Practical Impedance Measurement Using SoundCheck

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Introduction

Loudspeaker impedance measurements are made for many reasons. In the R&D lab, these range from the simple task of identifying a speaker's resonant frequency to more complex functions such as calculating the speaker's Thiele-Small parameters. On the production line, impedance measurement is a key quality control parameter that verifies that the speaker's motor properties are correct, that the magnet is charged correctly, the voice coil number of turns is correct and that the moving mass (cone and voice coil) is within specification.

There are two basic methods of making impedance measurements on loudspeakers, micro-speakers and headphones using sound card and software based systems. These are basic single channel measurements, and more complex, but more accurate, dual channel methods. Both methods are implemented in SoundCheck, and with some additional hardware these tests are simple to carry out.

Single channel versus dual Channel measurements

The single channel impedance measurement method is commonly used on production lines. Its main advantage is that it only uses one channel of the soundcard, so acoustic and impedance measurements can be carried out simultaneously with a 2-channel soundcard for high throughput. It is also simple to set up and understand. However, it has its drawbacks. Because it measures only the current across the reference (sense) resistor, any effect of the speaker load on the amplifier is not taken into account (an inductive load may actually affect the output of the amplifier), neither is the effect of cables and connections. Good calibration is also critical.

Dual Channel methods are used where high accuracy is required, and are common in the R&D lab. Both the voltage across the speaker and the reference resistor are measured simultaneously, which means that the amplifier does not require calibration. To a certain extent, the effects of the speaker wires are also removed. The trade-off is that it requires two measurement channels, which are not always available in production line situations. There are two different dual channel analysis methods, transfer function and post-processing. The measurement setup is the same for both; they differ in the way that the impedance is calculated. Post-Processing is the simpler method, but can only be used with sine wave stimuli. The Transfer Function method is more complex, using transfer function analysis to examine the cross-spectrum, and multiple post-processing steps to refine the result. This method works well with any test signal.

Single Channel Impedance Measurement Theory

Fig. 1 shows the electrical circuit for single channel measurement.

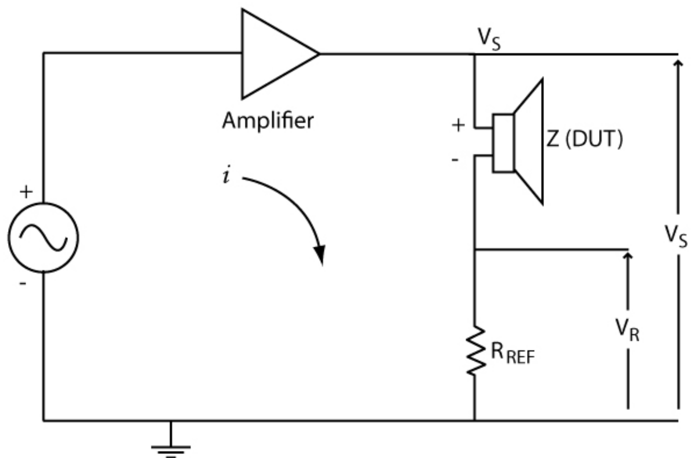

Fig. 1: Electrical Circuit for Single Channel Impedance Measurement

Vs is the voltage out of the amplifier. The reference, or sense resistor, R_{Ref} is used to calculate the current flowing through the loudspeaker. Note that the reference resistor may be either before or after the loudspeaker / driver, as long as the math is done correctly.

Impedance, Z, is calculated using the formula below.

$$i = \frac{v_S - v_R}{Z} = \frac{v_R}{R_{ref}} \Rightarrow Z = \frac{v_S - v_R}{v_R} R_{ref}$$

This method is simple as there are only 2 measurements; first the amplifier is calibrated and the voltage into the loudspeaker measured, then the voltage is measured across R_{Ref} and the voltage divider equation above used to calculate impedance. Pretty much any test system (or manual method) will use the same calculation.

It is important, however, to remember that this method makes two significant assumptions:

1) The amplifier is perfect with a flat frequency response, flat phase response, zero output impedance, and an output that remains constant with changing load (in other words, V_S is known and independent of any effects of the circuit)
2) That wires and connectors have no effect

Practical Implementation in SoundCheck

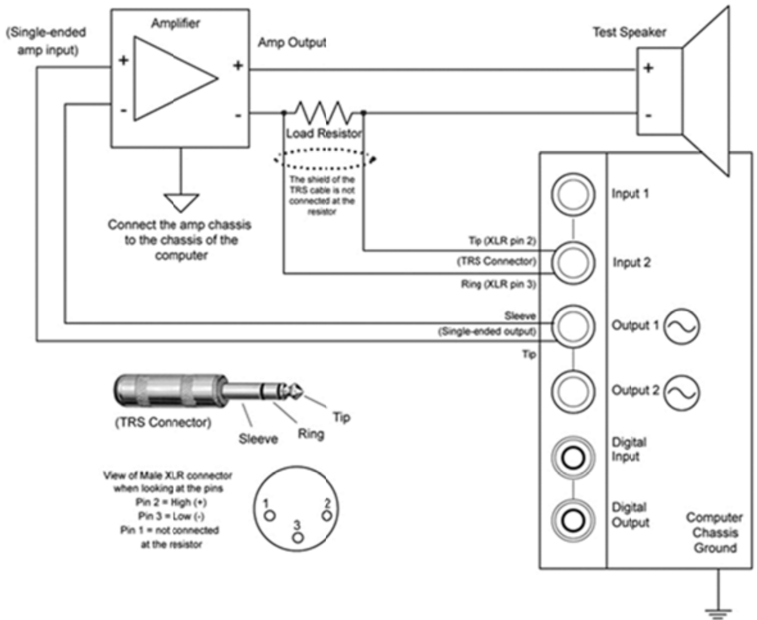

Fig. 2: Wiring Set Up for Single Channel Impedance Measurement

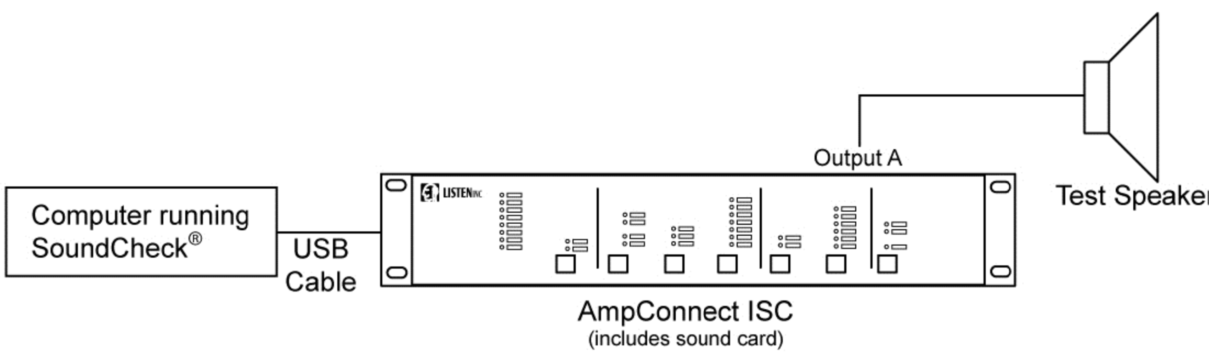

Fig. 2b: Set Up for Single Channel Impedance Measurement using AmpConnect

Fig. 2a shows a practical set up for single channel impedance measurement using SoundCheck (or indeed any soundcard based measurement system); Figure 2b shows the wiring setup using AmpConnect instead of a separate soundcard and impedance box.

The cables should be kept as short as possible to minimize their effects, and it is advisable to use a balanced connection between the soundcard and the sense resistor to prevent accidental shorting of the amplifier or damaging the soundcard. A power amplifier is usually needed as typically with soundcards, the output impedance is too high. When selecting an amplifier, the voltage and current requirements of the speaker should be considered. As a speaker with an inductive load can actually affect the frequency response of the amplifier, it is important to select an amplifier with an output load that is only minimally affected in this regard.

Correct calibration will remove the effects of the frequency and phase response of the amplifier, but the possibility that the output will change with load from the speaker remains; it is still assumed that V_S is known and independent of load.

Although any suitable amplifier may be used, we recommend the Listen AmpConnect ISC (an integrated box containing an amplifier and sense resistor as well as the sound card) or SC Amp, Listen's stand-alone audio test amplifier which also contains a sense resistor).

AmpConnect and SC Amp are designed specifically for audio testing and have a unique feature: active zero ohm output (patent pending). The sense resistor is built into the feedback loop of the amplifier, so that it has no effect on the voltage output of the amplifier. The difference between this and a stand-alone sense resistor is that with a stand-alone resistance, the amplifier voltage output is divided across the loudspeaker and the sense resistor, so if you calibrate without a loudspeaker and load resistor, when you put the resistor in series with the loudspeaker amplifier output voltage drop slightly. Having the sense resistor in a feedback loop ensures that the voltage output is exactly what you set it to, regardless of load.

If you are not using an Ampconnect or SC Amp featuring a built in reference resistor, any good quality high quality metal film or non-inductive resistor (not a carbon resistor) may be used. Its value should be 10-100 times less than the speakers nominal DC resistance to ensure a good signal to noise ratio – usually 0.1- 1Ω is appropriate. This is because the circuit is a simple voltage divider. With a resistor 1/10 the loudspeaker's nominal DC resistance, if there is 1V going through the speaker there is 0.1V going through the sense resistor. If a lower resistance is used, the voltage drop over the sense resistor will be too small – in the microvolt range. At the other extreme, for example, using a 1kΩ resistor a constant current circuit may occur which can present a signal to noise ratio problem as well as not driving the loudspeaker at high enough levels on the production line to measure non-linearities, e.g. Rub & Buzz, simultaneously. To be truly accurate, the resistance of your resistor should be measured.

An off-the-shelf audio testing resistance box (such as Listen's part number 4009) simplifies the test setup. Listen's impedance box contains a high quality 0.25Ω resistor (easily swapped out for a different value) that has a flat frequency response and a resistance independent of power. It features permanently attached, high quality balanced cables with a short cable that attaches to the amplifier and a longer one to connect to the loudspeaker. All cables and connections are low-resistance.

Fig. 3: Listen's Impedance Box

Calibration

Calibration is critical for single channel impedance measurement. The amplifier must be calibrated for frequency response (gain and phase), and the sound card must also be calibrated. If the soundcard is included in the amplifier calibration there is no need for it to be calibrated separately. A precision resistor of known value (4Ω or 8Ω) should be used in place of the loudspeaker, and measured in order to confirm the impedance results. The calibration result should be a flat magnitude and phase curve at the resistor value when measured.

To calibrate your system, simply follow the steps below:

- In SoundCheck, open the system calibration editor from the setup dropdown menu in the SoundCheck Main Screen.
- Select the output tab and set the output signal channel that you want to calibrate, and select the device you want to calibrate. If a new device is to be used with the system, click 'add' and enter a name for it.
- Select the output hardware channel that provides signal to the amplifier input and set the calibration sequence to amplifier calibration. The input channel signal should be set to a direct input; the sensitivity of this channel must be unity gain for accurate calibration.
- Turn the power amplifier off.
- Connect SoundCheck Output 1 to the input of the amplifier.
- Connect the corresponding output of the amplifier directly to SoundCheck Direct In 1. The amplifier output should not have anything else connected to it, including the loudspeaker and reference resistor.
- Turn the power amplifier on. The gain control should usually be set to maximum and not changed (otherwise recalibration is required).
- Click 'calibrate' to measure the amplifiers sensitivity (gain) and frequency response. The measured sensitivity of the amplifier is automatically saved to the output sensitivity field. The frequency response is normalized, inverted and applied to the measurement to correct for both magnitude and phase to 0dB @ 1kHz.
- If the measured sensitivity fails, check the wiring and connections and try calibrating again. If the measured response margin fails, check that the amplifier is not connected to anything other than the sound card and that it is properly grounded. A bump around 120 Hz (or 100 Hz if line frequency is 50 Hz) may indicate hum due to poor grounding or cabling. Using tip and ring of a balanced cable will usually overcome this.

Impedance Measurement

Once the circuit is calibrated, impedance can be measured. First connect the circuit as shown in the diagram. Next, the impedance test has to be set up in SoundCheck.

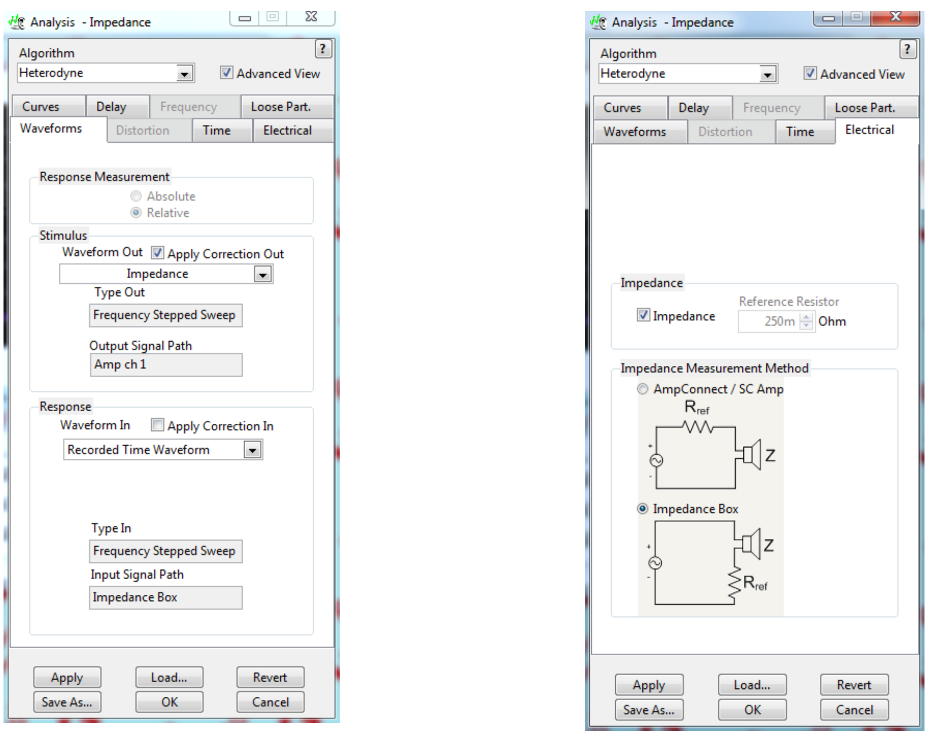

Fig. 4: Settings for Single Channel Impedance measurement in SoundCheck

The default impedance sequence supplied with SoundCheck is set up to measure impedance on input channel 2 (channel 1 is reserved for acoustic measurements).

In the "Analysis > Impedance" settings window, under the waveforms tab, impedance should be selected. This automatically sets the response measurement to relative because impedance is a relative measurement in terms of looking at the time signal and the recorded time waveform across the reference resistor. It is important to select "apply correction output" in the stimulus setup as that will apply a correction curve to the stimulus to remove the effects of the amplifier output or phase. Typically the test signal that is used for measuring acoustic parameters is also used for measuring impedance. On the production line this is typically a sine sweep, and this works well with single channel test methods.

In the electrical tab of the "Analysis > Impedance" settings setup, the reference resistor value is entered, and the set up - AmpConnect/SC Amp or Impedance box (or stand-alone resistor) - is selected.

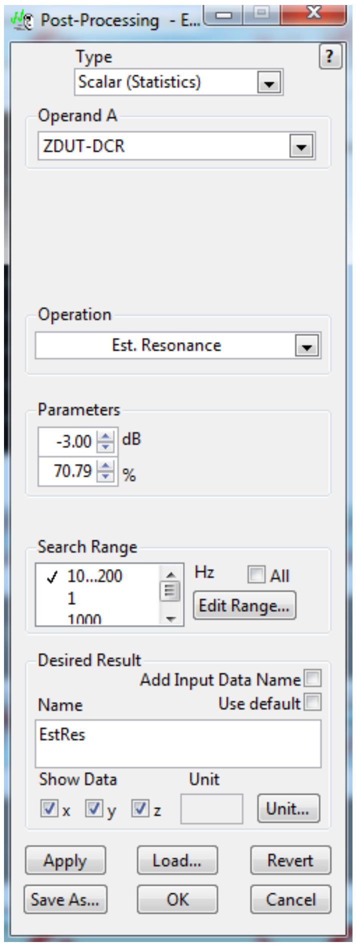

Fig. 5: Post-Processing Settings for Impedance Measurement in SoundCheck

Fig. 5 shows the post-processing setup, where the algorithms are applied for curve-fitting to determine F_0, Z_{Max}, and Q. The user can set the search range (to ensure the fundamental resonant frequency is found) to find the peak of the curve. The number of data points used in the curve fit is specified by the parameters setting (width control) in terms of either how many dB down from the peak or % of the peak. For most woofers, -3 dB will suffice, but for low Q drivers (such as tweeters) -1 dB may be required in order to resolve the resonance frequency from the fitted curve.

Results

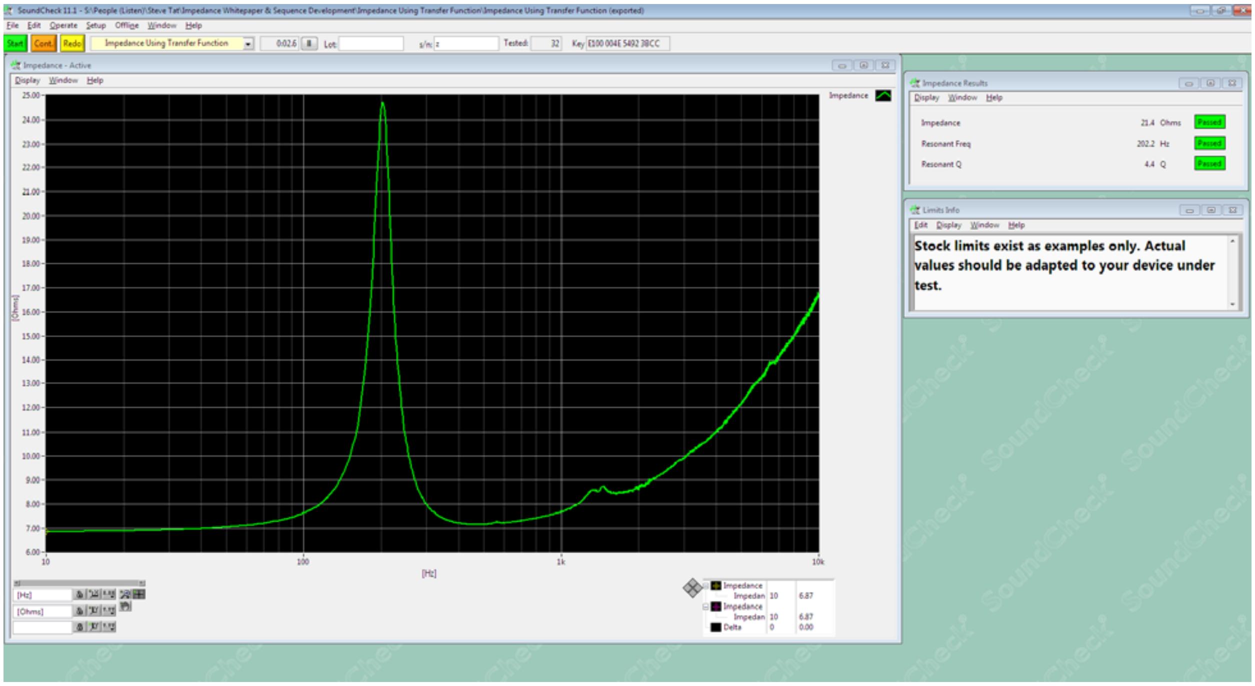

Fig. 6: Test Result from Impedance Measurement Test in SoundCheck

Fig. 6 shows the output from a SoundCheck impedance measurement. It can be seen that the curve becomes a flat line at low frequencies as the speaker approaches DC resistance. If, when running a test, the curve goes up at low frequencies, this is a sure sign that calibration is incorrect or the output correction is incorrectly applied. The peak at resonance is clearly seen around 200Hz, and above that the impedance increases with frequency as it becomes more inductive. SoundCheck has applied curve fitting and calculated impedance (Z_{Max}), Resonant frequency (F_0) at Z_{Max}, and the Quality or Q-factor, the width of the resonant peak (Q); these are displayed in the right hand window.

Dual channel Impedance Measurement Theory

While single channel impedance measurement is adequate for most production line tests, if superior accuracy is required or Thiel-Small parameters must be calculated, then a dual channel impedance measurement method is necessary. Fig. 7 shows the electrical circuit for dual channel measurement.

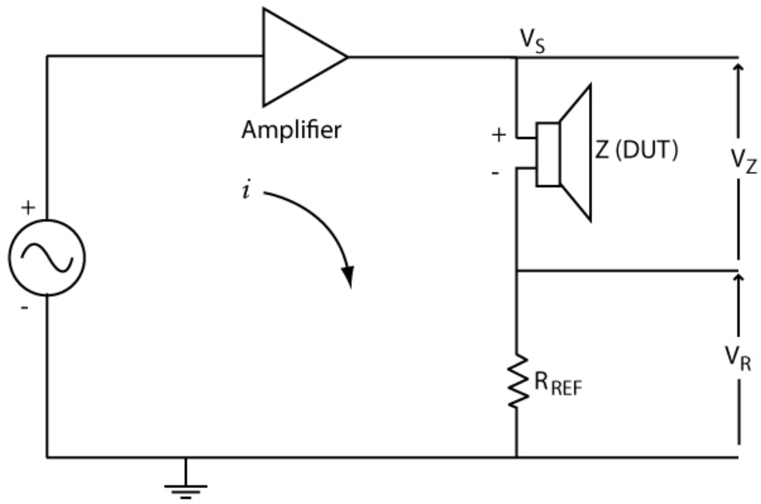

Fig. 7: Electrical Circuit for Dual Channel Impedance Measurement

V_Z is the voltage across the speaker and V_R is the voltage across the reference, or sense resistor.

Impedance, Z is calculated using the following equation

$$i = \frac{v_Z}{Z} = \frac{v_R}{R_{ref}} \Rightarrow Z = \frac{v_Z}{v_R} R_{ref}$$

The reason this configuration is so accurate is that no assumptions are made other than that the soundcard is calibrated and the input cables and connectors have a low resistance – everything is measured. It is not even necessary to calibrate the amplifier as voltage is measured across the speaker and reference resistor simultaneously, so the amplifier characteristics do not affect the measurement. Even the effect of the speaker wires is minimized. The only real trade-off is that a second channel is required, although sound card channels are getting pretty inexpensive these days

Practical Implementation in SoundCheck

Fig. 8 shows a practical set up for dual channel impedance measurement using SoundCheck (or indeed any soundcard based measurement system).

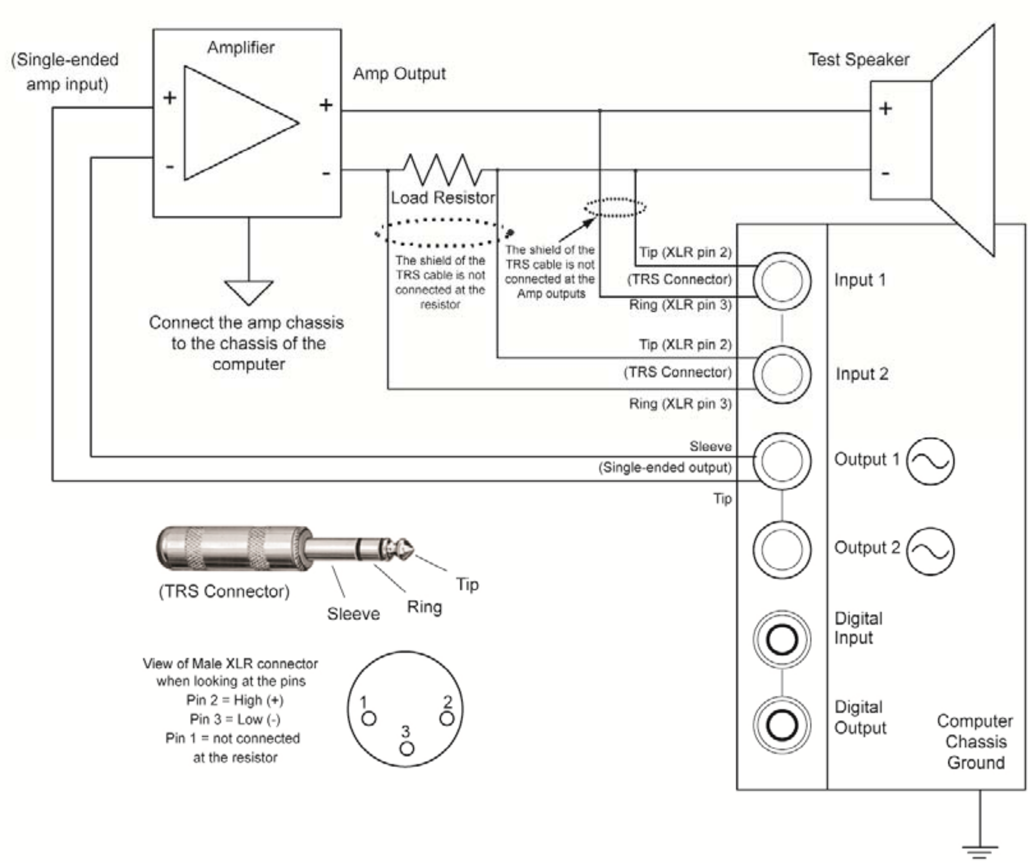

Fig. 8: Wiring Set Up for Dual Channel Impedance Measurement

As with single channel measurement, the reference resistor can be before or after the loudspeaker; the calculation is the same. Again, balanced inputs are recommended to prevent accidental amplifier shorting or soundcard damage.

It's important to note that in dual channel measurements, unlike single channel where you only measure the voltage across the reference resistor, the voltage is also measured across the loudspeaker. If a low value reference resistor is used, although the voltage across it will be low, the voltage drop across the speaker will be high; it is therefore important to consider the maximum voltage that your soundcard can handle and ensure that this is not exceeded.

Preparing for dual channel measurements is simple; since the amplifier voltage is measured across the speaker and reference resistor simultaneously there is no need for calibration, other than to know the stimulus level going into the loudspeaker.

SoundCheck offers two different methods for calculating dual channel impedance: post-processing and transfer function. The physical set-up is the same but the calculation method differs.

Math Post-Processing is the simpler method. It simply measures voltage and current independently at each point in the spectrum and divides one curve (both magnitude and phase) by the other. Measurements are corrected for the effects of the reference resistor before displaying the final curve. Although simple and accurate, this method has one significant drawback: it only works well with a sine wave stimulus. If a different stimulus is required, a more complex method must be used. It can be used with many analysis algorithms (e.g. HarmonicTrak).

Impedance measurement using Transfer Function overcomes the stimulus limitation of the Math Post-Processing method, although it is a little more complex. This method uses transfer function analysis to examine the cross-spectrum, and multiple post-processing steps to refine the result. Because it examines the cross-spectrum rather than simply dividing one curve by another, this method works well with any test signal. Noise and distortion are averaged out, and the coherence indicates the quality of the measurement.

Both techniques require that the measurements V_Z and V_R must be complex (i.e. magnitude and phase).

$$\text{Post-Processing: } Z(j\omega) = \frac{v_Z(j\omega)}{v_R(j\omega)} R_{ref}$$

$$\text{Transfer Function: } Z(j\omega) = \frac{\overline{v_Z^*(j\omega) v_R(j\omega)}}{\overline{v_R^*(j\omega) v_R(j\omega)}} R_{ref}$$

Although the physical set up is the same for both these methods, each requires specific settings in the Impedance Analysis editor.

SoundCheck Settings for Transfer Function Method

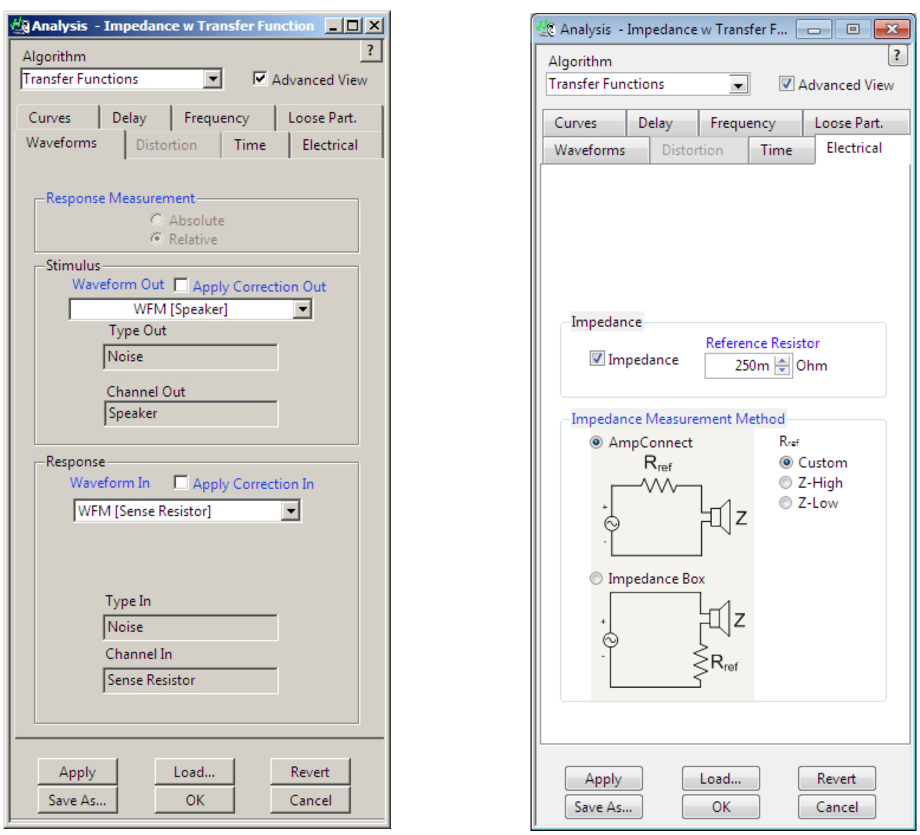

Fig. 9: Settings for Dual Channel Impedance measurement using the Transfer Function Method in SoundCheck

Fig 9. shows the Soundcheck settings for dual channel impedance measurement using the transfer function method. Note that the stimulus waveform is measured over the speaker and the response waveform measured over the reference or sense resistor. Also note that in the electrical tab, for dual channel measurement, the impedance method is always set to the AmpConnect method because both the voltage across the reference resistor and loudspeaker are measured in parallel.

SoundCheck Settings for Post-Processing Method

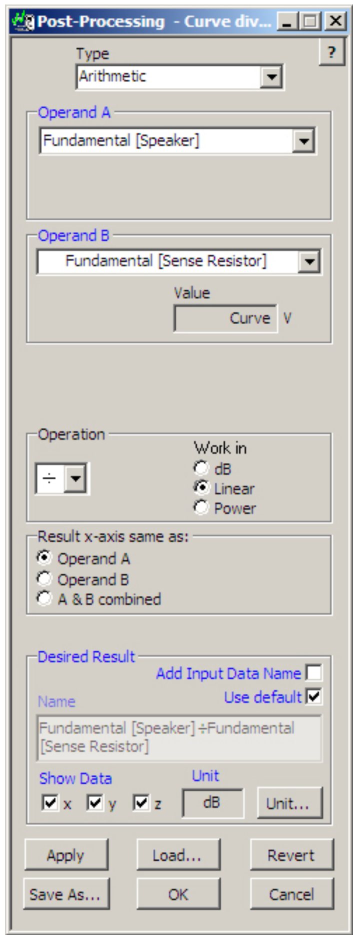

Fig. 10: Settings for Dual Channel Impedance measurement using the Post-Processing Method in SoundCheck

The set-up in SoundCheck for the post-processing method of impedance measurement is simple. In the SoundCheck post-processing step shown in Fig. 10, the fundamental (direct in 1) is the voltage across the speaker, and the fundamental (impedance box) is the voltage across the reference resistor.

Thiele-Small Parameters

Thiele-Small parameters are a common application of impedance testing. Thiele-Small parameters are a set of electromechanical parameters that define the specified low frequency performance of a loudspeaker driver. They are only useful at and below the speaker's resonant frequency. These parameters enable a loudspeaker designer to simulate low frequency acoustic response of a given loudspeaker and predict its behavior in a variety of enclosures.

There are three versions of Thiele-Small parameter measurement supported in SoundCheck: added mass, added volume and fixed mass. Essentially, to calculate Thiele-Small parameters, you need to find resonance (F_0), Z_{Max} and Q under various conditions (e.g. with and without an added mass, with a driver mounted in a known volume, and with various parameters known) and feed these values into SoundCheck's equation editor. Free sequences are available for the three Thiele-Small parameter measurement methods.

Care must be taken when measuring Thiele-Small parameters. All Thiele-Small parameters are based on a linear model, and they typically use a single channel constant current measurement method; this means that only small signal levels should be used.

The MLSSA system was widely used for measuring Thiele-Small parameters using a MLS signal (pseudo-random noise). The spectral density of this test signal is different to a sine sweep at the same voltage, so the impedance results using a sine sweep at 1 V will be different from a 1V RMS MLS signal. We include a MLS stimulus in SoundCheck to enable reproduction of / comparison with results obtained on the MLSSA system.

Summary

Measurement method	Accuracy	Number of channels required	Test Signals	Circuit	Test Setup
Dual Channel (Transfer Function Method)	Extremely Accurate	2	any stimulus	Fig. 7	Fig. 8
Dual Channel (Post-Processing Method)	Extremely Accurate	2	sine		
Single Channel with AmpConnect / SC Amp	Very Accurate	1	sine	Fig. 1	Fig. 2
Single Channel	Sufficiently accurate for most applications	1	sine		

A Final Word of Caution!

Be wary of exactly how something is tested. Test results will differ when using different combinations of stimuli and test levels. Typically, the speaker's Q, Z_{Max} and F_0 decrease as the stimulus level increases. This is due to non-linearities in the speaker which tend to increase with stimulus level due to increased voice coil excursion. If you are trying to replicate an impedance measurement (or Thiele-Small parameter test) that someone else has done, ensure that you are testing with the same stimulus and at the same level.