On the Directional Response of Multi-Driver Column Loudspeaker Configurations Using FEA and BEM

R. Balistreri

Klipsch Group, Inc, Indianapolis, IN, USA

Abstract: Column loudspeakers employ multiple drivers to get close to a radiating line source. A line source has several acoustic advantages over a point source, especially in highly reverberant environments. This property makes column loudspeakers the preferred solution in houses of worship, airports and large environments. Yet, being a Public Address (PA) application, sound quality of existing products is often inadequate to excellent music reproduction. Here, the exploration of a design suitable for home theater sound, but for bigger and untreated environments arises. This paper is a comparative study between a basic column design and a computer optimized configuration of transducer drivers' quantity, geometry and distance among them. Also, crossovers considerations, network delay in the system, etc., to control directivity, further retaining music reproduction quality as per Klipsch intent. An illustration of the model within COMSOL Multiphysics® is provided. The use of modules is reviewed for the electrical, magnetics, and moving parts components of the drivers. Moreover, for the acoustics in the cabinet and far field, the use of both Finite Element Analysis (FEA) and Boundary Element Analysis (BEM) is detailed.

1. Introduction

Consider a point source in an open sound field. Its radiation pattern is omnidirectional and will propagate as a sphere. By doubling the distance from the source, the reduction in sound pressure level (SPL) will follow the inverse square law registering a 6dB drop.

Introducing a second sound source aligned vertically near the first creates an interference between the pressure waves in the field. If both emit at the same frequency, the separation between them will create interference patterns dependent on the distance between the two sources in relation to the wavelength of the frequency radiated.

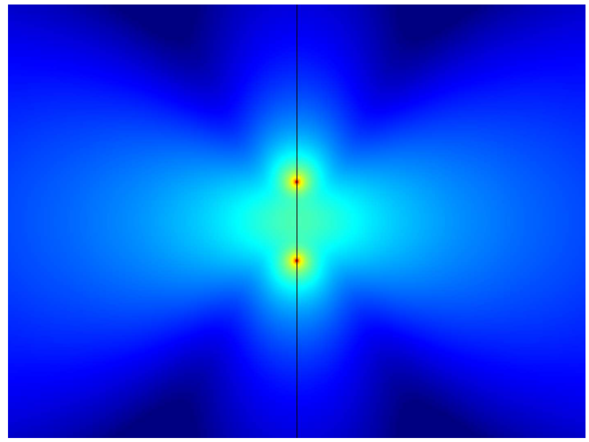

Figure 1: SPL example of two point sources

For example, if we use a source giving 100dB SPL at one meter, placing two coherent sources vertically at 200mm from each other, pressure will sum in phase on the horizontal plane at mid distance between them, producing an increase of 6dBSPL. While off that plane, the pressure waves will drop at linear intervals in frequency by the order of decades of dBs due to phase cancellation. We can approximate that once the emitted frequency's ¼ wavelength becomes of the order of the distance then this phenomenon becomes predominant. Directionality in the way sound propagates occurs after that. At the frequency where the wavelength is half the distance vertically there will be cancellation, specifically at 857.5Hz, thereof 2572.5Hz, 42875Hz, 6kHz etc., proportionally by the half wavelength.

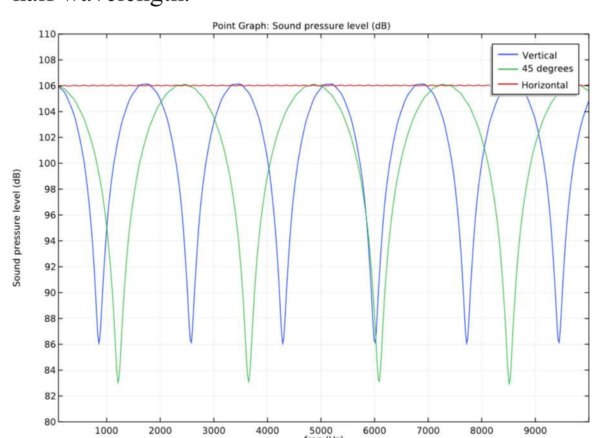

Figure 2: example of SPL response two point sources

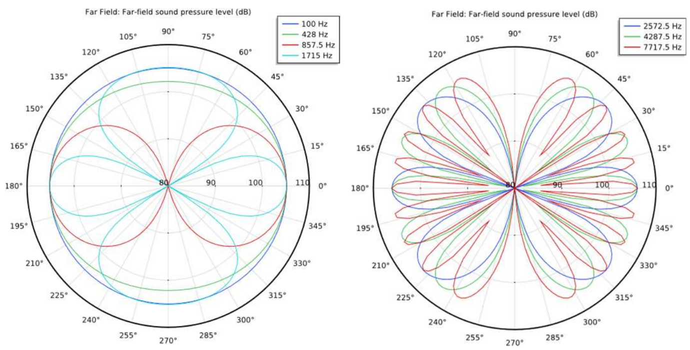

Figure 3: SPL Polar response showing lobes

By uniformly doubling the sources within the same distance we have another 6dB SPL increase. The lobing associated with the wave length now changes. The frequency at which the sound pressure distribution exhibits directionality has increased, and the overall behavior is of augmented beaming along the horizontal plane.

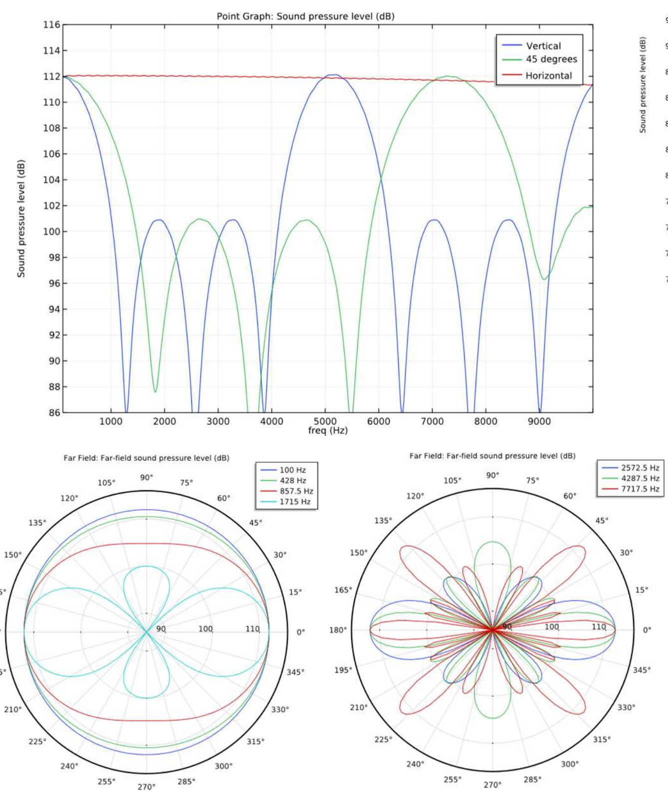

Figure 4: SPL and polar responses of four point sources

Out of curiosity, we can continue to double the sources within the 200mm, or, might as well, look at how a line source with the same power of a single point behaves.

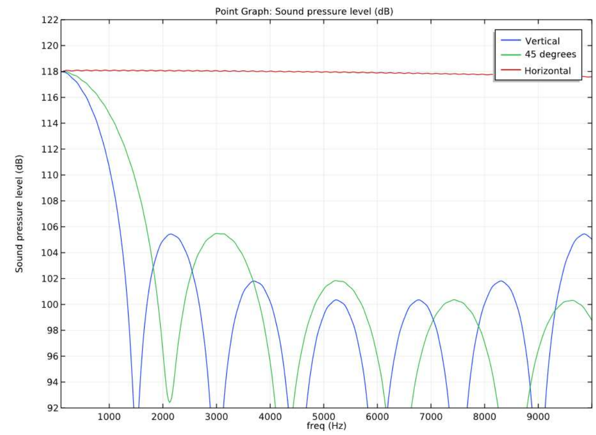

Figure 5: SPL example of eight point sources

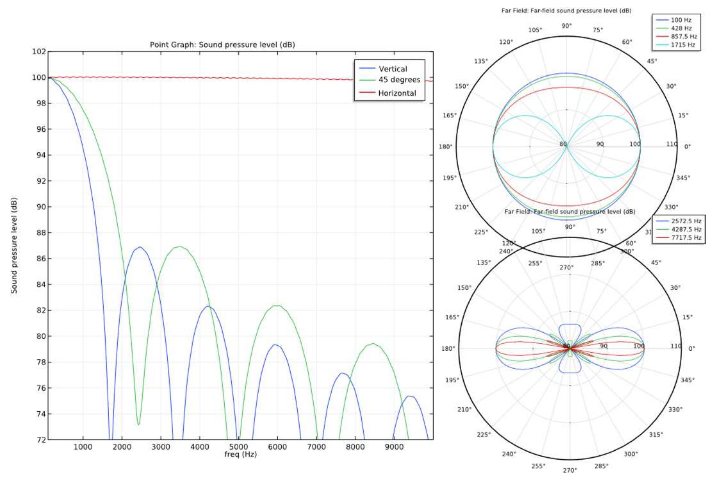

Figure 6: example of line source

It is discernible how the high frequency output around the source reduces proportionally as we go forward.

It is evident that arranging multiple sources in line alters the directivity, and the arrangement can be tweaked, giving some control to direct sound, but losses occur as the frequency increases.

In the real world, with electrodynamic transducers, things become more complex as we are not dealing with point sources. A column loudspeaker that reproduces sound with high fidelity quality would have to employ a transducer to reproduce the high frequencies. Such transducers (tweeters) are limited in low frequency output and are rarely used below a frequency of 2kHz thus requiring a crossover filter. However, this, along with the design for the high frequencies, is off the topic of this paper. We assume this study does not involve higher frequencies in the design.

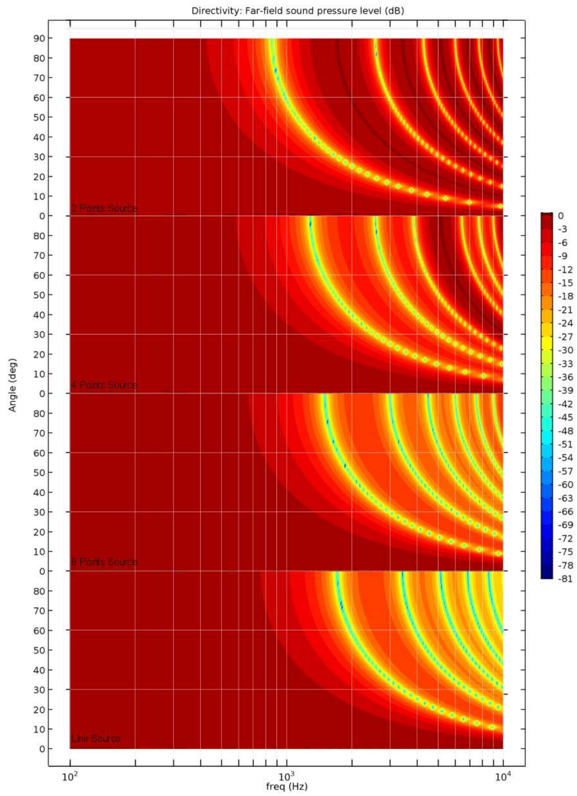

Figure 7: Directivity comparison (SPL normalized to 0°)

1.2 Column loudspeakers

Multiple loudspeaker samples to be evaluated before mass production is the norm at Klipsch. Upon completion, a colleague decided to have some fun by playing some very loud music. He had arranged speakers in stereo configured columns, while the speakers were not designed to work this way, the idea was intriguing.

Figure 8: the inspiration for the study

As seen in figure 8, with ideal sources, column loudspeakers are an appealing low-cost solution in PA loudspeakers because they achieve a certain level of directionality, optimizing speech intelligibility in highly reverberant environments like churches, airports, etc., and minimize the need for acoustic treatment. PA units are usually decent for voice and background music. But there is not many solutions available for large homes that want excellent sounding speakers.

The following steps involve optimizing the design for an eventual column loudspeaker.

2. The transducer model

Klipsch makes use of a lot of loudspeaker drivers. In this study, we use a driver that is 3½" in diameter. Using an existing unit helps the immediate verification of the simulation.

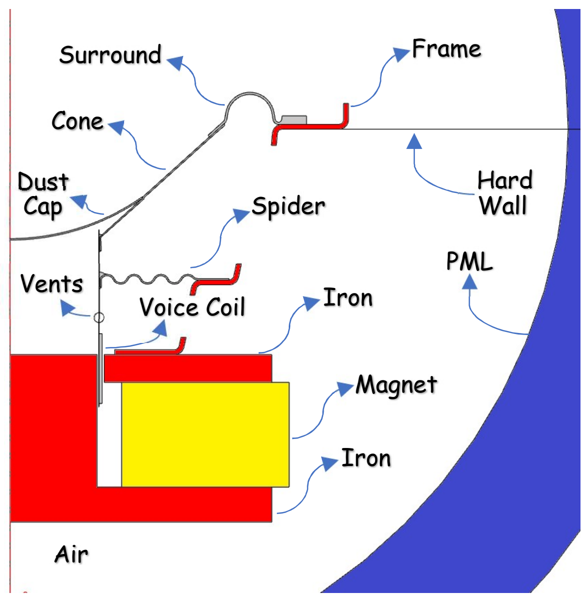

Figure 9: Axisymmetric model

The setup for the transducer model is axisymmetric. The radial direction is named “r” wile the axial to the central symmetry is called “z”. It uses multiphysics to verify the acoustics and impedance with the actual sample, utilizing the AC/DC module for the magnetic fields, Linear and Non-Linear Mechanics module for the moving parts, and Acoustics for the Pressure Acoustic study.

2.1 Magnetic Fields

In figure 9, Yellow represents the region of the permanent magnet. It is assigned a remanent flux density of 0.38T along z as common ferrite magnet. Red represents the iron regions to focus the magnetic flux into the gap where the voice coil is. The frame that holds the motor and moving parts together as a driver is also defined as being made of soft iron. It is permeable and can create some flux leakage as visible in figure 10.

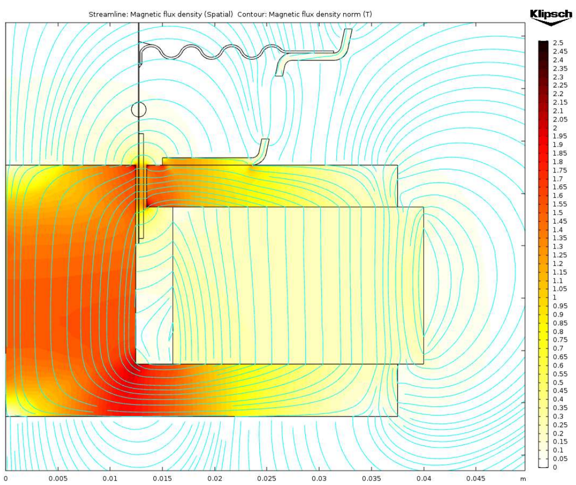

Figure 10: flux lines and magnetic field

The voice coil is defined with its wire diameter, material, and number of turns. The same area, although averaged and integrated in the definition section, receives feedback from the solid mechanics portion with its velocity vector component (Lorentz Term) that is defined manually in this section to get a proper impedance curve.

The model is run in stationary solving Ampere's law

$$\nabla \times \left(\mu_{\emptyset}^{-1} \nabla \times \mathbf{A} - \mathbf{M}\right) - \sigma \mathbf{v} \times (\nabla \times \mathbf{A}) = \mathbf{J}_e$$

Eq. 1

in the frequency domain evolves into

$$(j\omega\sigma - \omega^2 \varepsilon_0)\mathbf{A} + \nabla \times (\mu_0^{-1} \nabla \times \mathbf{A} - \mathbf{M}) - \sigma v \times (\nabla \times \mathbf{A}) = \mathbf{J}_e$$

Eq. 2

Where μ_0 is the permeability of vacuum, **A** is the magnetic vector potential, **M** is the dipole magnetic density (magnetic dipole moment per volume), σ is the conductivity, **v** is the particle velocity, and $\mathbf{J_e}$ is the current density vector from external sources.

When in the frequency response consideration comes for ω as the pulsatance, ε_0 is the permittivity of vacuum.

The model is run first stationary and in the frequency domain. The analysis in this physics setup gives the estimation of resistance and inductance for the audio spectrum of frequencies. This results will be used in the 3D model where will not be necessary to arrange a Multiphysics setup that includes a magnetic fields node.

2.2 Solid Mechanics

A node that considers the moving parts and their structural behavior in the different frequencies includes, at least, the geometries in gray from figure 9. Often material used for the moving parts includes rubber, and plastics like polypropylene. The accordion-like part in gray in figure 9, commonly called spider, is made of phenolic resin impregnated cloth that can be of a mixture of fibers. To make the matter worse, there are inconsistencies among suppliers. The inclusion of this node is important to determine, or at least approximate, material properties. This node will couple in a multiphysics setup with the pressure acoustic node to give results in the frequency domain on SPL that will have to match the sample measured data.

The equations solved for are the stress-strain relations in Hooke's law (below shown in tensor notation), with the stress tensor σ seen as in a replacement of the force, strain tensor ε in lieu of displacement, and c as the elasticity tensor

$$\sigma = \mathbb{C} : \varepsilon$$

Eq. 3

in this case of cartesian coordinates is expressed as

$$\sigma_{ij} = \sum_{k=1}^{3} \sum_{l=1}^{3} c_{ijkl} \varepsilon_{kl}$$

Eq. 3.1

from where then displacement **u** relates to it as

$$\varepsilon = \frac{1}{2}[(\nabla \mathbf{u})^{\mathrm{T}} + \nabla \mathbf{u}]$$

Eq. 4

and from Newton's Second Law, which mathematically completes the study for linear elastic material force and acceleration **ü** as second derivative in time of **u** with ρ density gives the equation of motion.

$$\nabla \cdot \sigma + \mathbf{F} = \rho \ddot{\mathbf{u}}$$

Eq. 5

For hyperelastic materials, on the nonlinear behavior of parts like the surround, the default model is neo-

Hookean, requiring the material to define the Lamè parameters λ and μ.

Once all material properties were matched to attain a satisfying correlation to the measured frequency response and impedance, the blocked coil impedance (no displacement allowed) and those material characteristics - that include nonlinear behavior and damping (either as loss factor or frequency dependent α and ß coefficient in Rayleigh damping model), will be utilized in the 3D model.

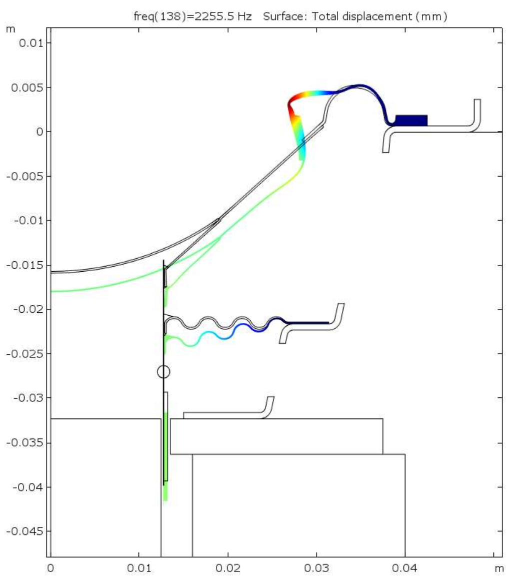

Figure 11: displacement with deformation of moving parts

2.3 Pressure Acoustics

The pressure acoustic model uses a Perfectly Matched Layer (PLM) on the outer part of the domains centered to the r=0 and z=0, represented in figure 9 in Blue, showing the total absorption of an infinite domain at the front and back of the driver as per half space anechoic (often referred to as 2π) measurements. The infinite baffle is the portion indicated there as hard wall.

The other domains are mainly air (figure 9 in white) and the small circle indicating vents that are often placed in the voice coil "former" connecting the copper windings to the rest of the mechanical assembly. The reasons for those vents are two, a pressure release from the cavity at the back of the dust cap, and heat exchange to help the cooling of the voice coil, thus improving power handling.

The vents are thus included in the pressure acoustic domain, but are still specified as the correct material (Kapton in this case), because they are structurally part of the mechanical domain. The vents are defined as a poroacoustic domain to represent the lossy pressure exchange through the holes in a Delany-Bazley-Miki model with custom C parameters and low flow resistivity.

The equation that is solved to calculate the pressure and consequentially the SPL is the Helmholtz equation

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

Eq. 6

from this inhomogeneous form for the 3D, where p_t is the total pressure (inclusive of background pressure), ρ_c is the density of the medium (in complex form where the imaginary part represents the damping), $\mathbf{q}_d$ is the dipole domain source, k_{eq} is the wave number (pulsatance/speed-of-sound, ordinary, out of plane, circumferential), Q_m is the monopole domain source.

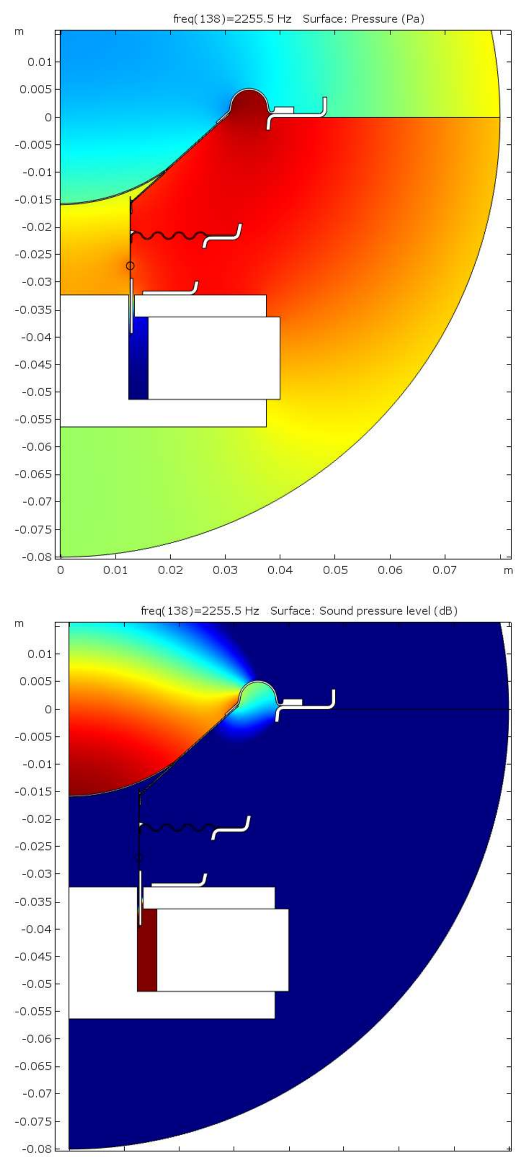

Figure 12: pressure and SPL

The iteration to determine correct values could be aided by an optimization routine. However, albeit great curiosity to determine which component was defined with too much damping not to show the peak at 6-7kHz in figure 13, because the 3D model is not planned to operate over 2000Hz, after some iterations, correspondence to SPL and impedance of the sample were deemed satisfactory.

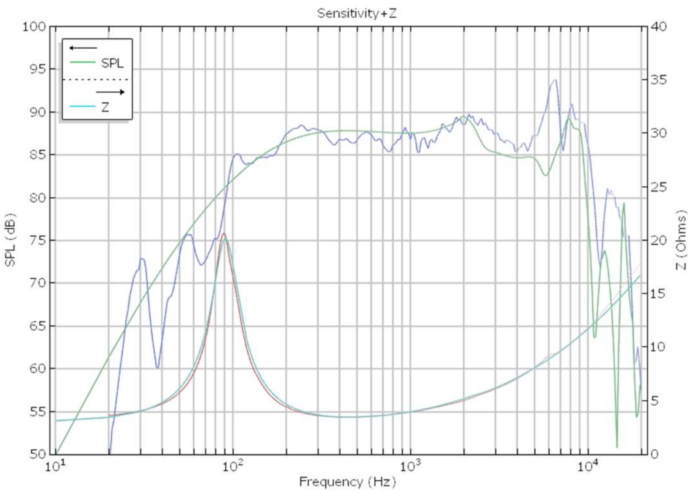

Figure 13: SPL and Impedance curve comparison

2.4 Notes about meshing

Naturally, guidelines were followed on the meshing of the domains regarding PML, with mapped mesh six layers deep. Air domains for the acoustic simulation had a maximum limitation in size related to the wavelength of the highest frequency to simulate - in this case subdivided into eight to achieve good resolution to minimize errors. Mechanical domains were more finely meshed given their small size and optional boundary layers were defined in the iron domains.

Where it applies these considerations were brought to the 3D model as well.

3. The 3D model

As all the details necessary to describe the driver are now available, we begin considerations on the 3D model. First, the model will easily be simplified by a vertical and horizontal geometric symmetries. The mounting wall is the other boundary on the z=0 plane. In terms of prototyping, for simple and practical verification, modelling an enclosure with a single driver unit simulated for pressure acoustic in FEA for the inner cavities, and BEM for the far field. This is a useful first step to calibrate the model for expansion to multiple driver units.

Having a pressure acoustic FEA model allows to include interactions with cabinet walls so that resonances and standing waves are considered. If such are present bracing and absorptive materials can be included in the study. Another advantage is in case there's necessity of opting for a vented enclosure. Tuning and the overall performance of the vent can be evaluated within the model.

3.1 The single driver model

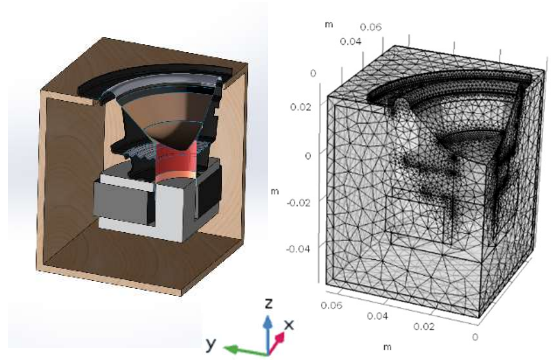

Figure 14: Single driver enclosure model

The model employs the use of shell elements in the shell interface node. This approach saves computational time, but requires care to define material thickness, which is not available directly from the geometry. The way multiple parts link together needs to be carefully considered when creating the surface geometry to substitute its original 3D.

3.1.1 Definitions, variables and parameters

The coil will have to be integrated and averaged as a boundary in the component's definition node (operator names int_coil and ave_coil apply to the portion of the voice coil where the windings are). The average is used in the variable definition to calculate the cone velocity averaged on the coil region to the z axis v0=ave_coil(shell.u_tZ). The integral is to calculate the volume, again, as variable named as vol_coil=4*int_coil(shell.d) where in the shell node variable "d" is the thickness and the volume from the integration in the ¼ sized portion will have to be multiplied by four.

The latter will be used in defining the body load to the coil together with the parameters Bl that is derived by the 2D simulation. This parameter, expressed in Tesla meters, often called the force factor, represents the average magnetic flux concatenation "B" to the coil windings "l" length, and is part of the lumped equivalent parameters used to electrically model loudspeakers that are named Thiele/Small parameters. It can actually be measured directly if dealing with an existing driver.

The other parameters delineated in the component definition node are the two interpolation functions, one for the resistance, and the second for the inductance in frequency from the blocked coil simulation run. This two tabled data could be directly measured by gluing the sample's voice coil in place and imported from a text file.

3.1.2 Shells

The Lorentz force applied to the coil is Bl·**i** where **i** is the electric current. Having Bl as parameter, V0 as driving voltage the current is calculated as V0/Zb, where the complex impedance of the blocked voice coil is the interpolation function "Rb(freq)+iomega·Lb(freq)" here iomega is the complex pulsatance. Another effect of a coil moving in flux lines is the Lenz's law back electromotive force (EMF) that contributes negatively to the total force applied to the coil. This contribution is dependent on the rate of change of concatenating flux lines expressed with the coil velocity as -v0·(Bl)²/Zb.

Calling Fe the combination of the two, it can now be defined a body load on the coil windings surface along the z direction as a force per volume Fe/vol_coil.

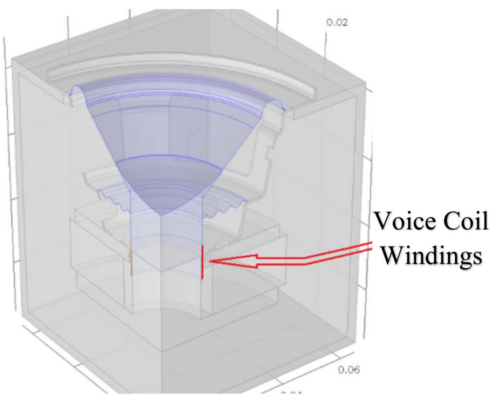

Figure 14: Shell structural mechanics surfaces

3.1.4 Multiphysics

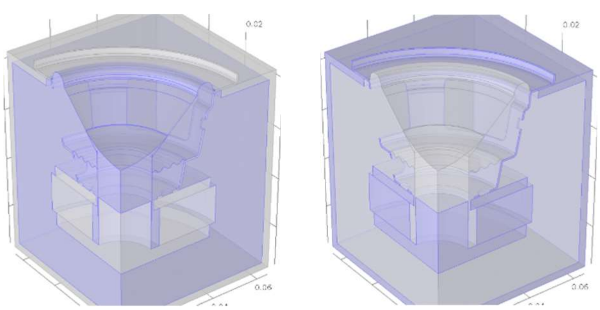

Figure 15: Pressure acoustic (L) and structural mechanics (R)

In this node the shell domains will interact through their displacement with the pressure acoustic domains in figure 15 on the left. The pressure acoustic domain then will interact with the solid structural mechanics on the right. The pressure acoustics boundary elements will calculate the pressure from both mechanical domains, the pressure generated by displacement of the diaphragm from shells, and the vibrations of the panels due to the inner pressure buildup inside the enclosure.

3.1.5 Results

Once the results are ready, some tweaks may be necessary. The results from the BEM analysis are then mapped to a "Grid 3d" from the desired size. If interested in a few point locations a "Cut Point 3d" to see the frequency response i.e. at 3 meters on axis (z) and 30 degrees off axis vertically and horizontally.

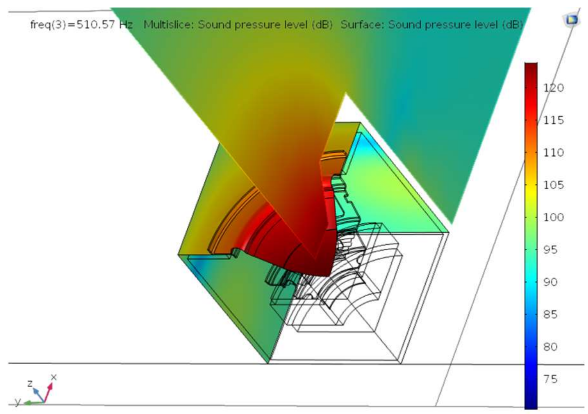

Figure 16: SPL slice at 511 Hz

In this specific case it makes no difference, but it will be of use if the geometry is not symmetrical, or a vent opening is present.

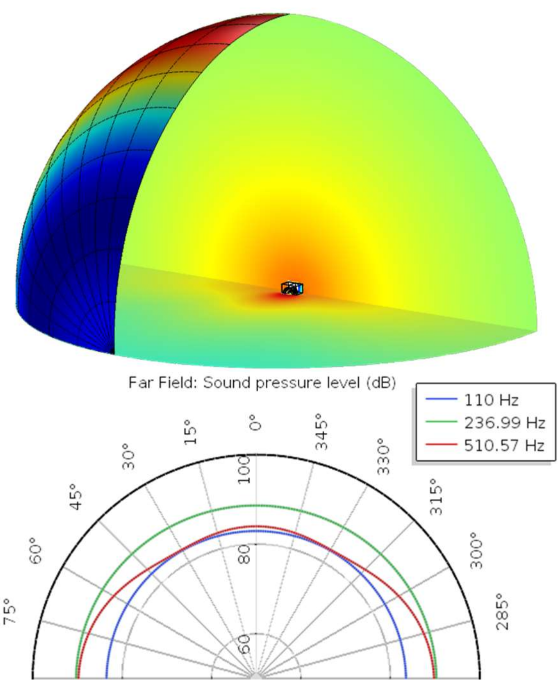

Figure 17: SPL slice on x and y plane with far field polars

Once the results of this smaller model with one driver have been verified with a prototype, the next step is to scale up the model with multiple drivers.

3.2 The column loudspeaker

Figure 18: Rendering of an initial design

The design in figure 18 is considered a first approach. Naturally, a more refined contemporary industrial design could be considered with a vent and incorporating horn tweeters and internal bracing. For simplicity, a patterned extension of the single driver 3d previously taken is used.

The only consideration to take from the previous 3D is on how to deal with the multiple coils. If one falls in the middle, like in this case, a multiplication by four has to be considered for the volume, while the others will be doubled.

If a study needs to be done on the filter design to taper or alter the polar responses, then different voltages would be fed to the coils coming from an AC/DC circuit node (cir) where all pass filters can be introduced for a delay to steer the directivity of the column, i.e. or placing in series low pass to the outer drivers, widening the response at certain frequency.

Other than this analysis, the structure of the study remains the same as the single driver little enclosure.

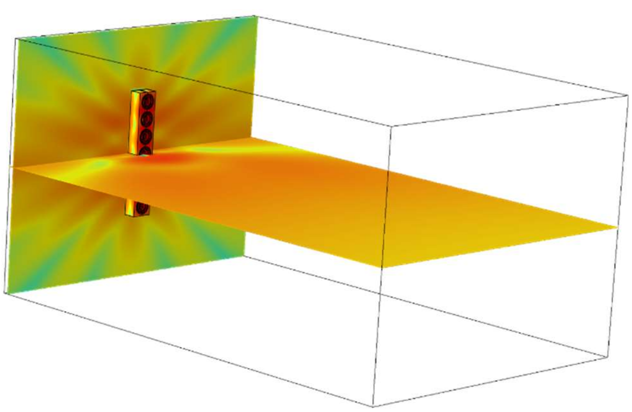

Figure 19: Horizontal SPL distribution at 2000Hz

Figures 19, 20, 21 display how the SPL is distributed along planes once the model is solved for a couple of frequencies.

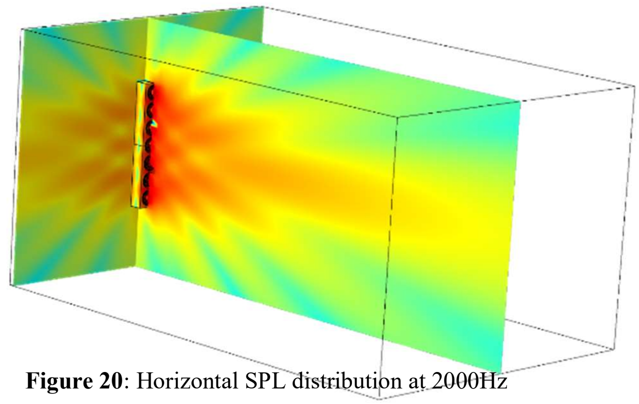

Figure 20: Horizontal SPL distribution at 2000Hz

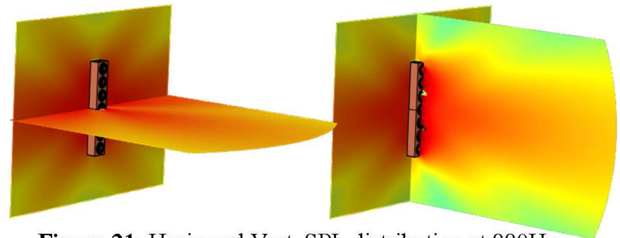

Figure 21: Horiz.and Vert. SPL distribution at 880Hz

4. Conclusion

The use of BEM in conjunction to the multiphysics setup is of great utility to examine the details of what happens to a design in several configurations with a geometrical model, given the size of the cabinet and relative domain it would require prohibitive amount or RAM. On the other hand, due to the longer computational times of the BEM algorithm, the analysis of the model cannot span a wide frequency range like commonly done with FEM. Instead, when using BEM, targeting a few frequencies of interest to gain insight, to then apply modifications based on results is the best approach.

5. References

[1] COMSOL manuals and tutorials, COMSOL (2018)

[2] L. Beranek, Acoustics, AES (1954)

[3] A. Neville Thiele, Loudspeakers in Vented Boxes: Part I and II, Journal of the Audio Engineering Society, Vol. 19, pp. 382-392 471-483 (1971)

[4] Richard H. Small, Vented Box Loudspeaker Systems, Journal of the Audio Engineering Society, Vol. 21, pp. 363-372 438-444 549-554 635-639 (1973)

6. Acknowledgements

I would like to thank Klipsch's Jill Escoll, the management, particularly my manager Chris Perrins for his vision, creative discussions, and to have agreed to a research time in a subject that is new to Klipsch, paving the road to what will eventually could become a product. COMSOL's team, Mads H.Jensen, Jinlan Huang, Cinzia Iacovelli, Jessica Allendorf.