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Measurement of Sound Pressure Contributions in Pass-By-Noise Tests Using Particle Velocity Sensors

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Summary
In conventional pass-by-noise tests, the vehicle noise emission level is determined with a microphone at a specified distance from a test track while the vehicle drives by. Although these tests offer a simple approach to assess the overall performance, they do not yield information about the sources of noise distributed across the vehicle. Methods to determine the influence of local excitations can be useful for manufacturs attempting to apply an effective noise reduction treatment.
Acoustic beamforming methods can be applied at high frequencies for moving structures to locate noise, but they have difficulties quantifying the impact of each source on the sound pressure next to the test track.
In this paper, a method is presented to determine the sound pressure contributions using a panel noise approach based on direct measurements of particle velocity. The sound pressure contribution for separate car positions is calculated by combining the sound radiation and the acoustic transfer path. The time-averaged result, representing the sound radiated from a vehicle driving by, is ultimately obtained by spatially averaging the contributions at these positions.
To validate the methodology, a measurement was performed with a set of loudspeakers mounted on a car. The measurement method and test results are presented, and the advantages and limitations of the novel method are discussed.

PACS no. 43.40.-r, 43.50.-x

1. Introduction

Traffic noise is one of the most important noise sources in industrialized countries. Regulations have been established to limit emission [1]. In the ISO 362 standard, a pass-by noise test is described for cars [2, 3]. However, with this method engine, tyre, exhaust, and aerodynamic noise are all measured simultaneously. Some of these sources can be excluded in engine bench or wind tunnel tests for example, but it remains difficult to determine the influence of separate components.

Sound pressure based methods, such as Nearfield Acoustic Holography, sound intensity, or Beamforming, are sometimes used to identify noise sources during pass-by tests [4, 5, 6, 7, 8]. Most of these techniques often encounter difficulties in terms of spatial resolution and accuracy when adapting from controlled experiments to industrial applications.

Here, an adapted version of the panel noise contribution analysis (PNCA) method is applied. The PNCA method used is based on the directed measurement of particle velocity with p-u probes, which contain a sound pressure sensor and a particle velocity sensor. With such probes, the noise radiation can be captured even in environments with a lot of reflection and background noise [9]. Initially, the technique was applied inside a car, where the sound pressure contributions from all panels in the car interior were determined at a reference position, usually the driver's ear [10, 11, 12, 13, 14]. The sound pressure at the reference position can be calculated by summing all contributions. The effect of applying additional damping materials or reducing the excitation levels of panels can be assessed by re-calculating the calculated sound pressure while partly excluding certain contributions. Compared to other PNCA techniques, the measurement time can be substantially reduced with the p-u based approach while keeping the sound field almost undisturbed [15, 16]. The technique has also been used for other applications such as pumps, HVAC's, helicopter and train interiors, [17, 18, 19, 20, 21].

In this paper, PNCA is used to determine the noise contribution from different components as would be experienced in a pass-by noise test. For the first time, the method is used to calculate the sound pressure contributions for a situation where the position of the source relative to

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the reference position changes over time. The PNCA tests themselves are performed for a set of fixed positions. By combining the results from several positions, the noise from a moving vehicle is reconstructed.

After presenting the fundamentals of PNCA, an extended method for pass-by measurements on cars is described and analyzed through a measurement.

2. Theory

The PNCA method involves the calculation of sound pressure contributions from a radiating surface to a specified reference position. Figure 1 shows a sketch of the scenario. As shown in [8], the sound pressure p_{ref} located at the reference position $\mathbf{M}$ due to a continuous radiating surface S can be derived from the Kirchhoff-Helmholtz Integral using Green's functions

$$p_{\mathrm{ref}}(\mathbf{M}) = \int_S \left(G(\mathbf{y}|\mathbf{M}) \frac{\partial p(\mathbf{y})}{\partial n} - p(\mathbf{y}) \frac{\partial G(\mathbf{y}|\mathbf{M})}{\partial n} \right) \mathrm{d}S, \quad (1)$$

where $p(\mathbf{y})$ is the sound pressure at position $\mathbf{y}$ on surface S, $\partial/\partial n$ denotes normal derivative on the surface and $G(\mathbf{y}|\mathbf{M})$ is the Green fuction that relates the propagation between the points $\mathbf{y}$ and $\mathbf{M}$. Under free-field conditions, Green's function can be determined via analytical solutions. However, most practical scenarios contain elements that affect sound propagation between the assessed points. Alternatively, Green functions can also be acquired experimentally by measuring the acoustic pressure perceived at a point $\mathbf{M}$ in response to a monopole sound source of controlled source strength $\mathrm{j}\omega\rho Q$ [22], therefore

$$G(\mathbf{y}|\mathbf{M}) = \frac{p^{\mathrm{TF}}(\mathbf{M})}{\mathrm{j}\omega\rho\, Q_y} \quad (2)$$

where Q_y is the volume velocity of the monopole sound source located at $\mathbf{y}$, ω is the angular frequency, ρ is the density of air and $p^{\mathrm{TF(M)}}$ is the sound pressure measured when a monopole source is exciting the sound field. It should be noted from Equation (2), that a monopole source needs to be placed at every measurement position $\mathbf{y}$. A reciprocal measurement is often easier to perform. According to the reciprocity theorem, source and receiver can be interchanged as long as the spatial domain can be considered time-invariant, as a result

$$G(\mathbf{y}|\mathbf{M}) = G(\mathbf{M}|\mathbf{y}) = \frac{p^{\mathrm{TF}}(\mathbf{y})}{\mathrm{j}\omega\rho\, Q_M}. \quad (3)$$

According to the Euler's equation of motion, the spatial derivative of sound pressure and the acoustic particle velocity are related as such

$$\frac{\partial p(\mathbf{y})}{\partial n} = \mathrm{j}\omega\rho\, u_n(\mathbf{y}). \quad (4)$$

This fundamental relationship makes it possible to obtain an expression for the spatial derivative of the measured Green's function given in Equation (3) as such

$$\frac{\partial G(\mathbf{y}|\mathbf{M})}{\partial n} = \frac{\partial p^{\mathrm{TF}}(\mathbf{y})/\partial n}{\mathrm{j}\omega\rho\, Q_M} = \frac{u_n^{\mathrm{TF}}(\mathbf{y})}{Q_M}, \quad (5)$$

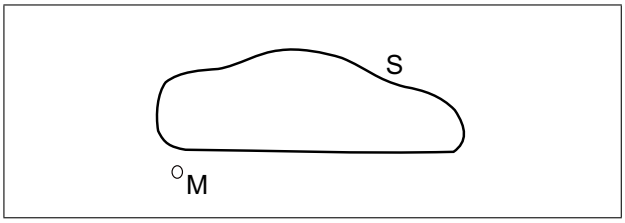

Figure 1. Schematic overview of a radiating surface.

where u_n^{TF} represents the acoustic particle velocity measured normal to the surface S when exciting the sound field with a monopole source located at the reference position.

The combination of above equations yields

$$p_{\mathrm{ref}}(\mathbf{M}) = \int_S \left(\frac{p^{\mathrm{TF}}(\mathbf{y})}{Q_M} u_n(\mathbf{y}) - p(\mathbf{y}) \frac{u_n^{\mathrm{TF}}(\mathbf{y})}{Q_M} \right) \mathrm{d}S. \quad (6)$$

In practice, surface S is subdivided into N small sections of area ΔS denoted as *panels*. Consequently, Equation (6) can be written in a discrete form as

$$\hat{p}_{\mathrm{ref}}(\mathbf{M}) \equiv \sum_{i=1}^{N} \left(\frac{p^{\mathrm{TF}}(\mathbf{y}_i)}{Q_M} u_n(\mathbf{y}_i) - p(\mathbf{y}_i) \frac{u_n^{\mathrm{TF}}(\mathbf{y}_i)}{Q_M} \right) \Delta S. \quad (7)$$

3. Measurement methodology

In the previous section, expressions were defined to determine the sound pressure at a distance from a radiating motionless object. The assumption for reconstructing the noise of a moving car during a driving-by test is that the continuously changing transfer function can be reconstructed from a set of static measurements. Thus, as shown in Equation (8) different car positions are considered, $i = 1...K$, and the sound pressure contributions $p^i_{contribution}$ are then combined in order to estimate the time-averaged noise as experienced during a pass-by noise test, $\langle p \rangle_t$. Note, Lmax could also be used as the highest exponential time average sound pressure level.

$$\left\langle p(\mathbf{M}) \right\rangle_t = \frac{1}{T} \int_0^T p(\mathbf{M}, t)\, \mathrm{d}t \approx \frac{1}{K} \sum_{i=1}^{K} \hat{p}_{\mathrm{ref}}^{(i)}(\mathbf{M}). \quad (8)$$

The procedure consists of the following steps which are explained in more detail further on.

1. A measurement of the sound radiated from the object under test in operational conditions.
2. A measurement of the transfer path from each panel to reference position M for a set of static car positions.
3. For each panel and car position, the sound pressure contributions are calculated by combining the results of the radiation tests and the transfer function tests.
4. Integration of those pressure contributions to estimate the time-averaged noise as would be experienced during a pass-by noise test.

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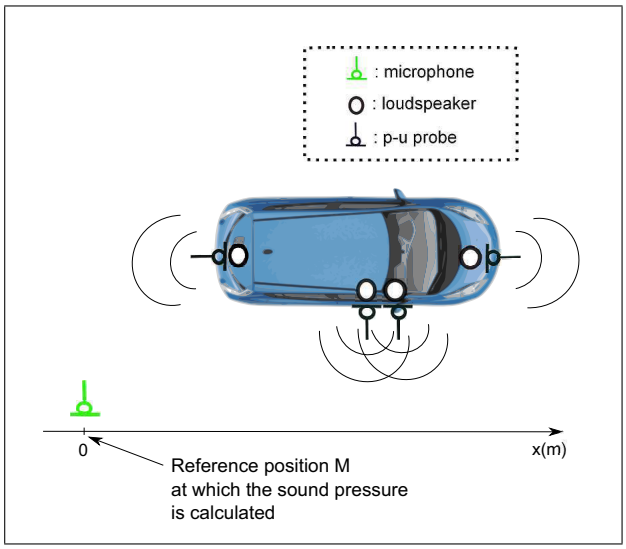

Figure 2. Sketch of the measurement procedure in operational conditions.

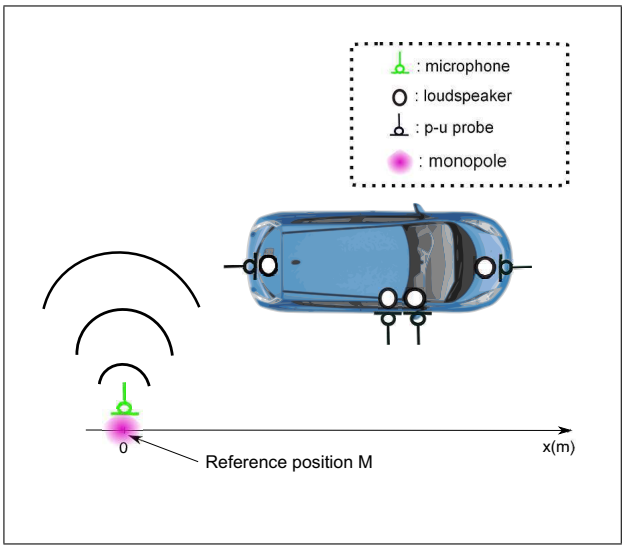

Figure 3. Sketch of the transfer path measurement procedure.

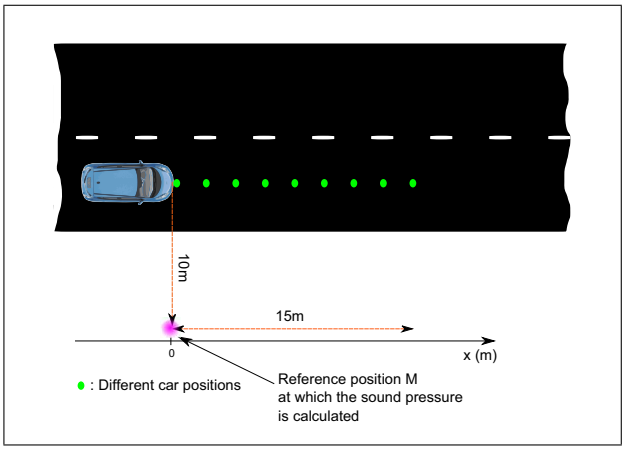

Figure 4. Sketch of a PNCA measurement.

In the first step, the acoustic excitation of the car, e.g, engine, tires, exhaust, is evaluated in a stationary operational condition. In order to attain such a condition, the car can be, for example, installed on a roller bench while the particle velocity and sound pressure from each panel are measured. In this paper, loudspeakers are installed on the car and used as the acoustic excitation instead of the car itself. Thus, all sources are captured by the probes, and a roller bench is not needed. The loudspeakers exceed the noise generated by the entire car, and produce the same white noise independent of the car's speed. So, in this paper, the operational source under investigation was a set of loudspeakers mounted on a moving car. This configuration enables the introduction of a dominant excitation that can be fully characterized with a small probe array. Figure 2 illustrates this first step.

In the second measurement step the acoustic propagation paths from each part of the structure to the reference position are determined. This step is performed for every position involved. The loudspeakers on the car are switched off and the transfer paths between reference position M and each panel are determined. This measurement is performed reciprocally using a monopole sound source at reference position M as mentioned in the theory section. Figure 3 illustrates the second step.

To assess the quality of the overall sound pressure estimation from the PNCA based method introduced, the values obtained can be compared to the time-averaged sound pressure measured in classical microphone based pass-by noise tests. In the tests hereby presented, this validation is performed for every car position and for the overall space-integrated value.

3.1. Measurement set up

A test was undertaken to demonstrate the performance of the PNCA pass-by noise estimation method. Figure 4 shows the measurement scenario, which resembles the geometries used in ISO 10844 and ISO 362 [23, 2]. A car is positioned on a road whilst the sound pressure is estimated at M located 10m from the test track. Between $x = 0$ and $x = 15$ m a measurement was performed every meter. Figure 4 shows a sketch of the described scenario.

To ensure that the radiation is constant amongst the PNCA tests and the pass-by noise validation test, and to limit the amount of sources involved, a set of loudspeakers was used as sound source instead of the car noise itself. By using this method, a roller facility for cars is not needed, and the results will be more conclusive as we consider fewer sources. The sound of the loudspeakers exceeded that of the car, as will be shown in the next section. Two loudspeakers were installed on the passenger's window, and two others on the rear and front windscreen. A p-u probe was installed in front of each loudspeaker using a spring system that highly dampens structural vibrations above 40 Hz, see Figure 5. A foam windshield was added around the sensors as shown on Figure 6.

A monopole sound source with a frequency range of 50 Hz to 6 kHz was installed at the reference position. A

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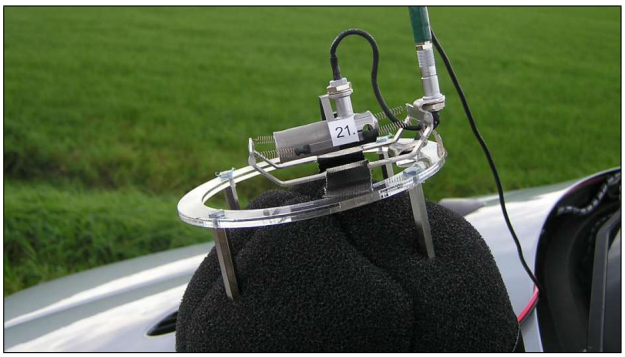

Figure 5. p–u probe mounting on a loudspeaker.



Figure 6. Overall view of the measurement set up.

fifth p-u probe near the end of the monopole duct measured the volume velocity.

All p-u probes and the reference microphone were connected to a 24 channel data acquisition system. The installation took around 30 minutes and measuring the sixteen car positions took approximately 45 minutes.

During this test campaign two car speeds were assessed, 10 km/h and 40 km/h. It should be noted that the sound perceived at the reference position was mainly caused by the moving loudspeaker system, and therefore similar sound pressure levels can be expected independent of the vehicle speed. To validate the results of the PNCA procedure, a microphone measured the sound pressure from the loudspeakers at the reference position. The ultimate results are compared to results of pass-by noise tests with a car driving at these speeds. To assess the results at specific car positions both measurements at fixed positions and the pass-by measurements were used. To evaluate the latter, a camera was placed 20 m distance from the test track to locate the car. The sound pressure was calculated from the part of the time signal acquired when the car covered one meter of road, centered at the reference position. This corresponds to a 0.36 s and 0.09 s long time signal for 10 km/h and 40 km/h car speed, respectively. In order to improve accuracy, the pass-by noise measurement was repeated 10 times for both speeds.

3.2. Results

The experimental results are presented in the next four sections. Firstly, the signal to noise ratio (SNR) of the loudspeaker-car system is presented. Then, the coherence

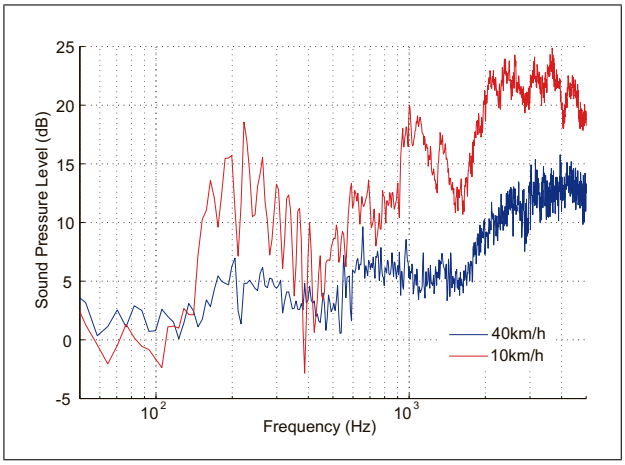

Figure 7. SNR of the loudspeakers-car system for different speeds.

during a transfer path test is shown and discussed. Thereafter, the calculated sound pressure at separate car positions is analyzed. Finally, the time-averaged results of the extended PNCA approach are presented.

3.2.1. Signal to Noise Ratio

For the measurements at separate positions, only the sound pressure contributions from the loudspeakers are determined, while the noises from the car and loudspeakers are measured simultaneously in the pass-by measurement. The sound emitted from the loudspeakers should sufficiently exceed the sound from the car in order to compare pass-by noise with PNCA measurements. To calculate the signal to noise ratio (SNR) of the loudspeaker-car system, pass-by measurements were performed with and without the loudspeakers turned on. Figure 7 shows the sound pressure difference between these measurements for 10 km/h and 40 km/h. As can be seen, the loudspeakers were louder than the car above 100 Hz, except at 10 km/h in a small band around 400 Hz where the car noise was dominant.

3.2.2. Coherence

In the transfer path measurement the monopole sound source is switched on and the transfer function between the volume velocity sensor of the monopole sound source and the p-u probes near the loudspeakers installed on the car is determined. The coherence between these sensors is an important indicator for the quality of this measurement. Figure 8 shows coherence curves for the p-u probe installed near the loudspeaker on the rear window for car position x=12 m. The coherence values are high between 150 Hz and 1 kHz. The main reasons for the coherence drop outside this frequency range are the lower radiation from the monopole and the long distance between the monopole and the p-u probe.

3.2.3. Separate car positions

Firstly, the sound pressure measured at separate car positions is analyzed. As an example, the results at x=1 m, x=5 m, and x=12 m are presented and discussed. The

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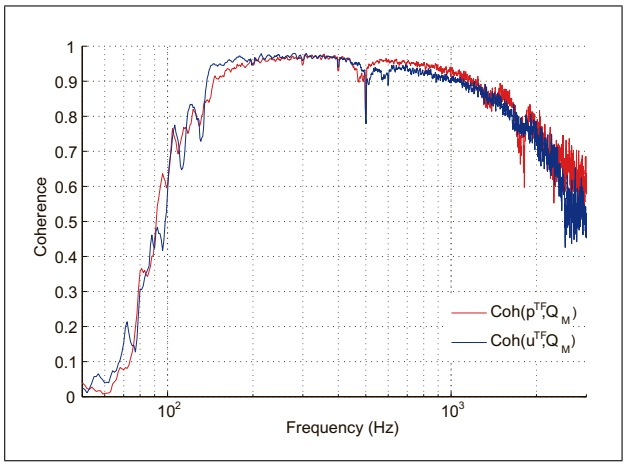

Figure 8. Coherence during the transfer path measurements.

sound pressure values obtained with the PNCA method from the summation of contributions of all panels are compared to the sound pressure measured by the microphone at the reference position with a still standing car – stationary condition– and with a car passing by using time signal sections corresponding to the particular car position.

As can be seen in Figures 9, 10, and 11, the estimated sound pressure and the sound pressure reference are in good agreement from 150 Hz to 1 kHz with a 1.6 dB average error. The differences above 1 kHz, with 15 dB error, might be caused by a low coherence as mentioned in the previous section, the Doppler effect may also have an influence, as well as the fact that the directivity change of the loudspeakers on the car at high frequencies is not considered in the radiation test. However, further investigations are necessary to improve the coherence. The values of the microphone at the reference position are similar for both a stationary car and for the pass-by test, except around 400 Hz where a 7 dB deviation occurs because the car noise is dominant at this frequency.

Below 150 Hz the results start to deviate,with a 10 dB mistake, mainly because the signal to noise ratio deteriorates in the radiation and transfer function tests.

3.2.4. The overall time-averaged result

Here, the time-averaged sound pressures as experienced in a pass-by test are compared. Figure 12 shows the values obtained with the microphone next to the test track in the pass-by test, and the results of the PNCA method and the microphone next to the test track obtained by spatially averaging the results at all 16 car positions.

As shown, the sound pressure estimated with the PNCA method is similar to the time-averaged microphone measurements with a moving car, except around 400 Hz where the car noise is dominant as discussed earlier. The results demonstrate the successful performance of the measurement methodology.

Figure 13 illustrates a comparison between the different sound pressure contributions from the loudspeakers to the reference position, considering the whole test bench. The most important contribution comes from the loudspeaker

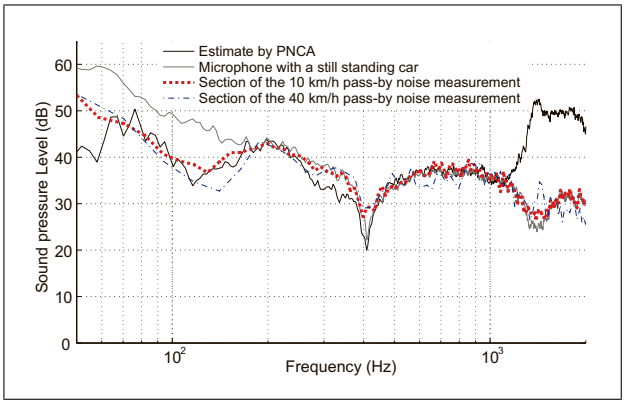

Figure 9. Comparison of sound pressure measurements at x = 1 m.

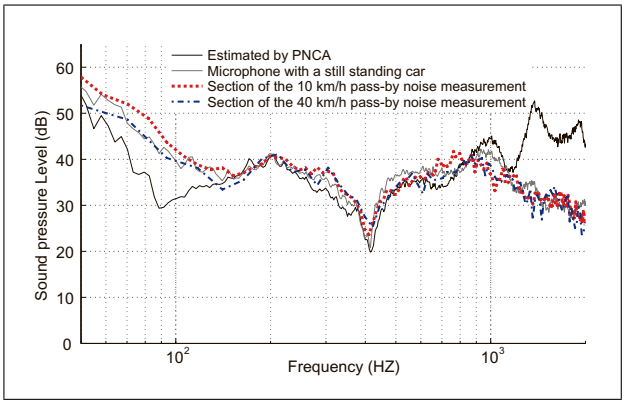

Figure 10. Comparison of sound pressure measurements at x = 5 m.

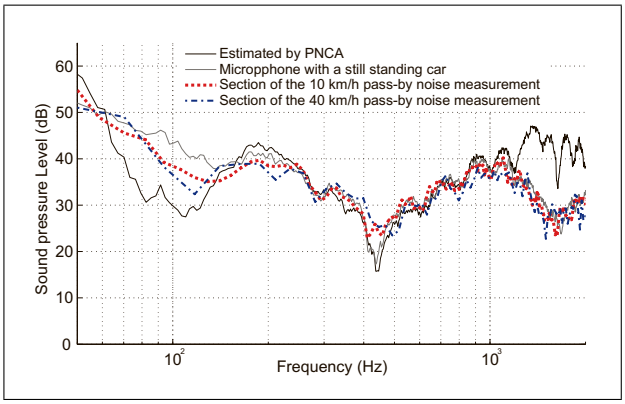

Figure 11. Comparison of sound pressure measurements at x = 12 m.

on the rear window, which is closest to the reference position. The lowest contribution comes from the loudspeaker on the windscreen, which is furthest and is blocked by the car for most positions. In addition, the both loudspeakers installed on the passenger's window have a similar contribution. This comparison shows that the method is able to localize and quantify the different noise sources.

3.3. Discussion

The measurement campaign described in this paper demonstrates that the PNCA method is suitable for predicting the noise of loudspeakers on a moving vehicle by

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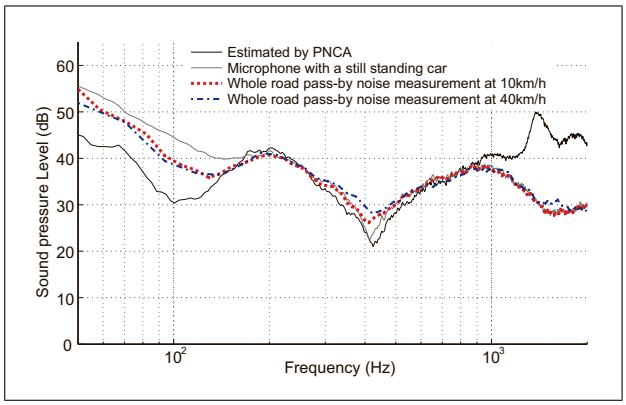

Figure 12. Comparison of sound pressure measurements considering the whole test bench.

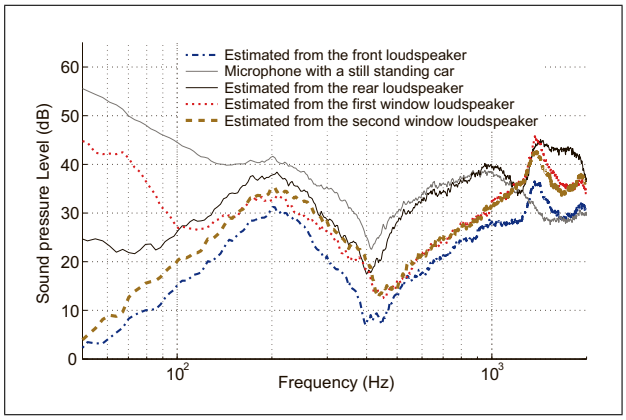

Figure 13. Comparison of sound pressure contributions considering the whole test bench.

combining the results from different car positions. The main advantage of the PNCA based method presented is that the noise contributions from individual sources to a reference point can be quantified. In addition, the quality of the radiation test can be higher than during classical pass-by tests because the signals can be averaged for a longer period of time. Although many transfer path tests should be performed, they only need to be determined once, and can be used even after modifications have been made to the car, as long as the geometry of the car remains similar.

The measurements presented demonstrate that reconstructing the noise contributions from a car in a pass-by test seems feasible. With few adjustments to the calculation methods, the acoustic contributions of the car components can be evaluated either for stationary speeds or for engine run-ups.

The main noise sources of a car are the engine, the tyres, the exhaust, and aero-acoustic noise. In [24, 25] it has already been shown that the sound radiation from the engine and the tyres can also be measured successfully with p-u probes. Measurements directly at the exhaust opening are difficult because of the high temperatures involved, but this problem can be circumvented by installing the probes at some distance from the exhaust where it is less hot. Aero-acoustic noise still seems difficult to capture at the moment. Developments of windcaps are ongoing, but validations are required to find out if the latest versions are already suitable for this application.

3.4. Conclusion

In this paper, a new PNCA based method is presented to measure the sound pressure contributions from different components as experienced during a pass by noise test. The method involves radiation tests in which the emitted particle velocity and sound pressure are captured and transfer function tests in which the propagation towards the reference position next to the test track is determined. The noise contributions are determined for multiple car positions that are ultimately averaged to calculate the time-averaged contributions. An accurate localization and quantification could be achieved for several loudspeakers mounted on a car. The results were validated with a microphone at the reference position next to the test track for separate car positions and for a moving car, and acuarte results were obtained between 150 Hz and 1 kHz.

The PNCA based method may be used in the future for assessing the contributions of car components during pass by tests. At low speeds, the engine, gearbox and exhaust noise are dominant, and their noise contributions can be captured thanks to the PNCA based method. To determine its performance, the results could be compared to those of a "classic" pass-by test at a low speed. At high speeds, tyre and wind noise become dominant instead. In [26] it was already shown that the distribution of the noise radiating from the tyres on roller benches can be captured using particle velocity sensors. PNCA tests on tyres might be compared to roller bench tests in an anechoic room. Perhaps even wind noise might be measured with the PNCA method, allowing comparisons to wind tunnel tests.

The PNCA method allows the sound pressure contribution of small parts of cars to be determined. However, different sources can be correlated, especially at low frequencies, and in that case the corresponding sources should all be measured. The actual number of sensors needed depends on the complexity of the sound source and on frequency. Usually, around 150 fixed sensor positions are used for a complete car interior [27]. The number of sensors required for exterior testing still needs to be determined. A high resolution scanning technique usually used for interior tests could be applied to determine the spatial distribution of the noise radiation and the optimal probe positions [28, 29].

Furthermore, aeroacoustic noise from wind and the exhaust is generated in the air and not at the surface. An assumption of the PNCA method is that all sources are on surface S. To avoid that aeroacoustic sources are disregarded, probes should be positioned away from the car surface where no turbulence induced noise is expected. For example, a cage array of probes surrounding the exhaust might be used to measure exhaust noise instead of one probe at the exhaust exit only. The distance required between the probe and the surface in practical situations

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need to be investigated and depends on the probe position and flow levels.

Perhaps the procedure of acquiring transfer functions might be enhanced. Real measurements are prefered to properly capture the radiation in the vicinity of the directional sound source, but models might be used to calculate how sound propagates further. Even the use of scale models to capture transfer functions can be attempted.

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