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Loudspeaker Electrical Impedance Measurements Methods: A Brief Review

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ABSTRACT

There are several possible methods to measure the loudspeaker driver electrical impedance. Those methods have followed the development of measurement instruments, starting from the era of the simple needle voltmeters to the PC based instruments widely available today. This paper will go through the theory and practice of impedance measurements with a series of examples where the pros and cons of each method are highlighted using real measurements. Effect of current sensor choice, noise, vibrations and test level will be discussed in detail.

1. INTRODUCTION

Moving coil loudspeakers exhibits a characteristic impedance curve as a function of frequency at their electrical port. This impedance curve serves as a basis for the extraction of the parameters of the loudspeaker (electrical, mechanical and acoustical) model, whether the loudspeaker is in free air or in a box. The impedance curve can also reveal information on the acoustical response of the loudspeaker which is reflected in the electrical port impedance. The measurement of this impedance curve is a key factor in design and manufacturing application of loudspeaker systems and boxes.

As an example, the lumped parameters model of a linear (small-signal assumption) loudspeaker in free air is reported in Figure 1. We will not get into the details of the model, here we only would like to point out that, if seen from the electrical terminals, a loudspeaker presents an electrical impedance that can be modeled as the circuit in figure 2.

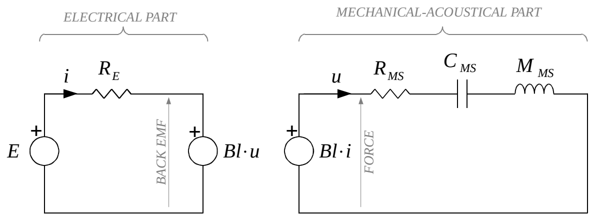


Figure 1 – Free Air Lumped Parameters Linear Loudspeaker Model

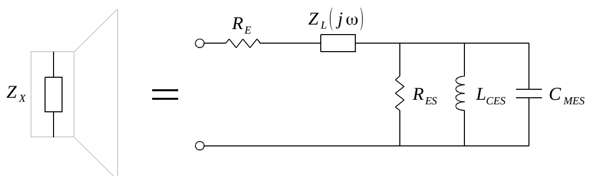
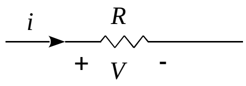


Figure 2 – Same Model as Above in the Electrical Only Domain

2. ELECTRICAL IMPEDANCE

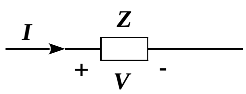
The electrical impedance is an extension of the concept of electrical resistance to AC circuits. If we consider the circuit branch below:



It is well known that the current i which flows through a resistance R is directly proportional to the voltage potential V across resistor terminals, as represented by the Ohm's Law:

$$V = R \cdot i$$

Where V, R and i are scalar quantities. In a similar fashion, electrical impedance $\boldsymbol{Z}$ is a complex quantity which describes not only the relative amplitudes of the voltage $\boldsymbol{V}$ and current $\boldsymbol{I}$, but also the relative phases.



The Ohm's Law become:

$$\boldsymbol{V} = \boldsymbol{Z} \cdot \boldsymbol{I}$$

Where the $\boldsymbol{V}$, $\boldsymbol{Z}$ and $\boldsymbol{I}$ are now complex quantities. The complex number $\boldsymbol{Z}$ can be wrote in Cartesian or polar form:

$$\boldsymbol{Z} = R + jX \qquad \boldsymbol{Z} = |\boldsymbol{Z}| e^{\mathrm{j} \cdot \arg(\boldsymbol{Z})}$$

In a circuit like the one in Figure 2 the voltage $\boldsymbol{V}$ at the impedance terminals and the current $\boldsymbol{I}$ flowing through it are frequency dependent. Following above definitions frequency dependence of the Impedance $\boldsymbol{Z}(j\omega)$ is obviously obtained as a ratio between two Frequency Responses:

$$\boldsymbol{Z}(j\omega) = \frac{\boldsymbol{V}(j\omega)}{\boldsymbol{I}(j\omega)}$$

3. LOUDSPEAKER ELECTRICAL IMPEDANCE MEASUREMENT METHODS

Therefore in practice the electrical impedance measurement is by itself indirect; the impedance value is derived from a voltage and a current measurements.

The typical circuit to measure the electrical impedance is reported in Fig. 17 of the Neville Thiele's seminal paper on loudspeaker parameters[1]. It involves the use of a frequency controlled sinusoidal generator, an AC ammeter and voltmeter.

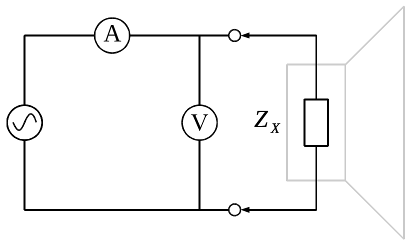


Figure 3 - Basic Impedance Measurement Circuit Schematic

The voltage generator impose a given voltage to the device under test, measured with the voltmeter, and the current is measured using the ammeter. Since the loudspeaker electrical impedance is frequency dependent, the measurement should be carried out in a number of sinusoids with a specific frequency (according to the required frequency resolution and system damping). This can be done point-by-point or using other techniques as swept sine or multi-tone analysis.

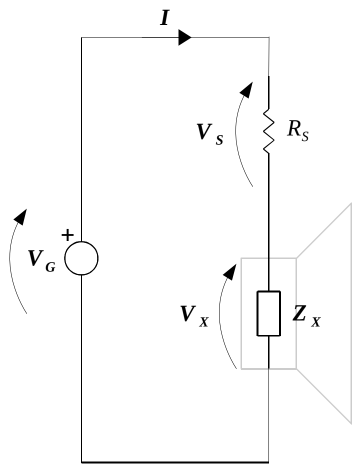


Figure 4 - Voltage Divider Circuit

One of the most simplest methods used to detect the current flowing in the $\boldsymbol{Z_X}$ impedance require the use of a shunt resistor in a voltage divider circuit[2] (see Figure 4). The needed quantities to estimate the DUT impedance are $\boldsymbol{V_X}$ and $\boldsymbol{I}$, and there are several ways to collect the data. Two of the three complex voltages must be measured to solve the above net since:

$$\boldsymbol{V_G} = \boldsymbol{V_S} + \boldsymbol{V_X}$$

Once $\boldsymbol{V_S}$ is measured or solved using the above equation, current can be estimated from $\boldsymbol{I} = \frac{V_S}{R_S}$. But this does not mean that the voltage and the current must be estimated at the same time, even though this is possible, one of the two can be known in advance or measured not concurrently. If the value of the shunt resistor R_S is much less than $|\boldsymbol{Z_X}|$ the voltage $\boldsymbol{V_X} \cong \boldsymbol{V_G}$, then the measuring method is called *"constant voltage"*, since the voltage on the DUT is barely modified by the presence of the shunt resistor. If the value of the shunt resistor R_S is much greater than $|\boldsymbol{Z_X}|$ the current flowing in the branch is not affected by the DUT impedance. Then the method is called *"constant current"*. Each method has its pros and cons, which are described in depth in the technical literature[2], particularly since the loudspeaker is a nonlinear device and different stimulus levels can lead to different outcomes.

The constant voltage and constant current methods are the legacy of the era when there were available only analog instruments, such as needle voltmeters. In those days it was trivial to generate a sinusoid with a given voltage (10 V for example), while measuring current across a relatively high sensing resistor (say 10 kΩ). In this way one could directly read Ohms on the voltmeter (set in mV) greatly simplifying the acquisition process, which had to be iterated for every frequency point. Phase related errors due to the reading of only the voltage magnitude are also minimized using an high sensing resistor value.

In modern computer controlled measurement instruments it is possible to avoid the cumbersome process of measuring point by point in frequency and use the precise knowledge of some circuit elements to simplify the data acquisition.

3.1. Generator With Known Output Impedance and Level

If both unloaded output level and output impedance are known, a simplified procedure can be adopted.

This is the case of the Audiomatica fw-01 interface, where the output level (in parallel with input impedance) is stored during calibration and output impedance is set by the precision resistors in the output path (660 Ω 0.1%). In the Audiomatica CLIO software this method is called *"internal mode"*. This mode is similar to the *"constant current"*, but even if the sensing resistor value is not high accuracy is retained by the fact that the software acquire complex data and not magnitude only[3].

Another case where output level and output impedance are known is the Audiomatica QCBox Amplifier. In this case the gain of the amplifier is stored during unit production and there is a precision shunt resistor of 0.1 Ω . In Audiomatica CLIO software this mode is called *"QCBox ISense"*. This puts the DUT in conditions equivalent to *"constant voltage"*.

3.2. Simultaneous Acquisition of DUT Voltage and Current

If it is possible to acquire both current and voltage on the DUT at the same time, the $\boldsymbol{Z_X}$ can be easily calculated from Ohm's law. Current can be measured with Hall effect transducers which are virtually non-resistive, but usually the voltage divider circuit is adopted.

In Audiomatica CLIO 11 Sinusoidal measurement menu it is possible to acquire both channels of the Audiomatica fw-01 hardware[4]. Selecting a shunt resistor R_S of proper value, is it possible to have situations similar to either constant voltage and constant current. But in this case we are free from the constraints of the classical modes, since both voltage and current are measured, and the R_S value can be selected to get the best signal to noise ratio and accuracy for the measurement. This mode is also inherently a 4-wire measurements, which removes the need for short connections to the DUT.

With reference to the circuit reported in Figure 4, the ratio of the magnitude of voltage at the DUT and at the generator $\frac{|V_X|}{|V_G|}$ as a function of the ratio of the impedance $\frac{|Z_X|}{R_S}$ has the form:

$$y = \frac{x}{1+x}$$

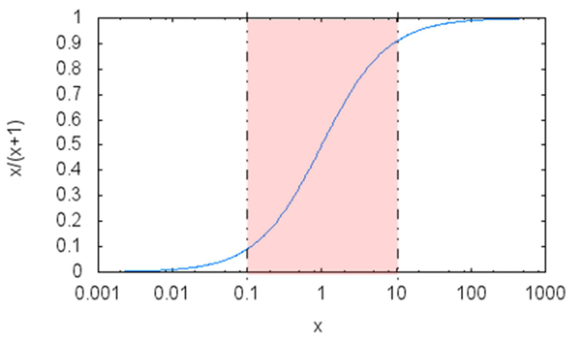


Figure 5 - Voltage Divider Characteristic

It can be noted that the maximum sensitivity (curve slope) is at the point $x = 1$, where measured voltage on DUT is half of the generated voltage and $|\boldsymbol{Z_X}| = R_S$. We can see from the graphic above that a meaningful range for the sensing resistor lies between $0.1 < x < 10$.

In Figure 6 is an example of measurement results of an high R_{DC} loudspeaker (nominal 24 Ω) with a sharp resonance peak, this is the kind of device which puts constant voltage measurement modes, as the Isense QC Box mode, into trouble. At the loudspeaker resonance peak the current has a minimum that corresponds to a minimum into the sensing voltage, which can easily fall into the measurement noise.

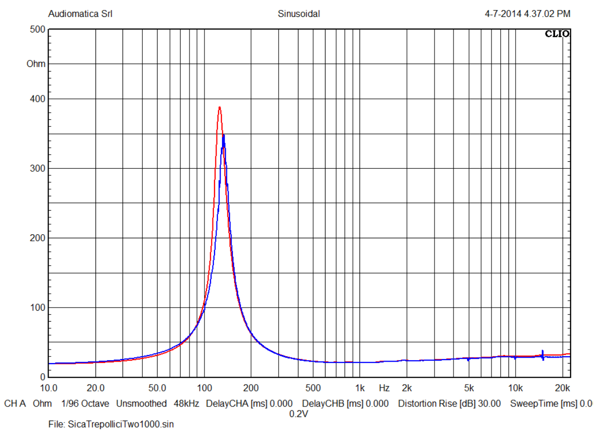


Figure 6 - Two Channels V, I Mode Results vs Isense

The blue curve is measured with the Isense mode 0.1 Ω resistor and the red curve with a 1 k Ω resistor. The effect of reduced signal to noise ratio and differences in damping are clearly visible.

4. FREQUENCY RESPONSE TECHNIQUES APPLIED TO IMPEDANCE MEASUREMENTS

As stated before the Impedance $\boldsymbol{Z}(j\omega)$ is obviously obtained as a ratio between two Frequency Responses, voltage and current. These two can be measured for each frequency point or using common techniques used to measure frequency responses. Several approaches are possible, between them it is possible to cite:

1. Impulse Response analysis with LogChirp or MLS signal

2. Sinusoidal analysis with swept sine and DFT analysis

An MLS sequence or a Logarithmic sweep of a given length (which is a power of 2) to get the impulse response of the device under test. In case of Linear and Time Invariant systems (LTI) the impulse response can be transformed in its dual: the complex frequency response. It should be noted that while the MLS signal has a white spectrum, the LogChirp has a pink one. This property of the LogChirp could be very useful in order to improve the signal to noise ratio. The Sinusoidal analysis uses a series of sinusoidal tones (which can be continuously generated or stepped) and DFT analysis to get the frequency response. The Sinusoidal analysis has the best signal to noise ratio of the analysis modes mentioned. When speed and low frequency resolution are not key factors, Sinusoidal analysis should be preferred to MLS or LogChirp.

5. INFLUENCE OF TEST DRIVING LEVEL

The simplified model of the electro-dynamic loudspeaker shown in Figure 1 is seldom applicable. There are several source of non-linearity in a loudspeaker, which start to appear even at low driving levels. The Bl product and C_{MS} are dependent on cone movement, and distortions arise from current flowing into the moving coil.

Figure 7 shows impedance curves taken with Audiomatica CLIO fw-01 system using *"internal mode"*. The output level range from -12 dBu to 18 dBu in 6dB steps. The blue curve refers to -12dBu, the red to +18dBu. It can be seen that the impedance peak amplitude and the resonance frequency are decreasing with an increasing driving level.

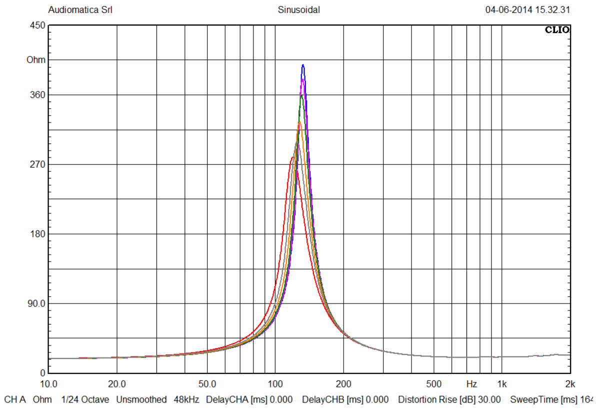


Figure 7 - Loudspeaker Impedance vs Test Level

6. INFLUENCE OF NOISE

Loudspeakers are electro-acoustical transducers in both directions and noise will appear as voltage exactly where the measurement instrument input is connected. To evaluate the problem we deliberately produced a disturbance by generating a 200 Hz single tone causing 70 dBSPL at the speaker cone.

We took three impedance curves in this condition: two with MLS&LogChirp (using either MLS and LogChirp as stimulus) and the third with Sinusoidal.

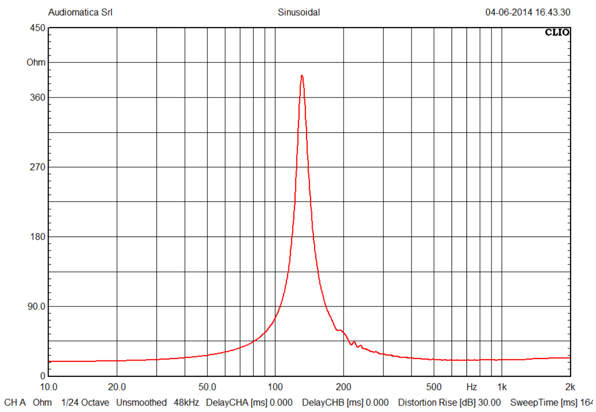


Figure 8 - Sinusoidal Impedance Measurement in Presence of Noise

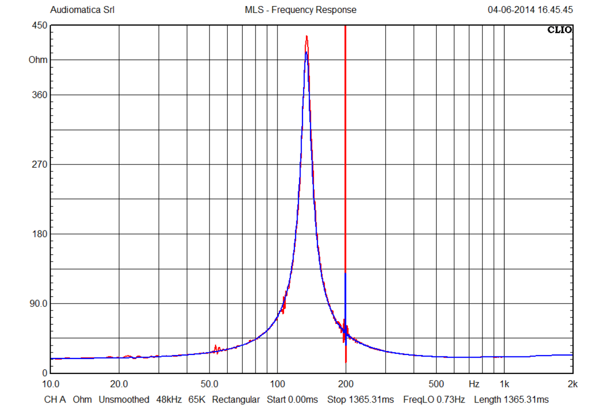


Figure 9 – MLS (red) & LogChirp (blue) Impedance Measurement in Presence of Noise

7. EFFECTS OF VIBRATIONS

Figure 10 shows an impedance curve taken with the loudspeaker positioned on a resonating structure (red curve) at around 200 Hz. During impedance measurements the loudspeaker should be positioned on a stable, non-resonating structure (as measured correctly in the blue curve).

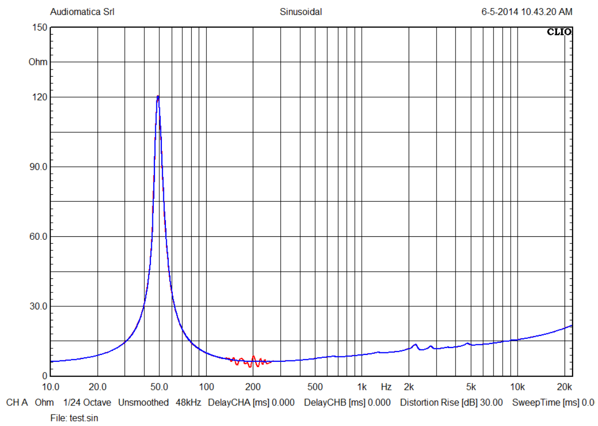


Figure 10 - Effects of Vibrations on Impedance Measurements

8. CONCLUSIONS

A brief review of the loudspeaker electrical impedance measurement methods has been carried out.

The widely used voltage divider circuit has been analyzed in depth.

Modern methods and measurement techniques based on DFT and Impulse Response have been introduced and discussed.

9. REFERENCES

[1] Thiele, Neville, *“Loudspeakers in Vented Boxes: Part 2”*, JAES Volume 19 Issue 6 pp. 471-483; June 1971

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