Particle velocity sensors for enhancing vehicle acoustic simulations

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Abstract

Numerical simulations are often required in the automotive industry to optimize not only the acoustic performance, but also the durability and crash behaviour of cars. Therefore, validating the model when a prototype is built is remarkably important for improving the current design. Most conventional updating techniques for adjusting the acoustic numerical models inside the cabin use microphones located at different reference positions to compare predictions with real measurements. However, sound pressure is a scalar quantity which does not give information about the often unknown excitation distribution across the structure. This problem can also be addressed by using particle velocity sensors close to the radiating surfaces due to their vector nature. In this paper, the use of particle velocity sensors for updating and validating acoustic models is studied. Furthermore, the spatial resolution for pressure and velocity methods is derived. It has been shown that the use of a combined solution (pressure and particle velocity sensors) improves the numerical model optimization since both materials and excitation sources can be characterized in situ.

Introduction

Vehicle acoustics involves complex interactions between various components and cabin characteristics that can result in unique NVH issues. Optimizing the acoustic performance of a vehicle requires an accurate characterization of the sound sources, as well as the analysis of the cavity interior. It is often difficult to formulate a sufficient physical model because of the complex nature of the problem. Although the wave equations of sound pressure and particle velocity can be easily derived, the boundary conditions are not often well understood [1]. It is therefore necessary to acquire experimental data for the simulated scenario in order to improve, and ultimately, validate the numerical model.

Most of the current simulation and panel contribution techniques require the use of a set of microphones distributed throughout the cabin interior in order to adjust the acoustic models using the real measurement data [2]. Theoretically, the pressure information acquired can also be used to locate the source distribution when applying near field acoustic holography (NAH) or beamforming techniques. However, in practical applications, the use of pressure-based methods for a cabin interior is very limited due to their scalar nature. The inclusion of alternative technologies, such as particle velocity sensors, allows us not only to validate the model but also to gain understanding of the measurement scenario and real source distribution. Features associated with the particle velocity sensor, such as spatial resolution, are discussed in the following sections.

Fundamental material characteristics, such as surface acoustic impedance and sound absorption coefficients, can be measured in situ with a velocity-based approach. A combined solution of a P-U probe (pressure-particle velocity) and a spherical sound source is used in this case, as shown in Figure 1 . The incoming sound field which is generated can be determined when using a calibrated loudspeaker at a fixed distance to the probe. This allows us to distinguish between the acoustic energy, which impinges into the assessed material, and the energy that is reflected back. The acquired acoustic signals can then be introduced into an analytical model to compute the local acoustic properties of the material.

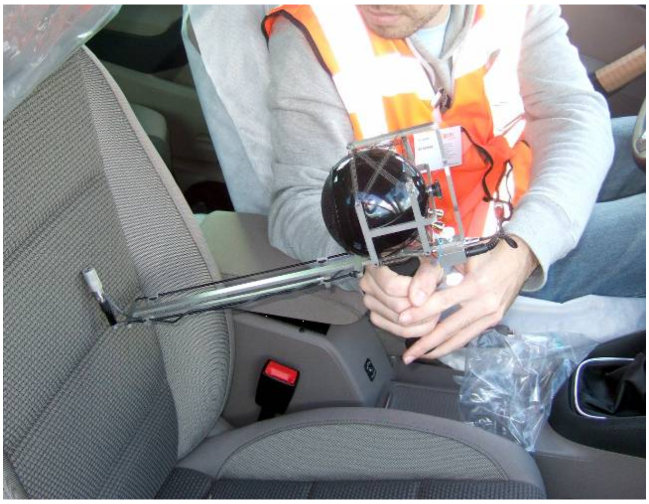

Figure 1: in situ acoustic absorption characterization of a passenger seat.

This paper explores the use of particle velocity sensors and P-U probes for enhancing acoustic simulations based upon the acquisition of experimental data. An overview of particle velocity-based techniques associated with acoustic holography and vehicle acoustics simulations is addressed. In addition, the spatial resolution of a pressure and particle velocity sound field investigation is derived.

Historical perspective

Vibroacoustic problems began to attract the interest of engineers and scientists in 1963 when Lyon [3] first studied the possibility of reducing noise levels in a small cavity, with a flexible wall separating the spectra into three different frequency ranges: low, middle and high. In 1966, Gladwell [4] used a variational formulation to study the fluid structure interaction analytically. In 1972, Craggs [5] started using finite element formulation in the study of vibroacoustics problems in vehicle cabins. Later on, a large amount of literature was focused upon the development of experimental techniques to validate these theoretical formulations, and also, to identify the vibroacoustic modes, i.e. the interaction between structural and acoustic mode shapes. Nowadays, one of the most significant discussions in industrial acoustics concerns finding suitable methods to link sound sources and noise levels at specific locations. There are two fundamental aspects that are commonly addressed separately. Firstly, the estimation of the sound pressure "contribution" from different radiating surfaces. Secondly, the prediction of how such "contributions" could change when an acoustic treatment is applied. Many measurement methods proposed in this area are based on Transfer Path Analysis (TPA) .Figure 2 presents a sketch of the problem.

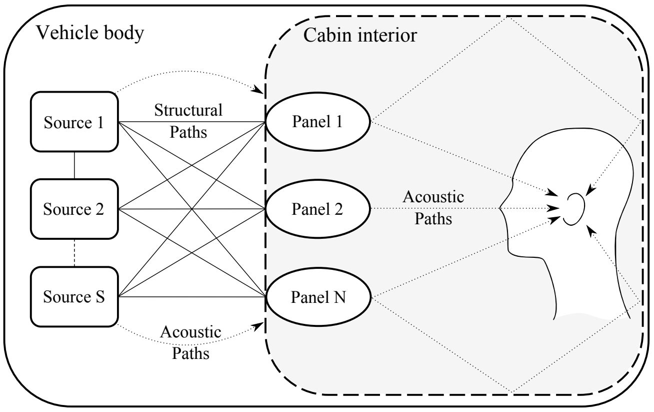

Figure 2: Sketch of a typical Transfer Path Analysis problem regarding structural and airborne transmission paths.

Over the years, particle velocity has been proven to offer several advantages either for use with TPA processing techniques, nearfield acoustic holography or as a numerical validation tool. The first acoustic particle velocity transducer, or "Microflown", was invented in 1994 at the University of Twente by Hans-Elias de Bree [6]. The Microflown transducer consists of two hot wires, situated very close to each other, which resistance difference changes proportionally to the acoustic particle velocity. This Micro-Electro-Mechanical System (MEMS) was introduced to the market in 1997, resulting in a rapid rise in popularity in the global acoustic world. The small size of the transducer, as well as its capability to measure a fundamental property of acoustic fields, inspired the research for its use in a variety of applications.

The validation of a numerical model using particle velocity sensors was first carried out by Visser in 2004 [7]. He performed several inverse acoustic simulations based on IBEM, which were validated separately using structure-borne and air-borne noise sources. Visser observed that the selection of a regularization parameter was more robust when using the particle velocity based method. Furthermore, it was also pointed out that source localization based on particle velocity is likely to yield reconstructed solutions of higher accuracy due its "less blurry" nature.

Several parallel investigations were presented during the following year in acoustic holography [8, 9]. Jacobsen concluded: "The superiority of the method based on measurement of the particle velocity has been confirmed by an experimental study in which the sound pressure and the normal component of the particle velocity were measured at some distance from a vibrating, baffled steel panel with a Microflown p-u sound intensity probe and used to predict the pressure, the normal component of the particle velocity, and the normal component of the sound intensity in a plane closer to the panel". It was also observed that particle velocity has a larger dynamic range than sound pressure since it decays faster when passing over the edges of a source region.

The first application of the Microflown P-U probe, to optimize a vehicle acoustic numerical model, was also presented during 2005 by Duval et al. [10]. The proposed technique, the Vehicle Acoustic Synthesis Method (VASM), did not require any specific measurement environment, enabling the measurement protocol to take a quarter of the time, therefore making it feasible to perform a VASM on a complete car within two weeks. The strong similarity between simulated and experimental results led to the design of an optimized acoustic package which achieved the challenging weight reduction target of 10%, whilst maintaining acoustic performance and the cost. In the following years VASM was also fully validated [11] and numerically adapted for unsteady operating conditions [12].

In 2006 the P-U in situ method was first used in the automotive industry for characterizing acoustic properties of a cabin interior [13]. The acoustic impedance of porous materials were tested using both Kundt's tube and P-U in situ methodology. The complex impedance estimated with the in situ method was shown to be almost independent of distance to the source of the confined environment and to small lateral shifts in source position. In 2007, this methodology was evaluated against a portable Kundt's tube [14] showing the superiority of the P-U method, especially when evaluating soft materials. One year later, a modelling strategy for damping and absorption was presented based on computational optimization and model updating techniques using P-U probes [15]. The comparison with simulated data from Finite Element analyses proved a good qualitative and quantitative agreement, although the estimation method for calculating absorption was in an early stage.

As has been shown, a series of studies have already implemented P-U probes for the validation of acoustic simulations. However, although it has been pointed out by Visser and Jacobsen that the use of particle velocity for detecting noise sources is superior, an analytical explanation have not yet been derived. Therefore, the following section provides a detailed explanation of this phenomenon.

Spatial resolution: pressure against particle velocity

The advantages of using particle velocity sensors instead of pressure microphones for accurately localizing and characterising sound sources with near field conditions are investigated in this section. For the shake of simplicity, we can begin by evaluating the sound field generated by a point monopole source [16]

$$p(r,t) = \frac{A}{r}\, e^{j\omega t - kr} \tag{1}$$

$$u_r(r,t) = \frac{A}{\omega \rho_0 r} \left(k - \frac{i}{r}\right)\, e^{j\omega t - kr} \tag{2}$$

where $p(r,t)$ and $u_r(r,t)$ denote the sound pressure and radial particle velocity, respectively; r is the distance to the source, k is the wavenumber and ω is the angular frequency. When detecting sound sources within a surface which has several excitation points it is interesting to study the spatial resolution of the method. This feature allow us to assess how accurate the estimation of the emitted sound will be, assuming free field conditions. The goal is then to find how much sound is received by the target source situated in front of the sensor compared to any noise source allocated within the same plane at certain distance D. Figure 3 presents a sketch of the evaluated scenario.

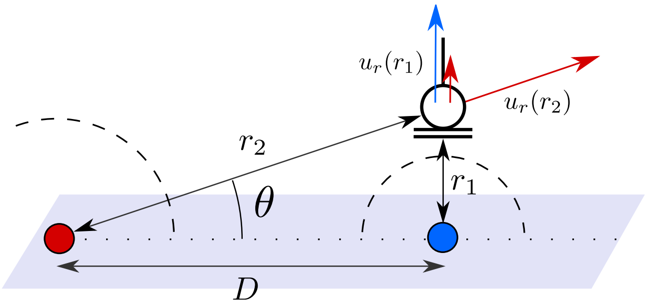

Figure 3: Sketch of the evaluated scenario.

The following conditions can be established in order to guarantee that the signal contribution from the target source is at least double that of any other neighbour excitation

$$p(r_1,t) \geq 2\, p(r_2,t) \tag{3}$$

$$u_r(r_1,t) \geq 2\, u_r(r_2,t) cos(\theta) \tag{4}$$

where r_1 and r_2 are the distances from the measurement probe to the target and secondary sources, respectively; and *theta* is the direction of arrival of the sound from the secondary source. Firstly, evaluating equation (1) using the conditions imposed in equation (3) leads to

$$\frac{r_2}{r_1} \geq 2e^{jk(r_1 - r_2)} \tag{5}$$

Taking the norm of equation (5) and defining $D = \sqrt{r_1^2 + r_2^2}$ results in an expression to describe the minimum separation between sources, guaranteeing the imposed conditions are only dependent on the distance to the source plane, i.e.

$$D_p \geq \sqrt{3} r_1 \tag{6}$$

It can be inferred from the above expression that a pressure microphone can then be linked to an angle of coverage of $(90 - \theta)$ of 60 degrees. The same analytical procedure can be repeated also for the normal particle velocity,

$$\frac{{r_2}^2(k - \frac{i}{r_1})}{{r_1}^2(k - \frac{i}{r_2})} \geq 2e^{jk(r_1 - r_2)} \tag{7}$$

Again evaluating the norm of the last expression leads to

$$\frac{{r_2}^2 \sqrt{(k^2 r_1 r_2 + 1) + k^2 (r_1 - r_2)^2}}{{r_1}^3 (k^2 {r_2}^2 + 1)} \geq 2 \tag{8}$$

Assuming that the measurements are taken under near field conditions $(r_1, r_2 << 1)$, then equation (8) is simplified

$$\frac{{r_2}^3}{{r_1}^3} \geq 2 \tag{9}$$

This leads to

$$D_u \geq \sqrt{2^{2/3} - 1}\; r_1 \tag{10}$$

Once again we can relate the proximity of secondary sources to the angular coverage of the transducer, which in this case corresponds to approximately 37 degrees. Next, the minimum distance D, which ensures a good estimation of the acoustic emission of a target source in presence of secondary excitation, is compared by taking the ratio between equation 6 and equation (10), hence

$$\frac{D_p}{D_u} = 0.44 \tag{11}$$

Therefore, equation (11) shows that, when measuring in front of a target noise source, the influence of secondary excitations is less than half when measuring with a particle velocity sensor instead of a pressure microphone. According to this argument, it is then possible to plot an equivalent spatial weighting function associated with each transducer. In Figure 4 the signal from the target source is compared with the contribution of a secondary excitation along the x-axis. As shown, the use of particle velocity for characterizing sound sources in near field conditions in the presence of other excitations has a far higher signal to noise ratio, which varies with the separation between sensor and radiating plane.

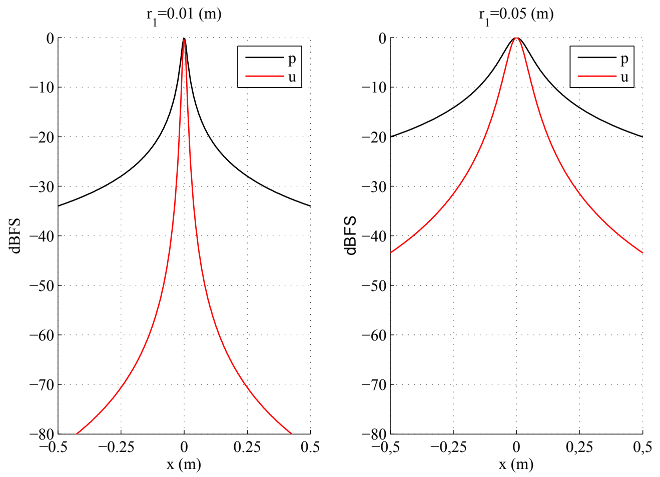

Figure 4: Inherent spatial weighting function of a pressure (black) and particle velocity (red) sensors.

An optical analogy can be used in order to understand Figure 4. If we assume the transducer acts like a light source, the area in front of the sensor would be iluminated following the spatial function shown in the last figure. The resulting acoustic quantity received by the sensor would be the result of integrating the illuminated area. Consequently, a particle velocity sensor would illuminate a narrower area than a pressure sensor, leading to a higher spatial resolution when exploring a sound field with a particle velocity transducer.

Conclusions

The application of particle velocity sensors and P-U probes for enhancing acoustic simulations has been explored. An overview of particle velocity-based approaches associated with acoustic holography, material characterization and vehicle acoustics has been addressed. Finally, it has been proven that the acoustic performance of a particle velocity sensor in terms of spatial resolution is far better than that of a pressure sensor. It has been shown analytically that, providing near field measurement conditions, the influence of secondary excitations is less than half when measuring with a particle velocity sensor instead of a pressure microphone.

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