

Caractérisation de haut-parleurs par le logiciel REW

1 Matériel nécessaire

- 1 ordinateur muni du logiciel REW et d'une carte son (apporté par les étudiants)
- 1 amplificateur de puissance (fourni)
- 1 câble jack – BNC en sortie de carte son (fourni)
- 1 câble boîtier 3 bananes – jack en entrée de carte son (fourni)
- 1 haut-parleur (fourni ou apporté par les étudiants)

2 Objectif du travail

L'objectif de cette expérience est d'estimer les paramètres équivalents au haut-parleur étudié. Pour cela, les étapes à réaliser sont :

1. montage du système de mesure
2. étalonnage du dispositif de mesure
3. mesure de l'impédance du haut-parleur seul
4. mesure de l'impédance du haut-parleur avec une masse ajoutée connue
5. estimation des paramètres équivalents au haut-parleur
6. Influence de la position du haut-parleur
7. Influence du niveau d'excitation
8. validation de l'estimation des paramètres (optionnel)

3 Réalisation du montage

3.1 Tests préliminaires

Vérifier tout d'abord quelle est la sortie de la carte son. Pour cela lancer le logiciel REW et utiliser la fonction « signal generator » du logiciel. Connecter successivement les 2 sorties (droite / gauche) sur l'amplificateur et écouter quelle sortie est fonctionnelle.

3.2 Montage de l'expérience

Réaliser le montage de la Figure 1. Tester le montage en réglant l'amplificateur sur un faible gain et en écoutant si le haut-parleur chante après avoir généré un signal test avec la fonction « signal generator ».

Tester les niveaux d'entrée de la carte son à l'aide de la fonction « check levels »

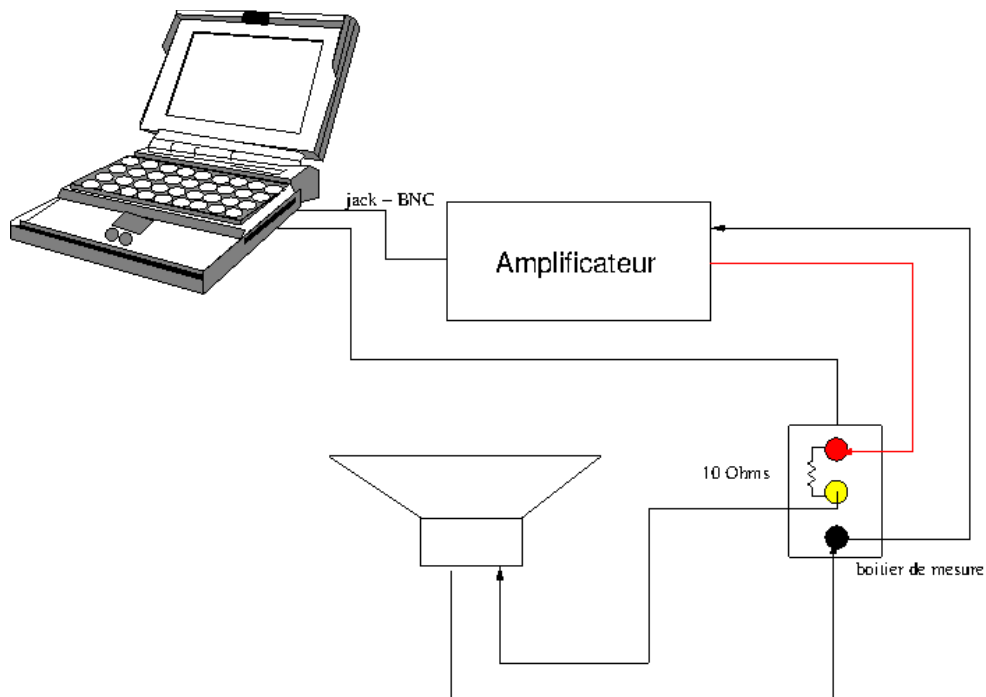


Figure 1 : principe de la mesure d'impédance à l'aide du logiciel REW.

4 Étalonnage du dispositif de mesure

L'objectif est ici d'étalonner la carte son de l'ordinateur avant de faire la mesure d'impédance. Pour cela, réaliser le montage de la Figure 2 et suivre les indications données à l'annexe 1 (§ 11.1), extraites de l'aide du logiciel REW.

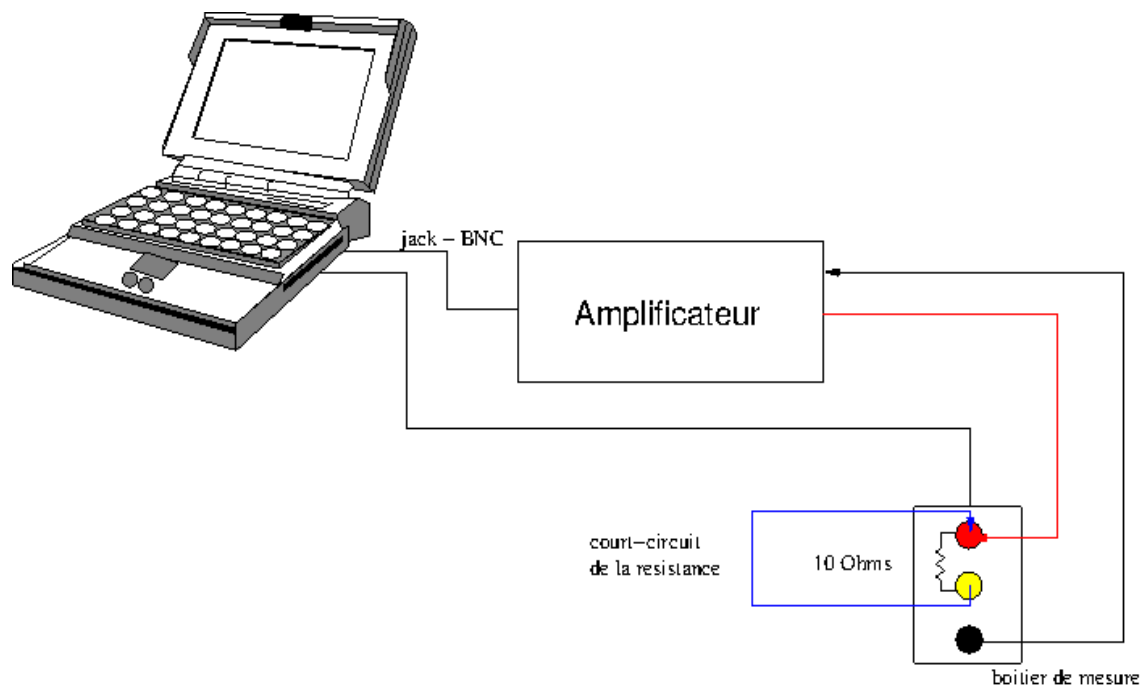


Figure 2 : Principe de l'étalonnage de la carte son.

5 Mesure de l'impédance du haut-parleur

5.1 Mesure du haut-parleur seul

Réaliser la mesure d'impédance du haut-parleur en suivant la procédure décrite à l'annexe 2 (§ 11.2). Utiliser comme fréquence limite basse la valeur de 10 Hz (voire 5 Hz) pour pouvoir bien estimer la résistance électrique du haut-parleur.

5.2 Mesure du haut-parleur avec masse ajoutée

Poser une petite masse sur la membrane du haut-parleur. On peut utiliser pour cela des pièces de monnaies dont les masses sont données à l'annexe 3 (§ 11.3). Refaire la mesure de l'impédance dans ces nouvelles conditions.

6 Estimation des paramètres équivalents au haut-parleur (paramètres dits « de Thiele & Small »)

A partir des deux mesures d'impédance réalisées ci-dessus, estimer les paramètres équivalents au haut-parleur en suivant les indications données à l'annexe 4 (§ 11.4).

7 Influence de la position du haut-parleur

Les mesures précédentes ont été réalisées avec le haut-parleur en position horizontale. Refaire une estimation des paramètres de Thiele et Small avec le haut-parleur en position verticale. Expliquer les éventuelles différences observées.

8 Influence du niveau d'excitation

Effectuer des estimations des paramètres de Thiele et Small du haut-parleur pour différents niveaux d'excitations (très faible, moyen, fort). Comparer les résultats obtenus et expliquer les différences observées.

9 Compensation de l'inductance du haut-parleur

En haute fréquence, l'inductance du haut-parleur peut être compensée en utilisant un réseau de Zobel.

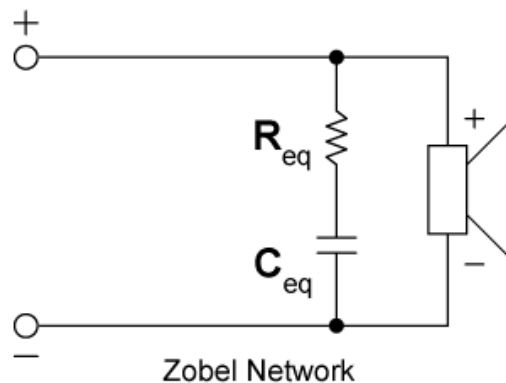


Figure 3 : Réseau de Zobel (Droits image Wavecor).

Montrer que l'inductance peut être compensée si $R_{eq}=R_{hp}$ et si $C_{eq}=L_{hp}/R_{eq}^2$.

Effectuer la compensation de votre haut-parleur à l'aide des composants fournis dans la salle de TP. Valider par une mesure d'impédance électrique.

10 Vérification de la validité des paramètres estimés

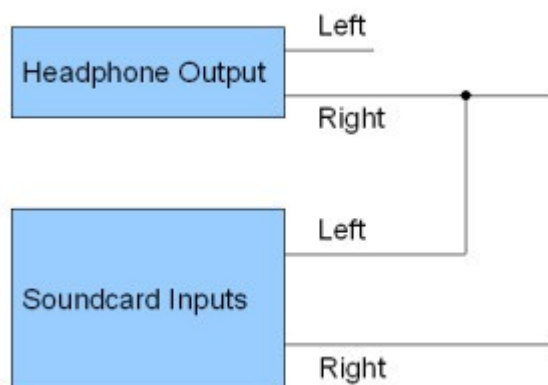
Pour les étudiants qui sont intéressés à aller plus loin, il est possible de faire une comparaison entre la mesure et le modèle à l'aide du logiciel de calcul scientifique matlab ou octave. Pour cela :

- exporter les mesures réalisées à l'aide de REW
- importer les résultats de mesure sous matlab ou octave
- réaliser un programme de simulation calculant l'impédance électrique d'un haut-parleur en utilisant le modèle simple (§ 11.4.c) ou le modèle plus complexe (§ 11.4.b).

11 Annexes

11.1 Annexe 1 : Calibrating the Impedance Rig

Small gain differences between the soundcard input channels cause incorrect calculation of the load current and the impedance. These can be calibrated out by making a measurement with the load disconnected and the sense resistor shorted out. **N.B. both soundcard inputs must be connected to the same output signal.**



- Press the Measure button (or Ctrl+M) to bring up the Measurement panel, select the Impedance button and set the sense resistor value to zero

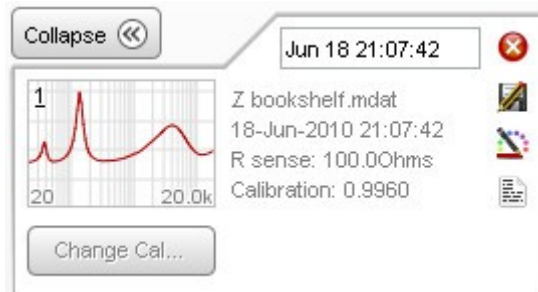


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- Press Start

Measuring to make a measurement. The completed measurement shows the level of the measurement channel (usually right) compared to the reference channel, where a reading of 100 Ohms corresponds to 100%, 99 Ohms would be 99% etc. If the difference between the 2 channels is too large (more than a couple of percent) the calibration is abandoned as it is likely there is a connection error, re-check the

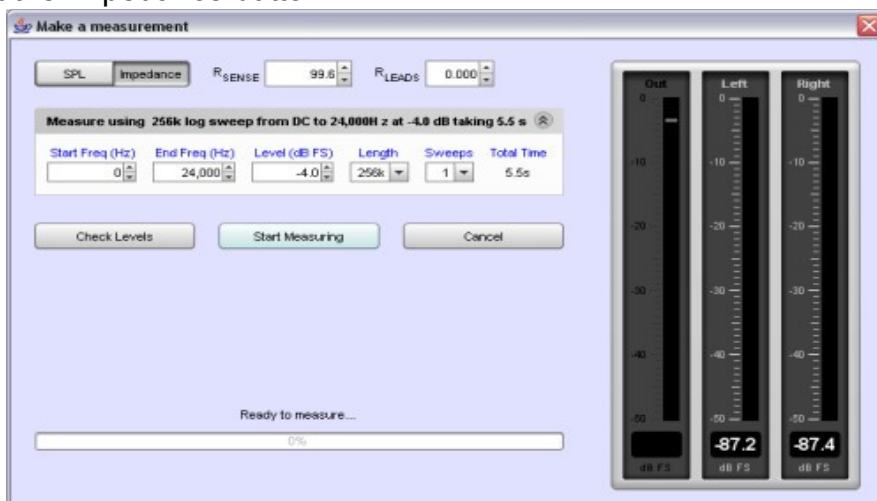
connections and try again.

The calibration factor used for impedance measurements is shown in the measurement info panel next to the measurement thumbnail, along with the sense resistor value.

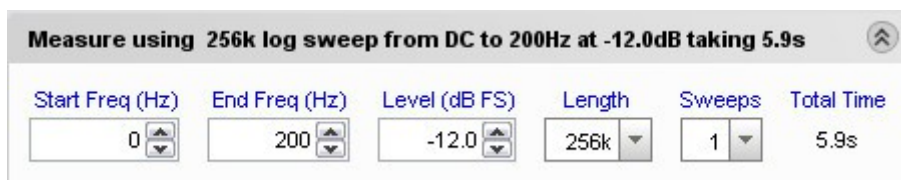


11.2 Making an Impedance Measurement

- Press the Measure button (or Ctrl+M) to bring up the Measurement panel and select the Impedance button



- Enter the **exact** value of the sense resistor. This must be measured accurately with a good quality, calibrated multimeter or impedance bridge, or a very high precision resistor (0.1%) should be used. Any error in the value of the sense resistor directly affects the measurement results.
- Click the expand button if necessary to show the measurement settings



Set the Start Freq to the lowest frequency for which you wish to see the response and End Freq to the highest. If measuring a drive unit to determine its Thiele-Small parameters measure up to 20 kHz. The sweep will span the range from half the start frequency to twice the end frequency (with an overall limit of half the soundcard sample rate) to provide accurate measurement over the selected range.

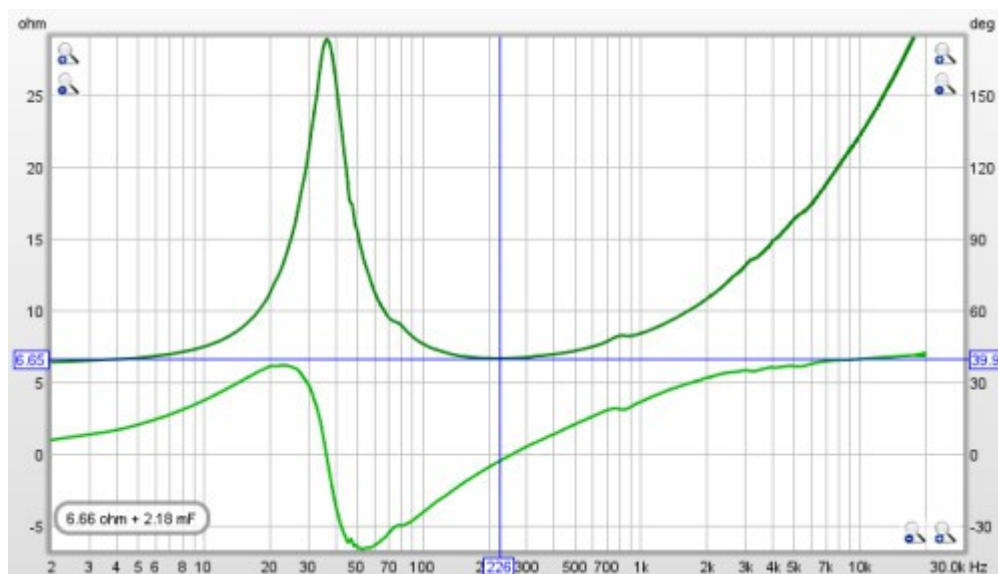
- Level controls the rms signal level at which the sweep is generated, relative to digital full scale. The maximum value is -3 dB FS, which would place the peaks of the signal at digital full scale - some soundcards may distort if -3 dB FS is used. For impedance measurements it is best to use a high sweep level, e.g. -6 dB FS, but if you are using a power amplifier beware of excessive levels.
- Length controls the duration of the sweep signal, specifying the number of samples in the sweep sequence. The default is 256k. Dividing the number of samples by the soundcard's sample rate gives the sweep duration in seconds. The overall duration includes silent periods before and after the sweep.
- If Sweeps is more than 1 REW uses synchronous pre-averaging, capturing the selected number of sweeps per measurement and averaging the results to reduce the effects of noise and interference. The pre-averaging improves S/N by almost 3dB for each doubling of the number of sweeps. Averaging is particularly useful if the measurements are contaminated by interference tones, whether electrical or acoustic, as they typically will not add coherently in the averaging and hence will be suppressed by the process.
- Total Time shows the overall duration of the sequence of sweeps
- The *Check Levels* button generates a few seconds of a pink noise signal that spans the frequency range selected for measurement and checks that the input level is not too high or too low. Pressing *Cancel* while the pink noise signal is playing will turn it off (it turns off automatically after 3 seconds). The rms level that was measured is shown on the measurement panel, with a warning if the level is too high or too low.



Press *Start Measuring* to make a measurement, progress is shown on the measurement panel along with a display of the measurement headroom.

The result of the measurement is displayed in the graph area, information about the measurement appears in the [Measurements Panel](#). Measurements are given a default name of the date and time at which they are made, a more appropriate name can be entered in the box at the top of the measurements panel.

When the mouse cursor is within the graph panel of the Impedance & Phase graph the equivalent series resistance + inductance or resistance + capacitance of the impedance at the cursor position is shown at the bottom left corner of the graph, this is useful when making measurements of inductors or capacitors to check their value. For capacitor measurements the values are most accurate at frequencies where the total impedance has dropped below a few hundred ohms.



11.3 Masses des pièces de monnaie

Pièce	2 euros	1 euro	0,50 eur o	0,20 eur o	0,10 eur o	0,05 eur o	0,02 eur o	0,01 eur o
Masse (g)	8,5	7,5	7,8	5,7	4,1	3,9	3	2,3

11.4 Thiele Small Parameters

The Thiele-Small Parameters window is used to calculate the parameters for a drive unit from measurements of its impedance. To calculate all the parameters two measurements are required, one in "free air" and a second with either mass added to the cone or with the unit in a sealed (air tight!) enclosure (ideally with a volume a little less than the expected V_{as}). Note that the drive unit must be rigidly supported during the measurements, and ideally mounted vertically (i.e. so that the cone is firing horizontally as it would be in a typical loudspeaker installation). Some pre-conditioning of the unit with signals at medium levels helps to stabilise the behaviour and suspension compliance and reduce memory effects in the suspension from periods of storage or lack of use. Quiet conditions are important for good measurements, drive units act as microphones and pick up noise and vibration, affecting the results. The measurements should be made up to 20kHz so that the lossy inductance of the voice coil can be accurately modelled, and the [impedance calibration](#) step should be carried out before making measurements.

Thiele-Small Parameters

Free Air Measurement
Select a measurement

Secondary Measurement
Select a measurement

Manually Entered Values

Voice Coil DC Resistance (ohm): 0.00

Effective Area (cm²): 176.7

Air Temperature (Celsius): 20

Air Pressure (mB): 1013.25

Added Mass (g): 0.00

Sealed Box Volume (Litres): 0.000

Compensate for Leakage Losses

Compensate for Air Load

Calculate Parameters

Write Parameters to File

Results area

Motional Impedance Parameters

R_{ES} (ohm): 4.00

C_{MES} (uF): 250.0

L_{CES} (mH): 1.000

R_{AMS} (mohm): 0.000

Blocked Impedance Parameters

dR (ohm): 0.10

L_{EB} (uH): 250.0

L_E (mH): 0.500

R_{SS} (ohm): 0.0

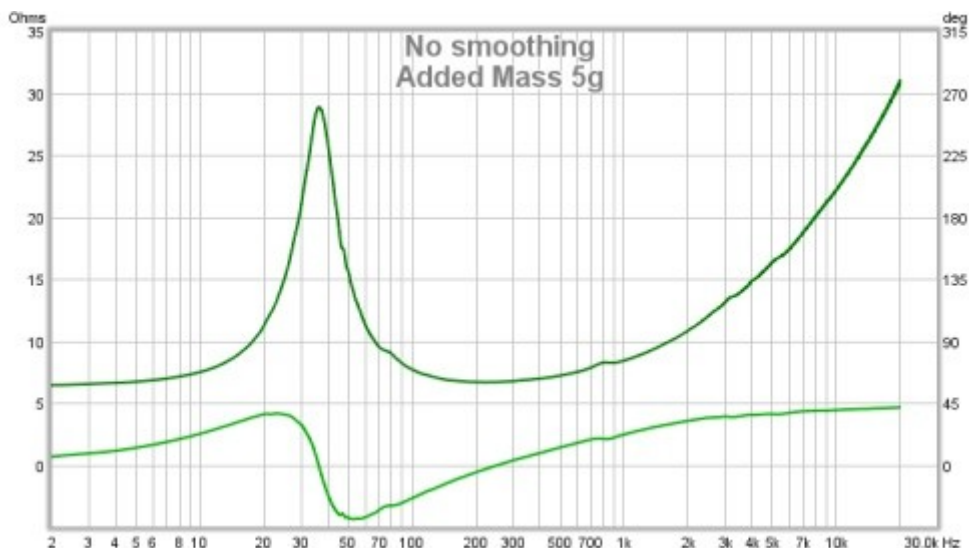
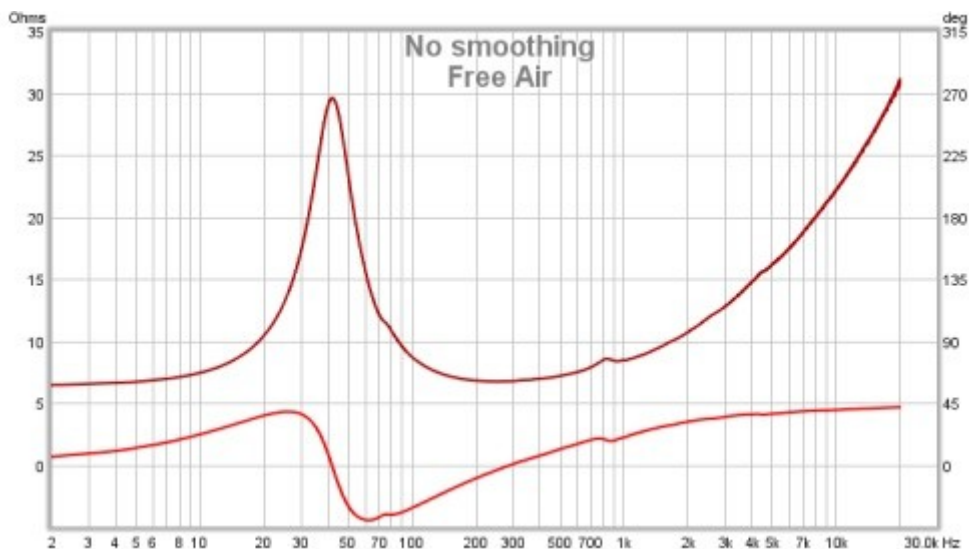
K_E (S-H): 0.1000

Simplified Model Parameters

Results area

11.4.a An Example Run

To show the results of a TS parameter calculation a small bass-midrange drive unit was measured. It has an effective area of 137cm². The plots below show the impedance measurements made in free air and then with a mass of 5g added to the cone. REW determines whether the secondary measurement is from a sealed box or added mass by looking at the resonant frequency, which is lower than free air for added mass and higher for a sealed box. A least squares fit of an electrical model of the drive unit impedance is carried out on the free air measurement to determine the model parameters. Another least squares fit is carried out on the secondary measurement to determine the modified motional parameters and the TS parameters are then calculated.



To calculate the TS parameters the two measurements are selected and the required values are entered:

- the DC resistance of the voice coil (R_{DC}) in ohms. Accurate measurement of low resistances is unfortunately not easy (see [footnote](#)), but the impedance model REW uses can easily compensate for a DC resistance which is slightly lower than the actual, so it is recommended to err on the low side
- the effective area in square centimetres, most driver data sheets include an effective area figure but if this is not available REW can calculate the figure for you given the effective diameter, which is the diameter of the cone plus a proportion of the surround, typically 1/3 to 1/2, just click the calculator icon on the left hand side of the effective area box
- the air temperature in degrees Celsius
- the air pressure in millibar
- the volume of the sealed box in litres, or, if the second measurement was made with

an added mass, the additional mass in grammes

The *Calculate Parameters* button is then clicked, with the following results.

Thiele-Small Parameters

Free Air Measurement
 1: SPH170 horz

Secondary Measurement
 2: SPH170 horz+5g

Manually Entered Values

Voice Coil DC Resistance (ohm): 6.20
 Effective Area (cm²): 137.0
 Air Temperature (Celsius): 20
 Air Pressure (mB): 1013.25
 Added Mass (g): 5.00
 Sealed Box Volume (Litres): 0.000

Compensate for Leakage Losses
 Compensate for Air Load

Calculate Parameters
 Write Parameters to File

Motional Impedance Parameters

R_{ES} (ohm): 31.57
 C_{MES} (uF): 364.4
 L_{CES} (mH): 39.510
 R_{AMS} (mohm): 4.677

Blocked Impedance Parameters

dR (ohm): 0.09
 L_{EB} (uH): 29.4
 L_E (mH): 1.189
 R_{SS} (ohm): 138.8
 K_E (S-H): 0.0867

Simplified Model Parameters

R _E 6.29 ohm	L _E 98.1 uH
R _{ES} 23.28 ohm	R ₂ 16.08 ohm
C _{MES} 364.4 uF	L ₂ 213.4 uH
L _{CES} 39.510 mH	R ₃ 4.23 ohm
	L ₃ 467.9 uH

TS parameters for measurement: SPH170 horz

R _E 6.29 ohm	f _s 41.7 Hz	M _{MS} 14.13 g
Z _{min} 6.71 ohm	Q _{MS} 2.220	C _{MS} 1.033 mm/N
f _{min} 251 Hz	Q _{ES} 0.600	R _{MS} 1.666 kg/s
f ₃ 1,473 Hz	Q _{TS} 0.472	V _{AS} 27.51 litres
L _E (f ₃) 0.470 mH	F _{TS} 88.2 Hz	Bl 6.227 Tm
Dd 13.21 cm	L _p 87.26 dB (1W/1m)	Eta 0.32 %
Sd 137.0 cm ²	Added mass 5.00 g	

Secondary measurement: SPH170 horz+5g
 Air temperature 20.0 C, pressure 1,013.25 mB giving density 1.2041 kg/m³, c 343.2 m/s

The first column of results in the bottom of the window show the loudspeaker resistance R_E, which is generally a little higher than the DC resistance; the minimum impedance Z_{min}

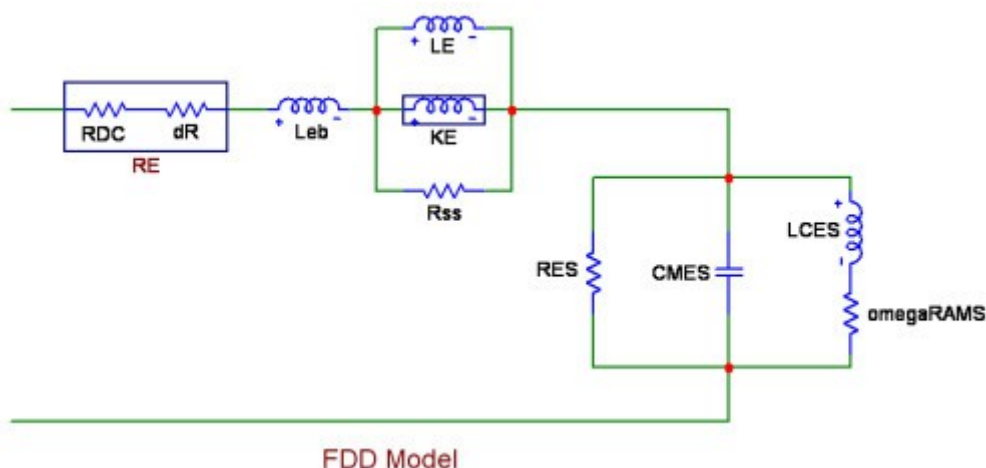
after the peak and the frequency f_{\min} at which it occurs; f_3 , which is the frequency at which the impedance has increased to $\sqrt{2} \cdot Z_{f_{\min}}$; the inductance at f_3 ; the effective diameter and the effective area. The second column shows the resonant frequency f_S ; the mechanical (Q_{MS}), electrical (Q_{ES}) and total (Q_{TS}) Q-factors and the F_{TS} figure (f_S/Q_{TS}). These parameters can also be calculated for any single measurement, without requiring a secondary measurement to be selected. The L_P figure and the M_{MS} , C_{MS} , R_{MS} , V_{AS} , Bl and Eta (efficiency) figures in the third column can only be calculated using both measurements.

The "Compensate for leakage losses" and "Compensate for Air Load" check boxes are only applicable for sealed box measurements, they take into account the leakage loss of the sealed box (which would be shown as Q_l at the bottom of the first column of results) and the air mass load due to the sealed box. These compensations use the Carrion-Isbert method described by Claus Futtrup in the documentation for his *Driver Parameter Calculator* application at <http://home1.stofanet.dk/cfuttrup/dpc.htm>

The results can be copied to the clipboard by right-clicking on the results area, or written to a text file using the *Write Parameters to File* button. When writing to file the separator between values, labels etc is as defined in the File -> Export menu.

11.4.b FDD Electrical Model

REW uses a driver impedance model that incorporates elements that cater for Frequency-Dependent Damping. The model is described in detail in the paper by Thorborg, Tinggaard, Agerkvist & Futtrup, "Frequency Dependence of Damping and Compliance in Loudspeaker Suspensions" J. Audio Eng. Soc., vol. 58, pp. 472-486 (June 2010). The diagram below shows the components of the model.

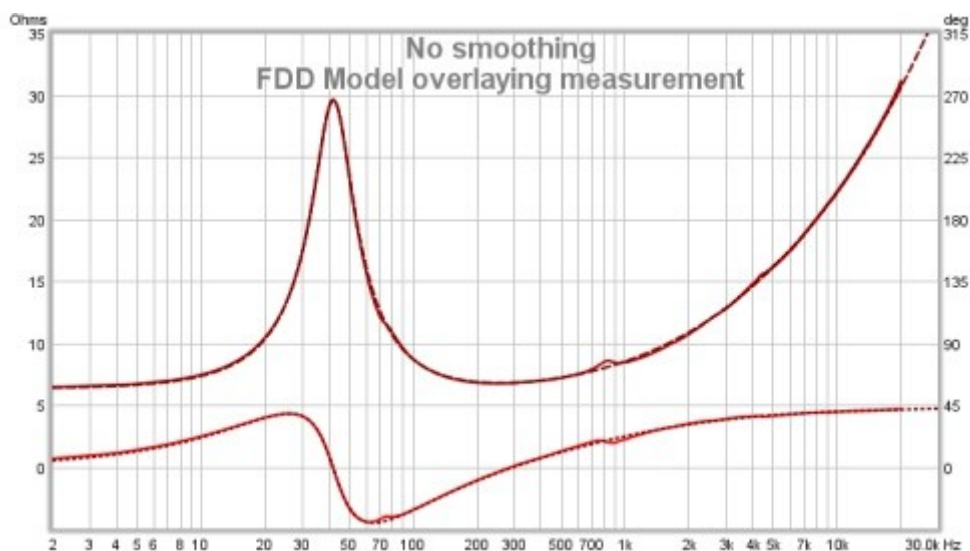


The model is split into two parts. The part at the right hand side models the motional impedance due to the movement of the driver, with parameters R_{ES} , C_{MES} , L_{CES} and R_{AMS} . This part reproduces the peak seen in the impedance plot. It differs from the

classical model by the addition of a frequency-dependent resistance ωR_{AMS} in series with L_{CES} . Note that the FDD model R_{ES} value is higher than that of the classical model due to the effect of ωR_{AMS} , which contributes an additional resistance that acts in parallel with R_{ES} .

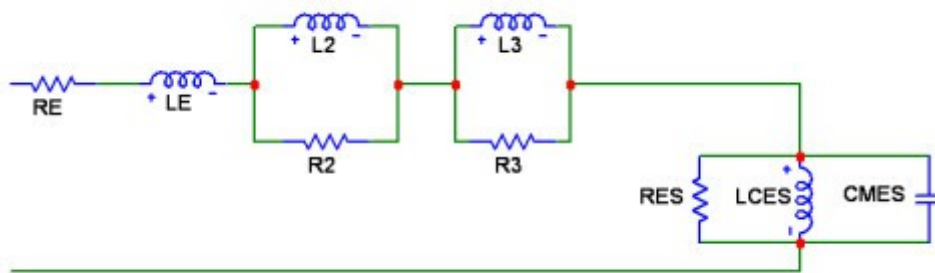
The other part of the model deals with the blocked electrical impedance of the driver. It is based on a model developed by Thorborg and Unruh, described in "Electrical Equivalent Circuit Model for Dynamic Moving-Coil Transducers Incorporating a Semi-Inductor," J. Audio Eng. Soc., vol. 56, pp. 696–709 (Sept 2008). That model begins with a drive unit resistance R_E which is the DC resistance R_{DC} followed by a small additional resistance dR which models the resistance contribution due to eddy currents. It is followed by a series inductance L_{EB} and then a parallel combination of an inductance L_E , a semi-inductance K_E and a resistance R_{SS} . L_E represents the inductance of the part of the voice coil located inside the motor gap. L_{EB} represents the part of the coil outside the motor gap. The semi-inductance K_E has an impedance that varies with the square root of $\omega \cdot j$. It models the effects of eddy currents and skin depth in the pole piece. The parallel combination of L_E and K_E models the transition of the coil's behaviour from largely that of a conventional inductor at low frequencies to a semi-inductor at high frequencies. The R_{SS} component models the effect of electrically conductive material in the magnet system, to be described in an AES paper that has not yet been published. The parameter values REW determines may be modified if desired and the effect on the modelled impedance and phase traces viewed on the graph, but the TS parameters which have been calculated will not be altered.

The plot below shows the modelled impedance traces (darker red and dashed) overlaying the measured values.



11.4.c Simplified Model

As frequency-dependent component values are not supported by many circuit simulators REW also calculates values for an alternative blocked impedance model using two parallel resistor-inductor pairs in series, labelled R2-L2 and R3-L3, and the conventional R_{ES} , C_{MES} , L_{CES} motional impedance model without the frequency-dependent damping. The values of these components are shown in the "Simplified Model" box. This diagram shows the simplified model components.



Measuring the driver DC resistance

Accurate measurement of low resistances is challenging, LCR meters that are in calibration may have a suitable range and give good results. If you do not have access to a calibrated LCR meter an alternative is to get an accurate measurement of a higher value resistor, perhaps 50 ohm or so, or purchase a very high precision resistor (such as a Vishay bulk foil part) and form a voltage divider with a DC source, the reference resistor and the driver. A decent multimeter can provide accurate voltage measurements, measuring the voltage across the driver and the voltage across the reference resistor allows the driver resistance to be determined from $(\text{ref resistor}) * (\text{driver voltage}) / (\text{ref resistor voltage})$.