LOUDSPEAKER IMPEDANCE WITH SIA SMAARTLIVE®

SIA SmaartLive Technical Note

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A recent addition to the capability of SIA SmaartLive is the ability to measure complex load impedance as a function of frequency. The potential to perform these measurements permits investigations of loudspeaker behavior in the field with accuracy previously available only in the laboratories of loudspeaker manufacturers. This tool may be used to troubleshoot loudspeaker drivers, systems, and constant voltage networks, as well as to design related systems and select optimal loading conditions for power amplifiers. This article provides an overview of the measurement technique and necessary theory for taking advantage of this useful tool.

1. AN INTRODUCTION TO LOUDSPEAKER IMPEDANCE

The term *impedance* is widely used in the professional audio industry, but frequently misunderstood and misapplied. Impedance is the total opposition to the flow of alternating current (AC current) in an electric circuit, and is a complex function of frequency as the ratio of voltage to current (Equation 1). The concept of impedance is analogous to *resistance* in direct-current (DC) circuits. While impedance includes resistance, it includes another element exclusive to AC circuits, *reactance*, which is due to the energy storage effects in AC circuits from components like inductors and capacitors, which vary as a function of frequency. In engineering circles, impedance is thought of as a complex quantity, meaning it includes both real (resistive) and imaginary (reactive) parts (Equation 2). It is this concept that accounts for the varying *phase shift* of impedance: current flows through resistive components *in phase* with the applied voltage, while current flows through reactive components with a phase shift relative to the applied voltage. The *impedance magnitude* (Equation 3) contains the effects of both the resistive and reactive components, and indicates the total opposition to current in the circuit (ignoring phase). It is this magnitude function that is typically quoted in loudspeaker specifications, as it is the impedance magnitude that affects the total current required from an amplifier when driving the loudspeaker. While the above general concept of impedance is universally used in many circuit analysis tasks, the concept of *load impedance* or the input impedance of a load (such as a loudspeaker) seen by a driving source (such as a power amplifier) is what we typically deal with when looking at loudspeaker characteristics (see Figure 1).

$$\mathbf{Z}(f) = \frac{\mathbf{V}(f)}{\mathbf{I}(f)} \qquad \text{(Eq. 1)}$$

$$Z(f) = R(f) + jX(f) \qquad \text{(Eq. 2)}$$

$$Z(f) = |\mathbf{Z}(f)| = \sqrt{R^2(f) + X^2(f)} \qquad \text{(Eq. 3)}$$

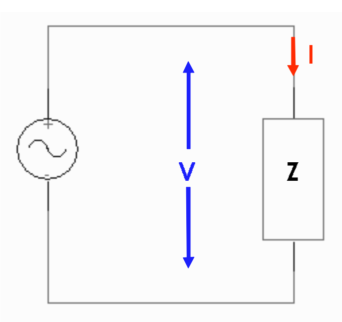

Figure 1:

The electrical input impedance function of a real loudspeaker is defined by many factors, including electrical, mechanical, and acoustical behavior. Electrically, the resistance and inductance of the voice coil dominates, along with the presence of any passive crossover components. The mechanical mass, compliance ("springy-ness"), and resistance of the drivers form another component of the total impedance. Additionally, the acoustical impedance seen by the drivers appears as part of the electrical impedance function, including the baffle loading effects, any loudspeaker ports, etc. All of these factors combine to create the impedance functions seen by measuring a typical loudspeaker.

Figure 2 shows the impedance magnitude-versus-frequency curve for a single low-frequency driver in both a sealed and ported enclosure. The strong dependence of impedance on frequency is easily seen. In the sealed example, the peak is created by the resonance between mechanical compliance and mass in the driver. The second peak appearing in the ported case is the acoustical tuning resonance of the vent. The rise in impedance at high frequencies is due to the inductance of the voice coil, while the minimum value of the graph is equal to the resistance of the voice coil. These characteristics are typical examples of measured data from real loudspeaker systems, providing vital information about the loudspeaker system for troubleshooting and design. The included bibliography lists several excellent references for interpreting and applying this information.

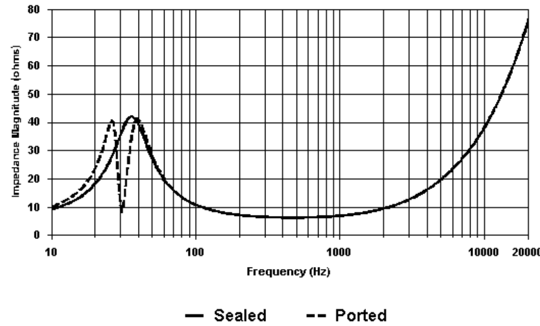

Figure 2: *Input impedance of a single low-frequency driver in both a sealed and ported enclosure.*

2. IMPEDANCE MEASUREMENT TECHNIQUES

Using the concepts developed in Section 1, we can now investigate methods of measuring load impedance. Based on Figure 1, we can see that the load impedance function may be obtained directly if we are able to acquire signals representing both the voltage and the current into the load impedance over all frequencies of interest. Since computer sound cards respond to voltage signals, a signal proportional to the voltage across the load is easily acquired by simply feeding the load voltage directly to the sound card. However, other techniques must be used to acquire the current signal. The current signal is most easily measured by inserting a *shunt resistor* in series with the load, creating a current shunt; the current in the load is then directly proportional to the voltage across this shunt resistance (see Figure 3). This is the method employed by most digital multimeters on the market to measure current. There are other methods of deriving the current signal, including the use of inductive current probes, etc., however, the shunt resistance method is the most practical technique for measuring loudspeaker impedance with SmaartLive.

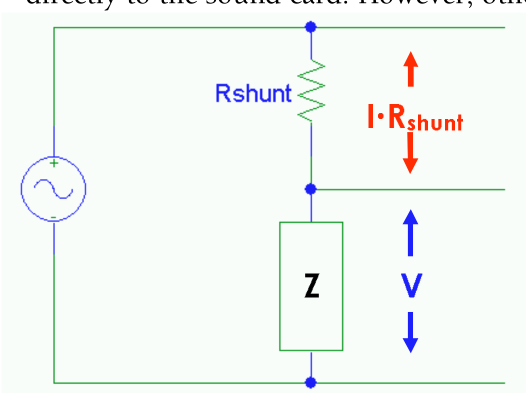

Figure 3: *Impedance measurement with a shunt resistor.*

As outlined above, if the voltage across the shunt resistance is measured, the current may be derived. However, if the source in Figure 3 is ground-referenced, the shunt resistor voltage is floating, so a differential amplifier must be used to *directly* measure this voltage. Using SmaartLive, the circuit required to use this *differential* (balanced) measurement technique is shown in Figure 4. The differential inputs may be provided using anything from a laboratory-grade differential amplifier to a balanced line-level input on a professional audio interface or mixer. However, for Smaart users desiring a simpler interface or lacking a differential input, a *single-ended* (unbalanced) measurement technique is possible, with SmaartLive calculating the exact load current internally. Both techniques have advantages and disadvantages, along with trade-offs associated with the selection of the value of the shunt resistor.

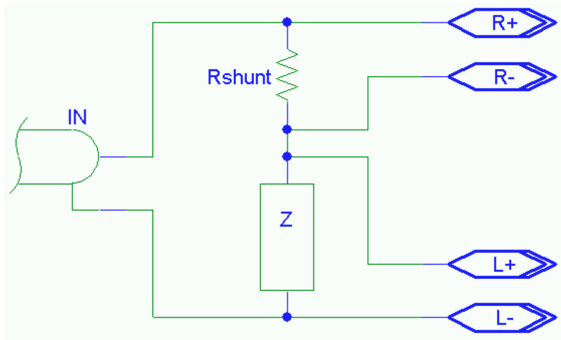

Figure 4: *Smaart impedance measurement circuit with a differential (balanced) input technique.*

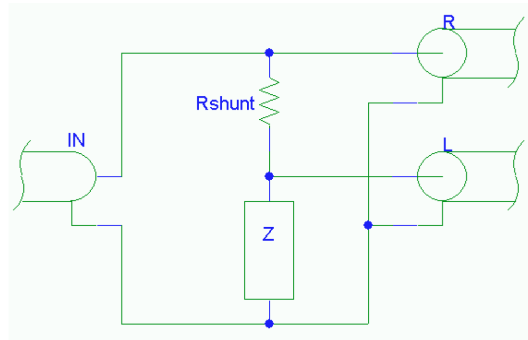

Figure 5: *Smaart impedance measurement circuit with a single-ended (unbalanced) input technique.*

Table 1 compares the two measurement techniques, presenting the trade-offs associated with each. In general, for a laboratory-grade measurement solution, choose the differential method with a high-grade balanced-input preamplifier. If you desire a simple, practical solution, choose the single-ended method, being certain to adequately calibrate your measurement system appropriately. SmaartLive requires you to use a *calibration resistor* to calibrate the measurement configuration based on this reference resistance for maximum accuracy. This calibration resistance temporarily replaces the load impedance during the calibration routine, which will be reviewed later.

Differential Method	Single-Ended Method
Advantages: • High-accuracy, large-range with low noise differential amplifiers • Insensitive to differences in input channel gains; simple calibration	Advantages: • Simple, passive design • No common-mode considerations
Disadvantages: • Complex input circuitry required	Disadvantages: • Sensitive to mismatch in input channel gains; requires careful calibration

Table 1: *Comparison of impedance measurement methods.*

3. OPTIMIZING THE MEASUREMENT HARDWARE

Before you jump in and start making impedance measurements, you should be aware of the practical issues involved in building an impedance measurement circuit and interfacing this device with your computer. Selecting appropriate shunt and calibration resistors will affect the quality of your measurements, and care must be taken when interfacing the computer with loudspeaker-level signals.

Driving the Circuit

Just like transfer function and impulse response measurements in SmaartLive, the impedance measurement function is dependent on a broadband excitation signal, such as random noise or a sinusoidal sweep, to perform its measurement. While transfer function measurements will use this signal to drive input of the device under test, the impedance function uses this signal to excite the load through the current shunt.

When a dynamic loudspeaker is driven by a source with relatively high source impedance (like a current shunt), the effect of the loudspeaker acting in reverse as a microphone may affect the quality of your measurements if there is sufficient acoustic noise in the measurement room. In order to minimize this problem in situations with a high ambient noise level (such as a construction site, manufacturing floor, etc.), the shunt resistance must be relatively small, and a small power amplifier used to drive the circuit. This, however, must be carefully undertaken in order to avoid damage to your computer hardware. Power amplifier signals can easily exceed the maximum input voltage capability of conventional computer sound cards, and the power handling capability of the shunt resistor becomes increasingly important as more current is drawn into the load. When using a power amplifier, the output voltage must be limited to a safe level and power resistors used in designing the current shunt.

In situations where ambient noise is not a concern (closed sites, laboratories, etc.), the headphone amplifier of the sound card may be safely used as the excitation source. Headphone amplifiers are typically rated for load impedances greater than ~30Ω, so the shunt resistance should be at least equal to this value. For typical loudspeaker loads, this shunt resistance limitation does not pose any question of accuracy to the measurement as long as ambient acoustic noise levels are minimal.

Selecting Resistors

The value, precision, and power handling capability of the resistances should be optimized when configuring the circuit based on the measurement conditions and load. Selecting an appropriate shunt resistance allows you to optimize the signal-to-noise ratio of the measurement while best taking advantage of the dynamic range and resolution of the system. Conversely, the calibration resistor should be of high precision and on the same order of magnitude as the unknown load impedance for maximum accuracy. For designs using a power amplifier, 2%-tolerance non-inductive wire wound resistors may be safely used, which are readily available with power ratings ≥10W. In current shunt designs where a headphone amplifier is used, 1%-tolerance metal-film resistors may be selected, which are obtainable with power ratings from ¼W-2W.

The value of the shunt resistance should be selected based on the limitations of the driving amplifier and the approximate expected value of the load. Selecting too low a resistance here may draw too much current from the driving amplifier, overheating the resistor or distorting the amplifier. Too high a resistance may cause the voltage drop across the load to become negligible compared to crosstalk, calibration errors, etc., producing inaccurate results. In general, the shunt resistance should be *comparable to the expected load resistance* and *no less than the minimum load impedance for the driving amplifier*, with the calibration resistor in the same range. For example, when testing 4-16Ω (nominal) loudspeakers with a headphone amplifier, selecting a 50Ω shunt resistor and a 20Ω calibration resistor is a reasonable choice. However, when testing a 10Ω /70V constant-voltage line, a 500Ω shunt resistor is probably better suited to the task. Table 2 shows suggested values for the shunt resistor when testing various loads using both a small power amplifier and a typical headphone amplifier as the driving source.

Load	R_{shunt} ***Power Amplifier***	R_{shunt} ***Headphone Amplifier***
4-16Ω loudspeaker	8Ω	50Ω
100Ω /140V line	200Ω	200Ω
10Ω /70V line	500Ω	500Ω

Note: The value of R_{shunt} should never be less than the suggested load impedance for the driving amplifier.

Table 2: *Suggested shunt resistances for various loads driven by typical amplifier configurations.*

When measuring high impedance loads, the input impedance of the sound card becomes significant to the measurement, rendering the calculation mathematics ineffective. In general, load impedances greater than $1/10^{th}$ of the sound card input impedance should not be measured. For loads in this range, use a quality high-impedance buffer amplifier.

$$P_{\text{rating}} \geq \frac{V_{\text{srcmax}}^2}{R_{\text{shunt}}} \quad \text{(Eq. 4)}$$

Power rating for shunt resistors. V_{srcmax} *is the maximum RMS output voltage of the driving amplifier.*

The power dissipation rating for the shunt resistor should be at least equal to the value calculated by Equation 4. For most standard loudspeaker measurements using a headphone amplifier as the driving source, a ½W resistor is acceptable. More attention must be given to this parameter when using a power amplifier. For example, a power amplifier sourcing $2V_{RMS}$ on its output into a 4Ω shunt resistance will require a shunt resistor rating of at least 1W (continuous). Following the above guidelines will help ensure that your impedance measurements are of the maximum accuracy possible, and that the possibility of overheating components or damaging hardware is minimized.

4. USING THE SMAARTLIVE IMPEDANCE FUNCTION

Building on the preceding review of the Smaart impedance measurement technique and the guidelines for configuring an impedance measurement circuit, this section will take you through a complete impedance measurement using SmaartLive. The desired measurement will be the load impedance of a small 5Ω (nominal) 2-way nearfield loudspeaker.

Step 1: Connect the Measurement Circuit

Based on the recommendations in Section 3, this measurement will be performed using the headphone amplifier of the computer sound card. Since the measurement is of a low-impedance loudspeaker, a 50Ω shunt resistor will be used, which is within the load capability of the headphone amplifier, and is reasonable to optimize the dynamic range of the measurement. Either the single-ended (Figure 4) or differential (Figure 5) technique may be used to measure the load impedance; their results are identical assuming the system is correctly calibrated. In either case, the loudspeaker and calibration resistors are substituted for the unknown impedance **Z** in the schematics.

Step 2: Configure SmaartLive

The preparation in SmaartLive for running an impedance measurement is similar to that for a transfer function measurement. The generator must be configured and gains adjusted to eliminate input clipping. Open SmaartLive and enter transfer function measurement mode. Turn on the generator, typically for a synchronized sine-sweep signal. The standard FFT size versus frequency resolution trade-offs exist as with standard transfer function measurements. For this example, a 32K-bin FFT is selected, as measurement time and update speed are not a significant consideration. *Disconnect any load* from the circuit, and set the generator level to provide a signal level close to clipping on the Smaart measurement input. At no time after connecting a load will a signal exceed this level (Figure 6a).

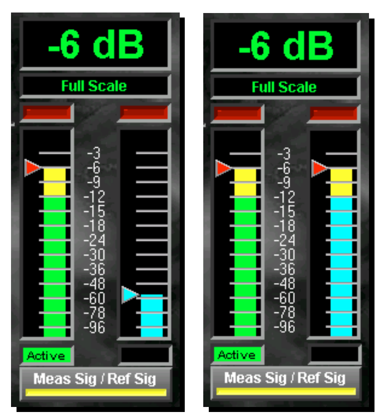

Figure 6: *(a) Adjust signal levels to eliminate clipping; (b) Match channel levels in single-ended mode.*

If you are utilizing the *single-ended* measurement technique, you must match the input gains for the two input channels using the sound card gain controls, the mixer balance control, etc. If you are using the *differential* technique, you may skip this step; the mathematics of the differential method automatically compensate for differences in channel gains. To perform the calibration, disconnect any load from the circuit and adjust the gain controls until the two channel levels are equal (Figure 6b). This may also be easily and somewhat more accurately accomplished by looking at the (logarithmic) transfer function magnitude and adjusting the controls until the curve reaches 0dB across the spectrum.

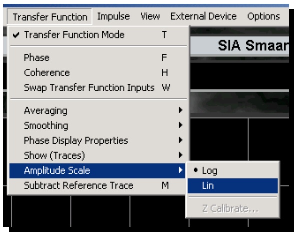

Figure 7: *Launching impedance mode.*

After performing these adjustments, the impedance mode may be launched by selecting "Lin" (linear) on the *Transfer Function > Amplitude Scale* menu (Figure 7).

Step 3: Calibrate with a Reference Resistor

Now that the impedance mode has been launched and the signal levels adjusted, connect the *calibration resistor* (discussed in Section 3) in place of the load. Double-click on the plot area, launching the calibration dialog box (Figure 8). Select the appropriate circuit topology (in this case, single-ended) and enter the value of the *calibration resistor* (not the shunt resistor) into the "Calibrated Impedance is…" edit box. In this example, we'll enter 49.9Ω, which was measured with a precision ohmmeter. Click OK to finalize the calibration.

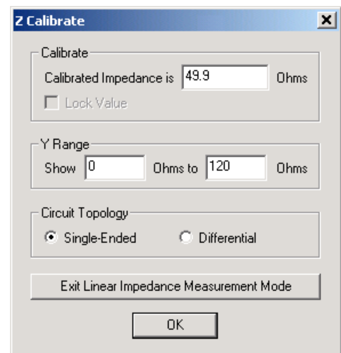

Figure 8: *Impedance calibration dialog box.*

Step 4: Perform the Impedance Measurement

After calibrating the system, the measurement shown on the display reflects the impedance of the calibration resistor, which, in this case, is a constant 49.9Ω (Figure 9). Now, the loudspeaker may be connected as the load, and the actual unknown load impedance measured. For this example, the resulting impedance magnitude measurement is shown in Figure 10.

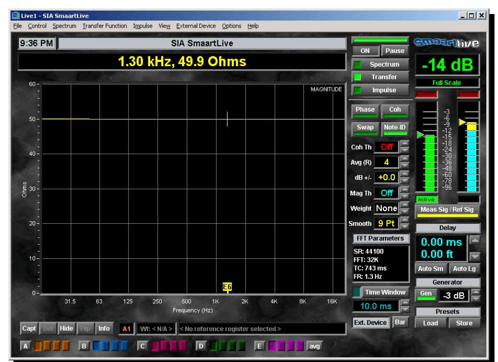

Figure 9: *Measurement of the calibration resistor.*

For this 2-way system, the mechanical resonance of the low-frequency driver is easily seen at approximately 90Hz, as well as the high-frequency peak created by the passive crossover network. One item to note: this loudspeaker is rated as having 5Ω nominal impedance, but the minimum value in the audio bandpass is only 3.9Ω. This information might influence decisions on how many devices to place on a single amplifier channel, etc. In more advanced applications, these impedance measurement results may yield Thiele-Small parameters for single drivers or other design information. This example demonstrates the accuracy and potential value of the impedance measurement capability in SIA SmaartLive.

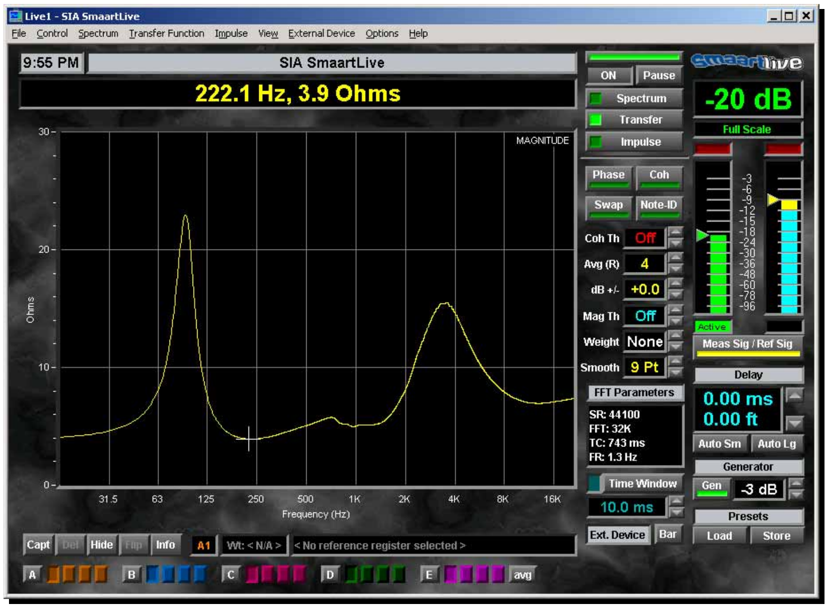

Figure 10: *Impedance magnitude measurement of a passive 2-way loudspeaker system.*

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