PA Loudspeaker System Design Using Multiphysics Simulation

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Abstract: This paper intent is to describe how to utilize COMSOL for the design of a PA system loudspeaker for the optimization of geometries and crossover topology with the idea of controlling sound directivity over a wide spectrum including minimizing side lobes due to the often overseen time/phase signal interaction between woofer and tweeter. Often in the design there's a focus on the on-axis frequency response, and for ceiling PA system speakers it is often the least utilized listening position. The use of simulation helps the analysis of the spatial response right in the computer, while the traditional process of prototyping and measurements on multiple points necessary for the polar response/balloon/DI/ or SPL vs frequency/angle plots is extremely time consuming.

Keywords: Lumped Parameters, Acoustical Simulation, crossover.

1. Introduction

A full range loudspeaker intended for Public Address use (PA) has, beside the common delivery of musical content, the responsibility do provide clear announcements to the public. Unlike sound reproduction in a room for personal use, PA speakers need to maintain speech intelligibility over a wide area and often used in conjunction with multiple units to cover workplaces, lobbies shopping malls. In this specific case the design of a ceiling speaker is taken in consideration to display the practical application of COMSOL to the investigation of the design in order to be optimized.

1.1 Disclaimer

The graphs and geometries represented in this paper are not representative of the end product developed at QSC, they are used to show a design approach used with the aid of COMSOL capabilities.

1.2 System description

The PA loudspeaker system will convert the electrical signal from a high-impedance/high-voltage (the so called 70V and 100V lines, which are coming from an amplifier impedance matched with a step up transformer to attain a maximum of 70 or 100 Vrms at full power) to a better matching power with its drivers that would be of a nominal 16Ohms with the use of a variable output step down transformer; although it could be part of this paper as the transformer introduces distortion and changes the frequency response would be interesting to simulate, it will not be considered in the simulation.

The next component is fundamental as it splits the signal between woofer (low audio frequency reproducing transducer) and tweeter (high audio frequency reproducing transducer), the crossover, because it is constituted of passive electrical elements, the AC/DC module in COMSOL takes care of the simulation of this components fully in the electrical domain.

There two transducers are facing the open space placed coaxially and the woofer rear is in the enclosure that contains the transformer, crossover and the "vent" (that is the opening of the Helmholtz resonator that also faces the open space). The enclosure fits in the ceiling baffle leaving only the round appearance of the PA speaker (see fig. 1).

1.3 Model Simplification of the system

The woofer and tweeter are simplified with the use of lumped circuit equivalent parameters[1] in this way the passage from the electrical domain to the mechanical gets interfaced to the acoustical domain with the use of passive electrical elements that can be easily simulated in behavior with the AC/DC module with the approximation of small perturbing signals to the transducer (the so called Thiele/Small parameters[2]). The enclosure and the vent are included in the acoustical domain together with part of the transducers geometries as they do affect the acoustic response.

2. Model

Given the typical geometry of the PA speaker its elements were simplified and built as an axisymmetric model, an outer PML domain, an air domain with a border to extrapolate the far field, an “infinite” baffle, a waveguide for the tweeter and diaphragms based on the woofer’s cone and dust cap and the tweeter geometry, the plastic baffle that holds them together and the motors space. The enclosure and vent were included to attain the same volume as the enclosure and the same vent surface area.

The AC/DC module takes care of the simulation of the circuit equivalents where from a generator that sets the voltage at which the system is driven it then handles the filter section to speaker equivalent to then calculate the velocity of the respective diaphragms of woofer and tweeter. This velocity at the frequency in analysis is then applied to the diaphragms in the Pressure Acoustic, frequency domain from which is possible to extrapolate far field information to build graphs like sensitivity, polar graphs, impedance, etc. by setting a sweep.

3. Use of COMSOL Multiphysics

For the analysis the AC/DC Module, and the Acoustic Module, in the specific Electrical Circuit and Pressure Acoustics are used.

The parameter section includes a limit of the frequency in consideration during the study as this is passed to size the mesh so that it is refined proportionally to the frequency range and save computational times i.e. if it’s just a run to observe woofer’s behavior. At this stage are also passed the Thiele/Small parameters. Similarly, Variables that define Voice Coil Inductance, Diaphragm velocity, force, SPL Geometry is simply imported from a 2d CAD software and only Air is used as material.

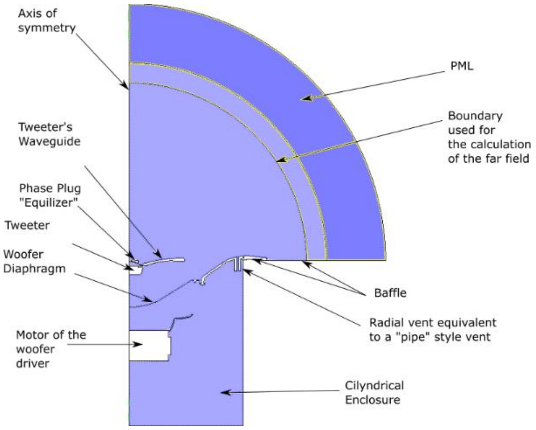


Figure 1. The PA speaker model.

The domains are meshed with triangular elements and mapped PML with a size that allows at least four elements per wavelength.

In the study section both, Electrical Circuits and Pressure Acoustics are solved and detailed results give guidance for improvements with the opportunity of investigation over the cause of eventual unwanted behavior, i.e. the below figure occurred during some iterations in the design where resonance were perturbing the frequency response in a very important area for speech intelligibility (yellow highlight).

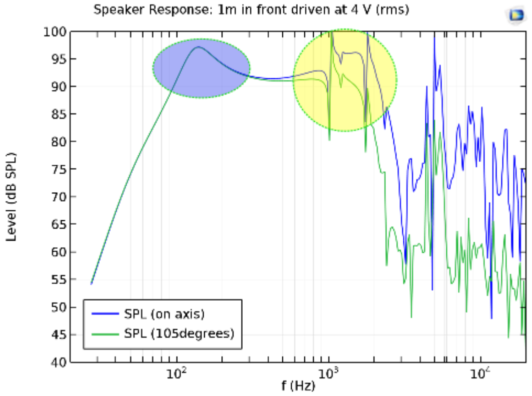


Figure 2. SPL printout showing resonances

With the aid of the display of the SPL intensity in the enclosure the nature of the resonances were clear and actions were taken to eliminate them.

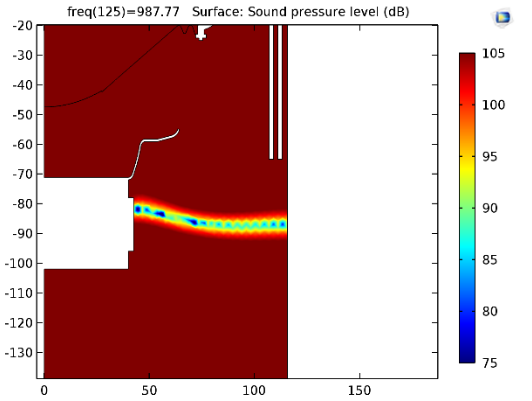


Figure 3. Standing wave at quarter wavelength

Figure 2 is also showing an improper tuning of the vents where the resonant frequency of the Helmholtz resonator constituted by the enclosure volume and the vent boosts the low frequency response aligning with it in with a high Q similarly to what is called a Chebyshev response in filter theory, not that it is something "bad," but somewhat like a Butterworth alignment was indicated as favorable for this application.

Again COMSOL can help greatly, especially in the case of vents that are of a geometry that is not possible of simple geometries like pipes, slits, square or triangular ducts. As an example, if the target frequency for the resonance is known and the optimization module is available then it is possible to have the dimensions of the port as a parameter in the optimization routine and target the drop of the diaphragm velocity in the optimization search. In fact, data that would require measurement of the impedance to say the least, if not a laser measurement of the displacement of the woofer diaphragm in a prototype to understand the tuning is available among the results of the simulation as shown below.

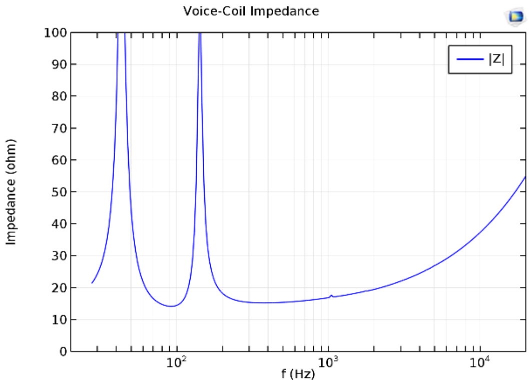


Figure 4. Woofer impedance in the vented enclosure

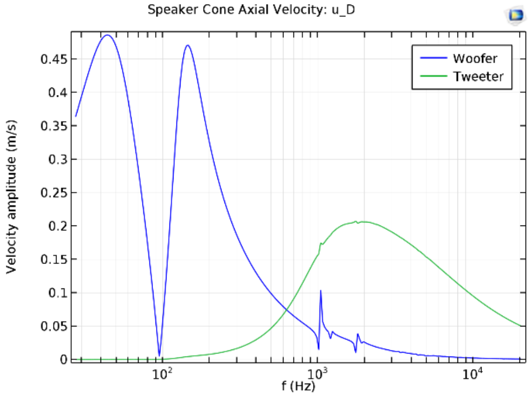


Figure 5. Diaphragms velocity

Surely other software that uses lumped circuit equivalents is able to derive such by "spicing" up simplified models of almost any kind of electroacoustic device, but COMSOL has the advantage of flexibility to handle multiphysics problems, detail in the representation of the model and results. Another example in that regard: during the design of the waveguide the frequency response of the tweeter had dips (fig.6) and the analysis of the behavior of the waveguide showed an interaction with actually the back of the waveguide at this frequency (fig.7).

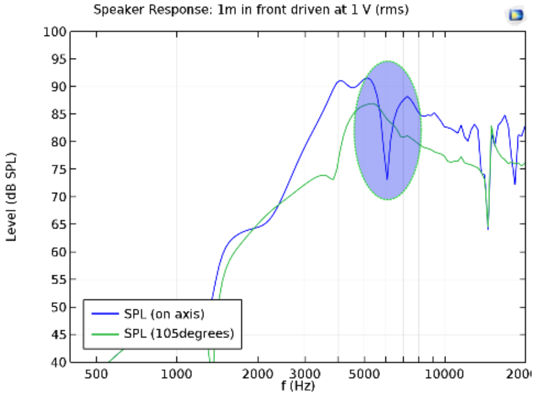


Figure 6. Simulated Tweeter frequency response

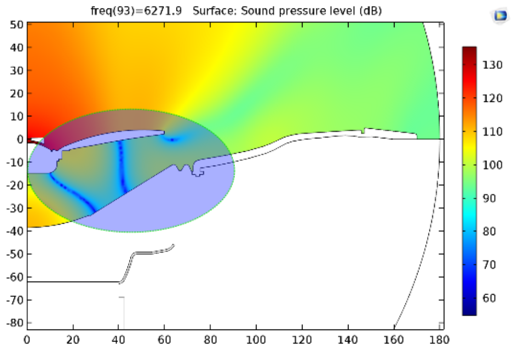


Figure 7. SPL at 6270Hz where the dip in frequency response occurs

It is possible with COMSOL to try several iterations with different geometries and the effects on the reduction of the cancellation at the back of the waveguide. What it would take months in terms of prototyping and guesswork can now be guided towards the desired results so that an "eccentric" but feasible geometry like figure 8 can achieve that by playing tricks like blocking and weakening pressure waves.

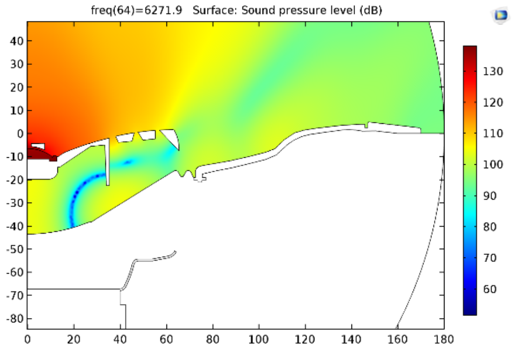


Figure 8. SPL at 6270Hz with a different geometry

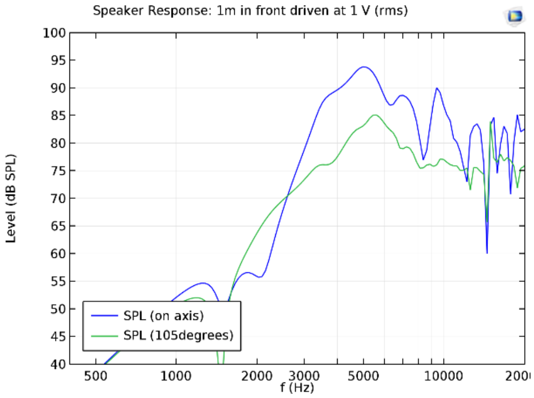


Figure 9. Frequency response with geometry from figure 8

5. Important considerations for PA speakers

Although from the above figures there's now a dip in the frequency response above 8 kHz, in terms of speech intelligibility the improvement on 6 KHz outweighs it. Another consideration is the fact that without the use of microphones, multiple measurements etc. there's the availability of observing the frequency response out of axis which, as mentioned in the introduction is fundamental in the design of PA loudspeakers.

Very often in fact contractors/installers look at different graphs then what the general public might understand as a good looking spec. for a speaker. Polar plots, those include directivity index plots, or the colorful "balloon" plot, or an SPL vs frequency/angle plot, the beauty is that all this information can be seen in the simulated model ahead of time without involvement with microphones and anechoic chambers and expensive cost in resources.

As an example, the following figures show the change in polar response between the tweeters in two models shown in figure 7 and figure 8 at 6270Hz where dip happens in the first geometry.

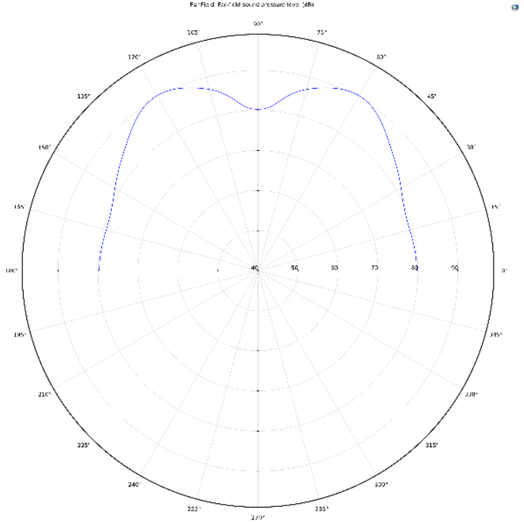


Figure 10. Polar plot 6270Hz geometry from figure 7

And then the polar for an improved version geometry that addresses that problem on the next page.

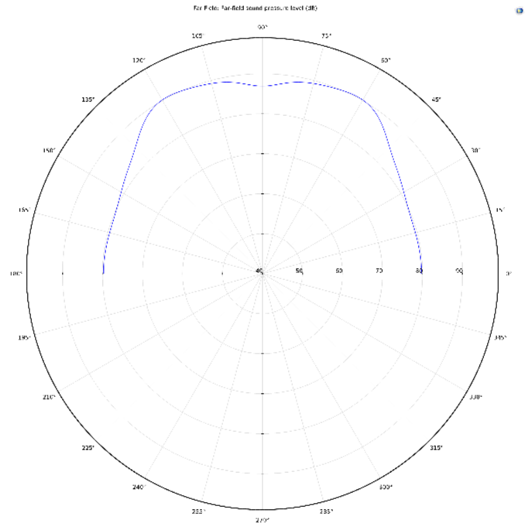


Figure 11. SPL at 6270Hz with figure 8 geometry

And below the same for a representation of the angle in the respect of the on axis response starting at minus 90 degrees position and going towards the other side of the baffle in an arc at a virtual 1 meter distance, this for a spectrum going from 440Hz to 20kHz. The SPL is represented with a range of color gradients intensities.

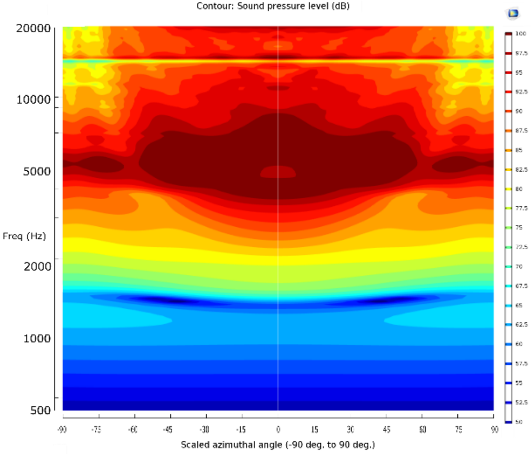


Figure 12. SPL map figure 7 geometry

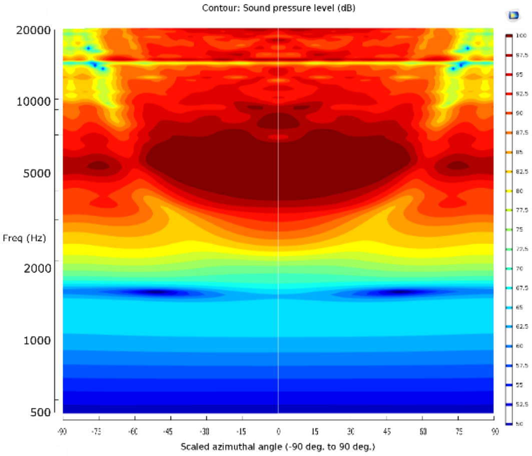


Figure 11. SPL map with improved geometry

Continuing with the crossover, this also has a very important role for PA speakers as it controls the interaction between the two transducers at a spectrum that is usually a fundamental range for speech intelligibility. In this case COMSOL gives space to experimentation and choice, for example a woofer response with a second order Bessel low pass filter at 600Hz.

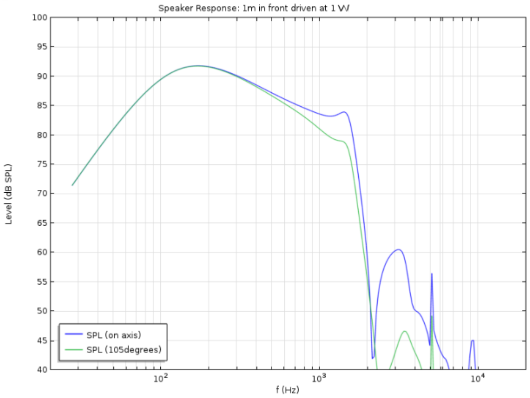


Figure 12. Woofer with a low pass filter applied

Or with a few clicks away a different woofer with a different crossover type.

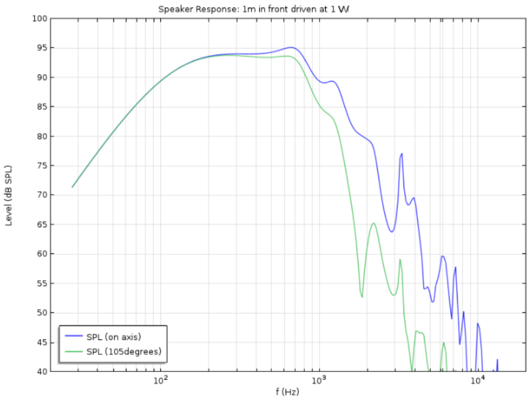


Figure 13. Different woofer a low pass filter applied

Naturally the same thing goes for the tweeter or their interaction together. So if place the tweeter with its crossover to the configuration in figure 13 we can see the outcome in figure 14.

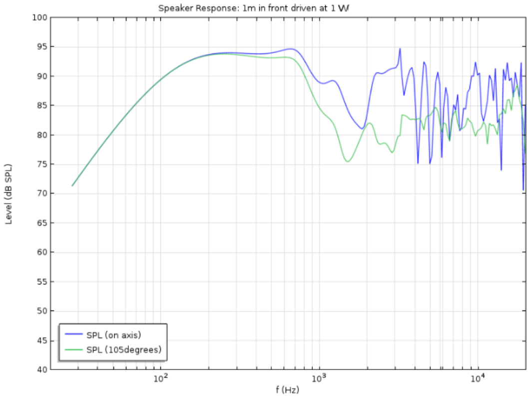


Figure 14. Woofer and tweeter response

Often when designing crossovers empirically we invert the tweeter polarity to see if the phase shift introduced by the passive components is such that with a 180 degree shift on tweeter they sum better. This is as easily as done in COMSOL by changing the sign of the velocity of the tweeter diaphragm.

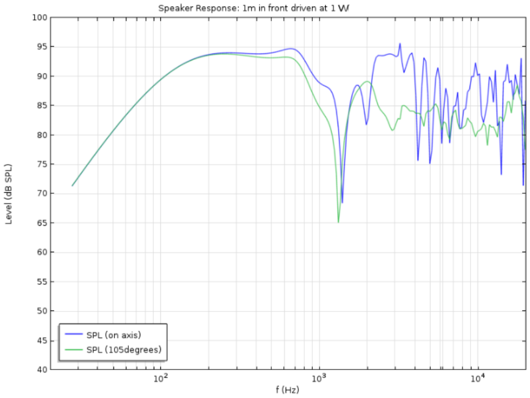


Figure 14. Woofer and inverted tweeter response

If the outcome is worse than that option is easily discarded. With several iterations it will be possible to attain a better overall response by changing components and geometries

6. Calculations

The circuit used are very similar between woofer and tweeter, the tweeter has extra components as to adjust the level with the woofer and at the crossover stage and the back chamber included as an air mass and compliance in the circuitry as if it was an enclosure.

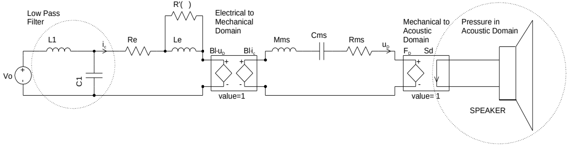


Figure 15. Woofer's circuit [ref. 3]

From this circuit is easy to extrapolate from the voltage at C1 the transfer function of the filter.

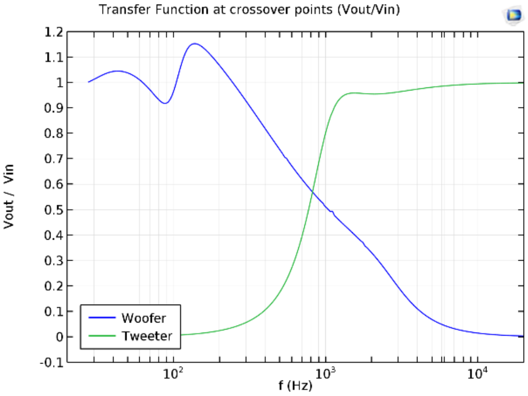


Figure 16. Transfer Function

The differential equations that COMSOL uses in solving the model is a inhomogeneous Helmholtz equation in the form

$$\nabla \cdot \left(-\frac{1}{\rho_c} (\nabla p_t - \mathrm{q}_d) \right) - \frac{k_{\mathrm{eq}}^2 p_t}{\rho_c} = \mathrm{Q}_m$$

where ρ_c will be the density of "air" in this case, $p_t = p + p_b$ the total pressure as the superimposition with the background pressure p_b, q_d is the dipole source (a body force with dimensions of N/m^3) and Q_m is the monopole source (mass injection equivalent with dimensions of s^{-2}), finally the wave number (m^{-1}) $k_{\mathrm{eq}}^2 = \left(\frac{\omega}{c_c}\right)^2 - \left(\frac{m}{r}\right)^2$. In the latter, m is the circumferential wave number that for axisymmetric cases is 0.

Reference pressure for SPL is 20µPa and speed of sound is set at 343 m/s.

7. Reality check

It is paramount to assure that the direction that the simulation of the models during the work in progress do not put us in the wrong direction.

The below is a measurement of a sample of the tweeter in the PA speaker with the waveguide, and the simulated response of the same design.

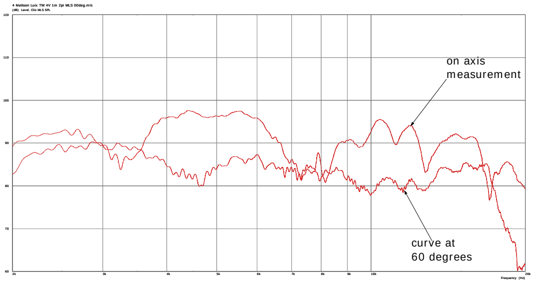


Figure 17. Tweeter response prototype (measured)

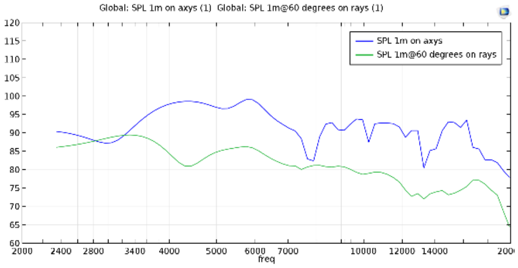


Figure 18. Tweeter response prototype (simulated)

8. Conclusions

It is possible, given the flexibility of COMSOL just with AC/DC and Acoustical to do a wide spectrum of considerations that are involved with the design of PA loudspeakers, basically almost all aspects (especially if the Mechanical license is available then even the nonlinear and modal behavior can be studied). Prototyping gets limited to few pieces while the amount of trials can go to a couple of dozen versions in matter of weeks, and given how much cheaper processing power has gotten, it is well worth investing as then otherwise analysis time becomes the bottleneck, yet still probably faster as prototype takes, when fully measured, at least two days even with in house FDM!

9. References

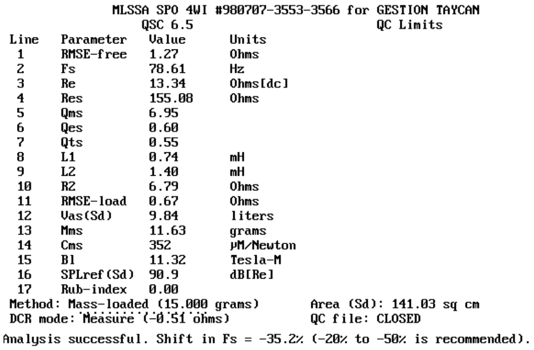
1. L. L. Beranek, *Acoustics*, the Acoustical Society of America (1993)
2. A. N. Thiele, Loudspeaker in Vented Boxes Part I, part II, *Journal of the Audio Engineering Society*, (May-June 1971)
3. COMSOL, *Lumped Loudspeaker Driver*, **Application Library** (2014)
4. M. Kleiner, *Electroacoustics*, CRC Press (2013)

10. Acknowledgements

I would like to thank the management of QSC for investing in COMSOL and supporting the participation to the conference which lead to this paper.

11. Appendix

Table 1: Example of Thiele/Small parameters for a woofer



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  1     RMSE-free  1.27       Ohms
  2     Fs         78.61      Hz
  3     Re         13.34      Ohms[dc]
  4     Res        155.08     Ohms
  5     Qms        6.95
  6     Qes        0.60
  7     Qts        0.55
  8     L1         0.74       mH
  9     L2         1.40       mH
  10    R2         6.79       Ohms
  11    RMSE-load  0.67       Ohms
  12    Vas(Sd)    9.84       liters
  13    Mms        11.63      grams
  14    Cms        352        µM/Newton
  15    Bl         11.32      Tesla-M
  16    SPLref(Sd) 90.9       dB[Re]
  17    Rub-index  0.00
 Method: Mass-loaded (15.000 grams)       Area (Sd): 141.03 sq cm
 DCR mode: Measure (-0.51 ohms)           QC file: CLOSED
Analysis successful. Shift in Fs = -35.2% (-20% to -50% is recommended).
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