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Measurements of Acoustical Speaker Loading Impedance In Headphones and Loudspeakers

Jason McIntosh[1]

[1] McIntosh Applied Engineering (MAE), 8592 Hiawatha Ave, Eden Prairie MN 55347
jasonmcintosh@maellc.com, jasonmcintosh@yahoo.com

ABSTRACT

The acoustical design of two circumaural headphones and a desktop computer speaker have been studied by measuring the acoustical impedance of the various components in their design. The impedances were then used to build an equivalent circuit model for the devices which then predicted their pressure response. There was seen to be good correlation between the model and measurements. The impedance provides unique insight into the acoustic design that is not observed though electrical impedance or pressure response measurements which are commonly relied upon when designing such devices. By building models for each impedance structure, it is possible to obtain an accurate model of the whole system where the effects of each component upon the device's overall performance can be seen.

1. INTRODUCTION

Designing acoustic products such as speakers and headphones primarily involves measuring the pressure response of the device for a fixed voltage input. When an impedance is referred to, it is almost always concerning the electrical impedance into the speaker's terminals, not the acoustic impedance of the acoustical components incorporated into the design. Just as electrical impedance is important for electrical designs, the acoustical impedance of the device's components are important for the acoustical design of the system. This paper looks at some of the acoustical impedance of the components in two headphones and a desktop speaker.

The impedance of the acoustic components are important because they form the basis for the "acoustic circuit" that defines the device's operation. A lack of a knowledge of their impedance is similar to having an electrical circuit where the impedance of the resistors, capacitors, amplifiers, etc. are unknown. While "experience and trial-and-error" would make it possible to design electrical circuits without this knowledge, a circuit designer wouldn't think of undertaking a design though such a method. However, due to a lack of the impedance of acoustic components, many commercial acoustic devices are frequently designed through the inefficient process of "experience and trial-and-error".

The acoustical impedance that will be used in this paper is the ratio of the pressure over the volume velocity, or

$$Z_a = \frac{P}{U}\left(\frac{Pa}{\frac{m^3}{s}}, Acoustic\ Ohms\right) \tag{1}$$

which we will give units of Acoustic Ohms. Acoustical impedance comes in two forms. It can be the impedance across a device, which is referred to as a flow impedance, or into a device, which is referred to as a surface impedance. The impedances reported in this paper will all be surface impedances.

Acoustical impedance in headphones has been investigated before, but the studies only looked at the impedance seen looking into the ear when the headphone was worn[1,2]. In this investigation, three devices will be studied. A headphone from Sennheiser, a headphone from Audio Technica, and a desktop speaker from Logitech. These devices will be completely disassembled, the impedance of the individual components will be measured. Then finally, they will be used to assemble a model of the complete device.

2. SENNHEISER HD558 HEADPHONE

The Sennheiser HD558 is a circumarual (over the ear) headphone with a single speaker and cloth covered ear cushions as shown in the photograph below.

Figure 1 Left: Sennheisser HD558 headphone. Right: The HD558 with speaker flange removed showing rear speaker and rear volume.

Figure 2 shows a rough sketch of one of the headphone's speaker assemblies and the various acoustical impedances present in the design.

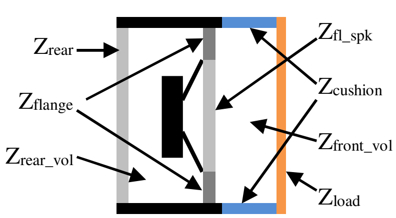

Figure 2 Sketch of the impedances from a typical circumaural headphone.

The different impedances in the design are:

Z_{rear}: Impedance of the outer rear headphone shell.
Z_{flange}: Impedance through the flange that allows for communication between the front and rear of the speaker.
Z_{rear_vol}: Impedance of the rear air volume.
Z_{fl_spk}: Impedance of the part of the flange immediately in front of the speaker.
$Z_{cushion}$: Impedance through the cushion.
Z_{front_vol}: Impedance of the front air volume.
Z_{load}: Impedance of the "load", or what the headphone is acoustically exciting. This will either be infinite (when the headphone is pressed up to a solid table surface), or it will be a human ear (the load the headphone is designed to drive).

These impedances will be measured with a new device called a SIMA[3], or Surface Impedance Measurement Apparatus. A SIMA is a small, hand held acoustic impedance measurement device that comes in two sizes. One, the MAE130, measures the impedance over a 25mm diameter area and roughly fills the palm of a person's hand. The other, the MAE131, measures the impedance over a 12mm diameter area and is roughly the size of an adult male thumb. The MAE130 is shown in Figure 3, being used to measure two different impedances of the HD558.

Figure 3 Left: An MAE130 being used to measure the impedance $Z_{fl_spk} + (Z_{cushion} \parallel Z_{front_vol} \parallel Z_{flange})$seen by the front of the speaker. The cushion is on a rigid table surface, so Z_{load} is infinite in this case. Right: The MAE130 being used to measure Z_{fl_spk}.

2.1. Z_{fl_spk}

The flange that holds the speaker is completely covered by a black cloth with very low acoustic flow resistance. Some areas of the flange are also covered by a white cloth-like material with a much higher flow resistance than the black cloth. In a more thorough study, the flow resistance of these cloths would be measured, but here the impedance of the assembly will be measured. The circular area directly in front of the speaker is shown in Figure 4. It has two areas: a small 18mm diameter area covered by just the black cloth, and an outer 36mm ring that is covered by both the black and white cloths. The impedance that the speaker sees on its front surface will be a parallel combination of these two areas.

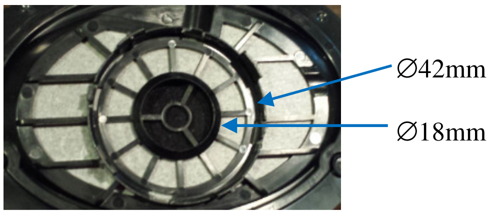

Figure 4 Photograph of interior flange surface. The center 42mm circular area is where the speaker mounts into the flange.

The impedance of the front flange as seen by the speaker is shown in Figure 5. The imaginary part of the impedance is roughly following a jω behavior as one would expect from a moving mass. However, the real part is also following a jω behavior, which is very unusual for such a structure. One would normally expect the cloth to present a nearly constant resistance behavior.

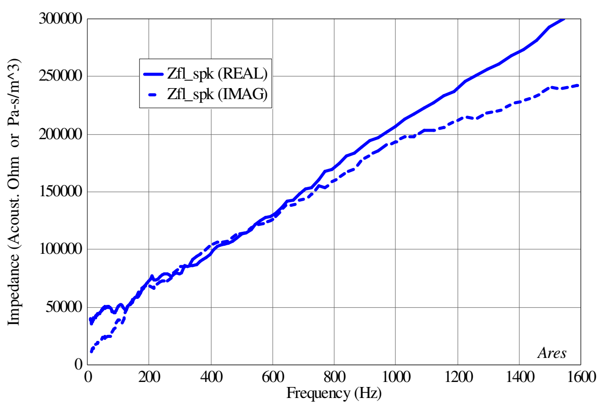

Figure 5 Plot of Z_{fl_spk} as measured by the MAE130.

To better understand the impedance behavior, an Ares[4] acoustic simulation model was built. The model is shown in Figure 6 with the model results shown in Figure 7. The first model includes the radiation impedance that's present in the measurements. The imaginary part of this model (green curves) follow the measured data very well, however the real part is significantly less than the measured term. The model without the radiation has a significantly lower imaginary term, indicating that a large part of the imaginary mass reactance comes from the radiation impedance. Ordinarily, one would want to understand why the real term isn't matching the model better, but here we'll just accept the impedance as is and move on.

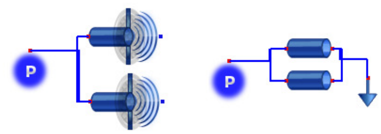

Figure 6 An Ares model of Z_{fl_spk}. The parameters for one port are: length=5mm, diameter=18mm, and resistance of 13 MKS Rayls. These parameters for the other port are: 5mm, 25mm, and 75 MKS Rayls.

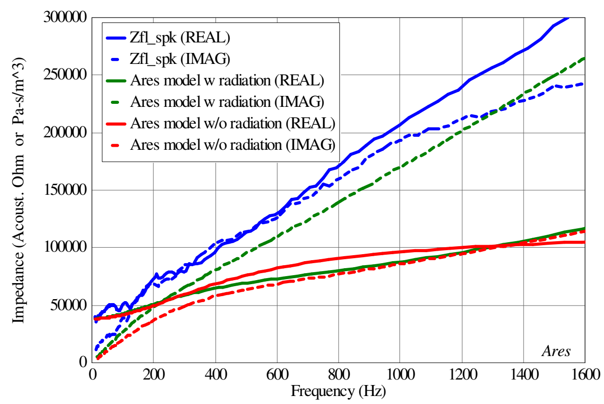

Figure 7 Plot of the measured Z_{fl_spk} as well as that from the Ares model from Figure 6, which shows the impedance with and without the radiation load.

2.2. $Z_{cushion}$ || Z_{front_vol}

It is not possible to simply measure the cushion impedance, $Z_{cushion}$, by itself. However, this impedance and the front volume impedance can be measured in parallel by removing the speaker and putting the MAE130 in its place and placing the cushion onto a hard table top surface. This is a similar arrangement to that shown in Figure 3, but the two side areas representing Z_{flange} impedance need to be sealed. The impedance from such a measurement is shown in Figure 8. Note that the impedance is dominated by the resistive term. The imaginary part follows a jω "mass like" behavior for low frequencies, but turns compliant above 1100 Hz. Therefore, $Z_{cushion}$ is largely a resistive term plus a mass reactance, or

$$Z_{cushion} \cong R_{cushion} + j\omega^* M_{cushion}$$

Zfront_vol will largely follow the impedance of a simple volume, or

$$Z_{front\_vol} \cong \rho c^2 / j\omega V_{front\_vol}$$

where ρ is the density air, c is the speed of sound, and V_{front_vol} is the volume in front of the speaker. The behavior of the imaginary part in Figure 8 likely comes from the $j\omega^* M_{cushion}$ term dominating at low frequencies and the $1/j\omega$ of Z_{front_vol} dominating the parallel impedance at high frequencies.

A simple Ares model (not shown) based on the above assumptions was built to model this structure, however instead of using a simple value for $R_{cushion}$ and $M_{cushion}$, a porous material model was used. The results from this model are also shown in Figure 8. The model comes close to capturing the impedance's imaginary behavior, but misses the real part by almost a factor of two. As with the Z_{fl_spk} impedance, this warrants further investigation which won't be pursued in this study.

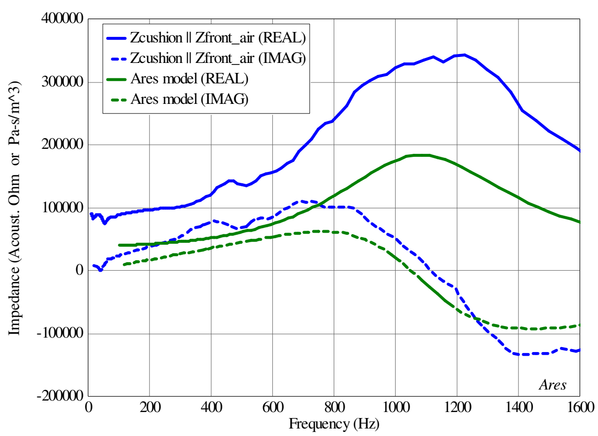

Figure 8 Measured $Z_{cushion}$ in parallel with Z_{front_vol}. and an Ares model that approximated the impedance.

An interesting behavior that's worth looking into is the impedance that the front of the speaker sees when the cushion is compressed. Figure 8 shows the Zfl_spk + ($Z_{cushion}$ || Z_{front_vol}) impedance as the cushion is compressed from 1 to 9 mm. As one may expect, the resistive term grows as the cushion's material is compressed and the air has to travel through smaller material pores to escape the front volume. The imaginary term loses its low frequency mass effect and behaves more as a smaller sealed volume. One would expect the resistance increase to keep more low frequency energy in the front volume. The imaginary part will change the reactive load that the speaker sees. The effect that this will have on the output will be dependent on the rest of the reactive load that the speaker's cone presents, and the rest of the acoustic circuit.

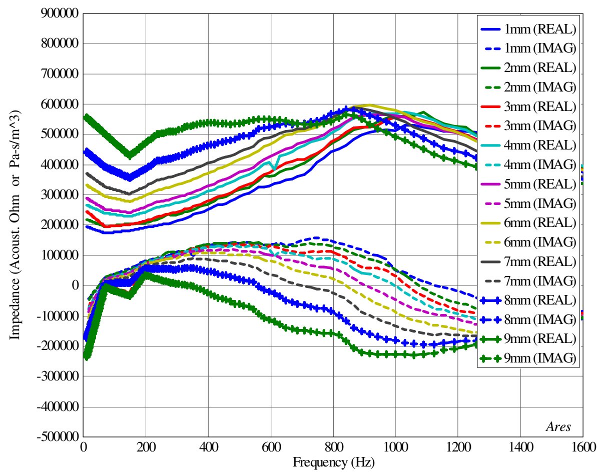

Figure 9 Zfl_spk + ($Z_{cushion}$ || Z_{front_vol}) for the cushion compressed from 1 to 9mm.

2.3. Z_{rear} || Z_{rear_vol} and Z_{flange}

The measured impedance that the speaker sees to the rear, and the separate impedance seen through the flange is shown in Figure 10. The back of the headphone is very open and covered with a thin cloth so the Z_{rear} impedance is very small and dominates the Z_{rear}||Z_{rear_vol} impedance combination. The openings in the back cause the impedance to be a dampened mass reactance. The Z_{flange} impedance is dominated by the resistive term, largely due to the relatively high resistivity of the white cloth. The Z_{flange} data has an unusual drop off under 200 Hz which may be due to the motion of the cloth.

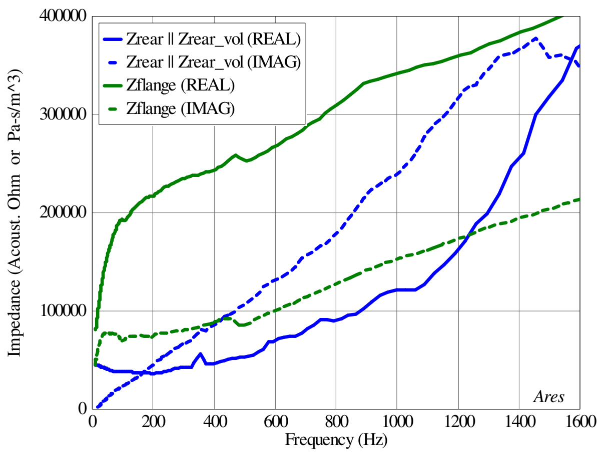

Figure 10 $Z_{rear} \parallel Z_{rear\_vol}$ and Z_{flange}.

2.3.1. Speaker Impedance

The last element to have its impedance measured is the speaker. Figure 11 shows the speaker being measured, the resulting impedance, and the impedance curvefit to a dampened mass/spring system. The curvefit parameters were used to generate the speaker's mechanical parameters (M_m, C_m, and R_m). The other speaker parameters (BL, R_e, and L_e) were obtained through curvefitting to a pressure response, the details of which won't be reported here. These parameters will be used in a model to predict the overall headphone response.

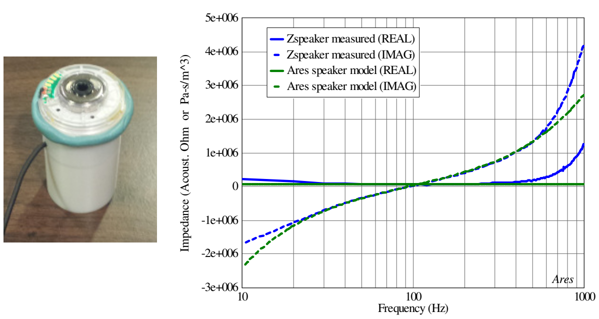

Figure 11 Left: photo of the MAE130 being used to measure the impedance of the speaker's cone. Right: the measured speaker impedance and the impedance fit using the mechanical parameters of 0.456g, 6.33mm/N, and 0.066 mechanical ohms for 36mm cone diameter.

2.3.2. Headphone Response

The measured impedances from the previous sections can be combined to build a model of the headphone. The Ares model for this is shown in Figure 12 below. The measured impedances were imported into the resistor elements as a complex frequency dependent lookup table. Figure 13 shows the measured and modeled frequency response for the the headset. The model does a reasonably good job of predicting the response for frequencies under 1500 Hz, but starts to deviate for higher frequencies. The main reason for this is due to the impedance approximation breaking down for very short wavelengths. For the impedance to be meaningful, the pressure and velocities must be uniform over the measurement area. The MAE130 has a 25mm measure diameter, so the wavelength should be 250mm or larger. In air, the wavelength of sound will be 250mm for frequencies less than 1400 Hz, which explains why the impedance based model is only matching the measured results up to 1500 Hz.

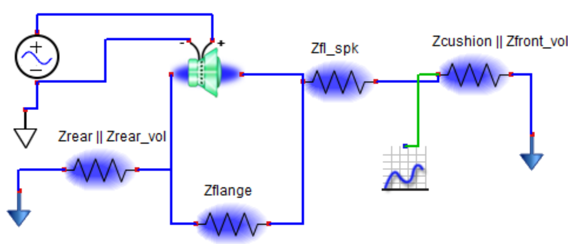

Figure 12 Ares model of headset using measured impedances.

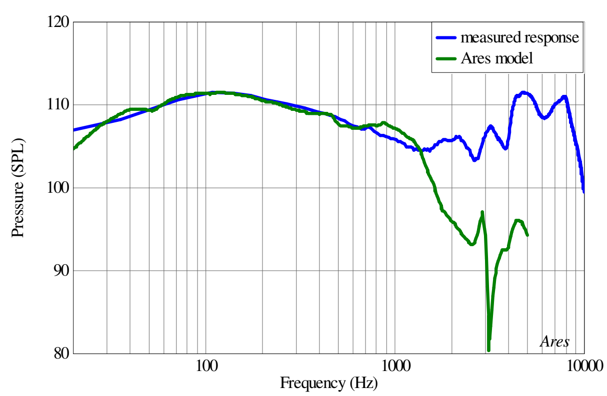

Figure 13 Measured and predicted frequency response of headset pressed against a hard table surface.

3. AUDIO TECHNICA ATH-M20 HEADPHONE

The Audio-Technica ATH-M20x is another circumaural headphone. This design is similar to the Sennheiser HD558, but has a solid rear housing and has an ear cushion with an impermeable vinyl skin. The ATH-M20x has a similar internal design as the HD558, with a Z_{flange} path and a speaker with a similar diameter. There isn't room in this paper to go into all of the acoustic design differences, but the impermeable ear cushion is worth taking a close look at.

Figure 14 Audio-Technica ATH-M20x headphones.

The $Z_{cushion} \| Z_{front\_vol}$ impedance for the two headphones are shown in Figure 15. One immediately sees that the Audio-Technica has a much large impedance at the very low frequencies (<400 Hz) due to the impermeable vinyl skin of its ear cushion. This large impedance will cause more low frequencies to be present than with the open cloth covered ear cushion used on the Sennheiser headphone.

Note that the Audio-Technica ear cushion impedance has a resonance at 25 Hz. As shown in Figure 3, the impedance was measured by placing the disassembled headset, with the MAE130 attached, onto a flat table surface. The 25 Hz resonance is due to the mechanical resonance of the headset mass "bouncing up and down" on the spring created by the front air volume and ear cushion. This was verified by adding weight to the system and seeing this resonance shift down in frequency. With the added *tension* of the headband, this mechanical resonance would be expected to shift up in frequency, however it's unlikely that this will be an issue while worn on a person's head due to the air leaking out around their hair, which will break the seal between the cushion and the head. Whatever the case may be, measuring the acoustical impedance provides great insight into the behavior of the system, which can help guide the design of these devices.

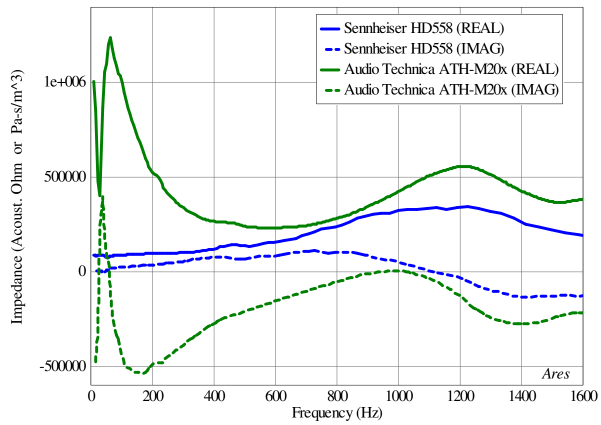

Figure 15 $Z_{cushion} \| Z_{front\_vol}$ for the Sennheiser and Audio-Technica headphones.

4. LOGITECH POWERED PC SPEAKERS

A pair of powered PC speakers from Logitech have also been studied. They are pictured in Figure 16 below. The enclosures are about 6 inches high and use a single 41mm speaker.

Figure 16 Logitech powered desktop PC speakers

4.1. Enclosure impedance

These speakers use a bass reflex design with a conical horn located just above the speaker. The MAE130 was used to measure the impedance that the speaker sees to its rear. The impedance with the bass port open and closed are shown in Figure 17. The bass port reduces the impedance at low frequencies and produces a resonance at about 150 Hz. This resonance will produce a modest bass boost in the speaker's response.

Note that above 2 kHz, there is a lot of internal cavity mode activity that can be seen through the impedance measurement. These resonances can affect the speaker's behavior as they will cause a great deal of variation to the speaker's rear loading. To reduce the effect of these cavity modes, the speaker was filled with a polyester porous material. Figure 18 shows this impedance plotted on a linear frequency scale. The porous material significantly reduces the effect of these modes and creates a much smoother high frequency impedance curve. This would reduce the high frequency loading varibility that the speaker sees and produce a more uniform freqeuncy response.

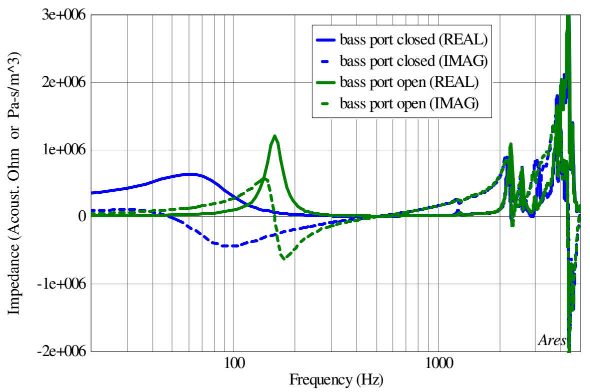

Figure 17 Impedance into the Logitech enclosure with the speaker removed. This is the impedance seen by the rear of the speaker.

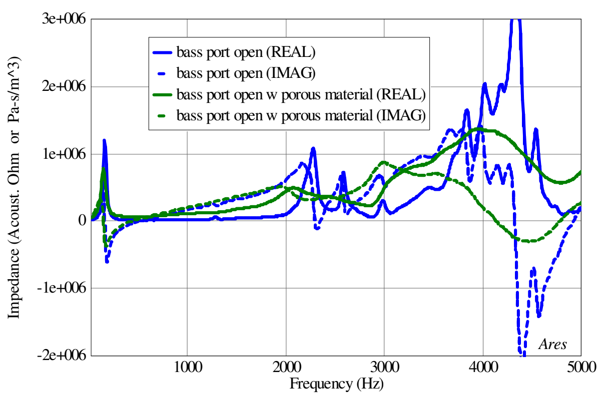

Figure 18 Impedance into the Logitech enclosure with and without porous material filling the enclosure volume. The bass port was open.

4.2. Bass Reflex Port Impedance

The smaller MAE131 was used to measure the impedance of the bass horn. This impedance, along with a simple Ares model, is shown in Figure 19. At low frequencies (<2500 Hz), the impedance is a simple jω mass reactance, but there is a standing wave resonance that occurs around 2200 Hz due to a standing wave in the horn. This resonance is also seen in an Ares model of the port. It will turn out that this resonance has little effect on the speaker's output response because the internal volume of the speaker has an impedance much less than the port at these frequencies. (The speaker sees the volume impedance and the horn impedance in parallel.)

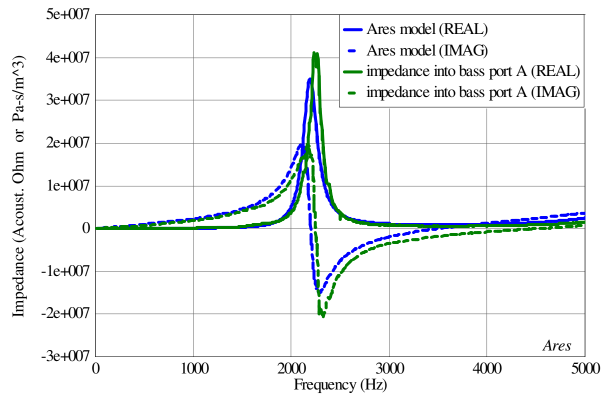

Figure 19 Impedance into the Logitech's bass port.

4.3. Frequency Response

The speaker was parameterized using a similar impedance measurement technique used with the Sennheiser headphone. The Ares model shown in Figure 20 was produced for the Logitech speaker using the measured impedances and the speaker parameters. The frequency response for the speaker was measured in an anechoic chamber at a distance of 12 inches. Figure 21 shows a comparison of the modeled and measured responses. The 125 Hz resonance is shown as a slight increase in the bass response. This is a relatively small boost for such a design, but the model is able to capture it. The measured response has some detail above 6000 Hz that isn't being captured by the model, however the model does show the effect of the internal volume cavity modes above 3 kHz. Overall, the Ares model matches the measurements reasonably well.

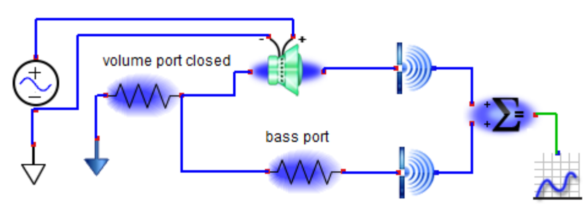

Figure 20 Ares model of Logitech speaker.

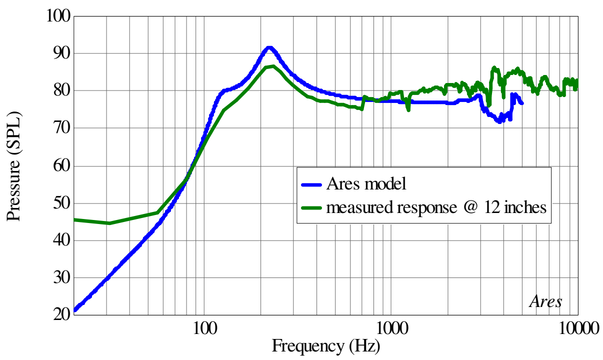

Figure 21 Frequency response of Logitech speaker.

5. DISCUSSION

It has been shown that measuring the acoustical impedance of audio devices such as headphones and speakers can be used to model their behavior. The measured impedance of the individual components provides insight into the behavior of the acoustic design. However, one will eventually want to know what's controlling the impedance of the components. By extending the analysis shown in this paper to include building a model that predicts the impedances of each component, an even greater understanding about the acoustic design can be obtained. Eventually, this will result in a model that allows one to vary the device's dimensions and material properties. Such a model can then be used to optimize the design.

It is hoped that this study will highlight the importance and benefit of measuring the acoustical impedance of the various components in a design. With greater knowledge and better design tools, this will hopefully become standard practice for designing audio devices.

6. REFERENCES

[1] M. Vorlandera, "Acoustic load on the ear caused by headphones", J. Acoustical Society of America, Vol 197, No. 4, pg. 2082, April 2000.

[2] D. Ciric, D. Hammershoi, "Coupling of earphones to human ears and to standard coupler", J. Acoustical Society of America, Vol 120, No. 4, pg. 2096, October 2006.

[3] SIMA, or Surface Impedance Measurement Apparatus supplied by McIntosh Applied Engineering. Details on the device can be viewed at MAELLC.com.

[4] Ares is an acoustic simulation program also supplied by McIntosh Applied Engineering.