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IDENTIFICATION OF ACOUSTIC CHARACTERISTIC OF TWEETER LOUDSPEAKERS FOR CAR CABIN SOUND QUALITY SIMULATIONS

Emanuele Garofalo[1*] **Gabriele Costa**[1] **Gioele Isacchi**[1]
Simone Talucci[2] **Marco Olivieri**[3] **Michele Ebri**[3] **Francesco Ripamonti**[1]
[1] Department of Mechanical Engineering, Politecnico di Milano, Milan (MI), Italy
[2] Teoresi S.p.A., Torino (TO), Italy
[3] Ferrari S.p.A, Maranello (MO), Italy

ABSTRACT

Numerical simulations are fundamental for the design of acoustic environments, and in this context, the modelling of sound sources is particularly relevant for the virtualization of the studied sound field. This paper presents a comprehensive modelling approach to simulate loudspeakers as sound sources for ray tracing simulations. The analysis focuses on the medium-high frequency range and it aims at modelling different types of loudspeakers, a tweeter based on a dome layout and a ribbon type tweeter. A detailed methodology for the complete simulation of the devices is developed starting from an experimental campaign characterizing the directivity of the loudspeakers by exploiting the geometrical symmetries of the devices. Then, numerical models are developed using COMSOL Multiphysics and validated with experimental data obtained from the loudspeakers mounted on a specially designed test rig. Finally, the two devices are compared in a potential application in the automotive field, demonstrating how this methodology can be effectively employed in acoustic modelling for vehicle interiors.

Keywords: *Ray Tracing, Directivity measurements, Automotive acoustics, Loudspeaker modeling*

**Corresponding author*: *emanuele.garofalo@polimi.it.*

1. INTRODUCTION

In car cabins, the sound quality depends on the acoustic emission of several loudspeakers that are designed to work together to achieve the desired sound shaping of the volume. In automotive applications, many types of loudspeaker devices are considered and they vary in dimensions, geometries, and operating principles depending on the frequency range of excitation. In this context, the most common loudspeaker types are the sub-woofers, the woofers, the midranges and the tweeters.

In this paper, the attention is focused on the tweeter loudspeakers. Tweeters are lightweight devices implemented in car cabins to reproduce high-frequency sounds without introducing distortions. Tweeters are generally more complex than the other types of loudspeaker. Indeed, they are characterized by particularly reduced encumbrances and moving parts that feature small dimensions. The shape and technology of tweeters depend on their applications. There are many models, such as ribbon or dome, distinguished by different geometric symmetries and different functional elements [1], [2] . In some cases, additional elements may be present to reinforce moving elements to avoid structural distortions, or to adjust the directivity of the speaker itself.

In the context of acoustic simulations, the modelling of tweeters is a challenging task because of their complex geometry and the typical high-frequency ranges at which they are designed to work. Indeed, the different design of tweeter loudspeakers does not allow the use of lumped parameters modelling approach for simulating their response, differently from moving-coil loudspeakers. Over the years, numerous technological advances have made it possible to gradually overcome the computational limitations imposed by software and hardware systems. Therefore, many common numerical techniques have been developed to obtain numerical acoustic simulations solving the acoustic wave equation. These methods, based on the finite element or boundary element approaches, provide very accurate results [3], but can be computationally expensive, especially for simulations of high frequency ranges or highly detailed geometries. To overcome these limitations, other techniques based on geometric acoustic (GA) assumptions have been implemented. Thanks to these methodologies, it is possible to optimize the computational effort and obtain faster simulations with an acceptable compromise in the quality of the results. One of the most widely used numerical methods based on GA is Ray Tracing (RT) [4]. This energetic approach simulates the propagation of sound from sound sources as a multitude of rays with a specific energy content emitted by specific locations according to the directivity of the original source. When a ray hits a boundary of the domain, new reflected rays are generated with energy content depending on the absorption conditions of the hit wall. This mechanism continues until the newly formed rays reach a threshold energy level [5]. This method is particularly useful for simulations of high frequencies where the wavelength of sound is short compared to the surface dimensions and the overall dimensions of the space. In addition, this method does not require a detailed geometrical representation of the sound sources, simplifying them as point entities [6]. For these reasons, the use of RT is particularly useful for the simulations of acoustic environments characterized by the sound emission of tweeter devices. In this context, this paper presents a comprehensive approach to correctly reproduce the tweeters as sources for RT simulations in COMSOL Multiphysics. The presented methodology is supported by the measurements obtained during the experimental campaign described in Section 2. The reliability of the model is validated with an experimental test shown in Section 2.2. Finally, an application of methodology in the automotive field is presented in Section 3 where the tweeters are modelled as sources for RT simulations of the sound field of a generic car cockpit.

2. MATERIALS, MODELS AND METHODS

To develop a complete procedure to obtain a faithful reproduction of a general tweeter in an RT simulation, extensive experimental campaigns are conducted in the Politecnico di Milano's Sound and Vibration Laboratory (PSVL), testing two different devices, a dome and a ribbon tweeter, in a $4 \times 4 \times 4\,\mathrm{m}$ semi-anechoic chamber with purely acoustically absorbent walls and ceiling and a reflective floor.

2.1 Experimental procedure for source synthesis

To represent a generic sound source as a point source in an RT simulation using COMSOL Multiphysics, the number of rays to be released, the source position, and the source emission characteristics must be provided. To do so, a directivity function $DI(f, \varphi, \theta)$, where φ is the azimuthal angle and θ is the polar angle, as well as a reference pressure level L_{ref} and a corresponding reference distance R_{ref} must be defined [7]. Using the same experimental setup of [8], to extract this information from the physical tweeters, a measurement of their frontal sound emission is performed by placing the devices on the ground, with their main emission axis pointing upwards, as shown in Fig. 1 and recording the generated sound pressure with microphones placed in a wooden hemispherical support. In particular, the measurements are made by positioning 19 calibrated $1/4''$ PCB microphones along a vertically positioned circumference arc that covers a right angle, with $5°$ resolution. The support, that has its centre point on the source, allows measuring the sound emission in the far field region, having a radius of $1.04\,\mathrm{m}$ which guarantees that the microphones are positioned far from the sound source for at least 1.6 times the wavelength of the lowest frequency to be measured (which for the case is fixed at $1\,\mathrm{kHz}$).

This special measurement setup is designed to take advantage of the geometric characteristics of the tweeters. In fact, the measurement procedure can be optimized to reduce the number of tests required for source synthesis, saving time and storage resources. Based on the dome tweeter fundamental assumption of axisymmetric emission, the results obtained on the circumferential arc can be distributed at $360°$ in the post-processing phase, to complete the full semi-spherical directivity described above. In contrast, in the ribbon tweeter case, where two axes of symmetry can be assumed (as a common rectangle), it is necessary to rotate either the microphone arc or the tweeter itself by at least $90°$ in steps small enough to adequately capture the directivity lobes, in this case $10°$.

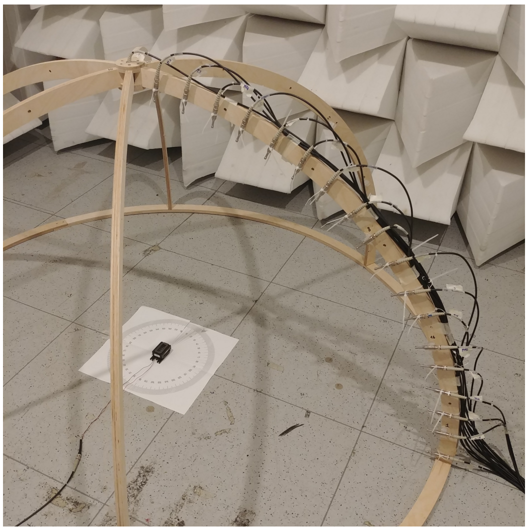

Figure 1: The measurement setup implemented to extract the parameters needed for the RT numerical simulation.

By reproducing a 1 W, 20 s sinusoidal sweep signal, spanning from 1 to 20 kHz, it is then possible to obtain the sound pressure level (SPL) perceived by each receiver. This approach enables the frequency trend of the SPL of the microphone corresponding to the frontal emission to be directly employed for the description of the source within COMSOL Multiphysics, thereby providing the L_{ref} parameter. The directivity is then calculated implementing the following relation:

$$DI_{k,\theta} = 10 \log_{10} \left(\frac{I_{k,\theta}}{\max \left(I_k \right)} \right) \tag{1}$$

where the intensity of the k-th one-sixth octave band is $I_k = \dfrac{H_k^2}{\rho_0 c}$. Here H_k is an array containing the values of the transfer function H between the tweeter and the microphone in the k-th one-sixth octave band, ρ_0 is the air density and c is the speed of sound. The subscript θ indicates that the value refers to the microphone located at the elevation angle θ.
Thanks to the aforementioned symmetric characteristics, the emission behaviour of both types of tweeters along all axes not directly measured are reconstructed through specific geometrical transformations. This methodology allows for a full description of the tweeter's frontal hemisphere. Two examples are shown in Fig. 2 and Fig. 3, at the same frequency of 7071.1 Hz for the two types of tweeters.

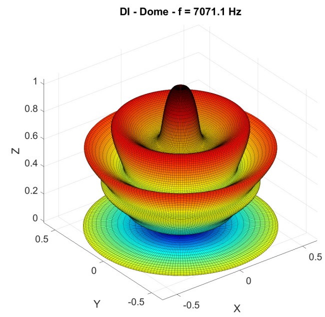

Figure 2: DI of the dome tweeter measured at 7070 Hz.

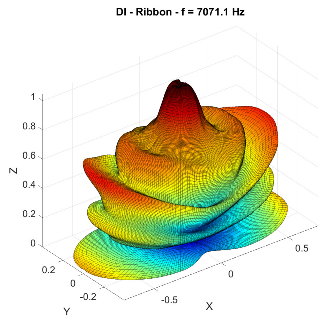

Figure 3: DI of the ribbon tweeter measured at 7070 Hz.

2.2 Source model validation tests

To validate the reliability of the derived directivities, a validation phase involving a further experimental campaign and numerical simulations is introduced.
A very simple experimental setup is adopted to easily obtain a virtual validation of the source synthesis without introducing elements or environmental conditions that could complicate the numerical simulations. Using the same measurement layout adopted in [9], both dome and ribbon tweeters are mounted on a simple structure consisting of a rigid box made of Plexiglas and measured in the semi-anechoic chamber using 19 microphones placed along a half-circle centred on the tweeter position (Fig. 4). The devices are tested by imposing a 1 W, 60 s sinusoidal sweep signal in the frequency range of 1 to 20 kHz and the radiated SPL is measured with the described microphone array at three different distances: 1, 1.5 and 2 m.

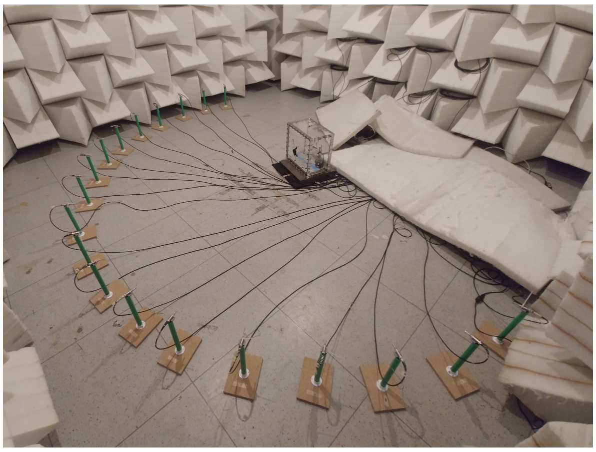

Figure 4: Tweeter directivity measurement setup with the 19 microphones positioned at $2\,\mathrm{m}$.

3. RESULTS

The experimental setup described in Section 2.2 is replicated in COMSOL Multiphysics. A RT simulation is performed replicating in the software the testing environment of the semi-anechoic chamber by imposing a total absorption condition on the walls and ceiling, and considering the floor as a total reflective boundary. The Plexiglas support described in Section 2.2 in which the devices are mounted is considered as a rigid structure and the tweeters are simulated as a point source with the directivity and reference level previously estimated using the procedure described in Section 2. Spherical receivers are placed at the microphone positions to compare the simulated and measured sound pressure levels. For sake of simplicity, this paper only reports the results of the sound pressure level (Lp) along the loudspeaker axial direction at $1\,\mathrm{m}$ distance.

The results reported in Fig. 5 and Fig. 6 show how the numerical model is able to reproduce the trend of the SPL, providing good agreement between the experimental and numerical curves. The RT simulation performed in the simulated test environment featuring reflecting floor and absorbing walls correctly simulates the interference effects derived by the reflection of the rays on the ground. However, due to the approximation made by considering the box as a rigid body and neglecting any possible dynamic interaction between the speakers and the box itself, the numerical simulations do not consider the possible effects given by the vibration of the box in the resulting acoustic field. This phenomenon seems to be more pronounced in the results of the dome tweeter, due to its operating principle, leading to greater differences between the simulated and measured curves with respect to the ribbon tweeter case.

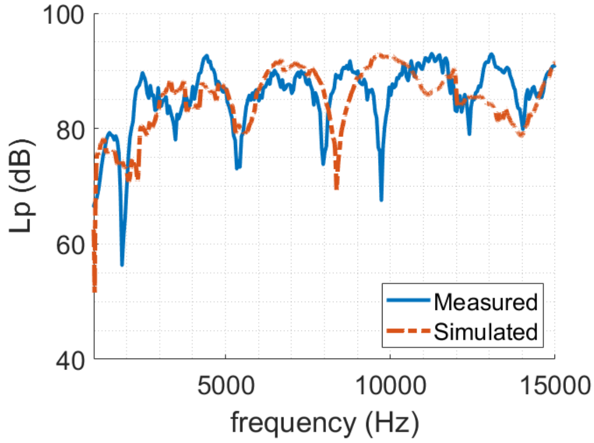

Figure 5: Comparison between the simulated and measured Lp on the loudspeaker axial direction at $1\,\mathrm{m}$ distance, dome tweeter.

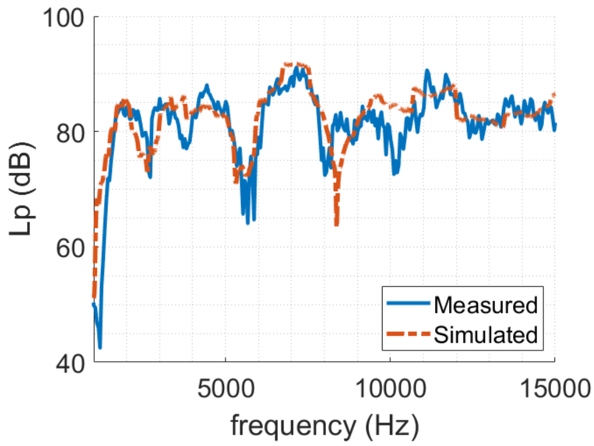

Figure 6: Comparison between the simulated and measured Lp on the loudspeaker axial direction at $1\,\mathrm{m}$ distance, ribbon tweeter.

To further check the capability of the model to simulate the speaker directionality, the numerical and the measured data are analysed by comparing the directivity index

(DI) obtained according to:

$$DI_i = 10\log_{10}\left(\frac{I_{mic_i}}{I_{max}}\right) \tag{2}$$

where I_{mic_i} is the sound intensity registered in the location of the i^{th} microphone in the circular array normalized with respect to the maximum sound intensity registered in the same circular array (I_{max}).

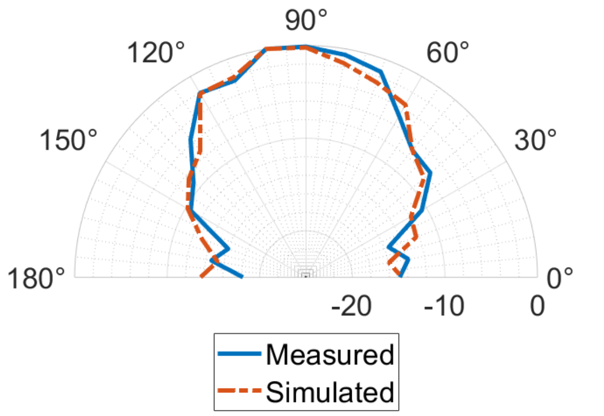

Figure 7: Comparison between the simulated and measured DI at $1\,\mathrm{m}$ distance evaluated at the third-octave band centred at $1\,\mathrm{kHz}$, dome tweeter.

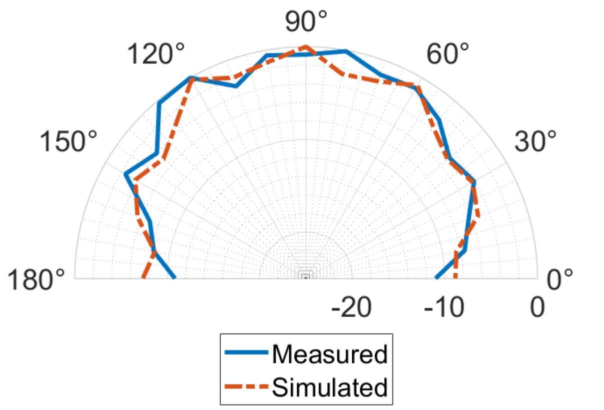

Figure 8: Comparison between the simulated and measured DI at $1\,\mathrm{m}$ distance evaluated at the third-octave band centered at $1\,\mathrm{kHz}$, ribbon tweeter.

Fig. 7 and Fig. 8 illustrate the directivity index at $1\,\mathrm{m}$ distance for the third-octave centred at $10\,\mathrm{kHz}$, showing how the numerical models also provide reliable results faithfully simulating the directivity of both devices.

Finally, an application of the synthesized sources in the automotive sector is presented by performing an RT simulation of the acoustic field generated by considering the two tweeters inside a generic car cockpit. COMSOL Multiphysics simulations are performed to highlight the differences between the sound radiation of the two tweeters placed in the same position in a specific location of the analysed domain. The geometry of an SUV cabin is imported into COMSOL Multiphysics and the relative acoustic absorption properties taken from the literature are assigned to each boundary of the domain. Then, a point source is placed at a point in the left front door and a receiver is placed in correspondence of the passenger's head as shown in Fig. 9.

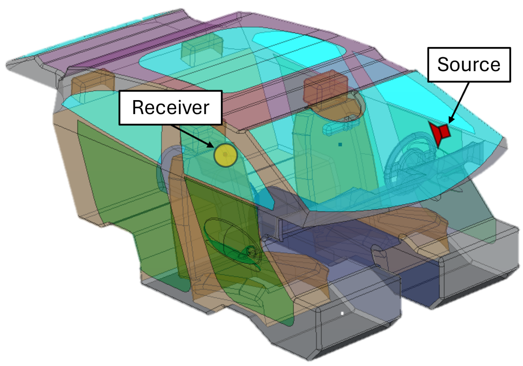

Figure 9: Overview of the car cabin model considered in the RT simulations performend in COMSOL Multiphysics to assess the sound field inside the vehicle.

The functionality of the two devices is compared by conducting two distinct simulations. The directivity and reference level synthesized in Section 2 are assigned to the point source, first considering the measurements obtained from the dome tweeter, and then the corresponding ones from the ribbon type.

The general assessment of the performances of the two loudspeakers is usually based on energetic considerations, by studying psychoacoustic indexes, or by comparing the different frequency responses obtained considering specific receivers placed inside the cabin. In this paper, a preliminary comparison is based on the frequency responses evaluated at the receiver position obtained by simulating the sound radiation of the two tweeters. The comparison, reported in Fig. 10, highlights the differences introduced in the frequency response evaluated at the receiver's position by simulating the sound radiation of the two devices placed the same position, considering the same command input. The sound pressure levels generated by the two devices are comparable at low frequencies, while at frequencies higher than 4 kHz the two trends present discrepancies that are related to their different layouts. These differences are coherent with the ones that can be perceived by comparing the experimental measurements reported in Fig. 5 and Fig. 6.

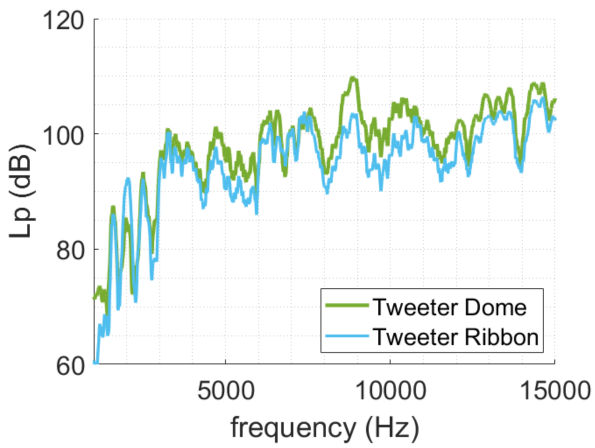

Figure 10: Comparison of the frequency response evaluated at the receiver position.

4. CONCLUSIONS

This paper presents a methodology for modelling tweeter loudspeakers in RT simulations. The proposed approach is based on an experimental characterization and a post-processing procedure that provides directivity information for accurately modelling tweeter loudspeakers of different types in COMSOL Multiphysics. Validation tests confirm the good correlation between experimental measurements and numerical results, providing minor discrepancies due to structural interactions and simplified boundary conditions. Furthermore, the paper illustrates an application of the proposed methodology in the automotive field, demonstrating the impact of tweeter design on the sound field and correlating it with the differences in frequency response. The RT simulations performed in a car cockpit setup illustrate how the choice of tweeter type can influence the sound distribution and the overall listener experience. The approach proposed in this paper improves both the accuracy and the efficiency of the numerical simulations of tweeter devices based on the RT methodology. Therefore, the results suggest the possibility of implementing the procedure described in the paper to support the optimization of the acoustic performance of car cabins.

5. ACKNOWLEDGMENTS

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