Simulation of Horn Driver Response by Direct Combination of Compression Driver Frequency Response and Horn FEA

Dario Cinanni
CIARE, Italy
Corresponding author: CIARE S.r.l., strada Fontenuovo 306/a, 60019 Senigallia (AN), Italy. d.cinanni@ciare.com

Abstract: Today a horn driver developing is still time and cost consuming. In addition compression driver behavior depends by the horn profile. To predict the driver/horn combination behavior, different methods are proposed in the last 15 years, for example by G. Behler and M. Makarski [1] [2] or A. Voishvillo [3]. These methods lead to a complex electrical and acoustical performance of driver/horn combination, using a matrix analysis of the two-port "black box circuit". However, to derive the desired matrix elements, different measurements have to be carried out on both electrical and acoustical ports. A new method related to acoustic behavior prediction is presented here, using only one acoustical measurement and FEA. Starting from a real compression driver acoustic response, measured on a Plane Wave Tube (PWT) and using Comsol simulated horn, with a simple procedure is possible to predict acoustic absolute response of the driver/horn combination. A new equation is presented, correlating measurement and simulation.
Case studies have been done and simulations results have been compared with measurements, in order to describe how well a fitted model matches the original data set.

Keywords: Acoustic, Horn Driver, Compression Driver, Horn, Plane Wave Tube.

1. Introduction

1.1 Description

Compression driver is a not direct radiating moving coil loudspeaker, it is coupled to horn and used as component in high efficiency audio systems, usually for bandpass mid and high frequency applications. Figure 1 shows an example of such component.

The acoustical behavior of a horn driver depends on the combination of both compression driver and horn. A standard device converts an electrical input signal, through the voice coil, into mechanical energy through the diaphragm, using the magnetic assembly as motor of this electromechanical system. The diaphragm movement produces a pressure variation compressing and rarefying air inside phase plug slots. Phase plug is a mechanical interface placed between the compression driver diaphragm and the horn, it acts as an acoustic transformer equalizing sound wave path lengths and increasing radiation efficiency when the slots area is smaller than the diaphragm area (also called Compression Ratio). Phase plug represents the first acoustic section of a horn driver that extends with horn flare shape. Horns have a cross sectional area which increases form a small throat at one end, to a large mouth at the other and acoustic pressure propagates from throat to mouth. The ideal electroacoustic efficiency is reached when acoustic impedance (phase plug and horn combination) is matched to the driver mechanical impedance (diaphragm and coil mass, mechanical resistance, suspension compliance, etc).

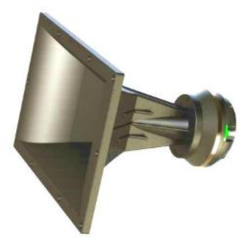

Figure 1. Example of high frequency horn driver. CIARE PR401 horn and CIARE CD1003T driver.

1.2 Paper Purpose

In Voishvillo [3] introduction we can read a panoramic on compression drivers works using different approaches, from B. Locanthi to M. Dodd and J. Oclee Brown. In this paper is proposed a new technique to model a combination of an existing compression driver and a virtual horn, in order to predict the horn driver behavior. In the current phase of development the method makes it possible to simulate on-axis frequency responses. Off-axis simulations and a refinement of the method are under analysis and will be subject of a future publication. This procedure comprises compression driver measurement and horn acoustical FEA model.

2. Compression Driver measurement

An absolute value of the sound pressure level at the driver mouth is required, for this purpose it's is possible to use a Kundt's tube [4] [5] [6], or a plane wave tube [7]. For this study a PWT system was used, figure 2. For final comparison between simulation and measurement the simulated horn, subject of next section, was realized and horn driver absolute value of the sound pressure level in anechoic chamber was made, figure 3. The horn is the high frequency commercial product CIARE *PR614 V-Shape*.

It's recommended to pay attention to make precise microphones calibration. It's suggested to use microphones with an extended and low distortion frequency response, also at high levels, because the level pairing between simulation and measurement depends on the calibration. For PWT compression driver measurements a ¼" B&K 4134 microphone capsule was used, for horn driver anechoic measurements a ½" B&K 4191 microphone was used, with the same B&K 2669 pre-amplifier for both capsules and a B&K microphone power supply type 5935L. The measured results were obtained by Audiomatica Clio system, exported data were stored with unsmoothed resolution and processed by a custom software program to produce frequency response graphs for comparison.

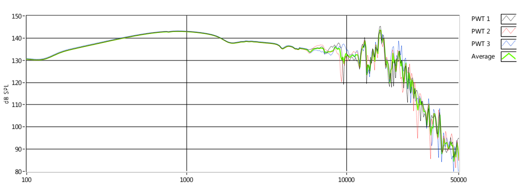

Figure 2. Absolute sound pressure frequency response of a 1.4" exit compression driver loaded by a PWT.

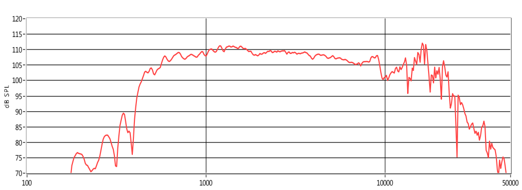

Figure 3. On-axis absolute sound pressure frequency response of the horn driver in anechoic chamber at the distance of 1 m.

3. Horn model definition

3.1 Description

A plane wave source enters in the horn throat and horn mouth radiating towards an open space (4π solid radiation angle). The air domains should ideally extend to infinity, to avoid reflections a perfectly matched layers (PML) was used, also the air front volume had to be more than ½ wavelength to work properly. To respect the last condition, for a minimum frequency of 1 kHz a dimension of about 200 mm from the external boundary of horn in a sphere-shaped air was considered.

Horn profile was generated with SpeakerLAB *Horn.ell.a* software, engineered using SolidWorks and imported by Comsol CAD module in a quarter space 3D model, figure 4. A pressure acoustic frequency domain simulation in a linear elastic fluid model without damping and with a monopole source Q_m equation

$$Q_m = \nabla \cdot \frac{1}{\rho} \left(\nabla p_t - \boldsymbol{q_d}\right) - \frac{k^2 p_t}{\rho} \qquad (1)$$

where

$\nabla^2 = \nabla \cdot \nabla$ represents the *Laplacian* operator
c = speed of sound [m/s]
ρ = air density [kg/m^3]
$p_t = p + p_0$ is total sound pressure [Pa]
$k = \frac{\omega}{c}$ is the spatial wave number [1/m]
$\omega = 2\pi f$ angular frequency [1/s]
f = frequency [Hz]
$\boldsymbol{q_d}$ = dipole source [N/m^3]

A reference pressure for the sound pressure level of 20 µPa ($20\cdot10^{-6}$ Pa) is used. A sound speed of 343 m/s is selected for PML.

The boundary conditions are of two different types. For all the solid boundaries including horn walls and stylized compression driver, sound hard (wall) boundary conditions are used

$$\mathbf{n} \cdot \left(-\frac{\nabla p_t}{\rho}\right) = 0 \qquad (2)$$

at which both the acceleration normal component and the dipole source are zero. The same condition is used for the two symmetry nodes.

The second type is a non-reflecting boundary condition plane wave radiation, with the complex form

$$Q_i = \mathbf{n} \cdot \frac{1}{\rho} \nabla p_i + i\frac{k}{\rho} p_i + \frac{i}{2k\rho} \Delta_T p_i \qquad (3)$$

where **n** is the outward unit normal vector in the domain boundary, Δ_T represents the *Laplacian* operator in the tangent plane at a given point on the boundary and p_i is the incident pressure field

$$p_i = p_0 e^{-i(\boldsymbol{k} \cdot \boldsymbol{r})} \tag{4}$$

where p_0 is the wave amplitude, $\boldsymbol{k}$ is the wave vector and $\boldsymbol{r}$ is the location on the boundary.

It is possible to select p_0 following two methods. In a first phase p_0 was chosen measuring the SPL output at the driver exit, this first method involves an additional measurement.
Otherwise, if we consider a plane wave tube measurement, we can have the right SPL output at the driver exit. Using PWT absolute SPL, in figure 2, for the wave amplitude in equation (4) it's possible to correlate measurement and simulation. This second method involves only one measurement.
The far-field pressure computations allows to extract sound pressure level anywhere; in this case the sensitivity is calculated on the axis at a radius of 1 m. Figure 5 shows the sound pressure frequency response of finite element analysis horn, in the frequency range 1 ÷ 20 kHz. This frequency range is selected in order to reduce computational burden in simulation estimation, in addition this is a common working range for most of commercial compression drivers.

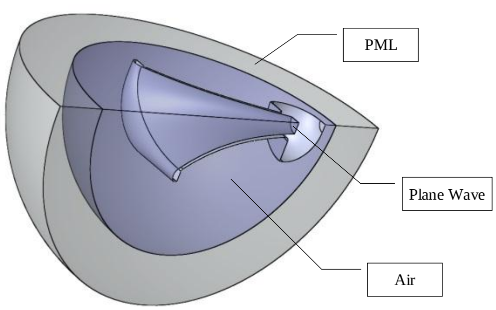

Figure 4. Geometry of the modeled horn.

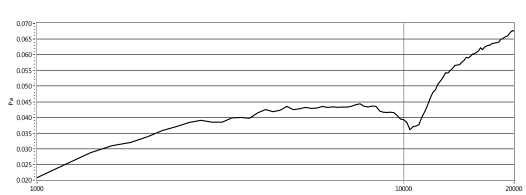

Figure 5. Throat-to-mouth sound pressure frequency response of the simulated horn.

3.2 Model Mesh

For PML scaling factor is selected a value of 0.5 instead the default value of 1. The results of this change is that the wave amplitude, while traveling out through the PML bouncing on the outer sound hard condition and traveling back in through the PML again, it decreases by approximately 50 dB instead of 100 dB. With this approach the systematic error, especially at low frequencies, increases in a still negligible form, but above all the solution gradient inside the PML becomes less steep and requires smaller amount of elements to resolve. A sweep method is selected for PML and a free unstructured tetrahedral mesh for air inside and outside horn, figure 6 and figure 7. The maximum tetrahedral element size δ is

$$\delta = \frac{1}{x} \cdot \frac{c}{f_{max}} \tag{5}$$

where
c = speed of sound [m/s]
f_{max} = maximum simulation frequency [Hz]

For accurate results a good value of the maximum element in expression (5) is given by $x \geq 5$.

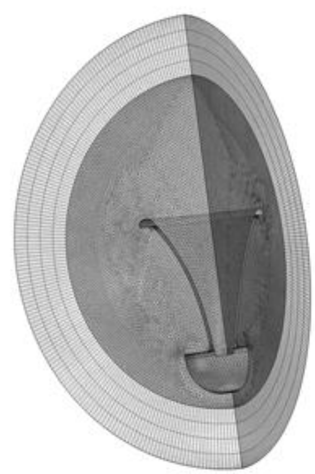

Figure 6. Mesh.

Figure 7. Tetrahedral mesh element quality histogram.

4. Combination of modeling and measurement

4.1 Description

This work concerns only linear domain and the resulting sound flow through fluid media is in a regimen knows as linear acoustics. In linear acoustic the resulting sound pressure is the algebraic sum of the contributions. Also in linear acoustics the sound-induced variations in pressure p, density ρ and temperature T are small compared to the baseline value of these quantities p_0, ρ_0 and T_0. Combining PWT measurement with horn FEA is possible to obtain absolute sound pressure level of the horn driver frequency response; this correlation can be expressed in the following equation

$$L_{pt_{fx}} = 10\log_{10}\left[10\log_{10}\left(\frac{L_{pPWT_f}}{20}\right)\cdot p_{sim_{fx}}\right]^2 + \left(L_{pPWT_{fx}} - L_{pPWT_f}\right); \qquad (6)$$

Where $L_{pt_{fx}}$ is the horn driver absolute sound pressure level calculated for each frequency, L_{pPWT_f} is the compression driver sound pressure level measured on PWT at a given frequency, $p_{sim_{fx}}$ is the sound pressure of the horn simulation calculated for each frequency, $L_{pPWT_{fx}}$ is the compression driver sound pressure level measured on PWT for each frequency. L_p are expressed in dB and p in Pa.

Figure 8 shows the final comparison between measurement of figure 3 and simulation. Simulation is modeled by the direct combination between PWT compression driver measurement (figure 2) and horn FEA model (figure 5) using equation (6).

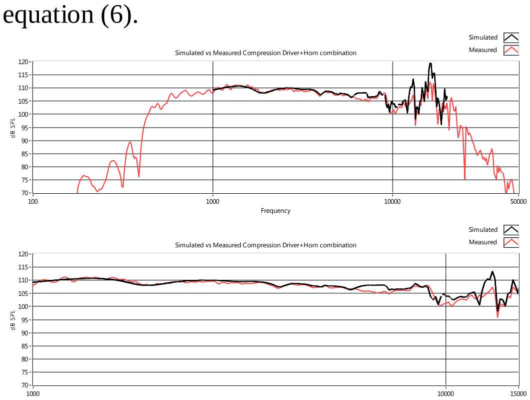

Figure 8. Measured and simulated absolute sound pressure frequency response of the horn driver A. 1 ÷ 15 kHz detail on the bottom graph.

Measurements and simulations are imported in a new software tool developed to post-process the model and compare the results. With application builder from the Comsol version 5.0 it might be possible to create an analogous routine. The tool resamples and arranges input data, permitting to correlate frequency information regardless of any number of imported points. This is useful to import records from different measurement systems and it is important to reduce errors for a low number of FEA sweep parameters. The tool will be available in free download on *www.speakerlab.it* web site. The next sub-section shows other study results plotted with the tool.

4.2 Other case studies results

Figures 9, 10, 11 show other results. In figures 9, 10 was used the same simulated horn of section 3 with different compression drivers.

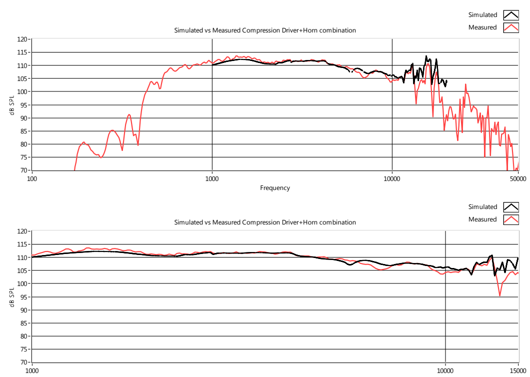

Figure 9. Measured and simulated absolute sound pressure frequency response of the horn driver B. 1 ÷ 15 kHz detail on the bottom graph.

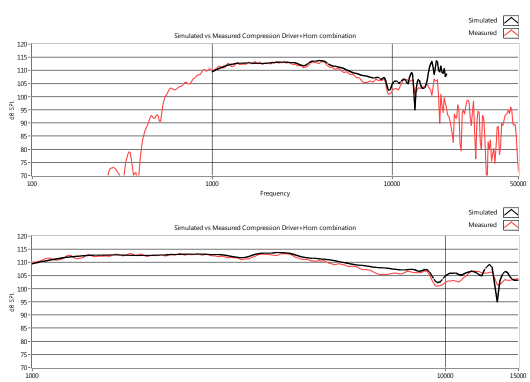

Figure 10. Measured and simulated absolute sound pressure frequency response of the horn driver C. 1 ÷ 15 kHz detail the on bottom graph.

In figure 11 another model results with the same driver of the figure 10, but a different horn profile was simulated. In this case acoustic horn was modelled as a mechanical cross over, adjusting the compression driver frequency response to obtain an extremely flat response, with a significant reduction in the number of physical horn prototypes.

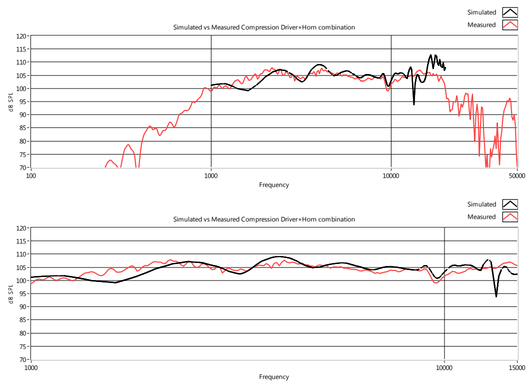

Figure 11. Measured and simulated absolute sound pressure frequency response of the horn driver D.
1 ÷ 15 kHz detail on the bottom graph.

4.3 Method Limits

In the FEA study there is a plane wave radiation condition on the horn throat, this model is more accurate as compression driver comply with this condition on its exit. For more precise results is suggested to start design of the horn directly on phase plug exit, considering air volume of the exit driver as a horn extension, moving plane wave radiation near as possible to phase plug exit. In this analysis on the high frequency range (from about >15 kHz) in some cases there is a difference between measurement and simulations, with a higher SPL of simulations compared to measurement.

A more investigation is necessary to study if this is a condition relative to a limit of the PWT system for its dimension or construction, for example at higher frequencies when the wavelength becomes smaller than twice the diameter of the tube higher modes can occur. In TABLE 1 of AES-1id-2012 [7] are described resonant modes. Another limit could be the microphone dimension, in TABLE 1 of ASTM E 1050-08 [6], in which two microphones are used, it is recommended that the microphone diameter be less than 20% of the wavelength for the highest frequency of interest. For this study was used a ¼ Inch microphone, in accordance with ASTM E 1050-08 the limit would be 11.5 kHz.

An alternative limit could be independent by measurement system, but related to the plane wave condition of the horn FEA, that at high frequencies in the real world could disappear. We need to consider that plane wave is always an approximation. Anyway in case of differences repeatability is sufficient to perform some experience with your personal measurement systems and compression drivers to equalize simulated curves and obtain a perfect match between simulations and measurements.

5. Conclusion and future developments

A new method of horn driver simulation has been developed. The method comprises horn FEA and driver PWT measurement. With the proposed method is sufficient only the SPL frequency response PWT measurement of the compression driver. The correlation between FEA and PWT measurement could be obtained using equation (6). Equation (6) can be expressed in different forms, it is important to keep PWT measurement absolute SPL as pressure reference of the horn FEA calculus in post-process. The proposed method is also useful to model SPL frequency response of a virtual horn combined with several real compression drivers' response and vice-versa. With compression drivers frequency response database is possible to fast predict SPL of each driver with the simulated horn, without physically building horn. The method comprises acoustic response, in this case only on-axis frequency response was studied, but prediction of the entire 3D "balloon" of responses, with real measurements comparison, is under investigation. It will be subject of a future publication. From 1 kHz to 15 kHz the agreement between the measured and the modeled responses is very good. Under further investigation is also high frequency enhancement (>15 kHz). If the high frequency limit is due to measurement system, to simulation accuracy or to the plane wave condition difference between FEA and the real world. A new software tool was developed for this study.

6. Acknowledgements
Thanks to SpeakerLAB for developing new software tool and build the application in a free license.

7. References
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