

Comprehensive Array Measurements of In-Car Sound Field in Magnitude and Phase for Active Sound Generation and Noise Control

Matthias Frank, Franz Zotter, and Alois Sontacchi
University of Music and Performing Arts

Stephan Brandl and Christian Kranzler
AVL LIST GmbH

ABSTRACT

When employing in-car active sound generation (ASG) and active noise cancellation (ANC), the accurate knowledge of the vehicle interior sound pressure distribution in magnitude as well as phase is paramount. Revisiting the ANC concept, relevant boundary conditions in spatial sound fields will be addressed. Moreover, within this study the controllability and observability requirements in case of ASG and ANC were examined in detail.

This investigation focuses on sound pressure measurements using a 24 channel microphone array at different heights near the head of the driver. A shaker at the firewall and four loudspeakers of an ordinary in-car sound system have been investigated in order to compare their sound fields. Measurements have been done for different numbers of passengers, with and without a dummy head and real person on the driver seat. Transfer functions have been determined with a log-swept sine technique.

According to the measurements, the shape of the sound field produced by the shaker is more balanced than one produced by the loudspeakers, albeit the shaker's frequency response is limited to low frequencies. As sound field control is in fact more interesting at those frequencies, our study suggests using shakers for active sound generation rather than loudspeakers.

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INTRODUCTION

Modern vehicles with down-sized combustion engines or electric engines lack the sound that most drivers are familiar with [1,2,3,4]. As a consequence, gears of down-sized engines are not shifted in the optimal engine speed. On the other hand, electric engines produce too little sound to provide reasonable acoustic feedback about engine speed, engine load, and vehicle velocity [5].

To diminish negative effects due to the natural sound of downsized engines (less comfort, manual shifting at too high engine speeds, etc.), the design of the interior sound is considered to be a major target.

For an active design of the engine sound at the driver position, one would like to obtain entire control of the interior sound. This does not only mean that one would like to enable playback of generated sound that is perceived to be coming from the engine (*active sound generation*, ASG, [6]). It also

means that one would like to be capable of erasing all sound that the physical engine produces, especially unwanted sound components that carry the wrong acoustic information (*active noise control*, ANC [7]).

How good can we achieve both goals? Are the goals harder to achieve under varying engine load, number of passengers, and with windows opened?

For ASG, we discuss different ways of producing sounds in a vehicle. A main goal to achieve the correct perceived sound origin is to create a sound field with even magnitude and phase distribution. Only this way we can avoid that sound is perceived to be coming from the loudspeakers of the in-car sound system. For this purpose, a series of sweep measurements [8] are investigated using different loudspeakers and an acoustic shaker. The microphone array employed in the measurements

provides information about the spatial distribution of magnitude and phase within the range of the driver's typical head locations.

ANC only works perfectly in the range of the driver's typical head locations if the sound field of the engine matches in magnitude and phase distribution what the loudspeakers/shakers are able to produce. That's why we employ the same microphone array to measure the engine sound under the same conditions in run-ups at different engine loads. Given the measurements, we can theoretically discuss the upper bound of the ANC performance with a single loudspeaker/shaker, and whether using multiple thereof improves the result. Exemplarily evaluating robustness, we check how good theoretically optimal ANC for one condition can be applied to another one.

MEASUREMENT SETUP

The measurements took place in a 12 m × 14 m × 5 m semi-anechoic chamber at AVL Graz providing entire absorption for frequencies above 85 Hz. The whole space is a box-in-box construction that is isolated from vibrations above 2.5 Hz. The run-ups used 4 dynamometers with 160 kW each.

The measurements employed a planar 6 × 4 array of 24 B&K microphones (B&K 4189 capsules and B&K 2671 preamplifiers) connected to a Müller BBM PAK MKII frontend. The distance between the microphones was 10 cm, cf. [Figure 1](#). The array was adjusted at different heights relative to the seating surface of the driver seat. Dummy head measurements used a B&K 4128C.

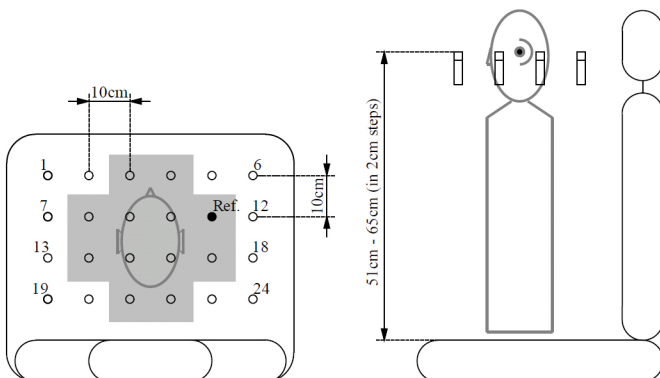


Figure 1. Microphone array employed for the measurements with reference position (11) near the driver's/dummy head ear. Gray area indicates the limited area covering 12 microphones used for a more local ANC.

The test car was a Fiat 500 0.9 TwinAir Turbo with 82 hp built in 2009. Available transducers in the car were the front left, front right, rear left, rear right loudspeakers and an electrodynamic shaker. As loudspeakers, the 4 loudspeakers of the Fiat's stock in-car sound systems were used on an Alpine PMX F460 4-channel amplifier. The Sinuslive Buss-Pump II shaker was mounted on the firewall and powered by a Raveland XCA-400 4-channel amplifier.

The log-swept sine running from 20 Hz to 20 kHz in 7 s was created in the open-source software Pure Data¹ and sent to the amplifiers using an RME Multiface II. For later deconvolution of the impulse responses, the sine sweep was also recorded to an additional channel of the PAK frontend.

COMPARISON OF LOUDSPEAKERS AND SHAKER

This section compares the transfer functions from each transducer (4 loudspeakers and the shaker) to the reference microphone position. Moreover, their magnitude and phase is examined for multiple positions around the reference position.

As varying conditions (number of passengers and open windows) will naturally occur in practice, we also investigate their influence on the transfer functions.

At the reference position close to the driver's right ear, the transducer's frequency responses are given in [Figure 2](#). In the frequency range of operation, all the responses can technically be equalized by filters [9]. For the shaker, frequencies above 300 Hz would require a boost of 40 dB. Without this equalization, it could only reproduce engine sound up to the third order. A combination of the shaker for sounds below 300 Hz with the loudspeakers for sounds above appears promising.

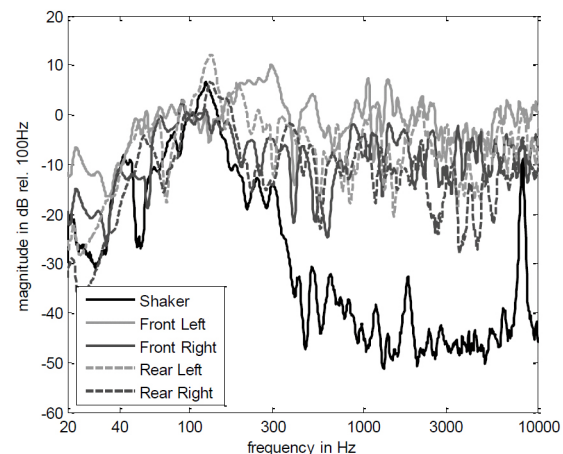


Figure 2. Frequency response (transfer function) from transducer (various loudspeakers and shaker) to reference microphone position, normalized at 100 Hz.

Along all the 24 channels of the measurement array, we can observe the spatial sound pressure distribution in magnitude and phase, as given in [Figure 3](#). This can be done for any transducer in the car interior at every frequency, and the contour reveals where the sound is originating from: phase grows positive towards the origin of the sound.

1. Pure Data (Pd) is a visual programming language for creating interactive computer music and multimedia works. Pd is an open source project with a developer base working on new extensions. It is released under a license similar to the BSD license. It runs on GNU/Linux, Mac OS X, and Windows.

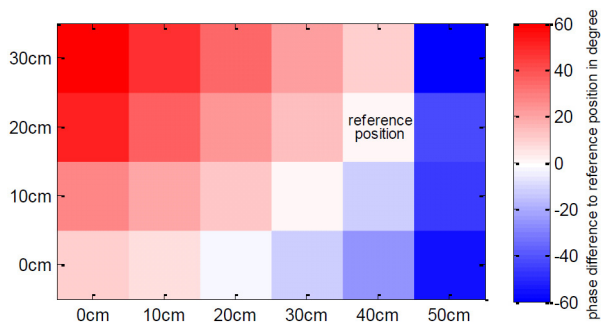


Figure 3. Spatial phase distribution of sound pressure created by the front left loudspeaker of the in-car sound system at 150 Hz. Phase values are relative to a reference position.

To provide reasonable large-scale ASG and ANC, we desire an as uniform as possible magnitude and phase distribution at the measurement positions. Phase should not fluctuate more than $\pm 30^\circ$ ($\approx \pm \pi/6$) and magnitude should stay within ± 3 dB in order to maintain good performance. For ANC one can easily check that a mismatch by a factor $\alpha = 10^{\pm \frac{3}{20} e^{\pm i \frac{\pi}{6}}}$ can be tolerated as it still causes a fair cancellation of $20 \lg(1 - \alpha) < -2.6$ dB. Mismatch greater than ± 4 dB and $\pm 40^\circ$ will increase the noise level instead of the intended reduction.

Providing an overview of the applicability of available transducers in the important frequency range, the number of measurement points within the $\pm 30^\circ$ and ± 3 dB tolerance are counted for every frequency and plotted in terms of an equivalent area. Obviously, the size of the area decreases towards smaller wavelengths of the sound, i.e. higher frequencies.

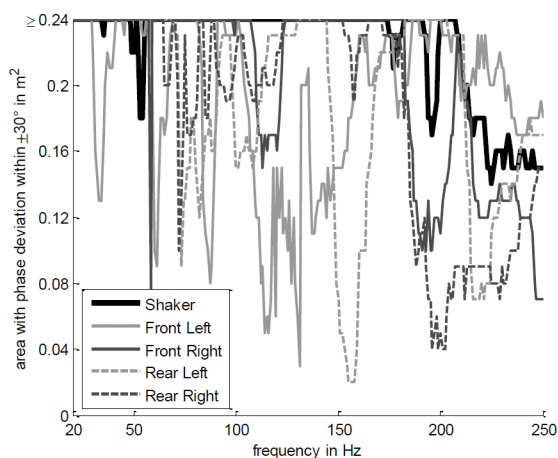


Figure 4. Equivalent area of tolerated phase for all transducers.

Figures 4 and 5 show the equivalent area of tolerated phase and magnitude, respectively. It appears for both phase and magnitude that the shaker is outperforming all the loudspeakers of the in-car sound system in the frequency range of 20 Hz to 250 Hz. Due to the smaller fluctuation of the equivalent area of tolerated phase and magnitude, the distant loudspeakers on the right side seem to be preferable over left-side loudspeakers directly next to the driver. As phase and

magnitude diagrams contain congruent information, the subsequent analysis of varying conditions focus on the equivalent area of tolerated phase.

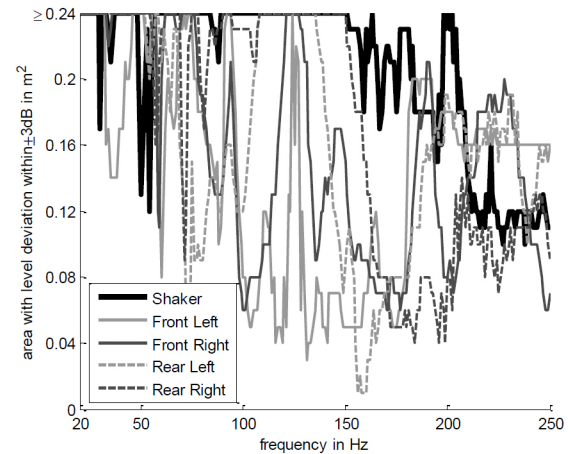


Figure 5. Equivalent area of tolerated magnitude for all transducers.

Influence of Array Height

The previous figures employed the microphone array at a height of 65 cm above the seating surface of the empty driver seat. Figure 6 presents the equivalent area of tolerated phase for the shaker measured for array heights from 51 cm to 65 cm. The array height barely influences the equivalent area. This holds true for the loudspeakers.

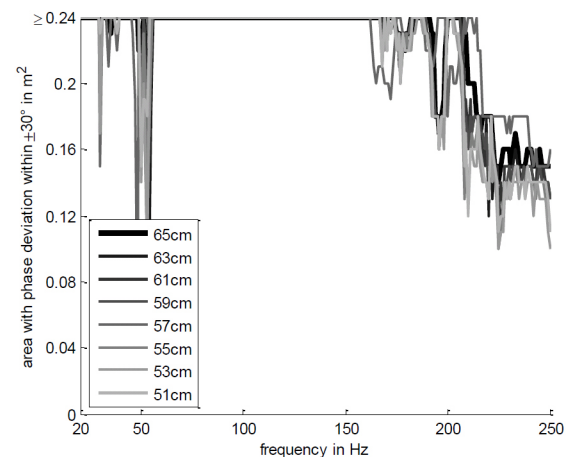


Figure 6. Equivalent area of tolerated phase for shaker measured at different array heights relative to the seating surface of the driver seat.

Influence of Number of Passengers

Figure 7 presents the influence of different numbers of passengers (0 to 4) on the equivalent tolerance area of the shaker for the microphone array at 65 cm on the driver seat. Note that the microphone channels 9, 10, 15, and 16 were not recorded when the dummy head or the driver was sitting within the microphone array. The phase values of these channels were set to the same values as at the reference position. Thus, the equivalent area cannot fall below 0.05 m^2 .