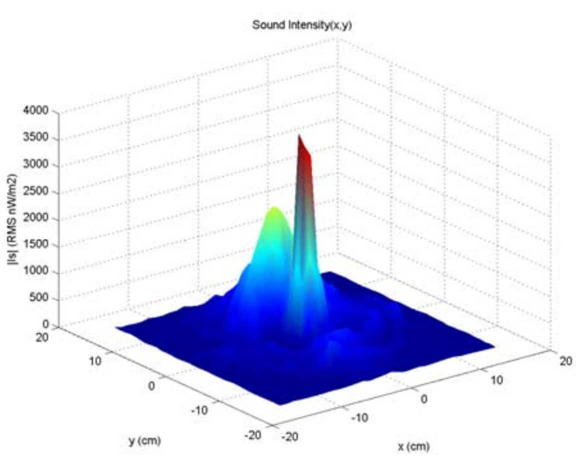

Figure 18: Magnitude of sound intensity across the surface of a speaker in an enclosed box being driven at 10,000.0 Hz

resolution the details of the speaker cone can be determined. Figure 17 is a plot of the magnitude of the sound intensity across the surface of the speaker mounted on a baffle board being driven at 3458.0 hertz. All data collection settings such as the driving amplitude and distance from speaker are exactly the same as in Figure 16 as they are in Figures 17 and 18. This clearly illustrates that the properties of the sound field are highly dependent on the frequency being driven. At the higher frequency the speaker acts as an oscillating cone, which is much more complicated to mathematically model. So the plane wave from a flat piston is commonly used to calculate radiation impedance and other acoustic properties of speakers, especially because most speaker measurements are taken at greater distances away.

Figure 18 is the magnitude of the sound intensity across the surface of the speaker in an enclosed box being driven at 10 kHz. The maximum sound intensity is even more centrally located her, with a much steeper spike. Figures 15, 16, and 17 were all driven with the same voltage from the function generator. However, the frequency response of the speaker decreases significantly after 6,000 Hz. So the maximum amplitude for the speaker being driven at 10 kHz is much less. There is a noticeable asymmetry in Figure 18, which is most likely due to the seam on the speaker cone. More measurements must be taken to confirm this.

With the speaker in the closed box, a frequency scan from 29.5 Hz to 20030.5 Hz was taken to observe how the speaker behaved at high frequencies.

Figure 19 is a plot of the power versus frequency for the speaker in an enclosure. The resonance around 120 Hz is still visible, however, more clearly it shows how as frequency increases the power decreases. The amplitude driving the speaker from the function generator remains the same over the frequency range. These characteristics of the speaker correlate with the frequency response of the acoustic intensity.

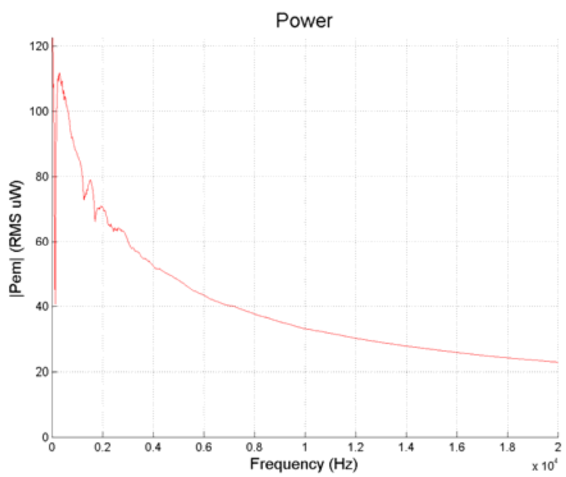

Figure 19: Magnitude of electromagnetic power for a speaker in a sealed box from 29.5 hertz to 20030.5 Hz

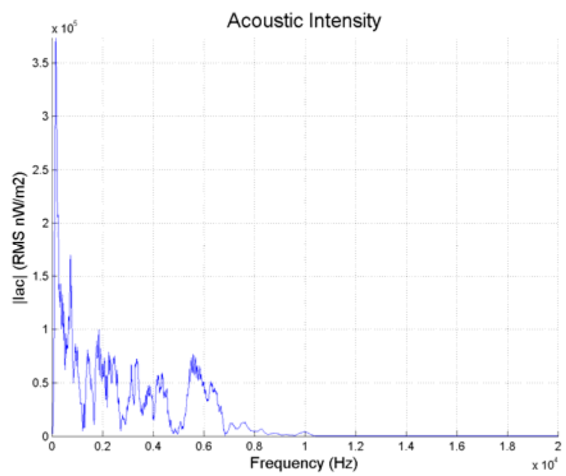

Figure 20: Magnitude of acoustic intensity for a speaker in a sealed box from 29.5 Hz to 20030.5 Hz

Figure 20 is a plot of the magnitude of the acoustic intensity versus the frequency for the speaker in an enclosure. After around 7,000 Hz the acoustic intensity is drastically reduced. This particular speaker is mostly used for electric guitars, which have comparatively low frequencies (The open low-E string on a guitar is ~ 82 Hz). However, the upper frequencies must also be accurately represented. The higher frequencies in any sound are what create the unique tonal characteristics of a sound.

Appendices A through D include all the frequency sweep data taken for the speaker in free air, the speaker on a baffle board, and the speaker in an enclosure.

IV. Conclusions

All of this data is interesting, but we must determine what good significance this has in designing better speakers. The idea of using phase sensitive equipment similar to the pressure and particle velocity microphones is not commonly, if ever, practiced in the industry. There is no literature of the techniques developed at the University of Illinois, Urbana-Champaign with Steve Errede. The pressure and particle velocity microphones were custom designed to suit these measurements.

There are many speaker cabinet simulation softwares on the market. However, very few of them take into consideration the complex, frequency-dependent properties of sound that affect how the energy in sound is distributed and then ultimately affects what we hear. By using phase sensitive equipment we could potentially develop new and more detailed methods of designing speakers and speaker enclosures.

Future work must be done on this project to determine what speaker parameters are really significant in the sound of an individual speaker. The speaker enclosure has a lot to do with how speakers sound, but the sound all starts at the speaker. Also being able to calculate a method of extracting the electrical equivalents associated with the physical characteristics of the speaker would lead into much more insight on speaker behavior. We must investigate multiple speakers and correlate certain electrical or acoustic characteristics with what we actual perceive when we listen to them.

V. Acknowledgments

Special thanks to Prof. Steve Errede for his limitless knowledge and incredible commitment to our projects. Also thanks to Gregoire Tronel for sharing the laboratory space and equipment and knowledge of such equipments, as well as Jack Boparai for his help in the lab. Thank you to the REU program for this research opportunity, which is supported by the National Science Foundation Grant PHY-0647885.

VI. References

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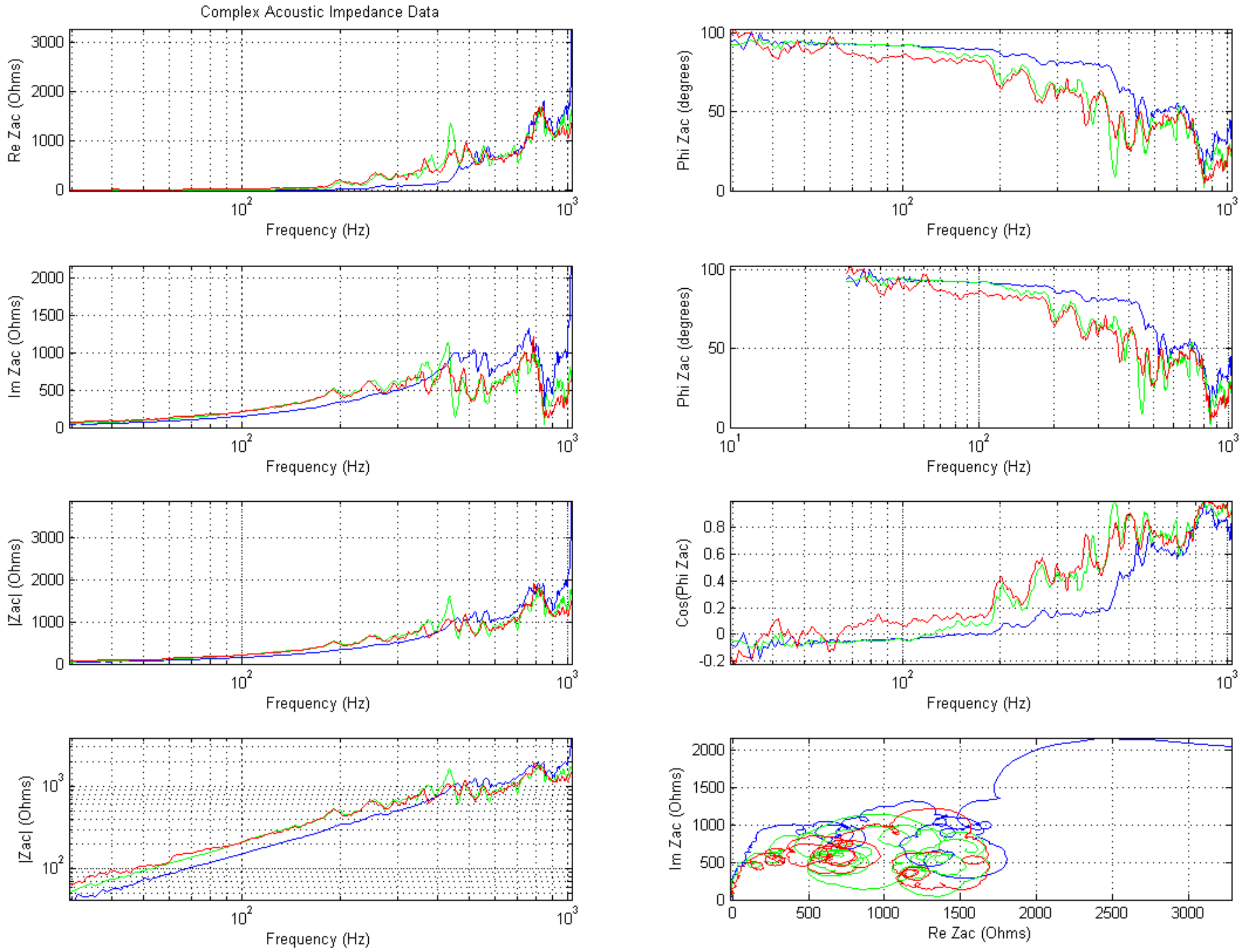
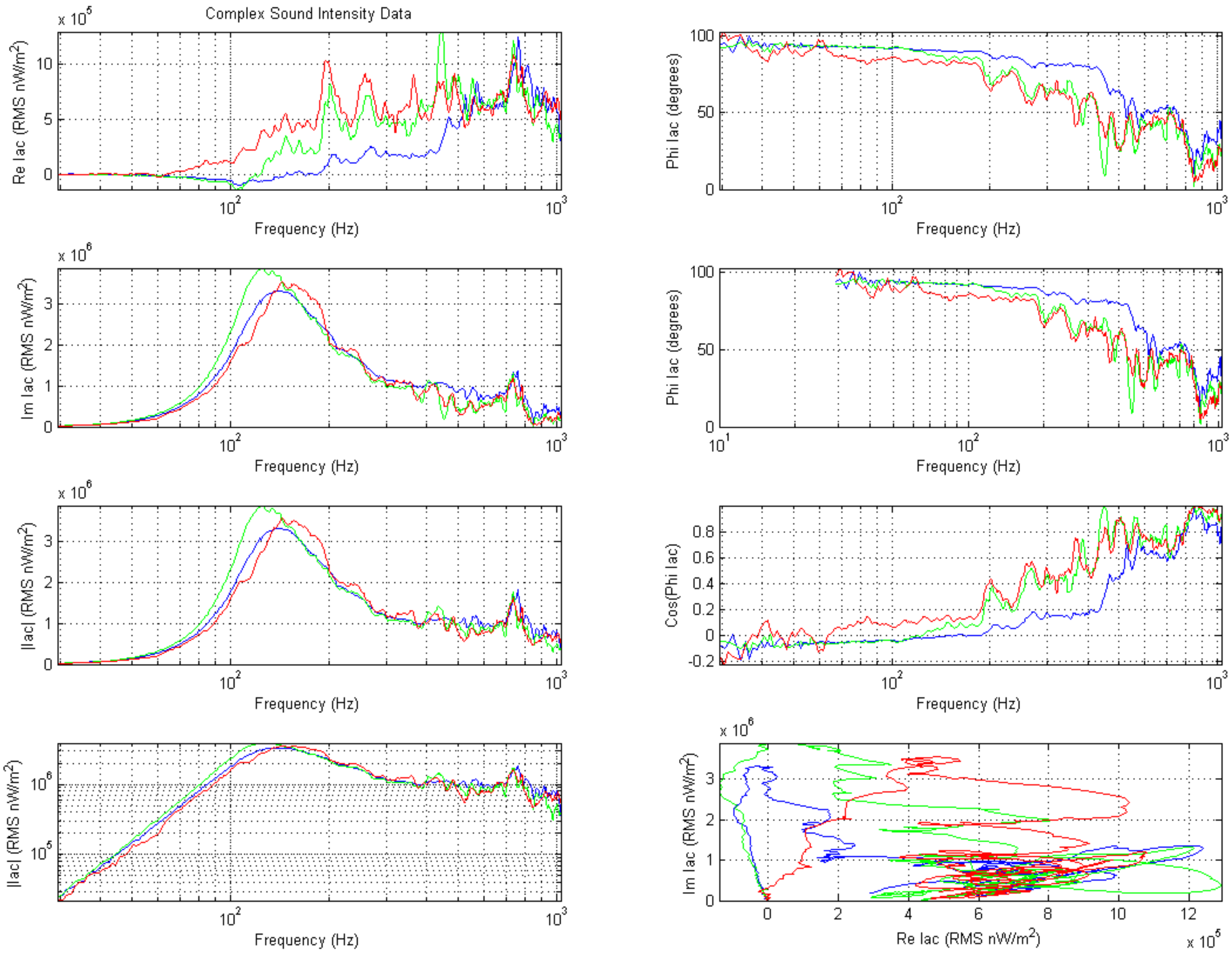
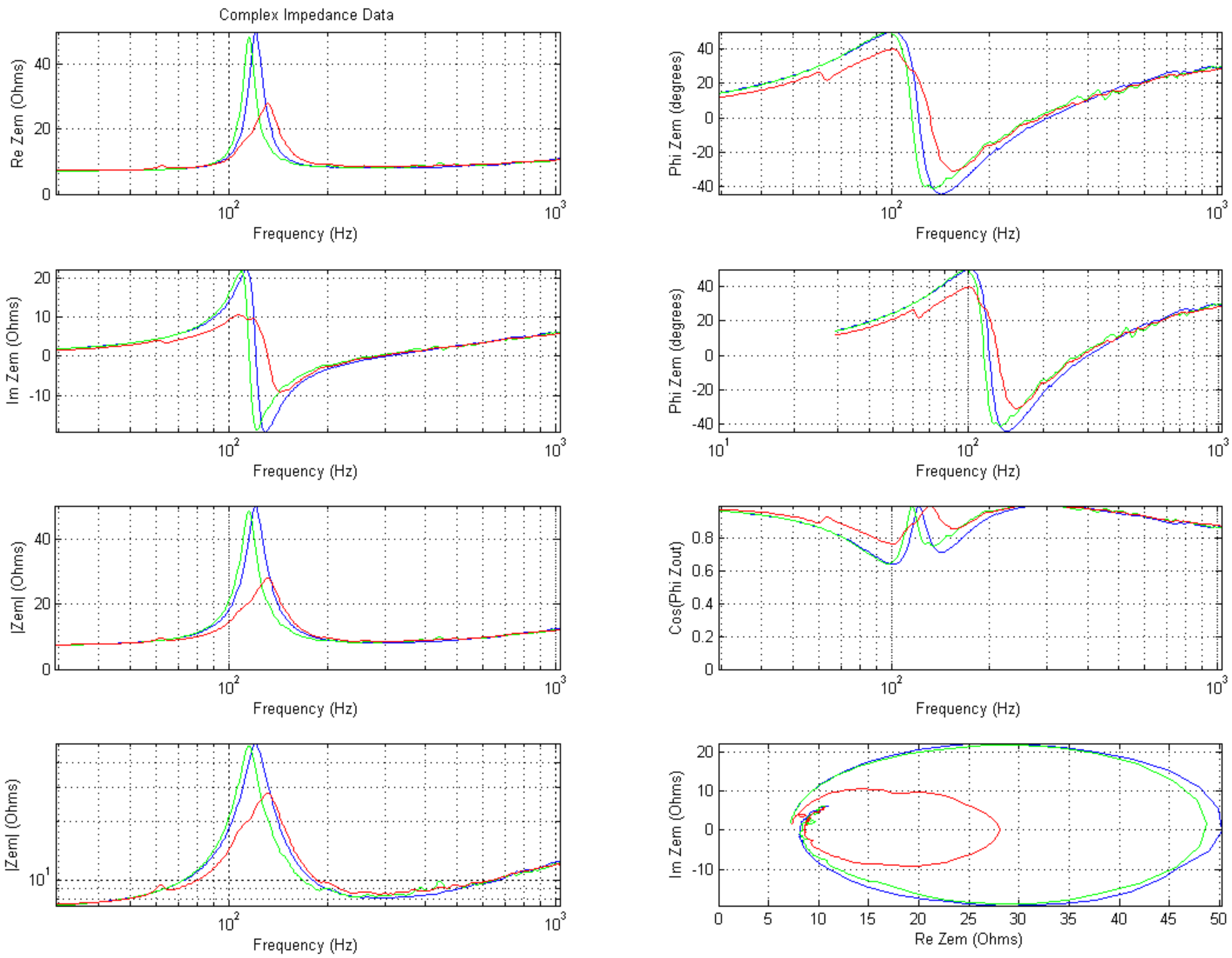
Appendix A – Complex acoustic impedance plots for speaker in free air (blue), speaker on baffle board (green), and speaker in enclosure (red).



Appendix B – Complex sound intensity plots for speaker in free air (blue), speaker on baffle board (green), and speaker in enclosure (red).



Appendix C – Complex electrical impedance plots for speaker in free air (blue), speaker on baffle board (green), and speaker in enclosure (red).



Appendix D – Complex electrical power plots for speaker in free air (blue), speaker on baffle board (green), and speaker in enclosure (red).