

Speaker Analysis Using Thiele-Small Parameters

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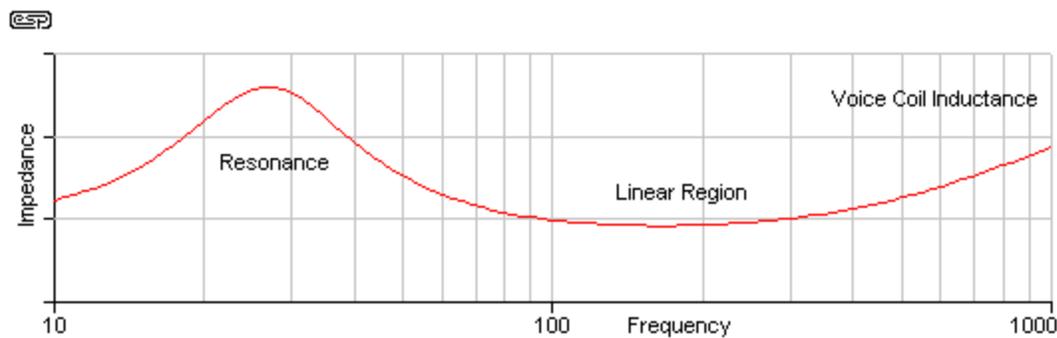
Introduction

Designing loudspeakers requires a great deal of research and development of many factors. The basis for which speaker enclosures are designed today are specifications called Thiele-Small parameters. There are a number of performance characteristics of speakers that were developed by Neville Thiele and Richard Small. These Thiele-Small parameters can be used to predict the performance of a speaker in different types of speaker enclosures. For this project, I was able to not only find various Thiele-Small parameters for many different types of speakers, but also produce accurate impedance curve plots for all of these speakers, which can tell you many things about a particular speaker.

In 1961, Neville Thiele first published his work on his study of loudspeakers in different types of vented speaker enclosures which was entitled “Loudspeakers in Vented Boxes”, and published in the Proceedings of the IRE Australia. In 1972, Richard Small published articles that built on the work of Neville Thiele and covered vented speaker enclosures and covered ones as well. This work is widely referred to even today for speaker enclosure design. Analyzing the acoustic output and characteristics of a speaker was made much simpler by the work of these two men. Simply using electrical circuit analysis to measure Thiele-Small parameters made designing speaker enclosures for different speaker setups much easier.

Speaker & Thiele-Small parameter theory

There are many Thiele-Small parameters that can be measured from loudspeakers, but the three most important ones are: free air resonance ($F(s)$), $Q(ts)$, and volume of suspension ($V(as)$). The free air resonance is the resonant frequency of the speaker found in free air. Below, a typical impedance frequency response of a loudspeaker is shown on a log scale.



At the resonant frequency, there is a clear increase in impedance for the speaker. The resonant frequency can clearly be seen here at about 25 Hz. After the resonant frequency, capacitive impedance reduces the magnitude of the total impedance until the linear region, in which the impedance stays relatively constant. Then, at high frequencies, the magnitude of the impedance rises due to inductive impedance, where the voice coil inductance contributes to the impedance. The resonant frequency is considered the threshold at which a speaker can be used. A speaker usually is unable to operate at a frequency lower than the resonant frequency.

The $Q(ts)$ or total Q of the speaker, also known as total quality factor, is basically describing the resonance curve of the speaker. The higher and thinner of a peak the curve has, the lower Q it will have. The rounder a peak the curve has, the higher Q it will have.

There are two parts that make up $Q(ts)$. These are the electrical Q ($Q(es)$) and mechanical Q ($Q(ms)$). Finally, the last main Thiele-Small parameter is $V(as)$. This refers to the volume of air that has the same compliance as the speaker. In other words, it is the volume of air that equals the volume of the suspension of the speaker.

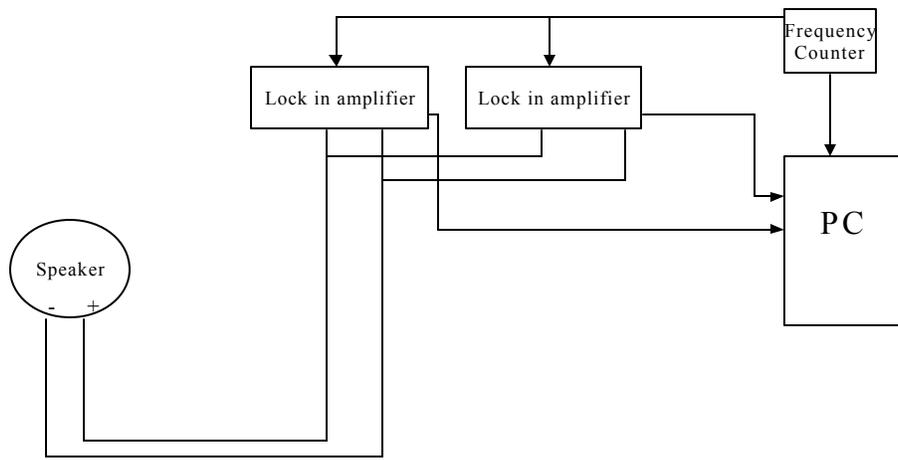
There are many ways to find the values of the Thiele-Small parameters, even if there is not advanced equipment available for one to make measurements with.

Fortunately, the Physics 398 lab had some very useful tools that enabled me to make accurate measurements.

Project setup description

By creating a setup to plot various characteristics of a speaker vs. frequency, I was able to determine many things about the speaker. Here, the process of carrying out the project will be explained. (Thanks to Professor Errede for helping set up the data acquisition system).

The equipment used to take these measurements from the speaker was: a function generator, a personal computer running the National Instruments LabWindows CVI data acquisition program, and two lock-in amplifiers. On the next page, a simple diagram of the data acquisition setup is shown.



Basically, the two terminals of the speaker are connected to two different lock-in amplifiers that measure both voltage and current throughout the range of frequencies determined by the frequency counter. Lock-in amplifiers are used to measure information from a signal such as phase and amplitude from a signal that might be obstructed by background noise. All that is needed to know for this project is that it is able to relate data about the speaker to the computer running LabWindows, which gathers the information and plots it. The program used to run this data acquisition program is written in C, and is a slightly modified version of the program used to measure the response of various guitar pickups. The original code was written by Steve Errede and Jack Boparai, and modified to work with speakers by Professor Errede. This program provides a very friendly user interface and very helpful options for analyzing data. Many different types of data could be graphed by using this program: total voltage, real voltage, imaginary voltage, and voltage phase, all vs. frequency, can be graphed using the code.

The same holds true for current and impedance. Also, there is an option to save the data and work with it in Microsoft Excel, if the user so desires. This proved very useful to me, as I could work with the data at home, since I had Excel, but not all of the equipment needed to take actual measurements. Another very important ability of the code was to control the frequency range for which the setup was supposed to keep track of data. The default setting is to test the speaker from 10 Hz to 20,000 Hz, which is the human frequency range of hearing. But sometimes it is advantageous to look at a smaller range of frequencies to better analyze the characteristics of the speaker. Measuring speaker parameters from about 10 Hz to 150 Hz was also done to get a “close up” view of the resonant frequency curve. This was necessary to more accurately find the $F(s)$ of the speaker. Now that we have the information recorded by the computer, we can do many things with it.

Determining Thiele-Small Parameters

With the data that was recorded by the computer, a couple of key Thiele-Small parameters can now be found. Finding $F(s)$ is relatively simple. It is just the frequency at which the highest point of the peak of the impedance occurs. The following method of finding $Q(ts)$ was found at www.epanorama.net/documents/audio/speaker_parameters. Measure the DC resistance of the speaker, and designate it as R_e . Now, measure the voltage of the speaker at this resonant frequency. This will be called $R_e + R_{es}$. Then find the ratio between R_e and $R_e + R_{es}$ and designate this ratio as R_c . Then, find two frequencies f_1 and f_2 , where the impedance is $R_e \cdot \sqrt{R_c}$ on both sides of the resonant

frequency. From this, we can calculate Q(ms), Q(es), and Q(ts). Below are the equations to find each of these values:

$$Q(\text{ms}) = \frac{F_s * \text{sqrt}(\text{Rc})}{f_2 - f_1}$$

$$Q(\text{es}) = \frac{Q(\text{ms})}{(\text{Rc} - 1)}$$

$$Q(\text{ts}) = \frac{Q(\text{es}) * Q(\text{ms})}{Q(\text{es}) + Q(\text{ms})}$$

Now, two of the major Thiele-Small parameters are known. Finding V(as), however is more difficult, and I did not have enough time to find V(as) for the different speakers.

However, I will mention a crude method to find V(as) that I came across. To find V(as), repeat all of the steps above, but the speaker has to be in a sealed box that will not leak.

Find the volume of the box Vb, and use the following equation:

$$V(\text{as}) = V_b * \left\{ \frac{F(\text{c}) * Q(\text{ec})}{F(\text{s}) * Q(\text{es})} - 1 \right\}$$

where F(c) and Q(ec) are equivalent values of F(s) and Q(es) in the sealed box.

Here are the Thiele-Small parameters that I calculated from the data I have obtained, by following the steps above.

Speaker	F(s)	Re	Re+Res	Rc	f1	f2	Q(ms)	Q(es)	Q(ts)
4" speaker	75	2.6	6.531	2.511923	57	90	3.602056	2.382434	1.433984
Jensen P8R-4	133	3.1	19	6.129032	112	152	8.231663	1.604916	1.343061
Eminence 8"	150	6.7	11.1	1.656716	110	200	2.145225	3.266593	1.294866
Celestion Vintage 8"	170	6.2	30	4.83871	140	200	6.232502	1.623593	1.28805
Celestion Vintage 10"	124	7	110	15.71429	104	145	11.98906	0.814791	0.76294
10" in Peavey	60	3.2	10.5	3.28125	38	82	2.470121	1.082793	0.752799
12 " subwoofer	25	5.2	62.18	11.95769	19	32	6.64998	0.606878	0.556126

Analyzing Thiele-Small results

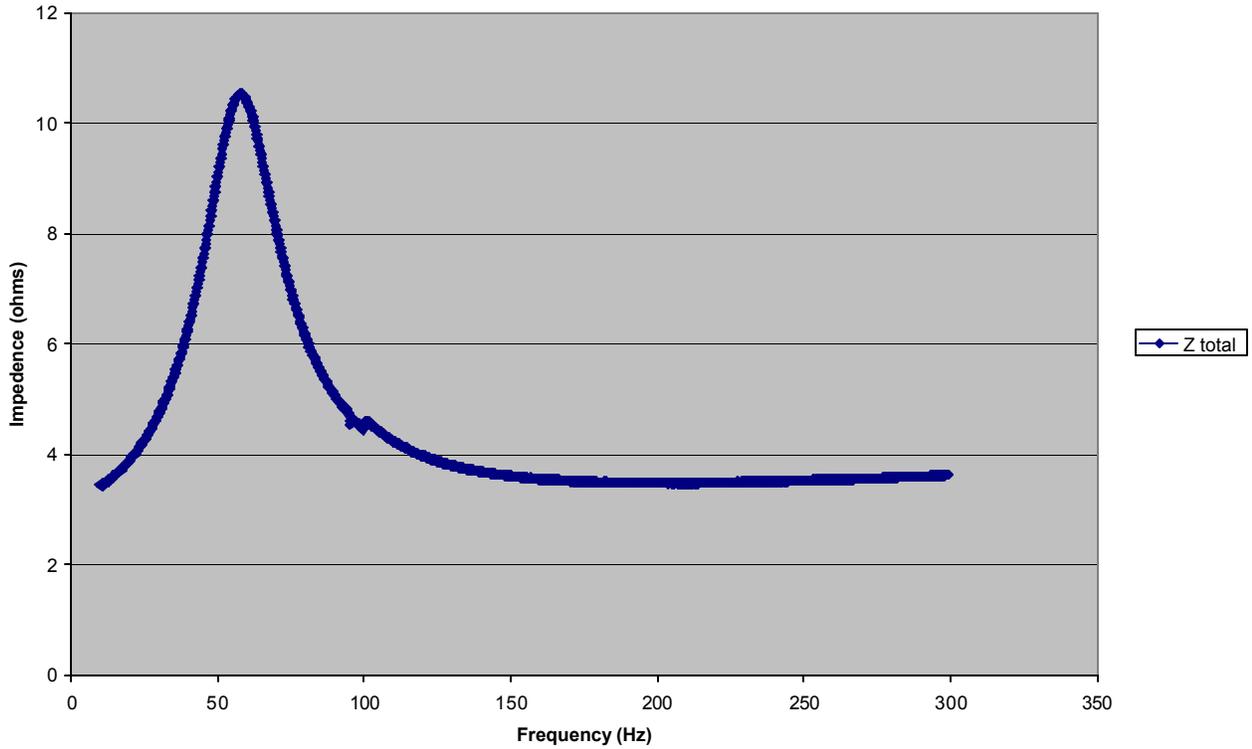
Now that the Thiele-Small parameters can be found, a further analysis of the Thiele-Small results can be done. First, $F(s)$ will be discussed. From the data compiled, I was able to see that larger speakers such as the subwoofer I tested had a much lower $F(s)$ compared to the other speakers. Manufacturers of speakers will create different types of speakers with a whole range of resonant frequencies. Basically, the resonant frequency of speakers determines what kind of speaker it will be. Subwoofers will operate with low resonant frequencies, while other types of speakers will typically have higher resonant frequencies. The $Q(ts)$ value of the speaker is an indicator of the “resonant magnification” of the speaker. This value is important in deciding what type of enclosure a speaker should go into. Also, a high value for $Q(ts)$ will have a “warmer” tone, while lower values have a more clear and “shallower” sound, according to The Loudspeaker Design Cookbook by Vance Dickason. A very high $Q(ts)$ or a very low value for $Q(ts)$ is not good. The speakers towards the middle of the table should be of higher quality and should sound better than those at the edges, since the table is sorted with respect to $Q(ts)$.

Comparing speaker data in free air vs. in cabinet

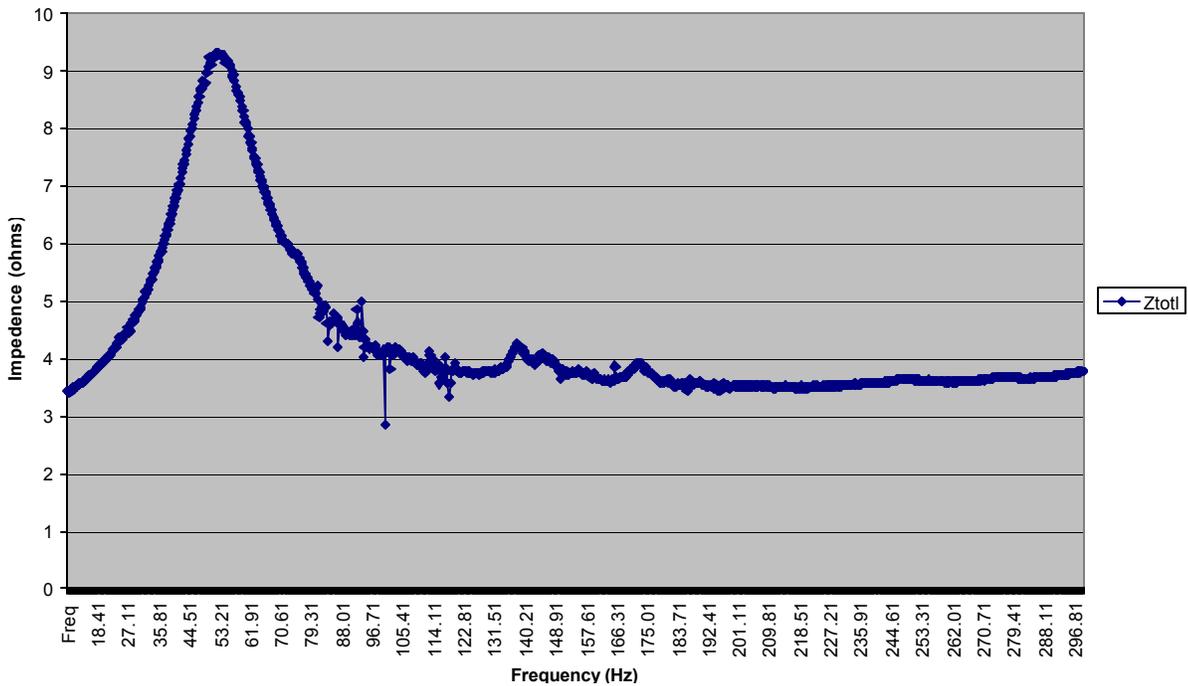
Other than Thiele-Small parameters, other things can be observed from looking at the impedance curves from a speaker. I decided to look at the results of a speaker measured in free air vs. a speaker measured in an open back cabinet, which served to simulate an infinite baffle board. I was surprised to see some differences. First, here are two graphs of the impedance curve of a 10” speaker found in a Peavey amp. The first

graph is of the speaker measured in free air, and the second graph is of the speaker measured in a cabinet:

Total Impedance vs. Frequency for Peavey 10" in free air zoom



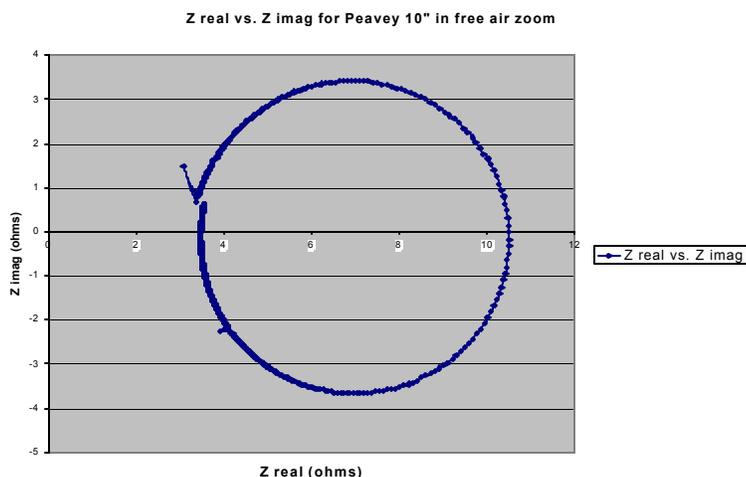
Total Impedance vs. Frequency for 10" Peavey in cabinet zoom



There are many interesting observations that can be drawn from looking at these two graphs. One of the biggest things that you can see is that the resonant frequency is actually shifted down when the speaker is in the cabinet as opposed to in free air. In the graphs, above, the $F(s)$ of the speaker in free air is about 58 Hz, while the $F(s)$ of the speaker in the cabinet is about 53 Hz. From these observations, we can draw the conclusion that speakers work better in a cabinet or infinite baffle rather than in free air. This is because when a speaker is in free air, the low frequency sound waves emanating from behind and in front of the speaker cone may interfere with each other and cancel out. If the speaker is mounted on an infinite baffle, the waves behind the cone will not interfere with the audio signals produced by the speaker in front of the baffle. The other obvious difference we can see from a speaker in free air and a speaker in the cabinet is that in the free air situation, the curve is much more smooth than in the cabinet. The true characteristic of the impedance curve is amplified in the cabinet. For example, at about 100 Hz, a jagged discontinuity in the curve can be seen in the free air graph. Looking at the cabinet graph, it is much larger and pronounced. There are many more discontinuities in the graph of the speaker in the cabinet. I believe that this is a much truer picture of the impedance, because the speaker will always be in a cabinet when it is being used, so the data received when testing a speaker in a cabinet is more useful. Overall, it was very important to look at and compare the effects of a speaker tested in free air and mounted in a cabinet.

Looking at other data

Of course, the total impedance curve is not the only important thing to look at when viewing the data plots from the speakers. Both voltage and current were also measured from each speaker. In each set of graphs, these curves were very similar. All of the data can be viewed in the graphs that are printed out separately from this report. On some of the speakers I tested, there are 4 sets of data. Either the data was taken from the normal range of frequency (10 Hz – 20,000 Hz) or in a smaller range of frequency (10 Hz – 200 Hz) to better view the resonant area of the impedance curve. Also, for each range, there was a set of data for the speaker in free air and for the speaker in a cabinet. Real voltage generally followed the same shape as the total impedance, as did total voltage. For the imaginary voltage, there was a sharp change of sign at the resonance. This is due to the capacitive resistance taking over and reducing the total resistance after resonance. The voltage phase behaved the same way. Real and imaginary current generally stayed constant throughout. Of course, this contributes to a constant total current. There might be some dips seen in the graphs, but keep in mind that it is a very small scale. Real, imaginary, and total impedance mimic the voltage data described above for the same reasons. An interesting graph to look at is the $\text{Re}(\text{Voltage})$ vs. $\text{Im}(\text{Voltage})$ and similarly the $\text{Re}(\text{Impedance})$ vs. $\text{Im}(\text{Impedance})$:



This graph shows the resonance associated with the speaker. The circular shape suggests perfect resonance with the speaker.

Possibilities for future experiments

There is much more to study and research on this topic. Even though I made some steps towards understanding speaker characteristics, there is much more to do. First of all, I was able to calculate $F(s)$ and $Q(ts)$ of certain speakers, but to take it further, one could try to calculate $V(as)$ by doing the measurements I did, except in a sealed box. Perhaps after finding all three of these important Thiele-Small parameters, there can be a better understanding of how these parameters can be used to design enclosures. Values for exact dimension projections of a cabinet and what type of cabinet, such as closed back, vented back, etc. can be researched. Possibly actually creating different cabinets with different sizes and types and testing how certain speakers sound and respond would be interesting to see. Further studying which types of speakers and enclosure would work in different types of purposes would also be interesting. How would a speaker cabinet designed for a home theater be different for a setup for a rock concert? There is an endless amount of extensions from this topic to pursue.

Sources used

Introduction to Loudspeaker Design

- John L. Murphy

The Loudspeaker Design Cookbook

- Vance Dickason

www.epanorama.net/documents/audio/speaker_parameters.html

www.sound.au.com/tsp.htm

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Professor Errede

(Thanks for brining in speakers for me to test and for the help along the way.)