Optimization of an Acoustic Waveguide for Professional Audio Applications

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Abstract: In modern live sound reinforcement there is a growing use of line sources, obtained through the stacking of many loudspeakers with properly controlled wavefront shape. Thus the use of waveguides is mandatory in order to modify the shape and size of the wavefront exiting from professional compression drivers.

With the help of COMSOL Multiphysics, we have designed a waveguide featuring an integrated acoustic lens that achieves the required phase coherence in the output sound field.

This paper compares the 2D and 3D simulations of two different prototypes with real measurements and with a third simulation without internal lens. A cost/benefit comparison is drawn between 2D and 3D results, and hypotheses are made about the discrepancies between simulation and measurements.

Keywords: waveguide, phase coherence, line source, compression drivers, loudspeakers

1. Introduction

During the last two decades, a growing number of large loudspeaker systems for professional audio applications has been designed with a “line-array” or “line-source” configuration. Those systems are generally designed as a series of modules having a wide and thin front panel, whose central part is occupied by the high frequency source, i.e. the loudspeaker driver reproducing frequencies roughly from 1 to 20 kHz. This HF (High Frequency) source is nearly as tall as the whole module, so that, when several modules are stacked together to form a complete system, all HF sources form an almost uninterrupted line from top to bottom and they work together as a single extended sound source.

Figure 1. A typical line array system design. One modular enclosure (above) and six modules stacked together (below). Notice the HF slot in the center. (From a NEXO White Paper, http://www.nexo-sa.com)

Each HF source must comply with precise criteria for the system to behave as the theory of line sources predicts. The most important criterion is phase coherence: the sound field just outside the waveguide outlet must be flat (isophasic) up to the highest frequency of interest. The maximum allowed deviation from flatness is a quarter wavelength, i.e. 90° or π/2 radians.

2. Waveguide design

The main goal of the waveguide design was to convert an incoming sound wave with a round cross section to an outgoing sound wave with a tall and thin rectangular cross section. In addition, the outgoing wave should comply with the isophase criterion for frequencies up to 16 kHz.

The waveguide we designed is made of two elements: a waveguide shell, whose cross section changes smoothly from a 36 mm diameter circle to a 153 × 25 mm rectangle on a 180 mm length; and an acoustic lens, made of several almond-shaped pegs that cross the width of the waveguide.

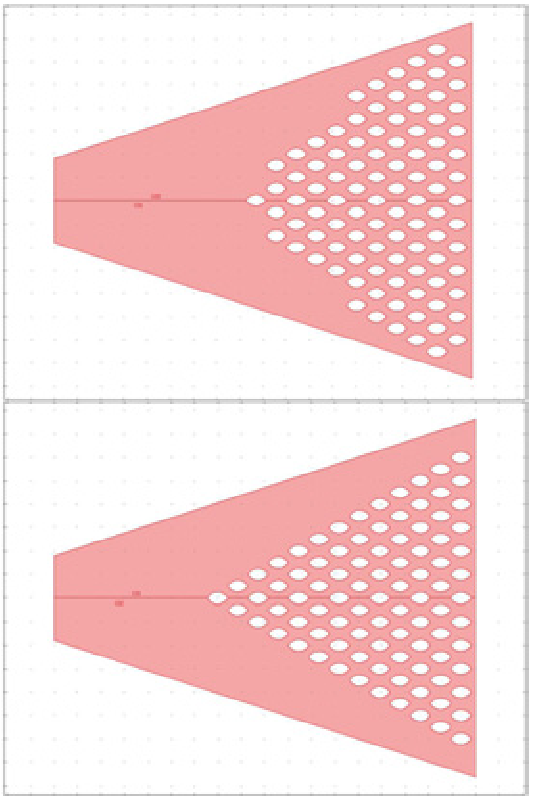

Figure 2. Cross section of first (above) and final (below) waveguide design

The goal of the shell is to provide the change of cross section shape, while the goal of the lens is to delay the central part of the wavefront in order to achieve the required phase coherence.

A first solution was designed using a conventional lens formula and an estimate of the refraction index of the pegs region (fig. 2, above). A prototype was build and tested, and the results were compared to the COMSOL Multiphysics simulations. Then we used COMSOL models to optimize number and distribution of the pegs, ending with the final design (fig. 2, below).

3. Numerical Modeling with COMSOL Multiphysics

The waveguide problem was implemented in COMSOL Multiphysics using the Acoustics Module, as a Time-Harmonic analysis in Pressure Acoustics.

Two different models of the waveguide were used: a 3D model and a 2D model.

The 3D model, taking advantage of symmetries, represents one fourth of the complete waveguide. The 2D model is a cross section of the waveguide through a vertical plane passing through inlet and outlet and represents half of the system. The lateral cross section of the waveguide has a width between 36 mm at the inlet and 25 mm at the outlet. This is the same order of magnitude of a 16 kHz wavelength (about 21 mm), but the symmetry conditions ensure that the amount of transverse propagation is negligible.

The mesh for 2D models consists of 2nd order triangular elements for the waveguide, 2nd order quadrilateral elements for air domain in front of the waveguide, and 2nd order mapped elements for the PML domains.

The mesh for 3D models consists of 2nd order tetrahedral elements for waveguide and air domain, and 2nd order swept elements for PML domains.

In both cases, the maximum element size is one fourth of the shortest wavelength, i.e. 5.4 mm for 16 kHz.

The input sound field is modeled as an incoming plane wave at the waveguide inlet. All the internal surfaces of the waveguide have the standard “Sound hard wall” boundary condition. An external air region is added to check the initial propagation of the sound field; the evaluation of the phase coherence condition takes place in that region, on a line 2 cm in front of the waveguide outlet.

The Dell workstation employed for FEM modeling has the following tech specs:
Intel Xeon Optcore E5520@2.27GHz CPU
24GB Ram
NvidiaQuadroFX1800 graphics adapter
O.S. Microsoft Windows XP Professional x64 Edition V2003 SP2

The solving process included 12 frequencies per octave band, ranging from 1 kHz to 16 kHz, thus resulting in a total of 49 frequencies.

The solver chosen for 2D models was Direct-UMFPACK, while for 3D models we have found that Direct-SPOOLES is faster.

Average computing time was about 16 seconds per model for 2D models, and 2100 seconds per model for 3D models (see Table 1).

4. Results and validation

4.1. Empty waveguide

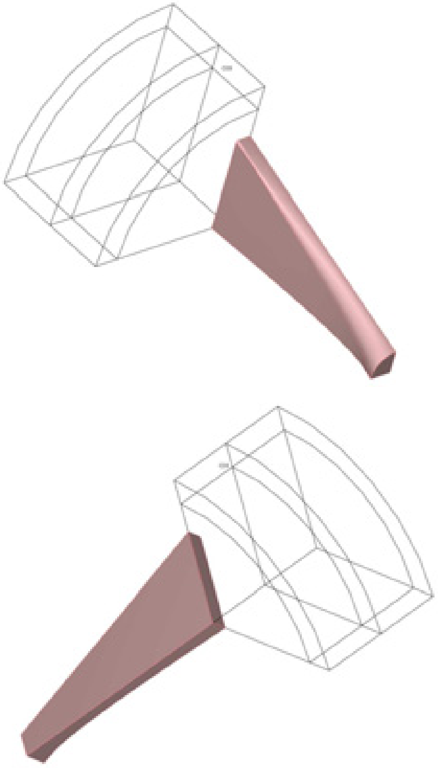

Figure 3. Two views of the empty waveguide 3D geometry

We simulated the empty waveguide first, in order to estimate the amount of phase correction that was needed. Fig. 3 shows the 3D model we used.

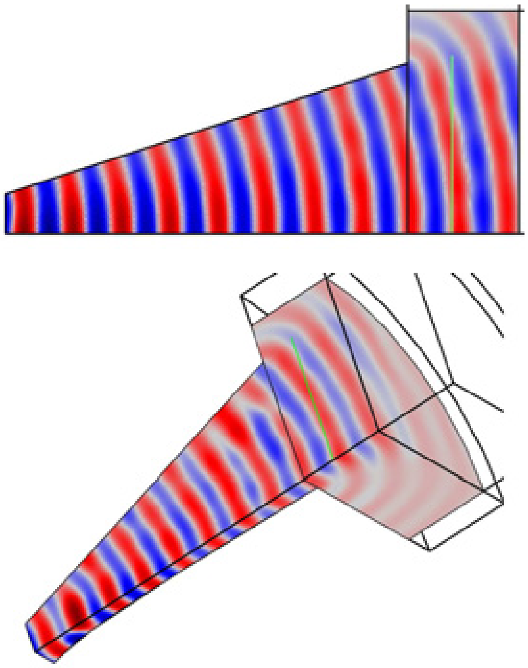

Figure 4. Sound pressure at 16 kHz in empty waveguide, 2D above, 3D below. Phase data are taken on the green line

From the sound pressure simulations in Fig. 4 it is easy to see that the wavefront curvature is excessive for the required flatness criteria. At 16 kHz frequency, the probe line spans almost a full period, from the red (positive) region on the center line to the blue (negative) one at the top.

This is confirmed by the phase data (Fig. 5.)

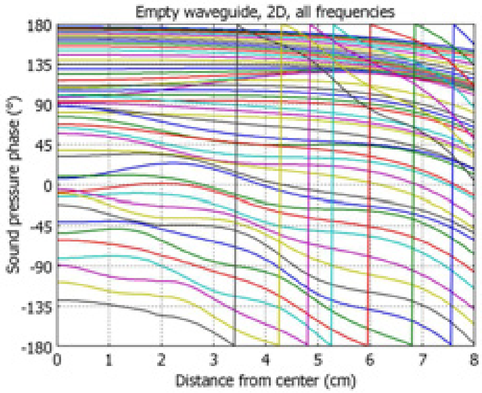

Figure 5. Phase variation across the waveguide outlet in the empty waveguide, 2D simulation, for all frequencies from 1 to 16 kHz

It is also evident from data that the most troublesome frequencies are the highest ones. The lowest frequencies already comply to the phase coherence criterion, thanks to their longer wavelength. The first frequency to violate the criterion is close to 7 kHz.

In the following, we only graph seven frequencies from 4 to 16 kHz, in steps of one third of octave.

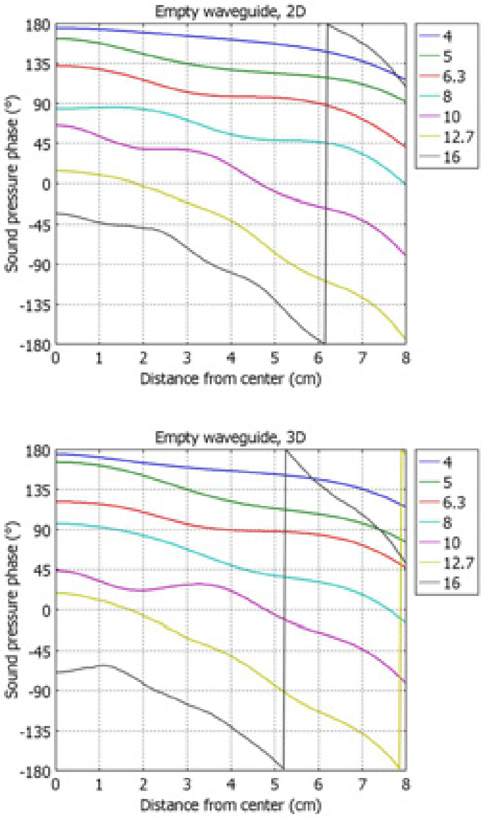

Figure 6. Phase variations in empty waveguide, 2D and 3D simulations

Comparing the phase variation in 2D and 3D simulation, it appears that the results are in close agreement, despite some minor deviation (see also Fig. 7). From those preliminary results, we concluded that we could likely use one or the other approach for the optimization. We decided anyway to continue using both and check the differences afterwards.

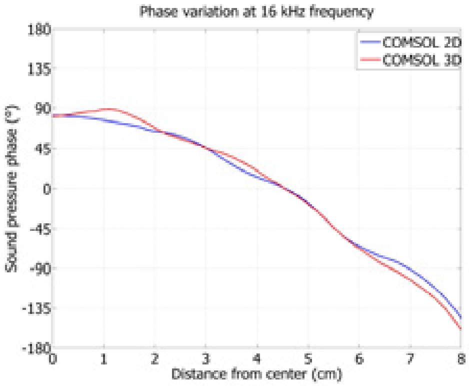

Figure 7. Empty waveguide, 2D vs. 3D: simulated phase variations are in close agreement

4.2. First prototype

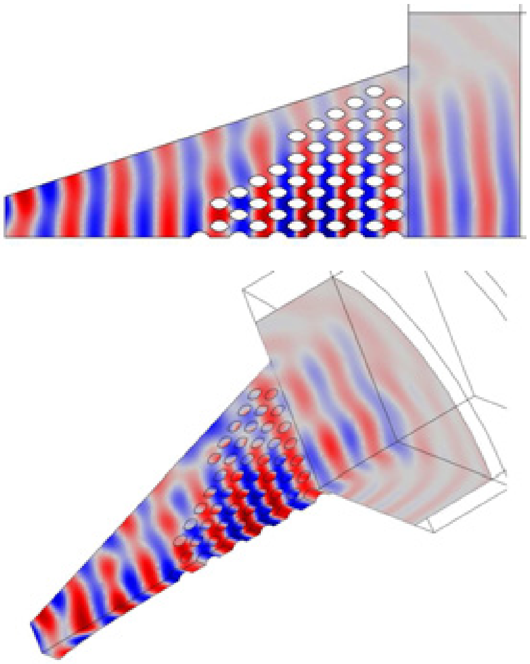

Figure 8. Sound pressure at 16 kHz in first prototype, 2D above, 3D below

From the sound pressure simulations in Fig. 8 it is easy to see that the wavefront has still some curvature at 16 kHz frequency, with phase jumps near the end of the probe line.

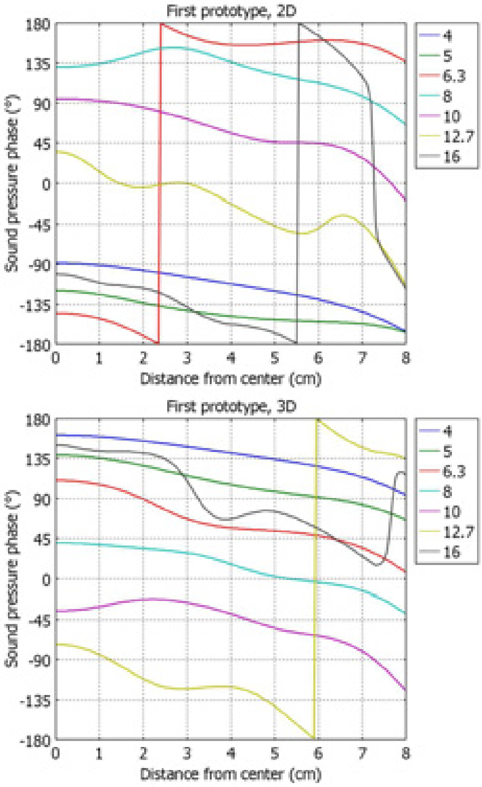

Figure 9. Phase variation of first prototype, 2D and 3D simulations

Phase variation data allow a more precise assessment of the performance of the first prototype. Some improvement over the empty case is evident, but the highest frequencies still violate the isophase criterion.

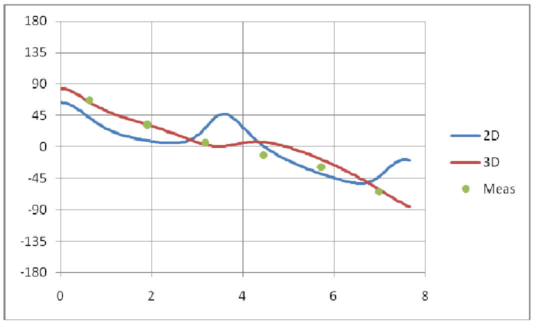

Figure 10. Phase variation vs. distance from center at 12 kHz, comparison between simulations and measurements in first prototype

The comparison with measurements shows an interesting result: both 2D and 3D give reasonably accurate prediction of the maximum phase difference, but 3D follows much more closely the pattern of experimental points. For example, Figure 10 shows the results at 12 kHz.

4.3. Final design

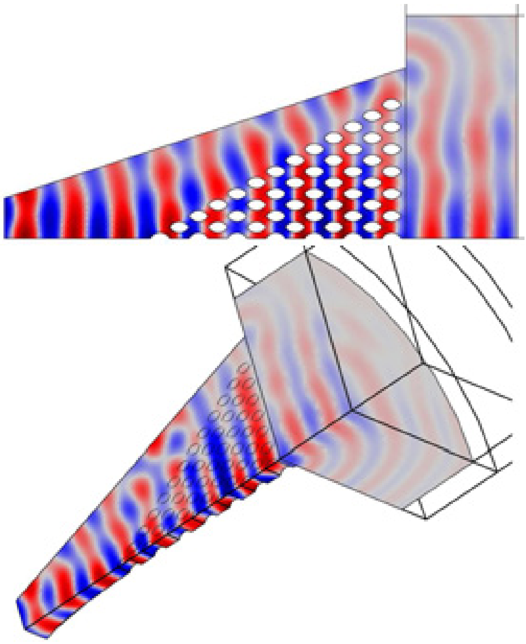

Figure 11. Sound pressure at 16 kHz in final prototype, 2D above, 3D below

Many different variations of the initial design were drawn and simulated before building a new prototype. The final design is shown in Fig. 11, together with the sound pressure simulation at 16 kHz.

It is clear from the picture that the wavefront is now almost perfectly planar at waveguide outlet.

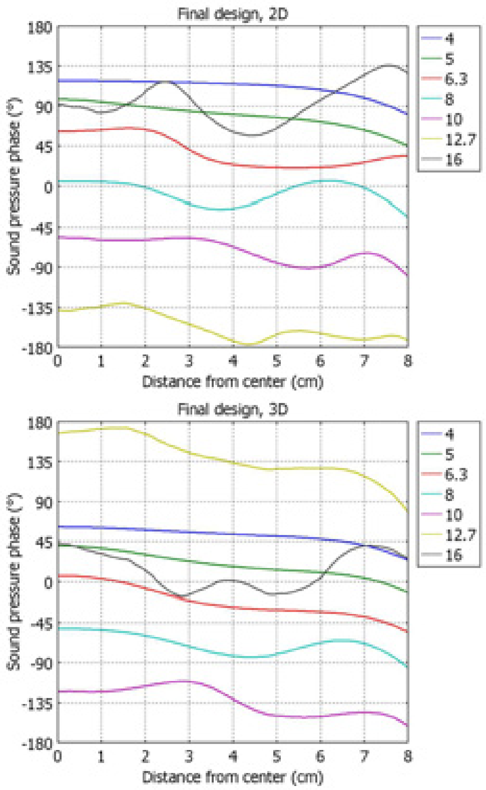

Figure 12. Phase variation of final prototype, 2D and 3D simulations

The evaluation of phase variation confirm the outcome: in the final design, all frequencies of interest comply with the isophase criterion.

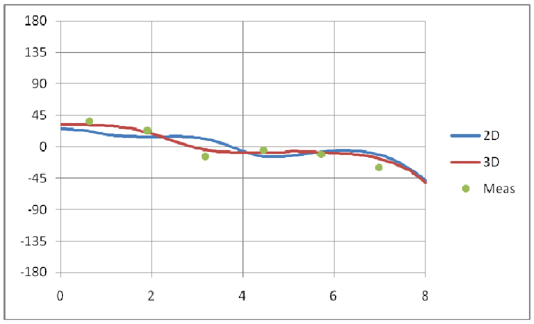

Figure 13. Phase variation vs. distance from center at 12 kHz, comparison between simulations and measurements in final design

The results of experimental validation confirm the expectations for all but the highest frequencies (15 kHz and beyond). Fig. 13 shows the data at 12 kHz. Notice how the 3D curve is again closer to the measurements.

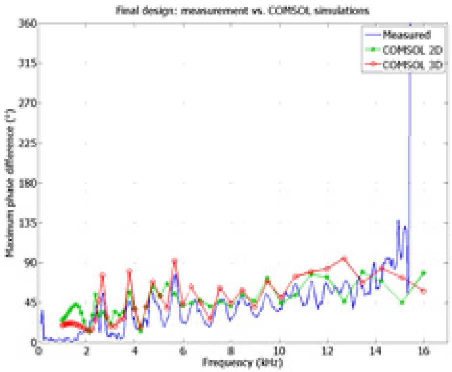

Figure 14. Maximum phase difference at all frequencies

Fig. 14 shows phase measurements on the final design compared to 2D and 3D simulations. The fit to experimental data is good for both simulations, with 3D following more closely the ups and downs of the measured curve. Both tend to slightly overestimate the phase difference; this could be due to the high number of points in the simulated probe line (161) compared to the measurements on the real waveguide (12).

Discrepancies in frequencies above 14 kHz are probably due to higher order modes excited from the non-planar wave coming from the compression driver, that shows breakup modes and chamber resonances resulting in non planar output.

5. Discussion

The fit of numerical models to experimental results is encouraging for the use of COMSOL Multiphysics as a virtual prototyping tool. Some improvements in the simulation of the system could be gained with a more accurate model of the sound source, but the standard plane wave condition is good for the evaluation of the waveguide alone.

	Time (s)	Elements	DOF
Empty, 2D	8	1450	4000
Empty, 3D	2800	62000	112000
First des., 2D	20	6700	15600
First des., 3D	2500	63000	117000
Final des., 2D	20	6500	15300
Final des., 3D	1050	50000	97000

Table 1. Mesh size and computing time for all models

Table 1 compares problem size and solution times for all models.

The difference in times is two orders of magnitude. The times for 2D are short enough to be used in case of an automated optimization of a first try design.

On the other hand, 3D gives an higher level of precision and detail, as well as much more information. For example, with 3D we could evaluate the horizontal angular coverage of the waveguide and compare to measurements, with good results (see figure below)

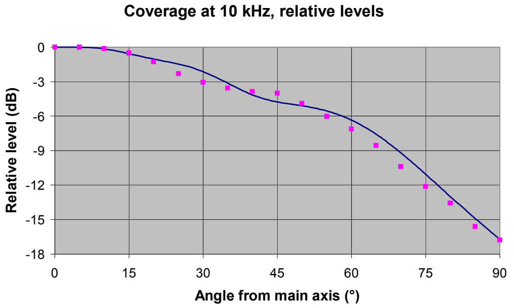

Figure 15. Comparison of simulated (solid line) and measured (dots) coverage data for final waveguide design

6. Conclusions

The Acoustics Module of COMSOL Multiphysics has been used for the design of an acoustic waveguide that had to comply with precise criteria on the output sound field. The predictive capabilities of COMSOL helped reducing the number of prototypes during the design phase. Validation with experimental data has been largely successful.

With the waveguide geometry shown in this paper, 2D simulations could estimate phase coherence in the vertical plane with reasonable accuracy. The very short solution time of a single problem – 20 seconds for 49 frequencies – would allow for an automated optimization.

On the other hand, 3D simulations offer higher accuracy and much more information on the complete behavior of the device, still with manageable solution times, in the range of 15 to 45 minutes. Therefore 3D is a good choice for the devices or geometries that cannot be reduced to a 2D problem and is recommended to fine tune the final design.

7. References

1. Heil C., Urban M., Sound Fields Radiated by Multiple Sound Sources Arrays, *Preprint n. 3269*, **92nd Audio Engineering Society Convention**, (Mar 1992)
2. Urban M., Heil C., Bauman P., Wavefront Sculpture Technology, *Journal Audio Eng. Soc.*, **Volume 51, n. 10**, pp. 912-932 (Oct 2003)
3. Mores R., Schröder N.B., Schwalbe T., The Performance and Restrictions of High Frequency Waveguides in Line Arrays, *Paper n. 6777*, **120th Audio Engineering Society Convention**, (May 2006)
4. Henwood D.J., The Boundary-Element Method and Horn Design, *Journal Audio Eng. Soc.*, **Volume 41 n. 6**, pp. 485-496 (Jun 1993)

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