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2aNSa7. Contribution analysis of vehicle exterior noise with operational transfer path analysis

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Vehicle development regarding the emitted exterior noise is a challenging task. In addition to stringent legal requirements to reduce noise exposure, also high expectations of the sound quality have to be considered during the development process. In order to manipulate the vehicle exterior noise in a manner more efficient than trial and error, knowledge about the vehicle's sound sources and their contributions to the overall noise is essential. In order to analyze the contributions of the several sound sources of a vehicle to the exterior noise Operational Transfer Path Analysis is used in the presented experiment. Therefore, transfer characteristics are estimated from measurements of the vehicle in typical operating conditions on an acoustic roller dynamometer. This data is used to synthesize the contributions at the response positions, i.e. the microphones of a simulated pass-by array, which also allow the simulation of the contributions during a pass-by measurement. Outcomes of the Operational Transfer Path Analysis are comprehensible contributions of the dominant sound sources to the vehicle exterior noise. The validation of the analysis results shows very good accordance between the simulated and measured overall vehicle exterior noise.

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INTRODUCTION

Driving factors for the improvement of vehicle exterior noise are high expectations of customers and the general need to reduce road traffic noise. The vehicle exterior noise is a quality which is not only important to the vehicle owner, but equally affects pedestrians and residents. In order to enforce lower sound pressure levels (SPLs), strict regulations have been approved by administrations. To meet these requirements during the development of a vehicle, detailed knowledge about the dominant sound sources and their contribution to the vehicle exterior noise is essential.

To characterize the vehicle exterior noise, measurements of the car in different driving conditions e.g. idle, constant-speed or run-up can be used. For the approval test of the vehicle exterior noise ISO 362-1:2007 is typically applied to measure the noise emitted by the accelerating vehicle passing by. Since exterior conditions like rain, wind or ambient noise can significantly influence the measurement results, it is preferable to conduct these measurements indoors. In order to transfer the vehicle exterior noise measurements described by ISO 362-1:2007 to the interior, simulated indoor pass-by noise measurement or simply simulated pass-by measurement methods have been developed.

In order to separate the contributions of the several sound sources on a vehicle to the exterior noise, the transfer paths from source to receiver have to be determined. Here the Operational Transfer Path Analysis (OTPA) method is used to estimate the transfer characteristics. It uses measurements of the sound sources on the vehicle and the exterior noise of the vehicle in typical operating conditions. The Transfer Path Synthesis (TPS) allows the synthesis of the contribution of a single sound source to the vehicle exterior noise.

After a brief overview of the applied methods, an overview of the measurement setup that was used for the contribution analysis measurements is given. The results of the synthesis are compared to measurements and the contributions of the dominant sound sources to the pass-by noise will be discussed.

METHOD

Vehicle test benches for simulated pass-by measurements are a versatile tool for the design of the vehicle exterior noise. By extending the measurement setup with source sensors, it is possible to analyze the contributions of the dominant sound sources to the vehicle exterior noise using OTPA. Of course other driving conditions than pass-by, e.g. idle or constant-speed can also be measured and evaluated.

Simulated Pass-by Measurement

Outdoor vehicle pass-by noise measurements according to ISO 362-1:2007 require a specific test site. For the measurement the vehicle drives on the test road and passes microphones placed on both sides of the road in 7.5 m distance and 1.2 m height. Several measurements of the vehicle accelerating and driving with constant speed have

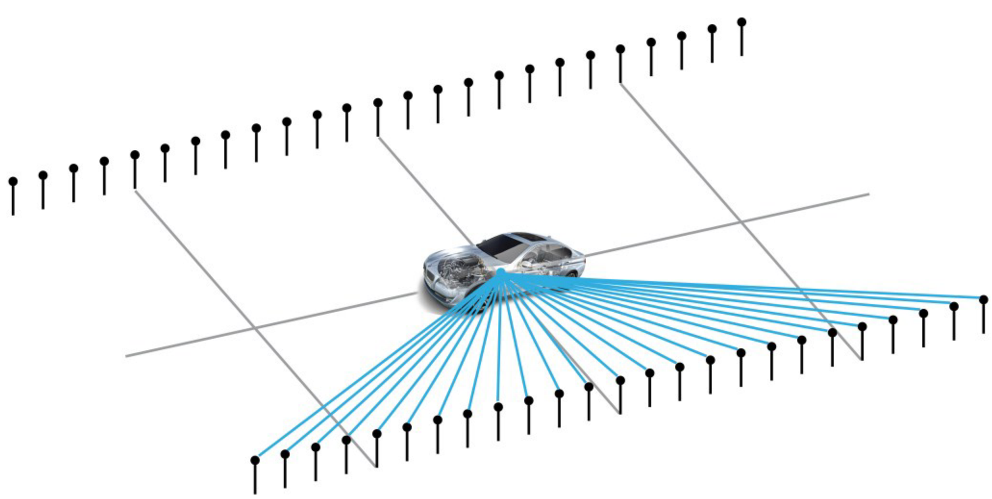

FIGURE 1. Layout of a vehicle exterior noise test bench for simulated pass-by measurements with the vehicle fixed on a roller dynamometer and the pass-by array microphones alongside the virtual pass-by road.

to be done. Results include the signals of the microphones left and right of the test track, the vehicle position on the track and additional data like engine speed. A typical result diagram is the exterior noise SPL displayed over the distance of the vehicle on the test track. For reproducibility of the measurements several ambient conditions for weather and background noise are specified. Since these conditions cannot be guaranteed outdoors, indoor measurement methods have been developed which show a high degree of accuracy.

Basic requirements for the simulated pass-by measurement are given in Annex E of the ISO 362-1:2007. The vehicle is fixated on an acoustic roller dynamometer in a semi-anechoic room. Since the vehicle does not move an array of microphones is placed on each side of the virtual test track in order to measure the noise emitted by the vehicle at different angles. References for the positions of the pass-by array microphones are for example given by Ryu (2005).

During a simulated pass-by, the synchronized signals of all array microphones are measured while the respective driving condition is simulated by the roller dynamometer. Aside from the array microphone signals, the velocity of the roller dynamometer is measured which is integrated over time in order to calculate the vehicle position on the virtual test road. Since the vehicle on the roller dynamometer does not move, one can imagine that the microphones pass the vehicle along the virtual test track. While the positions of the array microphones are constant, their signals are measured synchronously, so the signals of the microphones corresponding to the respective positions on the test track can be crossfaded to obtain the left and right pass-by signal.

Operational Transfer Path Analysis

To analyze the contributions of the dominant sound sources to the vehicle exterior noise, transfer path analysis (TPA) methods can be used. For that analysis the sound sources have to be measured and the simulated pass-by set-up has to be extended by sensors (e.g. microphones) at the so called reference positions. The simulated pass-by array microphone signals are responses to the excitation from the sound sources of the vehicle. TPS is used to calculate the contribution of each source to each pass-by array microphone, i.e. from each reference to each response position. For this synthesis, transfer functions characterizing the sound propagation from each reference to each response position have to be determined. Here OTPA is used to estimate the transfer functions, which has the advantage that it only needs simultaneous measurements of reference and response signals with the vehicle in typical operating conditions.

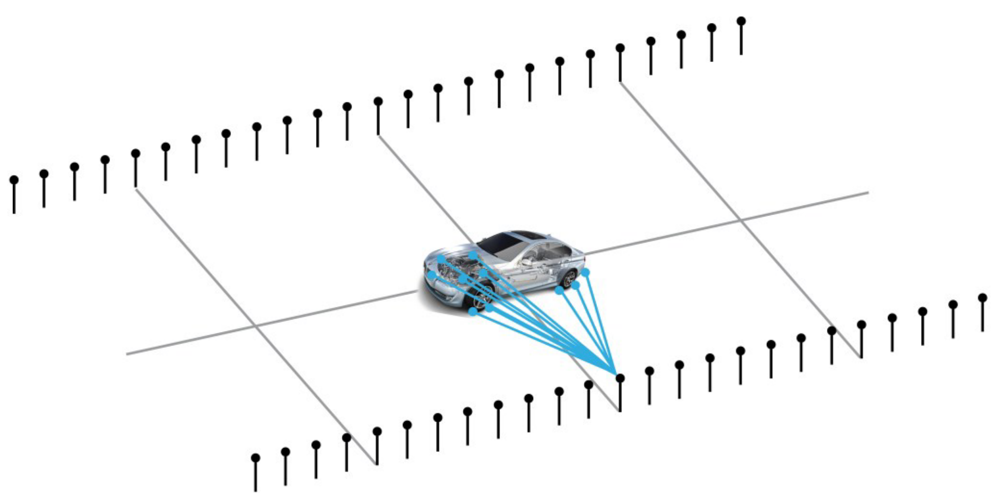

FIGURE 2. Extended simulated pass-by setup for Operational Transfer Path Analysis, with reference sensors near the sound sources on the car and the pass-by array microphones as response sensors.

Basic Principles

For the TPA calculation the relation between the reference signals $\mathbf{x}(j\omega)$ and the response signals $\mathbf{y}(j\omega)$ is described by a linear system

$$\mathbf{x}(j\omega)\mathbf{H}(j\omega)=\mathbf{y}(j\omega), \tag{1}$$

where $\mathbf{H}(j\omega)$ is the transfer function matrix and the frequency dependency is denoted by $(j\omega)$.

The OTPA method used to estimate the transfer functions was initially proposed by Nomura and Yoshida (2006). Measured reference and response signals are represented by time synchronous short-term Fourier transformations (STFTs). In order to calculate the transfer function matrix $\mathbf{H}(j\omega)$ Equation (1) must be solved for $\mathbf{H}(j\omega)$ and therefore the inverse of the STFT reference matrix $\mathbf{X}(j\omega)$ has to be calculated. For the calculation it is assumed that the number of STFTs is larger than the number of reference signals. The calculation of the inverse is an overdetermined least squares problem, to which a common solution is given by singular value decomposition (SVD). Due to the application of SVD certain amounts of crosstalk between the reference signals are cancelled out. Crosstalk occurs if a sound source influences the reference signal of another sound source. By neglecting small singular values measurement noise is typically rejected. A detailed description of the transfer function estimation is also given by Putner et al. (2012). The estimated transfer characteristics are approximated by finite impulse response (FIR) filters, which, applied to a measured reference signal, synthesize the contribution of that reference i.e. sound source to the response signal. The calculated contributions can also be added to calculate the overall synthesized response signal.

Sensor Positions

Determining the sensor positions for the OTPA measurements is a crucial point for the quality of the analysis and the interpretability of the results. The selection of the response sensor positions is typically given by the measurement task at hand. For a simulated pass-by measurement the response sensors are the microphones of the simulated pass-by array. Of course also a contribution analysis of the vehicle interior noise is possible, where a microphone at the drivers head position would be a suitable response sensor position.

For the selection of the reference sensor positions, to characterize the sound sources of the vehicle, all of the dominant sound sources have to be identified. Examples for typical dominant sound sources are the engine, the tires and the intake and exhaust system, but it remains important that all sources are identified. Sound localization measurements can be used to analyze the sound emission of the vehicle and thereby help to select the reference sensor positions. Typically the reference sensors are placed as close as possible to the sound sources to reduce the influence of nearby sources on the measured signal. Although the OTPA method does cancel certain amounts of crosstalk, care should be taken to separate the reference signals.

It is also important to measure all dominant sound sources of the vehicle, since neglected sources can lead to deceptive results, which was for example shown by Tcherniak and Schumacher (2008). If a sound source coherent to measured sources is missing in the OTPA analysis, the contribution of the neglected source will be distributed to the coherent sources. This will lead to higher contributions of the coherent sources and will not become obvious in the comparison of measured and synthesized overall noise. If a sound source incoherent to the measured sources is neglected, the contribution of the neglected source will be missing in the results of the OTPA. That means, that if the measured and synthesized overall noise are compared, the synthesis will have a lower SPL indicating a missing dominant sound source.

All response and reference sensors have to be measured synchronously for OTPA, which typically leads to rather large measurement setups. There is no restriction to a single measurement quantity, reference and response signals can be measured with different sensors, e.g. microphones and accelerometers. As pointed out by de Klerk and Ossipov (2010) it is also possible to target different noise problems by multiple OTPA configurations from the same highly equipped measurement setup.

Operating Conditions

To achieve high quality OTPA results it is important to consider the operating conditions of the vehicle. The excitation of the examined structure should vary over the frequency range of interest and represent all typical operating conditions. This variation in the measurements typically leads to low coherence between the STFTs, which is important for good estimates of the transfer characteristics.

For an automotive test scenario, run-up and coast-down measurements are common measurements fulfilling these requirements. During a run-up measurement the rotational speeds in the whole drivetrain vary over a wide range and the resulting orders will shift from low to high frequencies thus exciting the vehicle structure over a wide frequency range. In addition other measurements, e.g. constant speed measurements with varying load, can also be used for the transfer function estimation. However, it is important for the OTPA to cover all operating conditions of interest, which has been shown by Lohrmann (2008) and Putner et al. (2012).

MEASUREMENT SETUP

A testing facility developed for automotive exterior noise testing, especially simulated indoor pass-by measurements, described in detail by Finsterhölzl et al. (2006), was chosen for the measurement campaign. The vehicle was fixated on a four-wheel acoustic roller dynamometer for the simulation of various driving conditions. In order to perform simulated pass-by measurements comparable to exterior pass-by measurements, 36 microphones on each side of the vehicle form the simulated pass-by array. The array dimensions are deduced from the exterior pass-by test site, i.e. the microphones are in 7.5 m distance from the centerline and the array has a length of 30 m. The semi anechoic room encasing the measurement setup has slightly larger dimensions.

For the OTPA a vehicle with a six-cylinder diesel engine and rear wheel drive was chosen. Regular summer tires were mounted during all measurements, but it has to be noted that, due to the surface of the roller dynamometer, the tire noise is not downright the same as it would be on a test road.

To identify all dominant sound sources, sound localization measurements were performed on the vehicle and its underbody. With the detailed information about the vehicle's noise emission and findings of previous studies by Putner and Lohrmann (2011) the reference sensor positions were selected. This OTPA is based only on airborne sound, hence only microphones were used. A total of 22 microphones were placed as reference sensors near the sound sources of the vehicle, a breakdown can be seen in Table 1. For example eight microphones, one in front and behind each tire near the contact of tire and roller surface, were used to characterize the tire noise emission.

TABLE 1. Setup of the Operational Transfer Path Analysis Measurements, with reference and response sensor count; All sensors are standard measurement microphones.

Position type	Source	Number of sensors
Reference	Simulated pass-by array (left side)	36
	Simulated pass-by array (right side)	36
Response	Engine	8
	Exhaust	4
	Gearbox	1
	Intake	1
	Tires	8

Since the OTPA needs excitations over a wide frequency range and all operating conditions analyzed have to be regarded in the estimation of the transfer characteristics, different duty cycles were simulated with the roller dynamometer. Run-up measurements with half and wide open throttle as well as coast down measurements with durations of 25 sec were performed. Additionally measurements with constant engine speed of 1500, 2000, 3000 rpm and simulated slopes of 0, 30 and 50 % and 2 sec duration were used for the calculation. Of course for synthesis and subsequent pass-by analysis several measurements simulating a pass-by were done.

RESULTS

As already discussed, the quality of the OTPA is influenced by the measurement setup, mainly the selection of sensor positions to characterize the vehicles sound sources and the measured operating conditions. Therefore the analysis results should be checked before further interpretation of the results. The response signal of an excitation measurement should be approximated by the synthesized overall response signal, which is calculated by accumulating the synthesized contributions of all response signals. For stationary driving conditions, spectral analysis of measured and synthesized overall exterior noise can be used to evaluate the accordance of analysis result and real situation. Since it is the goal of the OTPA to analyze the contributions of the sound sources, there are typically no measurements of the contributions of single sound sources to the overall signal. This makes a validation of the single contributions during a standard OTPA not feasible. However, the contribution of the tires to the overall exterior noise is checked for plausibility, by comparison to measurements of the vehicle driving on the roller dynamometer while the engine is not running. Finally the contributions of the sound sources on a vehicle to the overall exterior noise are analyzed during a simulated pass-by measurement.

Comparison of Measured and Synthesized Exterior Noise

In order to validate the results of the OTPA the measured and synthesized overall exterior noise is compared. Since the excitation changes for different driving conditions, two constant speed measurements with 1500 rpm and 3000 rpm engine speed were selected for comparison. The measurements used for the synthesis were not used for the estimation of the transfer characteristics. As response position for the validation, the microphone of the simulated pass-by array at the center line to the left was selected.

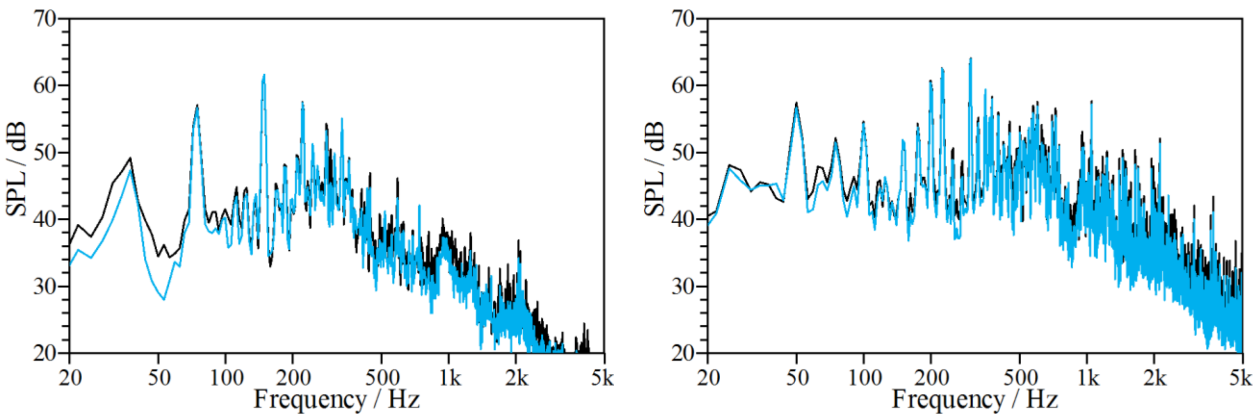

FIGURE 3. Measured (black) and synthesized (blue) overall exterior noise sound pressure level (SPL) for a constant engine speed of 1500 rpm (left) and 3000 rpm (right).

The sound pressure level of the measured and synthesized overall exterior noise differ in average by -1.5 dB for the 1500 rpm condition and by -0.9 dB for the 3000 rpm condition. Negative differences indicate an underestimation by the analysis, positive differences an overestimation. In Figure 3 and 4 a frequency range from 20 Hz to 5 kHz was selected for detailed display.

The good quality of the OTPA results is indicated by the amplitude spectra of measured and synthesized signals in Figure 3, which show very good accordance. Since the underestimation by the synthesis is rather small, no dominant incoherent sound source seems to be missing from the measurement setup.

Comparison of Measured and Synthesized Tire Noise

Since the contributions of single sources are typically unknown before the analysis, they cannot be validated in the standard OTPA process. However, measurements of the vehicle driving at a defined speed can be performed while the engine is switched off. During those measurements the roller dynamometer drives all axes and thereby changes the load conditions for the otherwise engine driven rear axle, which will alter the tire noise. Although other noise sources will still contribute to the exterior noise, the dominant source engine is eliminated. Due to these circumstances the measured exterior noise will not be the exact contribution of the tires to the exterior noise, but can nevertheless be used for a plausibility check.

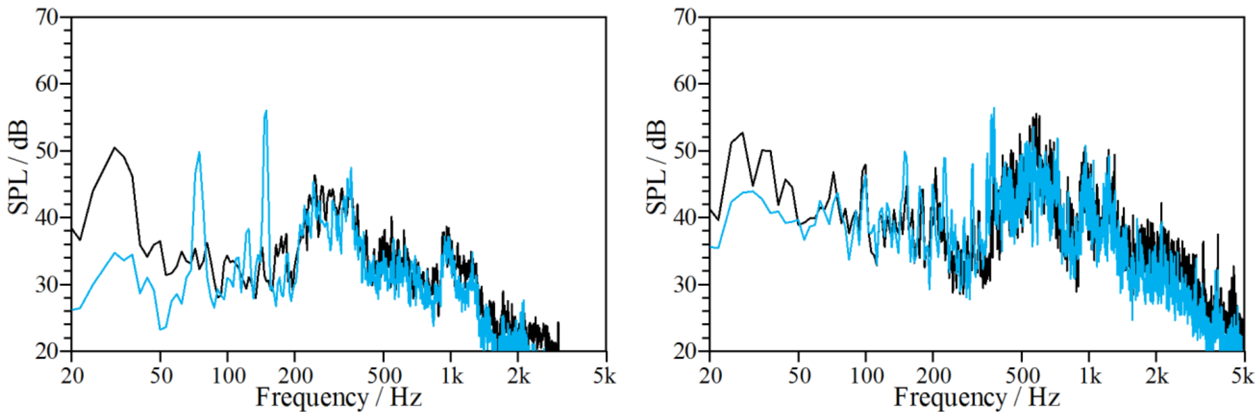

FIGURE 4. Measured (black) and synthesized (blue) exterior tire noise sound pressure level (SPL) for a constant engine speed of 1500 rpm (left) and 3000 rpm (right).

In Figure 4 the measurement with the switched off engine is compared to the synthesized contribution of the tires. The roller dynamometer speed i.e. the simulated vehicle speed is approximately 30 km/h for the 1500 rpm condition and 80 km/h for the 3000 rpm condition. The average difference of measured and synthesized tire noise is -0.3 dB for the 1500 rpm condition and -0.7 dB for the 3000 rpm condition. This is very small, especially since it was not expected that the measurements of the tire noise fully represent the simulated tire noise. If measurements and synthesis are compared in the frequency domain, still good accordance can be observed. In Figure 4 (left) two peaks at 75 Hz and 150 Hz in the synthesized signal largely overestimate the measured signal. The two dominant engine orders occur in the synthesized signal due to crosstalk between the engine and the reference microphones of the front wheels. This is a problem of the measurement setup since source microphones cannot always be placed were they measure only one source and the OTPA can only cancel certain amounts of crosstalk. However the contribution of the synthesized tire noise signals is at least 7 dB lower than the overall exterior noise for those frequencies and has therefore only a small influence, but leads to a slight overestimation at 75 Hz, which can be seen in Figure 3 (left).

Regarding the expected difference between the exterior tire noise signals due to different load conditions and overlooking the suboptimal crosstalk cancellation from the engine to tire noise contribution, the synthesized signal is in good accordance with the measured signal for the spectral comparison and very good accordance with respect to overall sound pressure levels.

Contribution Analysis of a Simulated Pass-By Measurement

Since the estimates of the transfer characteristics and the synthesized signals have been reviewed with good results, it can be expected that the contribution analysis of a simulated pass-by measurement, with this setup, will provide reliable results. For the analysis the transfer characteristics from the 22 reference positions to the 72 response positions are calculated by OTPA. With a simulated pass-by excitation measurement the contribution of each reference signal at each response position is synthesized and accumulated to the contributions of the analyzed sound sources. With the simulated pass-by analysis the contributions of the separate sources during a vehicle pass-by are calculated.

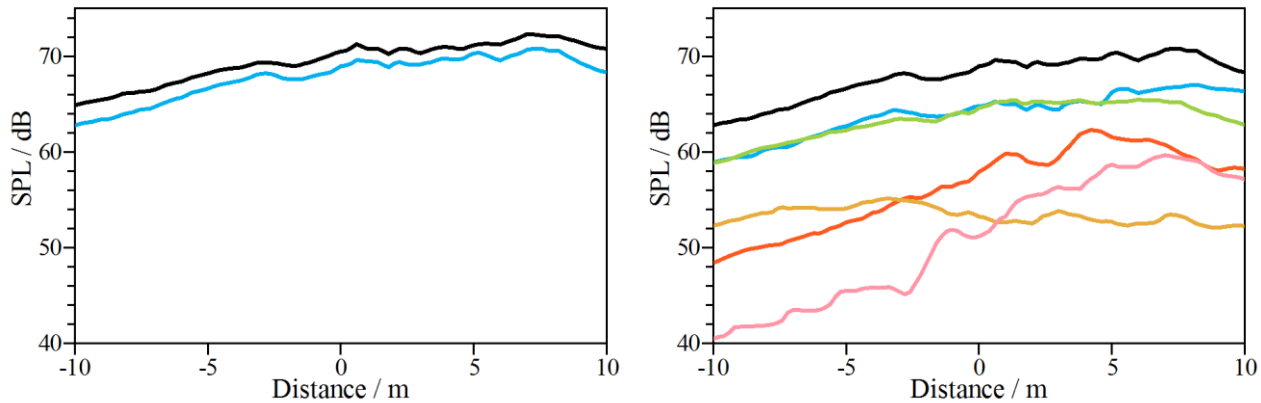

FIGURE 5. Indoor simulated pass-by measurement. Measured (black) and synthesized (blue) overall exterior noise sound pressure level (SPL) (left). Contributions to the overall exterior noise (black) by engine (green), tires (blue), gearbox (red), exhaust (pink) and intake (orange) (right).

Typically the resulting sound pressure levels of a simulated pass-by measurement are displayed over the vehicle position on the test track. This can also be done for the virtual test track of a simulated pass-by measurement, respectively the synthesized source contributions. In Figure 5 (left) the measured and the synthesized overall exterior noise SPLs are displayed for the vehicle pass-by on the virtual test track. The accordance between measurement and synthesis is good and the average SPL difference is -1.9 dB. The slight underestimation by the synthesis can occur since no structure-borne sound sources, which may lead to secondary noise emitted by the chassis, were considered for the OTPA.

The results from the contribution analysis are shown in Figure 5 (right). The dominant contributions to the pass-by noise originate from the engine and the tires. Both have approximately the same SPL in the first half of the test track, when leaving the test track the tire noise contribution is dominant. The intake, located at the vehicle front, contributes more while the vehicle is approaching the virtual center line. Whereas the exhaust, located at the vehicle tail, contributes more after the vehicle has passed the virtual center line. The OTPA provides reasonable results for the contributions of the various sound sources on the vehicle during a pass-by measurement, which provide detailed knowledge about the composition of the pass-by vehicle exterior noise.

CONCLUSIONS

For the analysis of the contributions of the various sound sources on a vehicle to the vehicle pass-by noise, the operational transfer path analysis (OTPA) method was chosen. The vehicle pass-by was simulated on an indoor simulated pass-by test bench that was extended by microphones to measure the sound sources on the vehicle. A brief insight to the applied methods of OTPA and simulated pass-by measurement was given and some crucial points were described in detail. For example a basic knowledge of the dominant sound sources of the vehicle is important to plan the measurement setup. Also measurements of the vehicle in different operating conditions contribute to high quality OTPA results.

A measurement campaign with the goal of a detailed analysis of the contributions of the sound sources on a vehicle to the exterior noise has been presented. The measurement setup was described and the analysis showed that reliable results can be achieved. In order to validate the results, measured and synthesized signals were compared for constant speed and pass-by driving conditions, which showed good accordance between measurement and synthesis. A comparison of the vehicle noise with switched off engine to the synthesized tire noise contribution showed that the basic characteristics and the sound pressure levels (SPL) are consistent.

The pass-by noise was separated in contributions of the vehicle's sound sources using OTPA, resulting in reasonable estimates for the different source contributions of a passing vehicle. The potential of the OTPA for contribution analysis of the vehicle exterior noise was shown, which proves the OTPA to be a helpful tool in the development of vehicle exterior noise.

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