Thiele/Small MLS Measurement Accuracy

When using digital sampling systems to measure loudspeaker acoustic transfer function or input impedance, one must be aware of "discrete" character of the process. Virtually all calculations are performed at discrete frequency points only. Therefore, it is of vital importance to understand factors affecting accuracy of the measurement process.

Here are some of the factors affecting measurement accuracy

1. Sampling frequency
2. MLS length / FFT length
3. Size of window (if any).
4. Smoothing (if any)
5. Display Window Frequency Range (data points mapping)
6. External noise/vibrations
7. Set-up errors.
8. Properties of the sound card.
9. Driver burn-in.

Sampling Frequency, MLS Length

Ideally, we would want the measurement process to mimic the continuous, analog-type of measurements. In order to get close to it, we need to optimize settings of the program and sound card, so that maximum resolution and accuracy in frequency domain is realized.

This is particularly important for input impedance measurements, because the slopes at driver's resonance peak are very steep. Therefore the modulus of the impedance changes fairly quickly from one frequency bin to the next.

Input impedance of the loudspeaker is computed by applying an FFT to the measured impulse response of the input impedance. The process's frequency resolution (F1 below in Hz) is given as the sampling rate divided by the FFT size (i.e. 48000/262144=0.183Hz). Please note, that FFT size is the same as MLS length +1.

To obtain better computational frequency resolution it is advisable to use longer MLS and subsequently longer impulse response. FFT size is adjusted automatically to MLS length, to compute the Zin transfer function.

Marked below are recommended settings for sampling rate and MLS length for TS measurements.

For a typical 48kHz sampling and MLS=262k, the error could be 0.183Hz, if an adjacent frequency bin is selected by the algorithm for subsequent computations.

	MLS=8192.0	MLS=16384.0	MLS=32768.0	MLS=65536.0	MLS=131072.0	MLS=262144.0
S = 11025 Hz	F1 = 1.346	F1 = 0.673	F1 = 0.336	F1 = 0.168	F1 = 0.084	F1 = 0.042
S = 12000 Hz	F1 = 1.465	F1 = 0.732	F1 = 0.366	F1 = 0.183	F1 = 0.092	F1 = 0.046
S = 22050 Hz	F1 = 2.692	F1 = 1.346	F1 = 0.673	F1 = 0.336	F1 = 0.168	F1 = 0.084
S = 24000 Hz	F1 = 2.930	F1 = 1.465	F1 = 0.732	F1 = 0.366	F1 = 0.183	F1 = 0.092
S = 44100 Hz	F1 = 5.383	F1 = 2.692	F1 = 1.346	F1 = 0.673	F1 = 0.336	F1 = 0.168
S = 48000 Hz	F1 = 5.859	F1 = 2.930	F1 = 1.465	F1 = 0.732	F1 = 0.366	F1 = 0.183
S = 96000 Hz	F1 = 11.719	F1 = 5.859	F1 = 2.930	F1 = 1.465	F1 = 0.732	F1 = 0.366
S = 192000 Hz	F1 = 23.438	F1 = 11.719	F1 = 5.859	F1 = 2.930	F1 = 1.465	F1 = 0.732

Display Window Frequency Range

Let's compare data point density at lower end of the frequency range for two SPL display screen frequency ranges settable from Preferences screen.

Frequency range 5Hz – 100000Hz

F0=5.07	F30=7.53	F60=11.19	F90=16.63	F120=24.71	F150=36.72	F180=54.57	F210=81.10
F1=5.13	F31=7.63	F61=11.34	F91=16.85	F121=25.04	F151=37.21	F181=55.30	F211=82.17
F2=5.20	F32=7.73	F62=11.49	F92=17.07	F122=25.37	F152=37.70	F182=56.03	F212=83.27
F3=5.27	F33=7.83	F63=11.64	F93=17.30	F123=25.71	F153=38.20	F183=56.78	F213=84.37
F4=5.34	F34=7.94	F64=11.80	F94=17.53	F124=26.05	F154=38.71	F184=57.53	F214=85.49
F5=5.41	F35=8.04	F65=11.95	F95=17.76	F125=26.40	F155=39.23	F185=58.29	F215=86.63
F6=5.48	F36=8.15	F66=12.11	F96=18.00	F126=26.75	F156=39.75	F186=59.07	F216=87.78
F7=5.56	F37=8.26	F67=12.27	F97=18.24	F127=27.10	F157=40.28	F187=59.85	F217=88.95
F8=5.63	F38=8.37	F68=12.44	F98=18.48	F128=27.46	F158=40.81	F188=60.65	F218=90.13
F9=5.71	F39=8.48	F69=12.60	F99=18.73	F129=27.83	F159=41.35	F189=61.46	F219=91.33
F10=5.78	F40=8.59	F70=12.77	F100=18.97	F130=28.20	F160=41.90	F190=62.27	F220=92.54
F11=5.86	F41=8.71	F71=12.94	F101=19.23	F131=28.57	F161=42.46	F191=63.10	F221=93.77
F12=5.94	F42=8.82	F72=13.11	F102=19.48	F132=28.95	F162=43.03	F192=63.94	F222=95.02
F13=6.02	F43=8.94	F73=13.28	F103=19.74	F133=29.34	F163=43.60	F193=64.79	F223=96.28
F14=6.10	F44=9.06	F74=13.46	F104=20.00	F134=29.73	F164=44.18	F194=65.65	F224=97.56
F15=6.18	F45=9.18	F75=13.64	F105=20.27	F135=30.12	F165=44.76	F195=66.52	F225=98.86
F16=6.26	F46=9.30	F76=13.82	F106=20.54	F136=30.52	F166=45.36	F196=67.41	F226=100.17
F17=6.34	F47=9.42	F77=14.00	F107=20.81	F137=30.93	F167=45.96	F197=68.30	F227=101.50
F18=6.43	F48=9.55	F78=14.19	F108=21.09	F138=31.34	F168=46.57	F198=69.21	F228=102.85
F19=6.51	F49=9.68	F79=14.38	F109=21.37	F139=31.76	F169=47.19	F199=70.13	F229=104.22
F20=6.60	F50=9.80	F80=14.57	F110=21.65	F140=32.18	F170=47.82	F200=71.06	F230=105.61
F21=6.69	F51=9.94	F81=14.76	F111=21.94	F141=32.61	F171=48.46	F201=72.01	F231=107.01
F22=6.77	F52=10.07	F82=14.96	F112=22.23	F142=33.04	F172=49.10	F202=72.97	F232=108.43
F23=6.86	F53=10.20	F83=15.16	F113=22.53	F143=33.48	F173=49.75	F203=73.94	F233=109.87
F24=6.96	F54=10.34	F84=15.36	F114=22.83	F144=33.92	F174=50.41	F204=74.92	F234=111.33
F25=7.05	F55=10.47	F85=15.57	F115=23.13	F145=34.37	F175=51.08	F205=75.91	F235=112.81
F26=7.14	F56=10.61	F86=15.77	F116=23.44	F146=34.83	F176=51.76	F206=76.92	F236=114.31
F27=7.24	F57=10.75	F87=15.98	F117=23.75	F147=35.29	F177=52.45	F207=77.95	F237=115.83
F28=7.33	F58=10.90	F88=16.19	F118=24.07	F148=35.76	F178=53.15	F208=78.98	F238=117.37
F29=7.43	F59=11.04	F89=16.41	F119=24.39	F149=36.24	F179=53.85	F209=80.03	F239=118.93

There are 52 frequency bins between 15Hz to 30Hz.

Frequency range 5Hz – 5000Hz

F0=5.05	F30=6.65	F60=8.77	F90=11.56	F120=15.24	F150=20.09	F180=26.48	F210=34.91
F1=5.09	F31=6.71	F61=8.85	F91=11.67	F121=15.38	F151=20.28	F181=26.73	F211=35.23
F2=5.14	F32=6.78	F62=8.93	F92=11.78	F122=15.52	F152=20.46	F182=26.98	F212=35.56
F3=5.19	F33=6.84	F63=9.02	F93=11.88	F123=15.67	F153=20.65	F183=27.23	F213=35.89
F4=5.24	F34=6.90	F64=9.10	F94=11.99	F124=15.81	F154=20.84	F184=27.48	F214=36.22
F5=5.28	F35=6.97	F65=9.18	F95=12.11	F125=15.96	F155=21.04	F185=27.73	F215=36.56
F6=5.33	F36=7.03	F66=9.27	F96=12.22	F126=16.11	F156=21.23	F186=27.99	F216=36.90
F7=5.38	F37=7.10	F67=9.35	F97=12.33	F127=16.25	F157=21.43	F187=28.25	F217=37.24
F8=5.43	F38=7.16	F68=9.44	F98=12.44	F128=16.40	F158=21.63	F188=28.51	F218=37.58
F9=5.48	F39=7.23	F69=9.53	F99=12.56	F129=16.56	F159=21.83	F189=28.77	F219=37.93
F10=5.53	F40=7.29	F70=9.62	F100=12.68	F130=16.71	F160=22.03	F190=29.04	F220=38.28
F11=5.58	F41=7.36	F71=9.70	F101=12.79	F131=16.86	F161=22.23	F191=29.31	F221=38.63
F12=5.64	F42=7.43	F72=9.79	F102=12.91	F132=17.02	F162=22.44	F192=29.58	F222=38.99
F13=5.69	F43=7.50	F73=9.88	F103=13.03	F133=17.18	F163=22.64	F193=29.85	F223=39.35
F14=5.74	F44=7.57	F74=9.98	F104=13.15	F134=17.34	F164=22.85	F194=30.13	F224=39.72
F15=5.79	F45=7.64	F75=10.07	F105=13.27	F135=17.50	F165=23.07	F195=30.41	F225=40.08
F16=5.85	F46=7.71	F76=10.16	F106=13.40	F136=17.66	F166=23.28	F196=30.69	F226=40.46
F17=5.90	F47=7.78	F77=10.26	F107=13.52	F137=17.82	F167=23.49	F197=30.97	F227=40.83
F18=5.96	F48=7.85	F78=10.35	F108=13.64	F138=17.99	F168=23.71	F198=31.26	F228=41.21
F19=6.01	F49=7.92	F79=10.45	F109=13.77	F139=18.15	F169=23.93	F199=31.55	F229=41.59
F20=6.07	F50=8.00	F80=10.54	F110=13.90	F140=18.32	F170=24.15	F200=31.84	F230=41.97
F21=6.12	F51=8.07	F81=10.64	F111=14.03	F141=18.49	F171=24.38	F201=32.13	F231=42.36
F22=6.18	F52=8.15	F82=10.74	F112=14.16	F142=18.66	F172=24.60	F202=32.43	F232=42.75
F23=6.24	F53=8.22	F83=10.84	F113=14.29	F143=18.84	F173=24.83	F203=32.73	F233=43.15
F24=6.29	F54=8.30	F84=10.94	F114=14.42	F144=19.01	F174=25.06	F204=33.03	F234=43.55
F25=6.35	F55=8.37	F85=11.04	F115=14.55	F145=19.19	F175=25.29	F205=33.34	F235=43.95
F26=6.41	F56=8.45	F86=11.14	F116=14.69	F146=19.36	F176=25.53	F206=33.65	F236=44.36
F27=6.47	F57=8.53	F87=11.25	F117=14.82	F147=19.54	F177=25.76	F207=33.96	F237=44.77
F28=6.53	F58=8.61	F88=11.35	F118=14.96	F148=19.72	F178=26.00	F208=34.27	F238=45.18
F29=6.59	F59=8.69	F89=11.45	F119=15.10	F149=19.91	F179=26.24	F209=34.59	F239=45.60

There are 75 frequency bins between 15Hz to 30Hz.

It is observable, that for TS parameters estimation, one should select lower end of the frequency range. This will result in more data point on the Log scale in the frequency range, where we expect to work on our data.

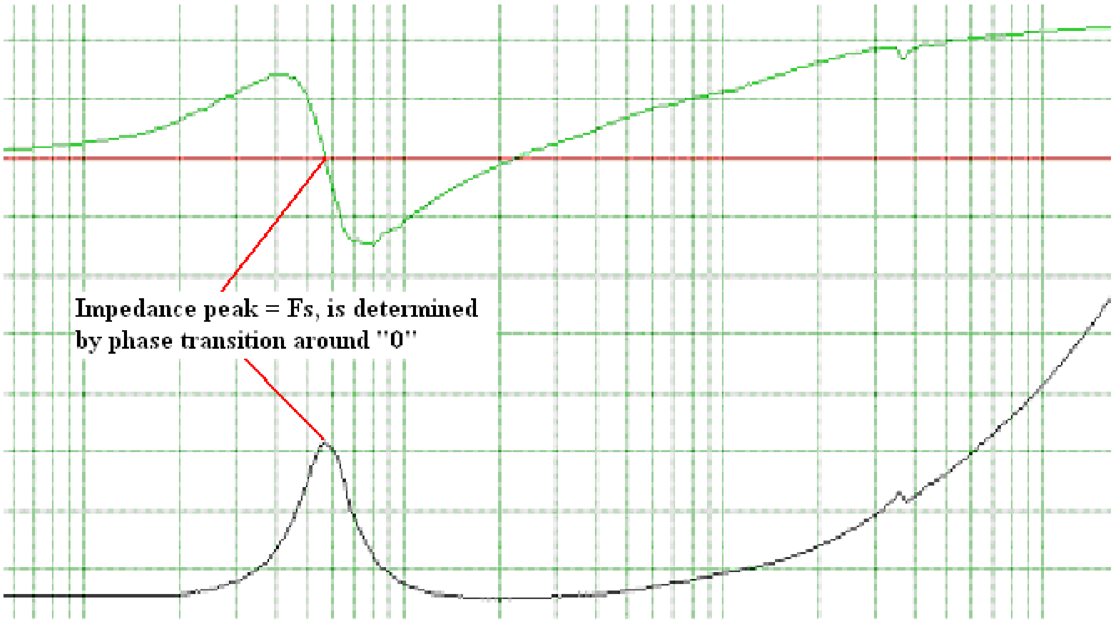
Some Comments on TS Algorithm

Here is some insights in the “inner works” of the TS parameters extraction algorithm. The algorithm starts with calculating Qms.

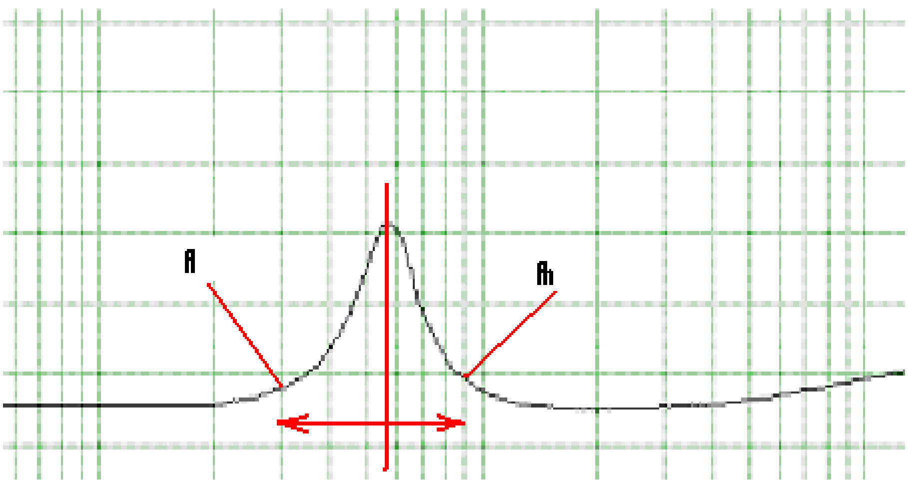
$$Q_{ms} = \frac{F_s * \sqrt{R_c}}{f_h - f_l} \qquad R_c = \frac{R_e + R_{es}}{R_e}$$

All the above variables are estimated from the Zin curve.

Fs is determined as the phase response transition point around zero.
Res is determined as the Zin value at phase response transition point around zero.
Re is either given by the data sheet or measured. Can be estimated from the impedance curve as well.



Fh and fl are estimated from Zin curve. The algorithm searches for fh and fl starting from Fs. The fh is the first frequency bin for which Zin < sqrt(Rc) when moving to the right. The fl is the first frequency bin for which Zin < sqrt(Rc) when moving to the left. As you can see, there will be a tendency to estimate bandwidth (fh – fl) as marginally wider.



This will typically result in Qms marginally lower, and perhaps Qes also marginally lower as well.

$$Q_{es} = \frac{Q_{ms}}{R_c - 1}$$

The resonant peak of the example driver above is not particularly high. Typically, the peak will be much higher for high Qms drivers. For example, the impedance may drop from it's peak value of 90ohms to 15 ohm over 34 frequency points. This will yield 2.2ohm/frequency bin of difference in Zin. This example illustrates the difficulty of estimating Rc / fh / fl for high Qm drivers. Fortunately, the slopes are usually less steep already, in the frequency range where fh and fl are located.

Frequency Points Mapping

Both, MLS and FFT processes run with the same fixed size frequency steps. Another way to put it is: MLS/FFT use linear frequency scale. On the other hand, we are used to display the results in Log-Log scale, so that linear frequency scale data points are being mapped onto Log scale, as there is no one-to-one relationship between those two scales. Mapping involves extrapolations, or picking frequency points of one scale as close to the frequency point of the other scale.

For instance, let’s assume MLS/FFT frequency resolution to be 0.183Hz. Then take 100’th bin, so this will result in 100x0.183Hz = 18.3Hz on the linear scale.

Now, if you use 5-100000Hz scale – the closest frequency bin is 18.48Hz, which will result in 0.18Hz mapping error.

However, if you use 5-5000Hz scale – the closest frequency bin is 18.32Hz, which will result in 0.02Hz mapping error.

Not every single data point mapping works to the advantage of narrower frequency range, but in general, you will reduce the error selecting denser frequency scale.

External Noise / Vibrations

MLS is essentially an LTI (Linear Time Invariant) process. This requires, that the measurement conditions must absolutely not change from start to finish of the measurement cycle. For instance, it would be risky to place the driver on it’s magnet side on the same desk as you desktop PC. The speaker may pick up vibrations of the PC’s cooling fan. Or a washing machine working two rooms away.

Generally, securing proper measurement environment is not a trivial task.

Setup Errors

Some of the setup issues affecting measurement accuracy may include poor quality reference resistor, R. This component has a great effect on the overall accuract of the measurement, and should be selected for low tolerance values, say 1-2%. You really need to know what is the actual value of this resistor, so measure it if you can. Loudspeaker impedance is measured using "Voltage Divider" method with two probes.

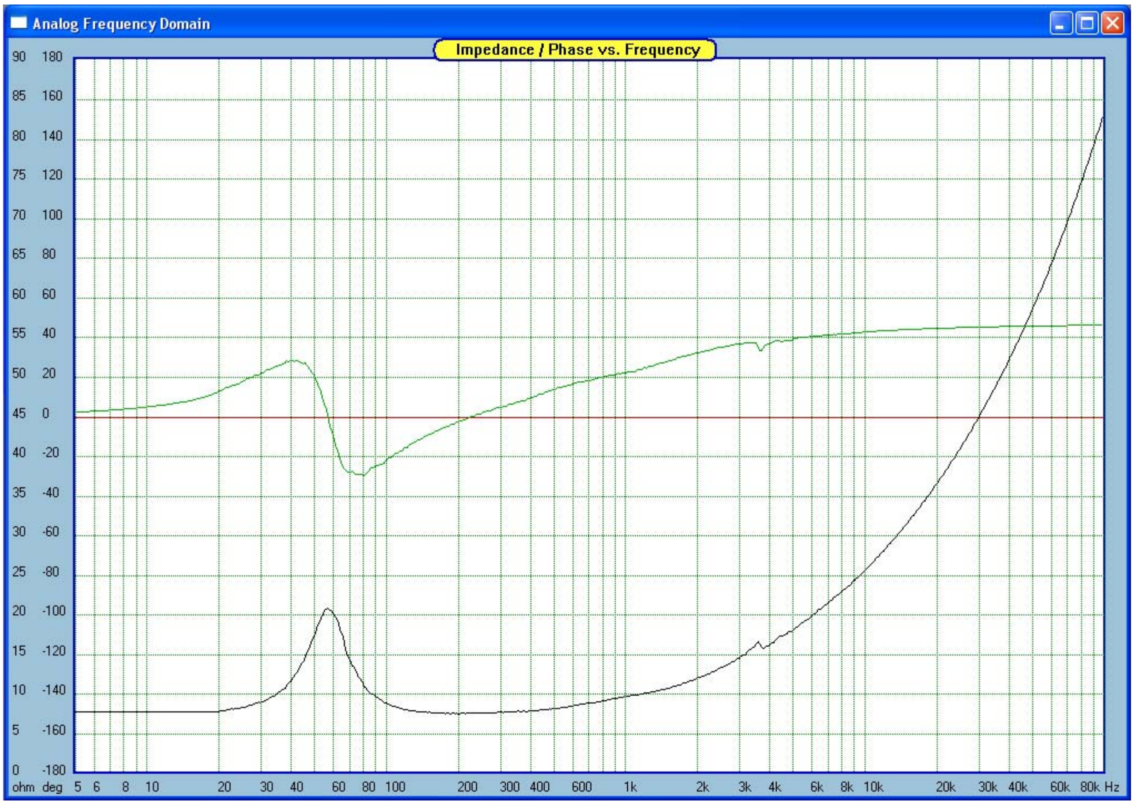
$$Z = R * \frac{k}{1-k} \quad k = \frac{V_2}{V_1}$$

k is a complex value.

V1 is the output voltage into the R/Z divider (Probe 1) and V2 is the voltage across Z (Probe 2).

Another problem may arise from running long, shielded cables with high capacitance to the ground. You need to be also aware of the effects of any pre-amplifiers, **mismatched probes** and so on, that these components have on the overall measurement accuracy.

Finally, please make sure, you are taking full advantage of the dynamic range of the sound card. It is recommended, to have Ref signal always at full input swing.



It is impossible to predict all variations of setup errors. Therefore, you should use figure above as a guidance. It is a very good example of what a typical electro-dynamic driver's input impedance curve should look like. Please note, that phase response (green curve) <u>always rises and approaches 45deg</u> moving towards high end of the frequency range. Also, magnitude of the impedance (black curve) has a distinctive resonant peak and then <u>always rises towards</u> higher frequencies.

If your measured impedance curves fails to exhibit these characteristics, then you need to start de-bugging your setup.

Driver Burn-in

There is some interesting information on http://www.gr-research.com/burnin.shtm

"*The spider is a piece of cloth, permanent pressed, and dipped in epoxy. When you break in a driver, you introduce micro-cracks throughout the epoxy, which will make the spider softer. All mechanical systems will wear and all mechanical springs will get softer; in this case, it's by design. You break/crack a lot of the epoxy bonds (phenolics are used as well) that permeate the spider, and thus it becomes softer.*
We often see a 20% drop in Fs over a lengthy break-in, and we quote numbers for drivers broken in. Out of the box all our drivers measure high; beat on them for 40-50 hours, though, and they will be permanently lowered (Fs, that is). One thing to note is that it would be expected Fs would drop, Qes and Qts would drop, and Vas would

increase; all these are exactly what happens when you raise Cms, which is the same thing as making the spider softer."

For instance, Driver with the original measurements:
Fs = 56.9Hz, Qms = 2.4, Qes=0.358, after 20-hour burn-in, showed:

Fs=50.47Hz, Qms=2.06, and Qes=0.314.

<u>Please make sure, you take the above into account, as manufacturers typically specify TS parameters after burn-in.</u>

Properties Of The Sound Card

Some of the sound cards available on the market are equipped with single, multiplexing DAC/ADC. These type of cards introduce inherent delay into one channel. You can easily determine, if your DACs are multiplexing, buy running loop test, described in the reference manual. If your card is multiplexing, you will need to compensate for this by adding/subtracting one sample time in the Pulse Delay data entry, so that the phase response during the loop test is perfectly flat.

Another issue to check is maximum input voltage range, so that you would not overdrive the sound card.

Size Of Window

Windowing technique is typically employed for SPL measurement in reflecting environment. However, input impedance measurements are well separated from the acoustical environment, therefore windows are not critical to use at all.

In fact, short, poorly chosen windows affect the impedance peak quite severely. This leads to errors in estimating Rc, and consequently errors in estimating Qms and Qes.

One way you could check if your window in not affecting the measurements, is to start with window of similar length as the MLS, eg for MLS=262143, use Window Length = 260000. You should see no visible changes to the impedance curve. Then try to shorten the window 230000, then 200000 and so on…. At some point you may notice that the impedance curve looks a little "smoother", but does not change in shape. This would be the shortest window to be used for this particular measurement.