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Advances in Impedance Measurement of Loudspeakers and Headphones

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ABSTRACT

Impedance measurement is often the sole electrical measurement in a battery of QC tests on loudspeakers and headphones. Two test methods are commonly used, single channel and dual channel. Dual Channel measurement offers greater accuracy as both the voltage across the speaker (or headphone) and the reference resistor are measured to calculate the impedance. Single Channel measurement methods are more commonly used on the production line because they only require one channel of a stereo soundcard, which leaves the other free for simultaneous acoustic tests. They are less accurate, however, due to the test methods making assumptions of constant voltage or constant current. In this paper we discuss a novel electrical circuit that offers similar impedance measurement accuracy compared to complex dual channel measurement methods but using just one channel. This is expected to become popular for high throughput production line measurements where only one channel is available as the second channel of the typical soundcard is being used for simultaneous acoustic tests.

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1. INTRODUCTION

The complex electrical impedance for single and multiple driver loudspeakers is a quantity representing a composite of several electromagnetic, mechanical, and acoustical parameters that have been historically well described. Loudspeaker researchers and manufacturers need to accurately measure this important parameter for a wide range of loudspeaker sizes and types. Manufacturers have a specific need for impedance measurements that can be implemented with a single analysis channel. Typical single channel measurement methods have their shortcomings that will be explained.

Voice coil impedance can be derived when the excitation voltage applied to the voice coil and the resulting current magnitude and phase through the voice coil are known.

A standard method for measuring the voice coil current is to insert a known value of electrical resistance, *Rsense*, in series with the voice coil. The voltage across this resistor, *Vsense*, is proportional to the current through the voice coil provided that the resistor does not have any reactive components in the frequency range of interest. If the voice coil voltage is known, the complex impedance is easily calculated. Unfortunately, this arrangement has its limitations and can produce misleading results.

While simple to implement, even small *Rsense* values cause a deterioration of damping factor by one or two orders of magnitude, affecting the measured impedance magnitude. Voice coil displacement is also affected since back EMF is not as effectively dissipated. The voltage across the voice coil is then no longer a known quantity since the back EMF term is not accounted for, requiring a second analyzer channel to measure the voice coil voltage.

Heating of *Rsense* becomes a factor during testing at higher power, as the value of *Rsense* will drift with time and temperature, introducing additional errors. Additionally, it is desirable to use the same test setup to measure small drivers, (e.g. those used in headphones), and large drivers, (e.g. low impedance woofers), without requiring different *Rsense* values.

The method described in this paper utilizes an active circuit that produces a *Vsense* signal that accurately represents the voice coil current. Further, only a single analysis channel is required since the voice coil voltage is held relatively constant and can be referred back to the generator. The proposed solution works independently of the driver size, does not alter the damping factor, and reduces thermal drift effects.

2. THEORY

Reference [1] provides detail on the nature and estimation of loudspeaker parameters that affect electrical impedance, for example:

- Voice coil resistance (electrical)
- Voice coil inductance (electrical)
- Voice coil mass (mechanical)
- Diaphragm mass (mechanical)
- Diaphragm suspension resistance and compliance (mechanical)
- Diaphragm radiation impedance (acoustical)
- Acoustic loading of any enclosures (acoustical)

Measuring the magnitude and phase of the current while the excitation frequency is varied over the range of interest yields data that can be used to identify various modes of loudspeaker operation. One of the most significant data points is the frequency where lowest resonance point of the loudspeaker is attained. This is predominantly produced by the mechanical interaction of mass and compliance within the loudspeaker, behaving as a spring-mass system. Accurate impedance measurement, especially around first resonance, is necessary for accurate calculation of subsequent small signal parameters.

The mixture of parameters becomes more involved for multiple driver loudspeakers with crossover networks between the amplifier and voice coils. Additionally, all of these parameters vary over time, temperature, and as the power to the loudspeaker is increased. Each unit manufactured will be unique in regard to these quantities resulting in a specific impedance characteristic.

2.1. Simple Impedance Measurement Methods

A simple method for measuring loudspeaker impedance is shown in Figure 1:

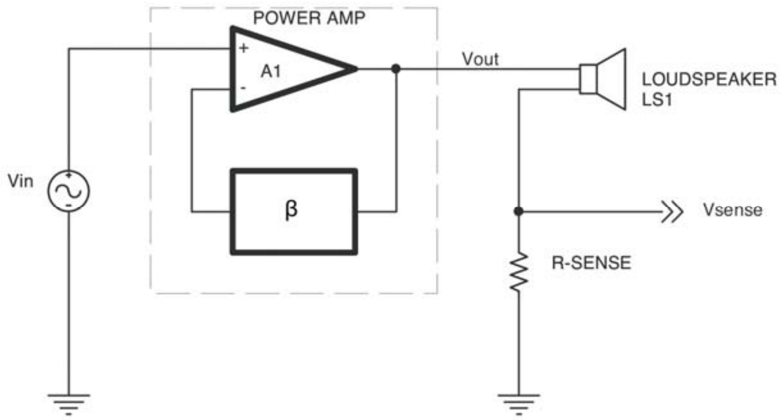

Figure 1: Simple Impedance Measurement Circuit

Signal source *Vin* feeds the power amplifier within the dashed line in Figure 1. The power amplifier drives a loudspeaker, LS1, which may have a DC resistance as low as a few Ohms to hundreds of Ohms.

The power amplifier closed loop voltage gain, A_{CL}, is the product of open loop gain A1 and feedback from network β. The A1 and β blocks are integral to the power amplifier; later sections will discuss a different arrangement of these blocks. Any power amplifier with a suitable A_{CL} may be utilized in this method. Typical values of commercially available units tend to be in the range of 10 (+20dB) to 31 (+30dB). *Rsense* is in series with the return leg of the loudspeaker. Values typically range between 0.1Ω to 1Ω.

Provided that *Rsense* does not have any reactive components in the frequency range of interest, the resulting signal *Vsense* is proportional to the current through the loudspeaker voice coil. Impedance may be calculated at any frequency point by simply applying Ohms law. Taking voltage gain into account, the complex loudspeaker impedance as a function of frequency, $Z_{LS}(s)$, is approximately:

$$Z_{LS}(s) = \frac{(Vin \times A_{CL})}{\left(\frac{Vsense(s)}{Rsense}\right)} \qquad (1)$$

In Eq. 1, the numerator is equal to the voltage across the voice coil and *Rsense*. The denominator is proportional to the current through the voice coil and *Rsense*.

2.2. Simple Impedance Measurement Limitations

While simple to implement with commercially available power amplifiers and components, the circuit in Figure 1 has limitations, most significantly the presence of *Rsense* in series with the loudspeaker interferes with the impedance measurement.

2.2.1. Damping Factor Effects

Damping factor, DF, is an indication of how well loudspeaker diaphragm movement is controlled by the power amplifier. As the voice coil moves in response to the electrical current sourced by the power amplifier, it generates current since it is immersed in a strong magnetic field in magnetic structure's gap. This is often referred to as 'back EMF'. The amplifier must be both a current source, to drive the voice coil, and a current sink, dissipating the back EMF as heat in the amplifier's output stage. The effect is prominent at resonance.

A high damping factor is desirable. It indicates that the power amplifier can simultaneously source current and sink the back EMF, effectively acting as what is often referred to as an electrical 'engine' and 'brake' that reduces ringing at resonance.

Including the internal output impedance of the power amplifier, *Rout*, damping factor DF is equal to:

$$DF = \frac{R_{LS}}{(Rout + Rsense)} \qquad (2)$$

Rsense is effectively in series with the power amplifier output impedance. This decreases the damping factor of the system.

In Eq. 2, R_{LS} is equal to the resistive component of the voice coil impedance. Commercially available power amplifiers can have damping factors in the range of 100 to 500. Without *Rsense*, Eq. 2 yields an output impedance of 0.008Ω to 0.04Ω for such amplifiers. If R_{LS} is 4Ω, an *Rsense* of 0.1Ω reduces DF to 40; 1Ω reduces DF to 4. This reduction in DF affects the measured magnitude of Z_{LS}.

2.2.2. Voltage Effects

In Eq. 1, the numerator is equal to the voltage across the voice coil and *Rsense*, which is equal to *(Vout + Vsense)*. An error is introduced into the numerator of Eq. 1 when *Vsense* is close in magnitude to *Vout*. To accurately measure impedance, only the voltage across the voice coil should be considered. One method of addressing this issue is by placing a differential amplifier from *Vout* to *Vsense*, providing *(Vout – Vsense)*, then performing a second measurement simultaneously while measuring *Vsense* on the second channel. The loudspeaker impedance at any frequency point is then:

$$Z_{LS}(s) = \frac{(Vout(s) - Vsense(s))}{\left(\frac{Vsense(s)}{Rsense}\right)} \tag{3}$$

This has the disadvantage of requiring two analysis channels since *(Vout – Vsense)* will vary as a function of frequency as Z_{LS} varies. It also does not address damping factor effects.

2.2.3. *Rsense* Effects

Reducing the value of *Rsense* to minimize the voltage effects described above raises DF but reduces the amplitude of *Vsense*, compromising the signal to noise ratio of the measurement. Increasing the value of *Rsense* increases *Vsense* amplitude but reduces DF and the amount of power that the amplifier can deliver to the load. For example, if *Rsense* is 1Ω, 1/5 of the amplifier's voltage swing appears across *Rsense* when a 4Ω loudspeaker is measured. Additionally, heating of *Rsense* becomes a factor during testing at higher power, as the value of *Rsense* will drift with time and temperature. This introduces errors in the denominator of Eq. 1.

2.3. Improved Measurement Method

2.3.1. Improved Impedance Measurement Objectives

Consider the following objectives to improve impedance measurement accuracy:

- Eliminate voltage effects (Eq. 1 numerator)
- Eliminate the effects of *Rsense*, including drift and heating (Eq. 1 denominator)
- Eliminate damping factor effects (Eq. 2)
- The ability to measure small drivers and large loudspeakers without requiring different *Rsense* values
- The ability perform either simple single channel measurements or two channel measurements as desired by the user

2.3.2. Improved Impedance Measurement Circuit

Figure 2 shows a diagram of an improved impedance measurement method:

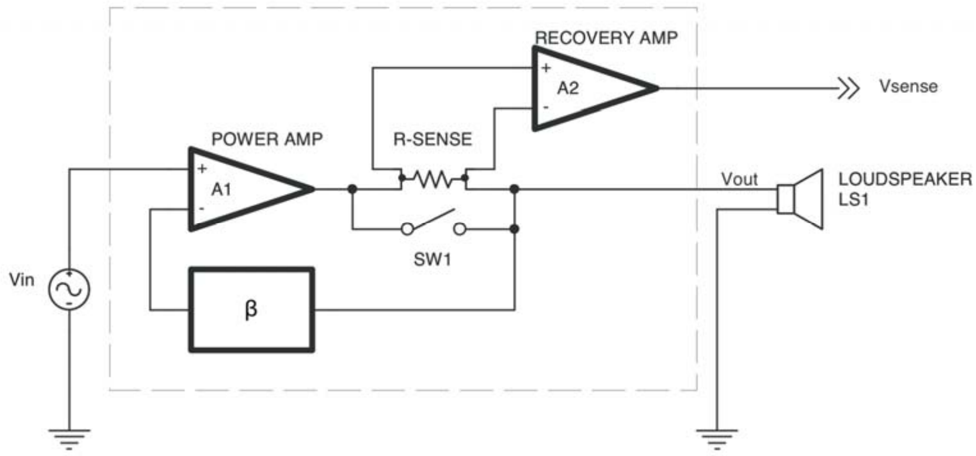

Figure 2: Improved Impedance Measurement Circuit (patent pending)

2.3.3. *Rsense* Feedback Loop Enclosure

In this configuration, the sense resistor has been removed from the grounded side of the loudspeaker and relocated in series with the output of A1. Feedback network β remains connected to the loudspeaker load. This arrangement places *Rsense* within the feedback loop. Negative feedback reduces the total closed loop output resistance of A1 in series with *Rsense* to:

$$r_{out} = \frac{\left(A1r_{out} + Rsense\right)}{\left(1 + A1_u \beta\right)} \quad (4)$$

$A1r_{out}$ is the intrinsic output resistance of gain block A1, $A1_u$ is the unloaded open loop voltage gain of A1, and β represents the feedback fraction presented to the inverting input of A1. The unloaded open loop voltage gain is distinguished here since, unlike most other applications, $A1r_{out}$ will not be much smaller than the real component of the load impedance [2]. Consider some practical values: A1 with an intrinsic output impedance of $A1r_{out}$ = 1Ω, *Rsense* = 1Ω, A_u = 10,000, and a feedback fraction β of 20. The output resistance r_{out} is theoretically 10μΩ in this case. In practice, the series resistance of PCB traces, wires, and connectors will be orders of magnitude higher than this theoretical value of r_{out}.

Importantly, negative feedback isolates the voice coil from *Rsense*, eliminating the effects of *Rsense* on the dynamic performance of LS1.

Rsense is shown as a 4-wire device in Figure 2. This reduces measurement errors for small *Rsense* values, and can be a commercially available, precision device intended for current measurements. Larger values of *Rsense* can utilize 2-wire devices. Also, switch SW1 has been added. SW1 allows larger *Rsense* values to be bypassed, reducing heat dissipation in the measurement amplifier and maximizing *Vout* when impedance measurements are not required. SW1 can be a switch or a relay contact.

2.3.4. Recovery Amplifier

Recovery amplifier A2 is a differential amplifier that rejects the common mode voltage signal on both sides of *Rsense* while amplifying the differential signal across *Rsense*. The resulting *Vsense* signal is directly proportional to the current through *Rsense*. The value of *Rsense* and the gain of A2 may be scaled to achieve a desired transfer function identical to that of a resistor. For example, a 0.1Ω *Rsense* value can be used in conjunction with an A2 gain of 10. The resulting transfer function in this case is 1V/A, identical to that of a 1Ω resistor. With proper design, the user obtains the sensitivity and signal to noise ratio of a 1Ω resistor without degrading DF.

2.3.5. Advantages

The circuit arrangement of Figure 2 has the following advantages:

- The circuit effectively eliminates the value of *Rsense* from consideration with regard to the value of r_{out}, maintaining the highest possible damping factor
- Negative feedback isolates *Rsense* from the voice coil, eliminating the effects of *Rsense* on the dynamic performance of LS1
- Circuit parameters can be optimized to enable a range of loudspeaker sizes to be measured with a single product
- Alternatively, the amount of power lost in *Rsense* can be minimized in some applications, making more power available to the loudspeaker being tested for a given power amplifier rating
- Alternatively, a relatively large *Rsense* value can be chosen for measuring very small currents while preserving a high damping factor
- With *Rsense* and A2 integrated into the measurement amplifier, rather than external components added by the end user, *Vsense* accuracy is assured by eliminating the effects of *Rsense* drift. For example, the value of *Rsense* can be minimized to limit thermal effects and / or temperature compensation circuitry can be added.
- The gain of A2 can be trimmed during manufacture, further assuring the accuracy of *Vsense*
- The user has the option of performing single or dual channel analysis to obtain impedance measurements, discussed in the next section
- All standard frequency domain measurements, including frequency response and distortion, can be performed with the added benefit of being able to measure the voice coil current simultaneously
- If power amplifier A1 and recovery amplifier A2 are accurate at DC, impedance measurements can be performed from DC to the high frequency limit of the system
- It is interesting to note that this configuration does not form a transconductance amplifier; the amplifier remains a voltage source, and does not become a current source by enclosing *Rsense* in the feedback loop

2.3.6. Obtaining Results

Single and dual channel measurements are available based on the needs of the user and analyzer capabilities; however, the focus is on obtaining accurate single channel measurements, especially in production line situations.

With *Rsense* contained in the feedback loop, single channel analyzer measurements can be made. The user must know the *Rsense* X $A2_{GAIN}$ transfer function in Volts per Ampere and the gain of A1. The loudspeaker impedance can be calculated as:

$$Z_{LS}(s) = \frac{(Vin \times A_{CL})}{\left(\dfrac{Vsense(s)}{(Rsense \times A2_{GAIN})}\right)} \tag{5}$$

Dual channel analyzer measurements are also possible if the user prefers. The user must know *Rsense* X $A2_{GAIN}$ transfer function in Volts per Ampere on one analyzer channel and measures *Vout* on the other analyzer channel. The loudspeaker impedance can be calculated as:

$$Z_{LS}(s) = \frac{Vout(s)}{\left(\dfrac{Vsense(s)}{(Rsense \times A2_{GAIN})}\right)} \tag{6}$$

3. EXPERIMENTAL RESULTS

Four measurement methods are compared:

- Simple Single Channel (Eq. 1)
- Simple Dual Channel (Eq. 3)
- Improved Single Channel (Eq. 5)
- Improved Dual Channel (Eq. 6)

Impedance measurements of a small 2-way bookshelf speaker were made using the simple and improved diagrams shown in Figure 1 and Figure 2. The speaker tested has a 4” woofer and small dome tweeter with a built-in crossover network, and a specified nominal impedance of 8Ω. The impedance measurements were performed using SoundCheck, Listen’s audio test and measurement system. In the case of Figure 1, *Rsense* was 1Ω. A product made by Listen Inc., the SC Amp™, was utilized for the setup shown in Figure 2. The (*Rsense* x $A2_{GAIN}$) product of SC Amp is 0.1V/A.

To compare single channel measurements, *Vin* was adjusted for a *Vout* of 1V RMS at 1kHz. *Vsense* was measured as *Vin* was swept from 20Hz to 20kHz. Eq. 1 was applied for the simple method and Eq. 5 was applied for the improved method.

To compare dual channel measurements, *Vin* was adjusted for a *Vout* of 1V RMS at 1kHz. *Vsense* and *Vout* were measured as *Vin* was swept from 20Hz to 20kHz. Eq. 3 was applied for the simple method and Eq. 6 was applied for the improved method.

Figure 3 is a plot of the real component impedance data. Data from three of the four methods are plotted. The simple dual channel method and the improved single channel data are nearly identical, except at the first resonance point. The simple single channel method is offset by an amount very closely equal to *Rsense*. Smaller *Rsense* values can be used to minimize the offset at the expense of signal to noise ratio of the measurement.

Figure 4 shows a close-up of the Figure 3 data at the first resonance point. The single and dual channel measurements using the simple method overestimate the impedance magnitude at resonance compared to the improved single channel method. Even if the simple single channel result is compensated by subtracting the 1Ω contribution of *Rsense*, changing the result at resonance from 42.8 to 41.8, the value is still overestimated from that produced by the improved single channel data.

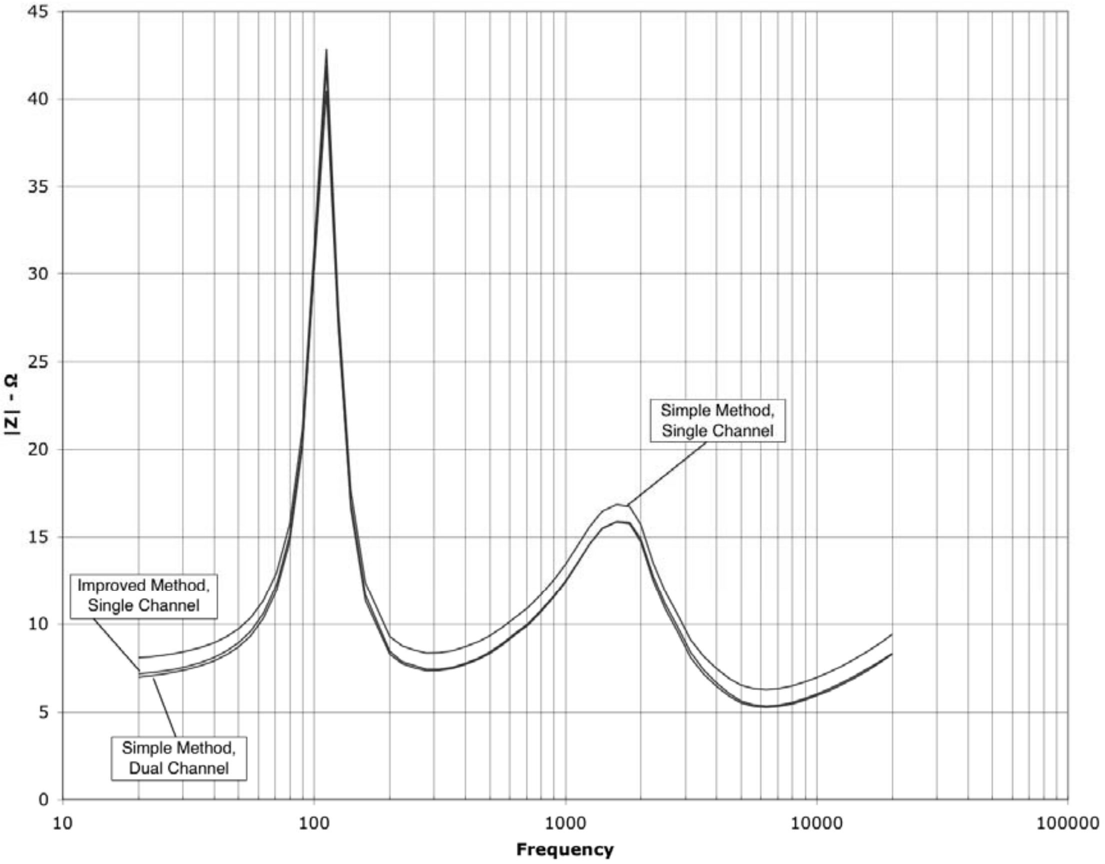

Figure 3: Simple and Improved Method Comparison

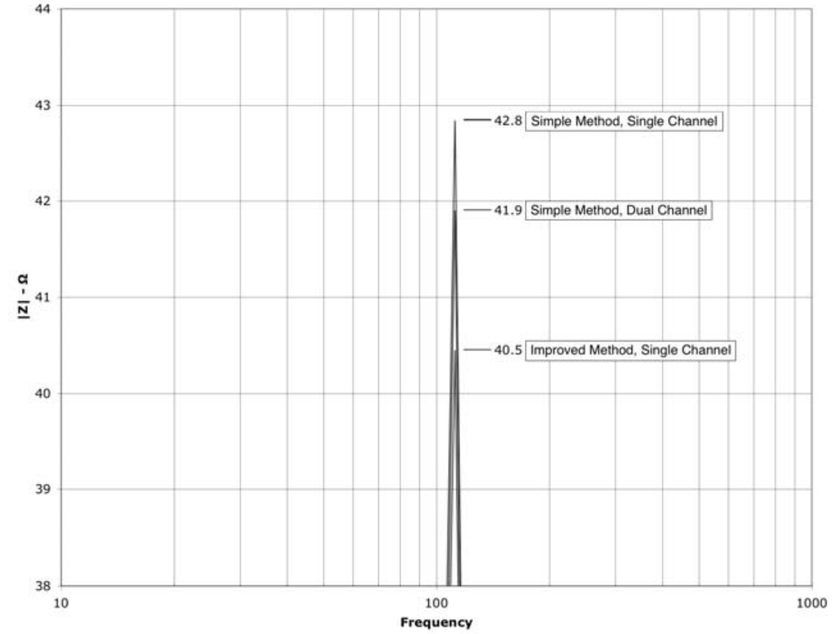

Figure 4: Simple and Improved Method Comparison - Zoomed in at Resonance

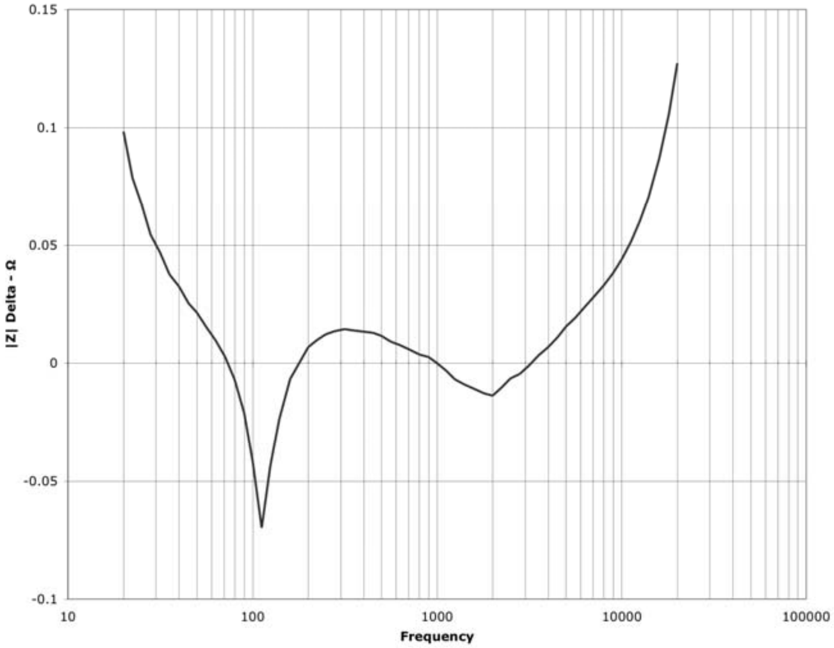

Figure 5: Improved Method Single to Improved Method Dual Channel Measurement Delta

The difference is most likely produced by the effects of back EMF, which is high at first resonance. The influence of back EMF most likely causes *Vsense* to be artificially lowered at this point, raising the measured impedance value. For visual clarity, the improved dual channel data is not plotted in since it is so close in value to the improved single channel data. The delta between the single and dual channel measurements is plotted in Figure 5.

For the tested loudspeaker, the difference was less than ±0.1Ω over most of the audio band. This small difference between the single and dual channel measurements in Figure 5 indicates that the improved single channel method is nearly as accurate as the improved dual channel.

4. CONCLUSIONS AND FUTURE WORK

The improved single channel measurement (Eq. 5) has produced impedance measurements that are more accurate than the simple single channel method (Eq. 1), and are accurate enough to not warrant the use of a second data acquisition channel, especially for production line applications.

The simple dual channel method (Eq. 3) produces results that are more accurate than the simple single channel method, but inaccuracies still occur at resonance, likely due to how back EMF is not being as effectively dissipated, and would require a second data acquisition channel.

If the simple single channel method is used, the contribution of *Rsense* needs to be subtracted from Eq. 1, however, data at resonance may still be inaccurate.

In the future, we plan to measure different types of loudspeakers over a range of power levels to gather more data, especially at first resonance.

These improved methods are implemented in Listen, Inc.'s SC Amp and AmpConnect products. The integral current monitoring output, marked '0.1V/A Out' in Figure 7 provides a *Vsense* signal in accordance with the improved method of this paper. SC Amp also offers DC offset capabilities. The improved impedance measurement circuitry in conjunction with proprietary DC offset circuitry (not described in this paper) is the subject of a U.S. patent application.

Figure 6: SC Amp™ by Listen, Inc.

Figure 7: SC Amp Rear Panel, including *Vsense* Output

5. REFERENCES

[1] Leo L. Beranek, *Acoustics*, Chapters 7 and 8 (Acoustical Society of America, 1993)

[2] Albert Malvino, *Electronic Principles*, Appendix 1 (McGraw-Hill, 1984)