

1.0 Introduction

1.1 About This Guide

I will make the assumption that you have at least a small appreciation of what Thiele-Small parameters are and why they are so important. Therefore I will concentrate on explaining how you can measure them, even if you are a beginner. I won't cover every single parameter possible, just the most commonly used ones -- basically all those necessary for useful modelling.

1.2 Impedance Curves

To give you a better idea of what is going on with a loudspeaker drive unit, here are generic/representative impedance curves for a closed box and a vented box. Note that these figures only show the portion of the impedance curve around the resonance frequency, as that is the main point of interest.

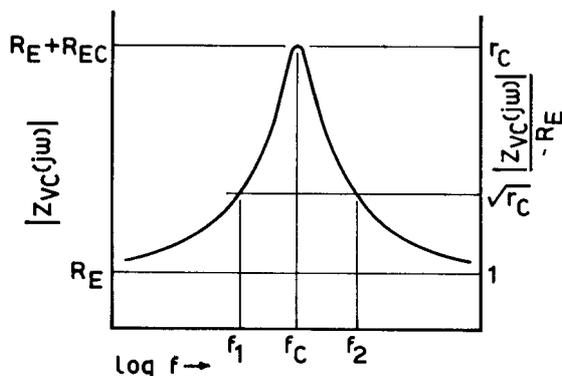


Figure 1: Closed Box Impedance Curve

A drive unit in free air will have an impedance curve very similar to that of a closed box. The closed box raises the resonance frequency and increases the Q-factor (the inverse of damping).

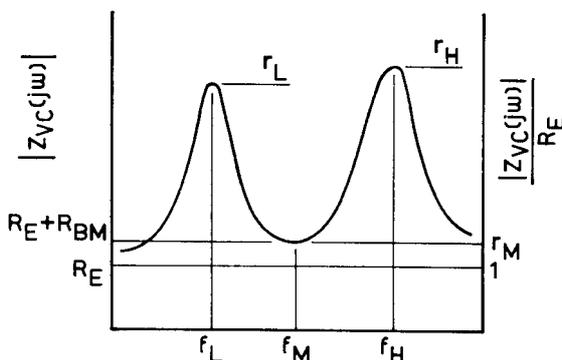


Figure 2: Vented Box Impedance Curve

The full frequency impedance usually exhibits a rising response a couple of octaves or so after the resonance frequency.

1.3 Getting Good Parameters

Thiele-Small parameters are 'small signal' parameters and so must be measured at relatively low levels. This means less than a volt applied to the voice coil. This also helps to keep any non-linearities due to suspension to a minimum.

Some people advocate testing at higher levels as this is more like what level the speaker will actually be used at. However, Thiele and Small designed these equations to be done at low levels, so that's what I recommend. You can always test at low level and again at higher levels to see what differences may occur.

2.0 Test Setup

2.1 Physical Layout and Environment

I feel that the physical layout is important and can affect the results, so the set-up should be consistent each time. Testing should be done in a very quiet and windless environment, as the loudspeaker will act like a microphone during testing and erroneous voltages can be produced that will skew measurements if the cone is disturbed at all.

Ideally, for the drive unit measurements the loudspeaker should be clamped/bolted to a vertical open frame, away from any walls and floors, but this is unwieldy and impractical for most people, as well as needing to be extremely sturdy and stout for today's high quality sub-woofer drivers. I just set the drive unit down on its magnet, on a small but solid table. For drivers with vented pole pieces, I stand the magnet off the surface using large blobs of Blu-Tack to allow airflow in and out of the vent. A drainpipe drilled with plenty of large holes could also be used.

The test set-ups described in the following text are used for all tests. They offer a way of measuring and recording the impedance curve of a loudspeaker. From this information the Thiele-Small parameters can be derived.

2.2 Two Methods

There are two methods we can use to perform an impedance sweep: voltage source and current source.

Voltage source is where you try to drive the loudspeaker as 'directly' from the amplifier as possible, so the voltage applied to it is constant (note I don't mean constant like DC -- which would quickly burn out your voice coil, I mean that the applied voltage stays the same regardless of the changing impedance of the voice coil). The best way to implement this method is to measure the voltage across a low value (typically 0.1 ohms) 'current measuring' resistor in series with the loudspeaker (as shown in Figure 3, overleaf). It is not recommended that you use an ammeter for this purpose because some ammeters may change range part way through the experiment which will cause a change in the impedance of the circuit, hence your results will be inaccurate.

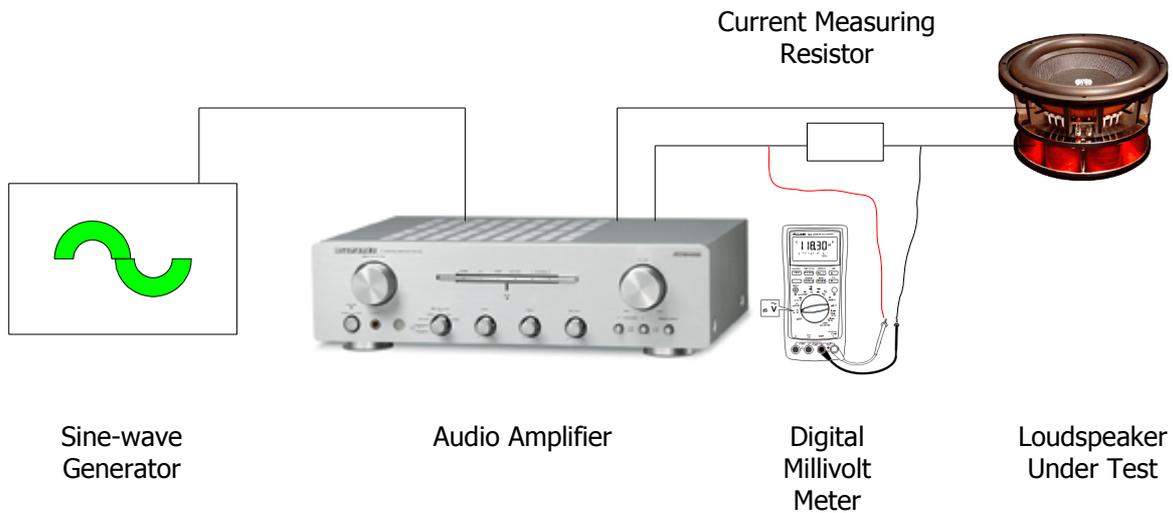


Figure 3: Voltage Source Method

Current source is where the current fed to the loudspeaker is constant (note again as above this is not like DC). This can be achieved in a basic fashion by simply 'swamping' the loudspeaker impedance by a relatively high value 'current source' resistor (as shown in Figure 4, below).

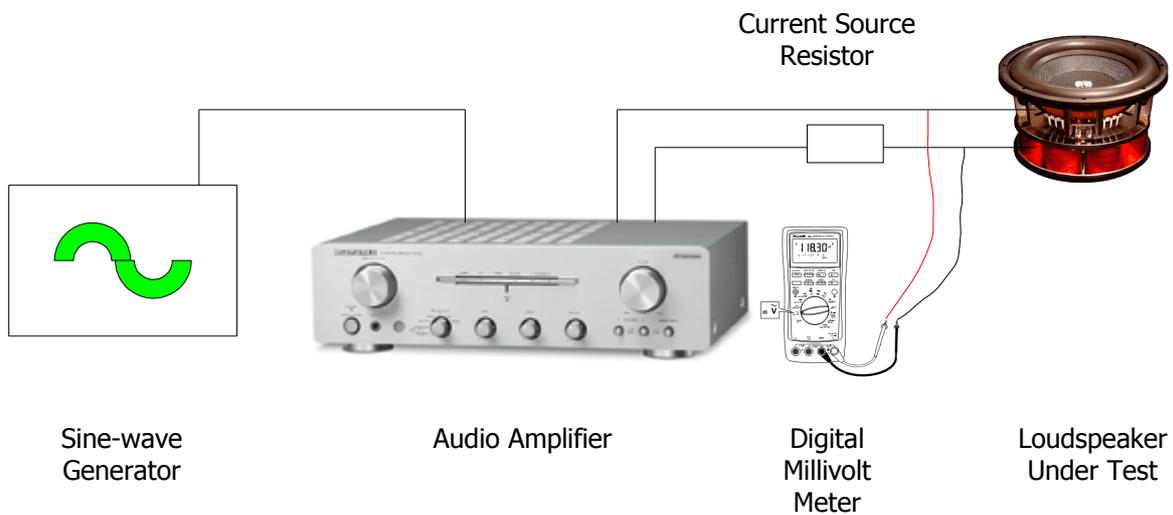


Figure 4: Current Source Method

Because of the potential divider action of the 'current source' resistor and voice coil impedance, an amplifier capable of clean output at 65 watts RMS into 8 ohms should be used with a 2.2k 'current source' resistor to ensure adequate drive voltage. If you have a lower powered amplifier you will need to reduce the resistance otherwise you will not achieve enough voltage swing and clip the amplifier, ruining your results. The table overleaf offers some guidelines on 'current source' resistor choice for a range of amplifier RMS powers into 8 ohms.

Amp	Ohms	Watts
100W	2.7k	0.50W
90W	2.4k	0.50W
65W	2.2k	0.50W
50W	1.8k	0.50W
40W	1.6k	0.25W
30W	1.5k	0.25W
20W	1.2k	0.25W

You will get more accurate results with higher value 'current source' resistors as the 'swamping' effect is greater, so try to use the highest powered amplifier (and consequently 'current source' resistor) that you can.

I prefer to use the current source method for a number of reasons:

1. It's easy to calibrate the set-up so that the reading you take is directly representative of the loudspeaker impedance, i.e. you can get 100 mV across the voice coil when the voice coil impedance is 10.0 ohms.
2. If you are measuring a low impedance loudspeaker it is also more accurate than the voltage source method as the 'current measuring' resistor becomes more than negligible.
3. Impedance peaks are easier to measure as they 'stand out' more due to the current drive.
4. Finally, it's also easier to get more consistent results as you always calibrate to the same levels.

I can vouch for the accuracy of this method because I have compared my own DIY results with measurements I have taken on the exact same drive unit using an extremely expensive Solartron Impedance Gain-Phase Analyser and they were within just a few percent.

2.3 Optimised Solution

To save having to pull out my amplifier from my hi-fi each time I want to measure a loudspeaker and because I want the best possible results, I designed and built myself a small current source module. This piece of kit senses the output current and keeps it constant. It's better than the conventional amplifier and 'current source' resistor because the resistor ideally needs to be of infinite impedance so that the loudspeaker impedance appears negligible. You can find the schematic and PCB layout on the 'Projects' page of the website, as the 'Class-A Multi-purpose Amplifier'.

You can download a neat and simple little sine wave generator from the 'Utilities' page of the website. This handy tool allows you to increment the frequency up and down in various step sizes. The advantage is that you can tweak the frequency accurately and easily, and see the true value displayed on the screen. So you don't need to have an oscilloscope or frequency meter to determine the true frequency, like you would if you used a traditional standalone signal generator.

As I prefer the current source method I will only go into detail on measurements using that method. The same methods apply whether you are using a conventional amplifier and 'current source' resistor or my true current source module.

3.0 Measurements

3.1 Why Sometimes Results Can Be Wrong

I have read a lot of websites and books on the subject and also done a lot of measurements myself. The one thing that is neglected in every other guide and that has been proven to be important by my own tests, is that of meter and driving amplifier accuracy. For your results to be any good you simply must know if your system is accurate over the whole range you are using it. Some meters are not consistent over the frequency band when performing voltage measurements, and a lot of amplifiers begin to roll off when you get down to the really low frequencies.

To prove this simply connect a volt meter to your amplifier and set the sine wave generator frequency to 60 Hz. Note the reading on the volt meter. Now change the sine wave generator frequency to 20 Hz and note the reading on the volt meter. Don't be too surprised if the reading has gone down a little from the original 60 Hz reading.

I will show you how you can overcome this problem by performing a calibration sweep before loudspeaker testing begins.

3.2 Calibration

Set up the stuff as shown in Figure 4, but first measure the exact resistance of the 10 ohm resistor and record it. (Whilst you have the meter set to measure ohms, you might also like to measure the resistance of your loudspeaker and record that as the parameter DC Resistance of Voice Coil (R_e .) Set the sine wave generator to 50 Hz and adjust the volume control on the amplifier or current source module so that the reading across the 10 ohm resistor is 10 mV per ohm, i.e. if your 10 ohm resistor actually measured 10.2 ohms set the volume control to give 102 mV.

Record frequency and volt meter readings every 5 Hz from 20 Hz to 100 Hz (for a bass drive unit) on a spreadsheet or piece of paper, remember not to touch the volume control at any point. Now take the 50 Hz reading as the baseline and subtract the volt meter reading for that frequency from all the other readings. This gives you your calibration data. To obtain calibration data for in-between each reading you can make an educated guess, but if you used a spreadsheet you can use the averaging function or produce a large graph which can be read across. The following steps are for producing a suitable graph using OpenOffice (version 2.x) (a great, free, office package) Calc spreadsheet:

1. Select your data then go to Insert > Chart... then click 'Next'.
2. From 'Choose a chart type' choose 'XY Chart', but before you click 'Next', check if you need to change 'Data series in:' to 'Rows' (if you did frequency from left to right you will need to choose 'Rows').
3. From 'Choose a variant' choose 'Lines with Symbols' or 'Lines Only' and under 'Grid lines' un-tick 'Y axis' (to make the graph a bit neater) then click 'Next'.
4. Under 'Display' un-tick 'Legend' (to make the graph a bit neater) and enable the x- and y-axis labels if you wish, then click 'Create' and hey presto; there's your graph. A quick resizing should be all that is needed.

3.3 Determination of F_s and Q

3.3.1 R_e

If you didn't do so prior to calibration, measure the resistance of your loudspeaker and record that as the parameter DC Resistance of Voice Coil (R_e).

3.3.2 F_s

Still using the set-up of Figure 4 that was used for calibration, swap out the 10 ohm resistor for your loudspeaker. Start from 100 Hz (for a bass drive unit) and sweep the sine wave generator down in frequency just a few Hz at a time and look for a high point on the volt meter reading. Tweak the sine wave generator until you reach the very highest reading you can get. This is the point of Maximum Impedance (Z_{max}) and the frequency is the Resonance Frequency (F_s). Record F_s and read off the volt meter to get the impedance and record this as Z_{max} . Remember that we calibrated earlier to give 10 mV per ohm, so if your volt meter reads 648 mV this corresponds to 64.8 ohms. Check your calibration data to see if you need to adjust the reading you took -- basically just add the calibration data to the reading.

3.3.3 Q

Load up the Loudspeaker Toolkit spreadsheet (found on the 'Utilities' page of the website) and enter the data gathered so far. It should then show you an impedance to search for whose value is 6dB below the maximum, Z_{6db} . Find the frequency above F_s where the volt meter shows the value Z_{6db} . Once found, enter that data into the spreadsheet as F_h , not forgetting to add the calibration data first. Then do the same with the frequency below F_s , as F_l . The spreadsheet will calculate the remaining parameters and display them all together.

3.4 Determination of S_d , V_{as} and a Few Others

Many websites and books choose to publish a relatively quick and fairly accurate method of determination of Volume of Air having Same Acoustic Compliance as Driver Suspension (V_{as}). I choose to spend just a little more time and obtain a more accurate result and a few more useful parameters to boot. It doesn't require any extra equipment and doesn't really take any longer in practice, so it's foolish not to in my opinion.

3.4.1 S_d

We shall start with an easy measurement; all you need is a ruler! Measure the diameter straight across of your loudspeaker cone including one-third of the surround at both ends. This is Diameter (D). To calculate Effective Projected Surface Area of Driver Diaphragm (S_d), simply divide D by two, square the result, then multiply that by Pi (3.142). However, this is one of the few parameters that you can trust the manufacturers data on, if it's available.

3.4.2 Test Box

As part of my V_{as} measurement procedure, the loudspeaker should be mounted to a test box. Ideally this should shift the resonance frequency of your drive unit up between 1.5 and 2 times. However, if your loudspeaker parameters are completely unknown you can use some typical internal volumes as shown in the table overleaf.

130mm driver: 2.76 litres
165mm driver: 5.38 litres
200mm driver: 9.30 litres
250mm driver: 17.65 litres
300mm driver: 29.92 litres
380mm driver: 59.58 litres

The test box must be unlined and well sealed. 18 mm thick wood is fine, and 12 mm would do for the boxes of less than 10 litres. There is no need to add any bracing or strengthening as only very low level signals will be used with the box. If you add anything to the inside of the box it will count against the volume inside, which you need to know accurately.

3.4.3 Basket Volume/Cone Volume

If you are intending to mount your loudspeaker basket facing inside the test box, you need to subtract the basket volume of your drive unit from the test box internal volume in order to arrive at the actual volume that will be left inside the box once your loudspeaker is mounted to it. If you are mounting your loudspeaker basket facing outside the test box, you need to add the volume of the cone volume to the test box internal volume in order to arrive at the actual volume that will be left inside the box once your loudspeaker is mounted to it. Therefore you need to know either one of these volumes.

To determine the basket volume, carefully cover the basket with cling film/food wrap. Make sure you don't make it tight on the basket -- you don't want it to tear and it must be able to be pushed a little into the gaps between the basket. Then get a bucket or bowl and fill it to the brim with water. Now carefully lower the drive unit into the bucket or bowl such that the surface of the water comes up to where the basket will mount flush to the box. The amount of water displaced is your drive unit volume. You can find out the volume by refilling the bucket or bowl with water from a measuring jug.

To determine the cone volume, carefully cover the cone with cling film/food wrap. It only needs to be gently laid over the cone as it will need to move down with the filling. You can use either water, couscous or rice from a measuring jug to find out the volume -- just fill up level to where the basket will mount flush to the box. Remove the filling afterwards with a small cup or scoop.

I prefer to mount the basket inside the test box, hence use the first method, as you need to know the basket volume anyway for when you do any modelling on your actual box. It also avoids the cone being depressed by the filling, which could be significant or possibly damaging if the suspension is very weak and the travel small. For connections I just drill a hole wide enough to accommodate common figure-8 wire in the opposite panel to the loudspeaker opening, then seal it in place with hot melt or epoxy glue.

3.4.4 Vas

Now you can mount your loudspeaker to the test box. Use the method for finding F_s as previously but, record the new frequency as F_c . Use the Loudspeaker Toolkit spreadsheet again and enter the new data gathered. The spreadsheet will calculate a few parameters and display them all together.

3.5 Determination of Fb and Ql

If you have built a vented box, you should check the accuracy of the tuning frequency (Fb) and quantify the leakage (Ql). Fb is commonly thought to simply correspond to the point of measured minimum impedance. However, due to voice coil inductance and crossover inductors, phase shift can occur when measuring for the point of minimum impedance thus skewing the frequency. You can account for this as I will explain below.

3.5.1 Fb

Using the current source set-up described previously and shown in Figure 4, calibrate your system. With the drive unit mounted to the box and all crossovers, etc. in place, but the vent covered over by a secure means (I clamp a slab of wood over it), swap out the 10 ohm resistor for your loudspeaker. Start from 100 Hz (for a bass drive unit) and sweep the sine wave generator down in frequency just a few Hz at a time and look for a high point on the volt meter reading. Tweak the sine wave generator until you reach the very highest reading you can get. Record the frequency as Fc.

Remove the cover from the vent and. Start from 100 Hz and sweep the sine wave generator down in frequency just a few Hz at a time and look for a high point on the volt meter reading. Tweak the sine wave generator until you reach the very highest reading you can get. This is one of the two points of maximum impedance. Record the frequency as Fh. Now continue sweeping the frequency down a few Hz at a time and look for another high point on the volt meter reading. As before, tweak the sine wave generator until you reach the very highest reading you can get. Record the frequency as Fl.

Calculate the true value of Fb by the following equation (all you need is a simple calculator!):

$$Fb = \sqrt{(Fh^2 + Fl^2 - Fc^2)}$$

3.5.2 Ql

Now set the sine wave generator to Fb and read off the volt meter to get the impedance and record this as Zmin. Remember that we calibrated earlier to give 10 mV per ohm, so if your volt meter reads 52 mV this corresponds to 5.2 ohms. Check your calibration data to see if you need to adjust the reading you took.

In the Loudspeaker Toolkit spreadsheet there is a second tab labelled 'Vented'. Use this sheet and enter the new data gathered. The spreadsheet will calculate a few parameters and display them all together for you.

3.6 Troubleshooting

Some extreme sub-woofer drive units may have such stiff suspension and heavy cones that testing at the recommended 100 mV gives readings that are a bit spurious. In this situation you can double the drive to 200 mV or quadruple to 400 mV.

Referring back to section 3.2 on calibration, if your calibration resistor was 10.2 ohms you would adjust the volume control to give 204 mV (giving 20 mV per ohm) or 408 mV (giving 40 mV per ohm). Then you must remember to divide the volt meter reading by 2 or 4 to get the actual impedance.

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