inter noise
2013 | INNSBRUCK | AUSTRIA
15.-18. SEPTEMBER 2013
NOISE CONTROL FOR QUALITY OF LIFE

Analysis of the contributions from vehicle cabin surfaces to the interior noise

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ABSTRACT

In order to optimize the acoustic package of a vehicle, cost and weight are, besides the acoustical performance, the fundamental objectives. Detailed knowledge about the noise emitting surfaces in the vehicle interior is important for an efficient development process. To analyze contributions from vehicle cabin surfaces to the interior noise, the panel noise contribution analysis method is applied. In a first step, a transfer path analysis from the surfaces to a response position in the vehicle is performed. For the reciprocal method a monopole sound source with measured volume velocity and particle velocity sensors near the panels are used. To preserve phase information while repositioning the panel sensors, pressure microphones complete the setup. The second step is to actually measure the particle velocity at predefined panel positions while the cabin is excited from the outside. The analysis results are contributions from the cabin surfaces to the interior noise, identifying critical panels, which have to be regarded in the further selection of damping and insulation during development of the acoustic package.

Keywords: Panel Noise Contribution Analysis

1. INTRODUCTION

In the acoustic engineering of a vehicle the important goals are to achieve a specific sound and to reduce the perceived loudness in the cabin. For an efficient engineering process it is essential to have detailed knowledge about the contributing sound sources. The various panels of the cabin radiate sound to the interior and contribute to the overall sound pressure. In the sound engineering process the contributions of the panels have to be evaluated, for example to rank the panel contributions according to the interior sound pressure levels, in order to decide where to apply noise reducing materials.

The complex sound field in a vehicle cabin sets high demands on the analysis method. An airborne transfer path analysis (TPA) method, based on particle velocity measurements, has already shown its applicability [1]. With this method the contributions of the various panels to the vehicle interior noise can be analyzed in a quite fast way on the vehicle test bench [2] and in real operating conditions [3]. Common issues like airborne sound leaks in the cabin or contributions from other panels on the re-

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garded panel are resolved [4]. This so called panel noise contribution analysis (PNCA) is of course not only applicable in the automotive sector, but for example also in aviation [5] and railroad [6] engineering, where noise problems in enclosed spaces have to be assessed.

It has been shown that in typical automotive applications the particle velocity should be measured at approximately 150 panel positions [7]. Since the entire measurement setup would therefore require 150 particle velocity sensors and a measurement frontend capable of simultaneously recording more than 150 channels, the particle velocity is typically measured in multiple runs with a smaller setup, where sensors are moved between measurements. However, if the measurements are split, phase relations between the particle velocity signals are lost, which will lead to analysis errors. To compensate this effect, the method is extended by sound pressure measurements at a reference position to reconstruct the particle velocity with regard to phase relations [8].

After a brief introduction in the basics of PNCA, an overview of the measurement setup used for the presented measurements will be given. The reconstruction of the sound pressures and particle velocities near the radiating panels from one or multiple reference sound pressure signals and its effects on the analysis result will be discussed. For the reconstruction operational transfer path analysis (OTPA) [9] was applied, which has already been used for vehicle interior noise analysis [10]. The panel noise contributions will be presented with special focus on sound pressure and particle velocity contributions to investigate the simplification that the sound pressure contribution can be neglected [11].

2. THEORY

The PNCA basically consists of two measurements, the recording of sound pressures and particle velocities near the radiating panels and the measurement of the transfer functions from the panel positions to a response position. The sound radiation of the panels can be measured in any operating condition which needs to be addressed, e.g. in case the vehicle is excited with an external sound source, on a vehicle test bench or on the road. In order to measure the particle velocity and also the sound pressure, a special sensor is used that is able to measure both quantities near the radiating panel [12]. For the transfer function measurement between both panel signals and response signals the reciprocity principle is applied, using a monopole sound source with measured volume velocity [13].

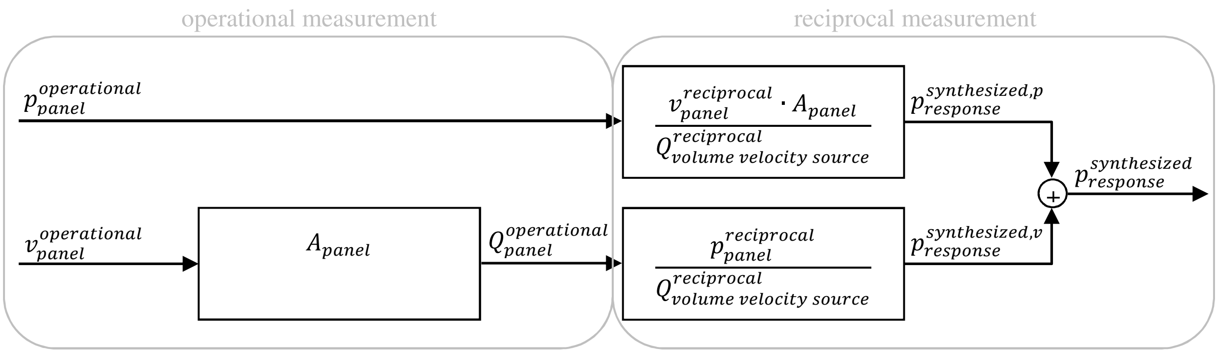

Figure 1 – Calculation of the panel noise contribution for a single panel, i.e. one sound pressure *p* and particle velocity *v* sensor, with panel size *A* and volume velocity *Q*.

An outline for the calculation of the contribution of a single panel to the sound pressure at a response position, e.g. the driver ear, is given in Figure 1. The sound pressure and particle velocity near the radiating panel from the operational measurement on the left side, and the transfer functions calculated from the reciprocal measurements on the right side, are used to calculate the contributions to the sound pressure at the response position. The upper path calculates the sound pressure related part of the panel contribution and the lower path the particle velocity related contribution. This calculation has to be repeated for all panels to receive the contribution of each panel to the interior noise. The sum of all contributions should be comparable to the sound pressure at the response position during the operational measurement. As already stated, the typical number of panels for a car cabin is about 150, which poses a problem for the measurements, since such a large measurement setup is rarely available. To solve this dilemma, several operational and reciprocal measurements each with a different subset of panels are conducted. The number of measurements depends on the number of available sound pressure and particle velocity sensors. An issue with this solution is that for the separate measurements the phase relations between the panels are not preserved.

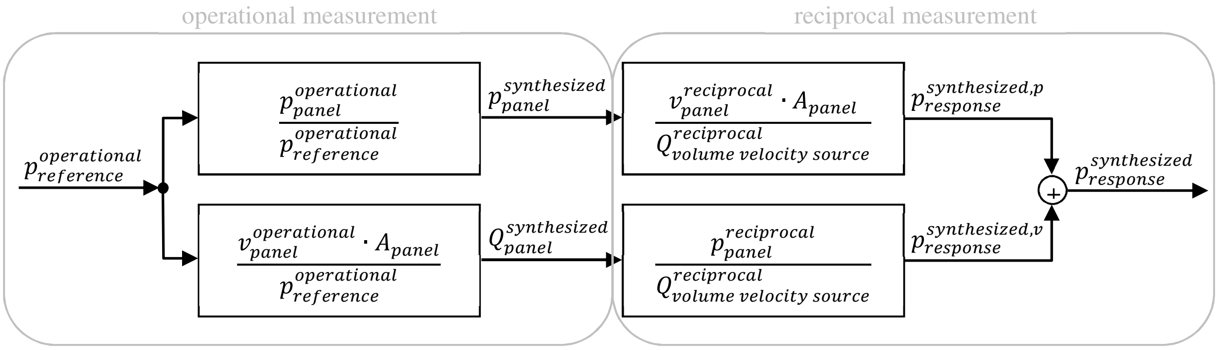

Figure 2 – Calculation of the panel noise contribution for a single panel, i.e. one sound pressure p and particle velocity v sensor, with panel size A and volume velocity Q, extended to preserve the phase relation between the panels of the vehicle cabin.

A solution to the problem of phase relations between panels is given on the left side of Figure2. Instead of using the operational panel signals that were measured in different runs, the idea is to reconstruct all panel signals from a reference signal of a single measurement. Therefore the operational measurements are extended by reference sensors, e.g. sound pressure microphones in the vehicle cabin. Transfer functions between the sound pressure and particle velocity at the panels and the reference signals can be calculated directly for a single reference signal or with OTPA for multiple reference signals. With the operational transfer functions the sound pressure and particle velocity signals for all panels can be reconstructed from the reference signals of a single measurement, thus preserving the phase relations between the panels and accordingly the calculated panel contributions.

3. SETUP

For the measurements presented here, a middle-class limousine in a semi-anechoic room was externally excited with a dodecahedron loudspeaker for the operational measurements. The loudspeaker was positioned outside the vehicle cabin in a distance of approx. 50 cm to the right front side window. Only panels on the passenger side of the vehicle cabin were measured for the analysis.

Figure 3 – The measurement setup with loudspeaker and sound pressure and particle velocity sensor array.

An array of 12 combined sound pressure and particle velocity sensors has been used to measure the interior side of the cabin panels. The sensors were organized in a fixed grid of 3 by 4 with a distance of 7.5 cm between the sensors. This array was moved to measure the entire passenger side, keeping the distance of 7.5 cm between the sensors, resulting in 140 panels. This resolution leads to an upper frequency limit for the analysis of approx. 2 kHz due to spatial aliasing [14].

The reciprocal measurements of the transfer functions between the panel positions and the response position were done using a mid to high frequency volume velocity source with a frequency range from 200 Hz to 4 kHz [15], placed at the response position, in this case where the right driver ear would have been. To assure the same sensor positions for operational and reciprocal measurement, both measurements were done in successive order, i.e. before repositioning the sensor array. The volume velocity source imposes the lower frequency limit of the analysis at 200 Hz.

In order to calculate the operational transfer functions used to preserve phase relations between the panel signals, several reference positions in the cabin were selected. Most positions were possible passenger positions, i.e. driver left and right ear, front passenger left ear and rear right passenger left ear. Two positions were selected near the driveshaft tunnel, one close to the dashboard and one near the front seat. Each reference position was equipped with a standard ½" measurement microphone.

4. RESULTS

Before the final results of the analysis, i.e. the panel contributions to the interior noise, are discussed a closer look on the operational measurements will be presented. Since the panel noise contribution analysis is done with 19 separate measurements to cover the whole right vehicle side, an analysis without phase consideration is not presented here. Some overlap of the panel sensors due to the rectangular array size leads to a larger number of measurements than estimated by the real sensor count and the panel positions. For phase matched panel sound pressure and particle velocity signals, the panel signals are synthesized from one or multiple reference microphone signals from a single operational measurement. The transfer functions for this synthesis are calculated from the operational measurements.

4.1 Panel Sound Pressure and Particle Velocity

Since the originally measured panel sound pressures and particle velocities are not directly used for the contribution analysis, but synthesized signals with matched phase, calculated using transfer functions between the reference positions and the panel positions, the match of measured and synthesized panel signals has to be reviewed.

4.1.1 One Reference Position

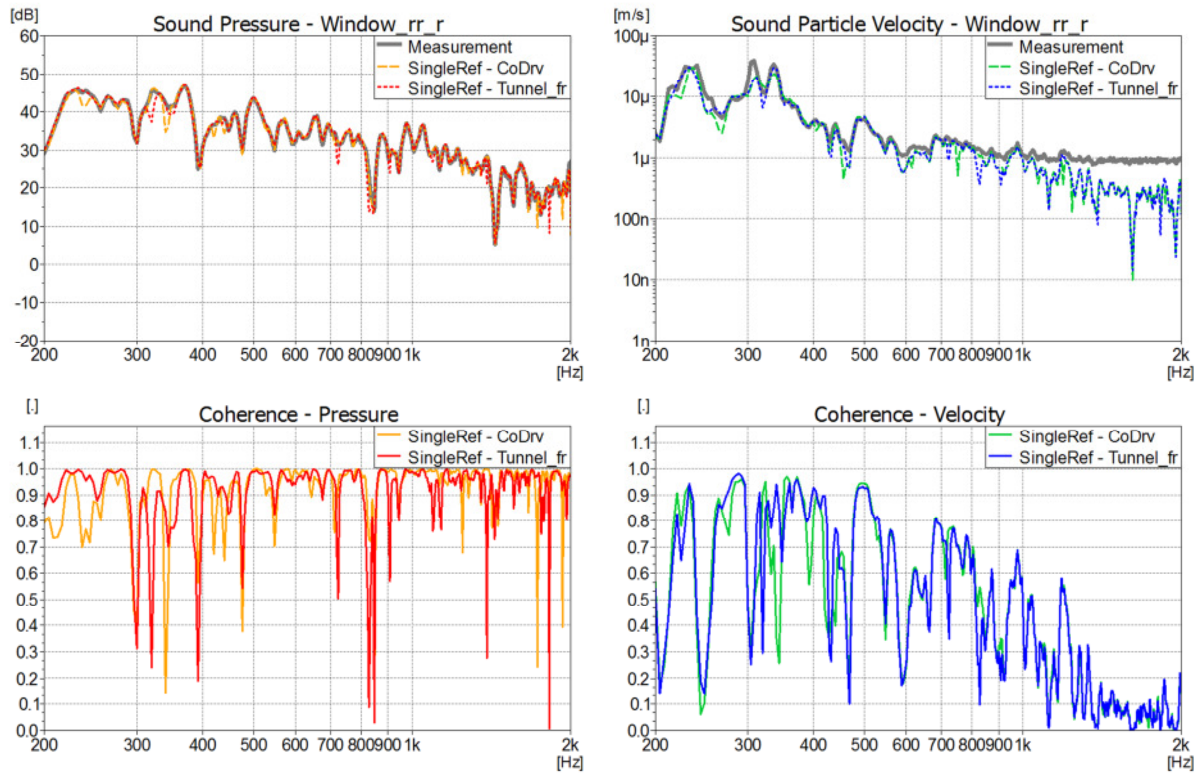

Figure 4 – Reconstruction of the sound pressure (left) and particle velocity (right) at one panel on the rear window for two different reference positions, the front passenger left ear (CoDrv) and the driveshaft tunnel close to the dashboard (Tunnel_fr). In the upper diagrams magnitude spectra also of the measured sound pressure and particle velocity and in the lower diagrams coherence between measured sound pressure and particle velocity at the panel and sound pressure at the reference positions are shown.

For the case of a single reference signal a comparison between measured and synthesized panel sound pressure is given in Figure 4 on the left, and for the particle velocity on the right. Both sound pressure and particle velocity were measured and synthesized for a single panel position on the rear window. Two reference positions were chosen for comparison of the synthesized panel signals, the front passenger left ear and the driveshaft tunnel close to the dashboard. The synthesis of the panel sound pressure, the upper left diagram in Figure 4, shows very good agreement to the measured signal over the whole analysis frequency range. Also the coherence between the signals used for the transfer function calculation, i.e. the reference and the panel sound pressure, illustrated in the lower left diagram of Figure 4, is very high. In case of the particle velocity the synthesis of the panel signal, shown in the upper right diagram of Figure 4, is very good up to 1 kHz and from there on gets worse with increasing frequency. The corresponding coherence of reference signal and panel signal, illustrated in the lower right diagram of Figure 4, shows a similar trend. The low coherence and the low particle velocity values above 1 kHz indicate that the actual particle velocity was below the sensitivity of the sensor leading to a bad signal to noise ratio for higher frequencies.

Even though quite different positions of the reference sensors were chosen, e.g. at the front seats, the back seat or the driveshaft tunnel, none of the single reference positions was significantly better or worse for the reconstruction of the panel signals.

4.1.2 Multiple Reference Positions

Instead of applying a single reference signal to reconstruct the panel signals, multiple signals measured at different positions in the vehicle cabin from one operational measurement can be used. For the estimation of the transfer characteristic between multiple reference and panel positions OTPA is applied. Each contribution from one reference signal to one panel sound pressure or particle velocity is calculated separately. Subsequently the contributions of the multiple reference signals are summed up to the panel sound pressure or particle velocity signal.

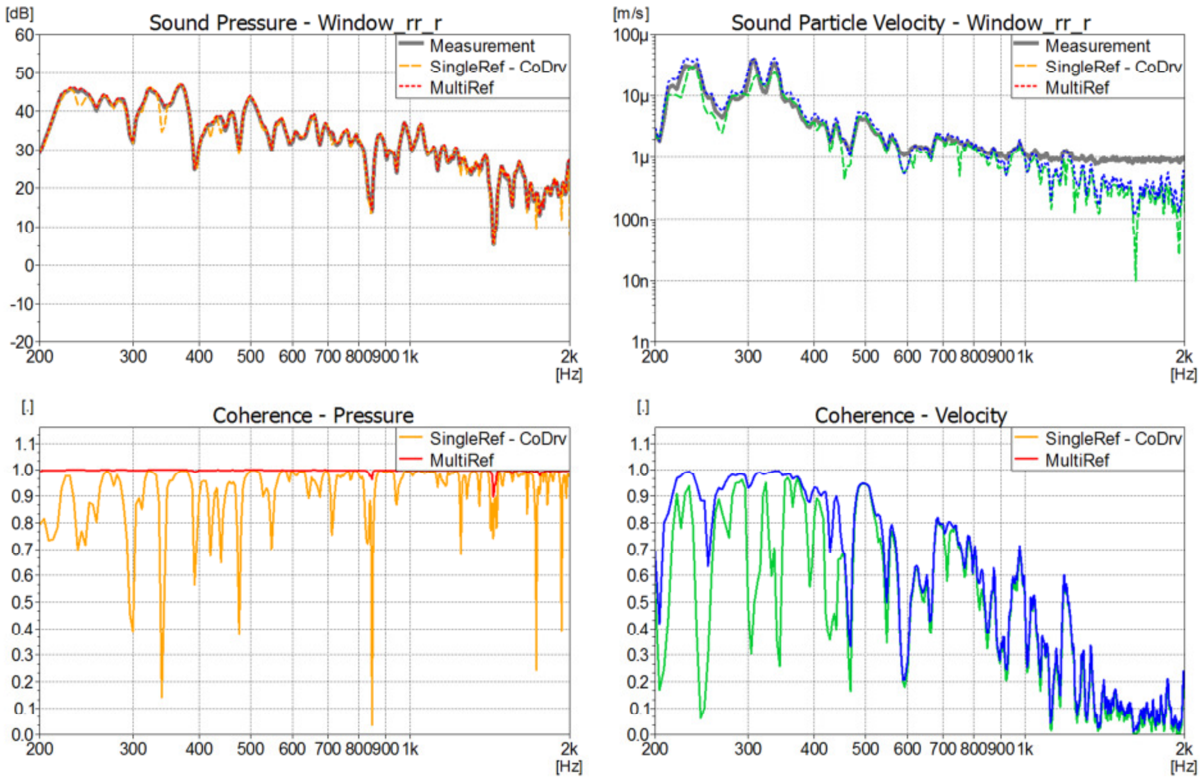

Figure 5 – Reconstruction of the sound pressure (left) and particle velocity (right) at one panel on the rear window for a single reference position, the front passenger ear left (CoDrv), and multiple reference positions (MultiRef). In the upper diagrams magnitude spectra also of the measured sound pressure and particle velocity and in the lower diagrams coherence between measured sound pressure and particle velocity at the panel and sound pressure at the reference positions are shown.

The synthesis of the panel sound pressure in the upper left diagram of Figure 5 is very good for both single and multiple reference signals, only for some frequencies the synthesis from multiple reference signals is better. The same trend can be seen for the coherence in the lower left diagram of Figure 5, over the entire analysis frequency range the coherence between the reference and panel signals is very good. The results for the panel particle velocity are quite similar, both synthesis and coherence are very good and at some frequencies the analysis with multiple reference signals shows better results. Of course the same restrictions for the frequency range as already discussed in Chapter 4.1.1 apply. Above 1 kHz the deviation between measured and synthesized particle velocity increases with increasing frequency.

At some frequencies the synthesis results are better if the calculation used signals from multiple reference points. However, the synthesized sound pressure and particle velocity signals using a single reference signal are already very good, so one can argue if the higher effort for measuring and analyzing multiple reference signals is essential.

4.2 Panel Noise Contributions

In order to analyze the contributions from different panels to the interior noise, transfer functions from the panel sensors to a response point in the cabin must be measured and calculated. The transfer functions are calculated directly from the reciprocal measurements with the measured volume velocity of the monopole sound source and the corresponding sound pressure and particle velocity signals at the panel positions. Together with the synthesized panel sound pressure and particle velocity signals the corresponding contributions to the interior noise at the response position can be calculated.

4.2.1 Contributions from Doors and Windows

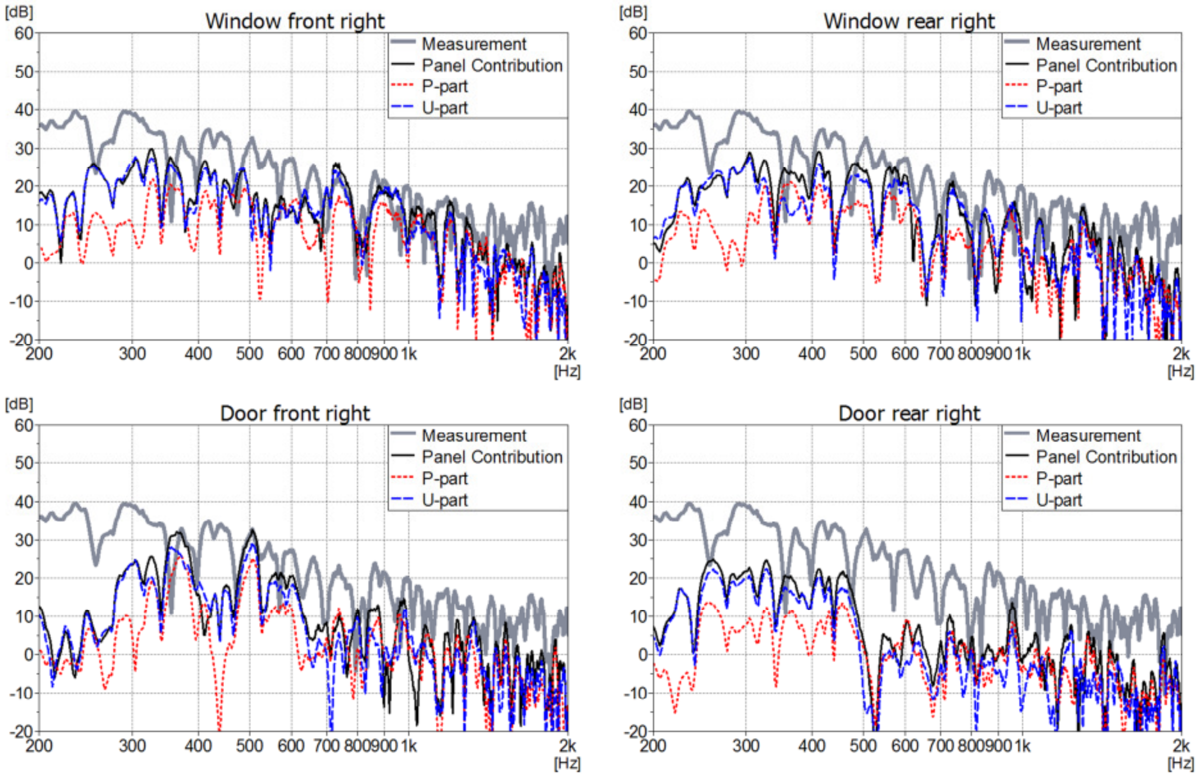

Figure 6 – Sound pressure and particle velocity related contributions to the vehicle interior noise for different panels on the right vehicle side, i.e. the windows in the upper diagrams, the doors in the lower diagrams, the vehicle front on the left side, and the rear on the right side.

Depicted in Figure 6 are the contributions of the windows in the upper, the doors in the lower, for the vehicle front on the left and the vehicle rear in the right diagrams. The separate contributions of all 140 panels, each with sound pressure and particle velocity, were calculated and summed up for the graphs in Figure 6. It can be seen that the different panels or areas of the doors contribute more or less to the overall interior noise. For example the lower part of the doors, where damping material and a porous surface structures are mounted, contribute generally less to the sound pressure at the driver position than the windows. Two exceptions have to be pointed out, around 360 Hz and 500 Hz the front door seems to have a dominant influence on the interior noise. Otherwise the windows are the dominant contributors to the interior noise, at different frequencies one or the other. The front window, which is closer to the excitation and the response position, is not always the crucial contribution.

Also noticeable in the diagrams of Figure 6 is that the particle velocity related contribution is nearly always the dominant one. This confirms the common simplification to analyze only the particle velocity based contributions. Here, it is not only the case for the rigid surface of the glass windows, but also for the rather soft and porous surface of the door.

4.2.2 Contribution from all panels

Of course the contributions can be further combined to an overall contribution, which can be compared to the response signal measured during an operational measurement, thereby testing the analysis results for possible errors.

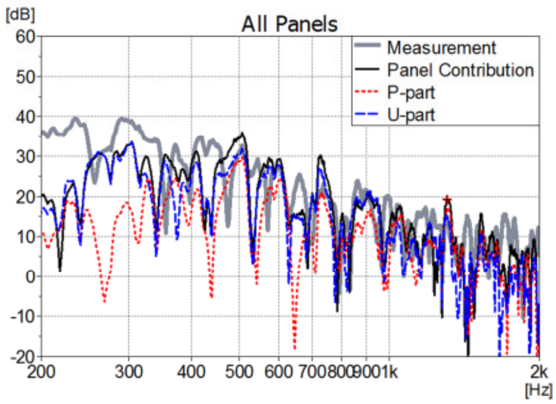

Figure 7 – Sound pressure and particle velocity related contributions to the vehicle interior noise for the right vehicle side.

The comparison between synthesized overall interior noise and the measured interior noise can be seen in Figure 7. The general agreement is quite good, but for some frequencies rather large differences can be found. However, one has to keep in mind that only the right side of the vehicle was measured and therefore contributions from other vibrating panels are missing in the analysis. Again up to 1 kHz the particle velocity related contributions are the dominant share of the vehicle interior noise, confirming previous findings.

4.2.3 Contribution map for all panels

For a general overview of the contributions of the 140 panels to the interior noise and their respective locations in the vehicle, a map of the calculated contributions can be laid over a picture of the vehicle interior.

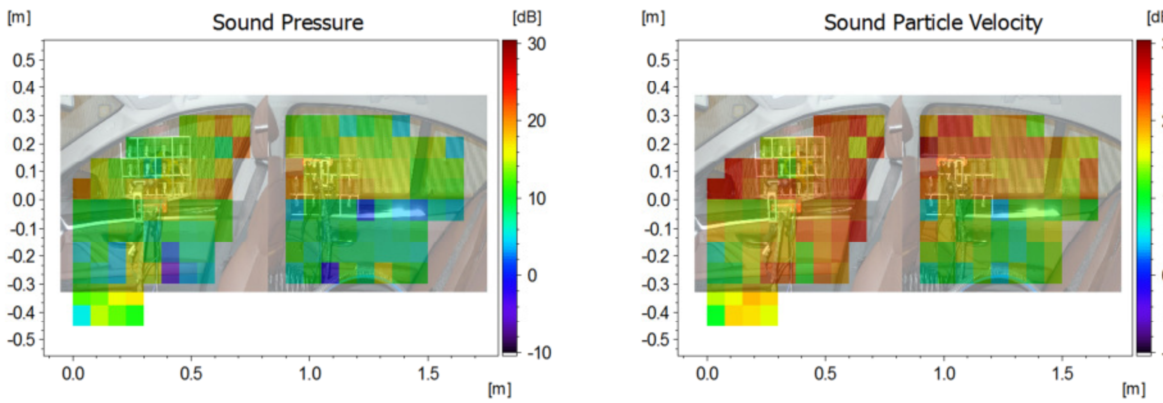

Figure 8 – Sound pressure (left) and particle velocity (right) related contributions to the vehicle interior noise for the panels on the right side of the vehicle.

A map of all contribution sound pressure levels over the whole analysis frequency range from 200 Hz to 2 kHz is displayed in Figure 8. As already expected the sound pressure related contributions in the left diagram are generally low compared to the particle velocity related contributions in the right diagram. Some bigger sound pressure related contributions near the window edge may be explained by leakage, i.e. airborne transfer paths into the vehicle. The particle velocity related contributions are, as already seen, bigger in the front than in the back and bigger for the windows than for the lower door. This was expected since the loudspeaker is positioned outside the front window and the response position is on the driver seat.

5. CONCLUSION

Sound pressure and particle velocity related contributions of radiating cabin surfaces to the vehicle interior noise were analyzed by panel noise contribution analysis. Since the cabin panel sound pressure and particle velocity have to be measured at many positions, e.g. 140, the measurement of the panel positions is typically split in separate runs. In order to preserve the phase relation between the panel signals over several measurements, the method was enhanced by reference signals to synthesize the panel signals from a single excitation measurement.

The results of the measurements showed that the reconstruction of the panel sound pressure and particle velocity signals works very good. Also the panel noise contribution analysis demonstrated its applicability. Resulting sound pressure and particle velocity based contributions show, frequency dependent, the dominant panels for the vehicle interior noise, allowing efficient optimizations of the acoustic package of the vehicle.

ACKNOWLEDGEMENTS

This work was supported by the Bavarian Research Foundation as part of the FORLärm research cooperation for noise reduction in technical equipment.

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