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Application of laser vibrometer for the study of loudspeaker dynamics

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Abstract

This paper presents an experimental and numerical study of vibrations of loudspeakers. The experimental part consisted of measuring vibrational responses of cones of the loudspeakers to the sine sweep excitation signal. Acquisition was performed by means of a laser vibrometer. The numerical analysis employed finite element simulations of the cone and suspensions, based on estimation of viscoelastic properties for loudspeaker components. Having acquired accelerations of hundreds of points on the radiating surface, the radiated sound pressure level at one-meter distance has been computed. Confronting SPLs obtained from the two approaches the authors attempted to match the numerical model with the experiment. The matching was confirmed by the comparison between the simulated and measured operational deflection shapes.

Keywords: vibrations; loudspeaker; viscoelasticity; laser vibrometry.

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1. Introduction

The purpose of this research was to analyse loudspeaker vibrations from a mechanical point of view and to determine the variety of factors that have negative influence on the performance of loudspeakers. Since loudspeakers are operating on high frequencies, the vibration modes that occur are paramount for the acoustical response and, furthermore, for the quality of sound perceived by listeners. The acoustical response is sensitive to even minor quantitative and qualitative variations in the materials and assembling of the device. Hence, it is important to

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Nomenclature

p_0 reference sound pressure
ρ_0 air density
a acceleration of a point or a node
$\mathbf{r_c}$ position of a point on the radiating surface
S_c radiating surface
$\mathbf{r_a}$ position of the reference point in which the sound pressure is calculated
f frequency in Hz
j imaginary unit
k wave number defined as $2\pi f/c$
c speed of sound in air

develop a procedure capable of providing sensitivity analysis of the loudspeaker response with respect to small modifications, with the goal of explaining, and possibly reducing, the variations of acoustical performance found by the quality assessment procedure being applied at the production line.

The research was conducted for loudspeakers used in an automotive sound system with a specific focus into the high frequency range, between 500 Hz and 10 kHz, where the so-called "breakup" of the cone dominates the acoustical response. The experimental analysis was executed by means of a laser vibrometer, whilst the numerical analysis was developed employing a finite element method software. These activities combined allowed to get an insight on specific properties of loudspeakers and their components. The results are presented in comparison with physical measurements of the radiated sound pressure carried out in an anechoic chamber with a microphone.

2. Experimental acquisitions

The experimental measurements were carried out in the laboratory of the Department of Industrial Engineering at the University of Parma, Italy. The experimental setup was composed of a laser vibrometer Polytec OFV-5000 accompanied by an XY positioning system with two stepping motors for the laser sensor head Polytec OFV 505, a QSC power amplifier and a Roland Studio Capture sound card, all controlled via a laptop computer. The software controlling acquisition procedure and further elaborations of data was coded in Matlab. The Device Under Test (DUT) loudspeaker was positioned on the floor and fixed in a rigid wooden frame, well insulated from the floor by means of a mass-spring system, under the laser sensor as pictured in Fig. 1.

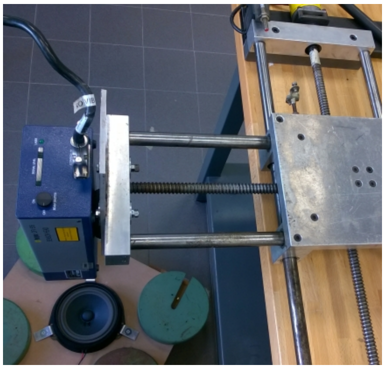

Fig. 1. Laser sensor head and positioning system.

The program for data acquisition generated a two-dimensional grid of roughly-equispaced points, the number of which was optimized throughout comparison of repeated tests with different grids. The surface of the speaker from the point of view of the laser was presented as a two-dimensional plane, however, the vertical profile of the surface was considered afterwards in the calculation of the two surface-integrated quantities: sound pressure level (SPL) and accumulated acceleration level (AAL).

The concept of the experiment was to excite a loudspeaker with an exponential sine sweep signal [1] and to record the output signal represented by vibrational response of the radiating surface of a loudspeaker (cone, dust cap and roll surround) for every point of the grid. Subsequently, the impulse response (IR) was computed by convolving the output signal with a proper inverse filter, which "packs" the energy spread over the duration of the test signal to a short impulse, and simultaneously performs differentiation (hence operating the conversion from velocity to acceleration). One of the main advantages of the linear deconvolution in time domain is the elimination of distortion products that appear in the IR of the system [1]. In this way the authors managed to extract a “clean” linear IR. Afterwards the Fast Fourier Transforms (FFT) and the frequency response function (FRF) were computed from the IR of each point of acquisition. The FRF expresses the ratio between the acceleration of each point and the voltage applied to the loudspeaker. The experimental chain was fully calibrated for ensuring that the whole process produces SPL and AAL curves with a correct dB scale, making the results directly comparable to acoustic tests and numerical simulations.

3. Finite element simulations

The numerical modelling was focused primarily on the mechanical vibrations of loudspeakers, without considering effects of magnetic field created by the voice coil or of acoustic medium represented in reality by the air. A three-dimensional model of a loudspeaker was studied in the finite element software Abaqus. It consisted of a radiator (in other words, the sound-radiating surface composed of cone, surround and dust cap), voice coil and glue where the components were assembled. The model was constrained with appropriate boundary conditions: the exterior edge of surround was clamped and the spider was modelled with springs.

The excitation force was modelled by means of a surface traction load applied along the voice coil. A steady sinusoidal signal was specified, and its frequency was stepped up with 5 Hz steps. This type of analysis provides solution directly in the frequency domain for the prescribed frequency range of 100 Hz – 10 kHz with almost 2000 equispaced points. The resulting FRF represents the steady-state response of the system, exactly as the FFT applied to the measured impulse response expresses the steady-state response of the system at each frequency. In this case the results of the numerical simulation are complex accelerations of the model nodes, which directly correspond to the experimentally acquired FRFs. Thus, further elaboration of the results was performed with the same algorithm coded in Matlab both for experimental and simulated FRFs. Another advantage of the stepped frequency domain analysis was the possibility of taking into account variations of the voice coil impedance with respect to the frequency of excitation, which can be easily measured, and provides frequency-changing values of the forces applied to the voice coil. When this is done, the resulting simulated FRF represents the ratio between acceleration of the cone and voltage applied to the voice coil, exactly the same quantity obtained by the vibration measurements performed with the laser velocimeter. The radiating surface of a loudspeaker with a diameter of 164 mm was meshed by 3000 4-nodes shell elements with 6 DOF. The glue was modelled with added masses and solid elements.

4. Characterization of viscoelastic materials

Overall, one of the main issues of realistic FEM simulations is appropriate modelling of damping. In FEM software, material damping can be implemented by defining certain coefficients, e.g. of the Rayleigh damping model. For some materials the mechanical properties, referred to as viscoelastic, depend on time or frequency. In case of a loudspeaker both paper (cone) and foam (surround) exhibited viscoelastic properties. After running simulations with ordinary elastic material models as a first iteration, it was evident that the results were not satisfactory when confronted with the experiments, hence, prediction of strongly frequency-dependent viscoelastic behaviour of the loudspeaker parts had to be included.

The dissipative material behaviour is described via the time/frequency-dependent complex elastic modulus, which consists of real and imaginary parts (storage and loss moduli, the ratio is known as the loss factor). The FEM software Abaqus demands on providing frequency-dependent real and imaginary parts of shear and bulk moduli, considering also the possible variation of the Poisson’s ratio. Normally experimental characterization of viscoelastic parameters with an automatic dynamic viscoelastometer is a nontrivial and expensive procedure. Having confronted the lack of data on the viscoelastic parameters, the authors used the inverse approach of numerical modelling: the FEM analysis was used to “tune” approximated material parameters throughout confrontation of numerical and experimentally measured responses. A good match of the first three peaks of the FRF was found for the following material models. The frequency-dependent elastic modulus and loss factor for the foam material of the surround were simulated with a third-degree polynomial and a logarithmic function correspondingly. For the cone paper a linear dependency was imposed for the elastic modulus and the loss factor increased proportionally to the natural logarithm of frequency. Fig. 2 illustrates the tuned material parameters as functions of frequency.

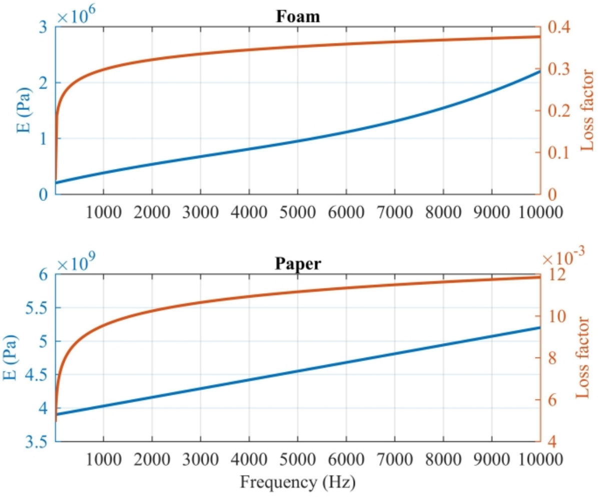

Fig. 2. Elastic modulus and loss factor of foam (surround) and paper (cone).

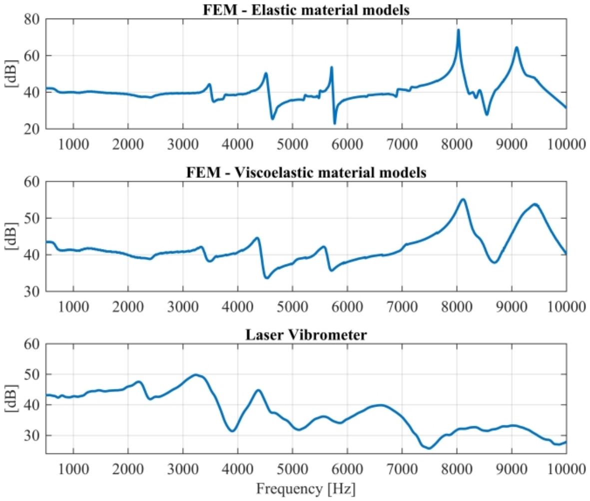

Fig. 3. FRFs: laser vibrometer and FEM analysis with simple elastic and viscoelastic material models.

The described models rendered possible significant smoothing of some of the resonant peaks on the FRF curves obtained from FEM that were not present in the experimentally measured FRFs, as shown in Fig. 3. Subsequent testing of several material models revealed that variation of frequency dependent parameters of the paper has the most influence on shifting of resonant frequencies and their amplitudes. Tuning of the viscoelastic parameters in their combination allowed to reach a good correspondence with the experimental spectrum on the frequency range up to 7kHz, thus, the models are subject to alteration for improvement on higher frequencies.

5. Calculation of SPL and AAL

In order to compare the experimental vibrometeric measurements, numerical simulations and acoustical tests carried out in an anechoic chamber, the sound pressure level (SPL) curves were computed. SPL is a fundamental characteristic of a loudspeaker, which measures the radiated sound pressure at a distance from the cone large enough for the evanescent modes to vanish. So the SPL curve is representative of the effective sound field generated by the loudspeaker. The SPL is defined in absolute dB scale, according to Eq. (1).

$$SPL(f,r_a) = 20log\left(\frac{|p(f,r_a)|}{p_0}\right)dB \tag{1}$$

The sound pressure p in Eq. (1) is obtained from the Rayleigh integral in Eq. (2), representing the approximation of Kirchhoff – Helmholtz formula [2] for sound radiation.

$$p_{SPL}(f,r_a) = \frac{\rho_0}{2\cdot\pi}\cdot\int_{S_c}\frac{a(f,r_c)}{|r_a - r_c|}\cdot e^{-jk|r_a - r_c|}\cdot dS_c \tag{2}$$

The SPL curves have been computed at the reference point at a one-meter distance from the tip of the dust cap. In Eq. (1) complex accelerations a were taken at each frequency from: 1) FRFs obtained via the laser vibrometer, and 2) FRFs from the FEM analyses.

In both cases only the acceleration component along the loudspeaker's axis was taken into account. Similarly, the distances from the reference point to each node $|\mathbf{r_c} - \mathbf{r_c}|$ were computed from: 1) the two-dimensional grid and the vertical profile of the loudspeaker for the laser measurements, and 2) the three-dimensional CAD model used for FEM simulations. Results of the SPL computations are presented in the next section.

Another integrated quantity was computed: the accumulated acceleration level (AAL). Accumulated acceleration is represented by an integral summation similar to Eq. (2), but without taking into account the phase, as shown in Eq. 3. Hence AAL represents the total mechanical energy of vibration of the radiating surface. The values of AAL and SPL coincide in the frequency range below the break-up, while the loudspeaker is vibrating in the so-called piston mode, when the cone is moving up and down as a rigid body and consequently there is no effect of acoustic cancellation.

$$p_{AAL}(f, r_a) = \frac{\rho_0}{2\cdot\pi}\cdot\int_{S_c}\frac{|a(f,r_c)|}{|r_a - r_c|}\cdot dS_c \tag{3}$$

6. Results and discussion

SPL curves obtained from laser vibrometric tests, FEM analysis and acoustical tests in the anechoic chamber are presented in Fig. 4. Despite the differences in the magnitude of amplitudes the approximate calculation managed to "catch" most of the significant peaks of the SPL and AAL. From the comparison it was concluded that FEM is rather to be used as a tool for sensitivity analysis and qualitative assessment of the loudspeaker response. Fig. 4 shows the congruency of SPL peak frequencies for up to 7 kHz for numerical and experimental results.

Multiple samples of the same 164-mm loudspeakers were tested. Some of them were marked as the "reference", as they provide a response, which is within the manufacturing specifications. Others had defects or deviations from nominal properties or even were far from the nominal SPL curve. Dependency between a particular malfunction and the fluctuation of SPL/AAL is the key to understand the real reasons of good and poor performance. Studying the responses of good and imperfect samples we could draw conclusions about this cause-effect relationship. Subsequently the modal shapes at the peak frequencies, the so-called operational deflection shapes (ODS), were reconstructed from acceleration maps. The ODSs extracted from the experimental measurements with the laser vibrometer correlated quite well with the FEM simulations, an example is illustrated in Fig. 5.

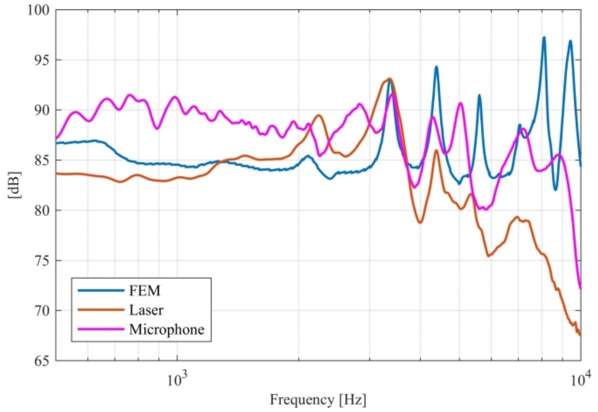

Fig. 4. SPL: laser vibrometer, FEM and acoustic test in anechoic chamber.

Deformations of the cone after the break-up frequency cause the phenomenon of acoustic cancellation, when some areas of the cone start to vibrate in anti-phase with respect to the others, which is the reason why above the break-up frequency the SPL curve always remains below the AAL curve and presents several peaks and valleys, as shown in Fig. 6. The effect of maximum acoustic cancellation results in notches on the SPL curve. From the acoustical point of view smoothing the SPL curve and reducing the quantity and depth of these anti-peaks would deliver better and more stable sound quality on a wider frequency range. But, generally speaking, these notches are not audible, and are not the main problem. The problem is that all the manufactured loudspeakers should, in theory, provide exactly the same SPL curve. Even minor manufacturing variations (weight, quantity of glue, dissymmetry) cause significant modifications of the radiated SPL curve, so that the loudspeaker, albeit working correctly, has an SPL curve which deviates too much form the reference SPL curve, making the unit to be classified as "defective".

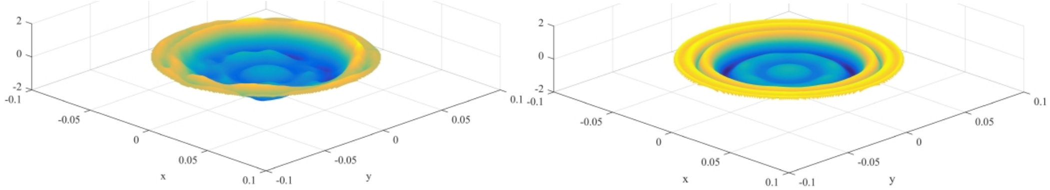

Fig. 5. Operational deflection shapes at 4383 Hz (laser vibrometer) and at 4389 Hz (FEM).

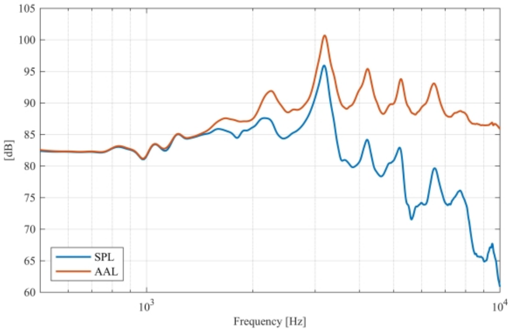

Fig. 6. SPL and AAL curves obtained by laser vibrometry on the “reference” loudspeaker.

Understanding the correlation between these manufacturing deviations and the resulting SPL curve enables to grasp the origin of these “failures”. FEM simulations and experimental laser vibrometry revealed to be powerful tools for evaluating this cause-effect relationship.

7. Conclusions

The study of loudspeaker cone dynamics presented herein consisted of laboratory testing with a laser vibrometer and finite element simulations. The experimental approach benefited from the exponential sine sweep excitation technique coupled with advanced post-processing, which allowed to compute the radiated sound pressure field. Modelling of the loudspeaker in commercial FEM software required estimation of viscoelastic material parameters for every loudspeaker component. This combined approach provided an insight on the vibrational behaviour of a loudspeaker and how small deviations of the manufacturing process modify the acoustic performance of the device. Further investigation on a lager set of samples should help to detect the individual causes of failures (SPL curve out of spec).

Acknowledgements

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References

[1] Farina A., Simultaneous measurement of impulse response and distortion with a swept-sine technique. 108th AES Convention, Paris. February 2000.

[2] Klippel W., Schlechter J., Distributed Mechanical Parameters Describing Vibration and Sound Radiation of Loudspeaker Drive Units. Audio Engineering Society Convention paper 7531. AES Convention 125. October 2008.