MÜLLER-BBM
VibroAkustik Systeme

EFFICIENT TESTING BY COMBINING SIMULATED PASS-BY MEASUREMENTS AND OTPA

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1. INTRODUCTION

Within the NVH based development cycle both interior and exterior noise are usually thoroughly investigated. The latter is lately of major importance, as it is underlying strict regulations regarding type approval on the one hand. On the other hand, the sound characteristics is of major importance, as it is able to underline the vehicles and hence the drivers character. Finally, the desired sound design and the limitations of the regulations have to meet. With the first implementation of the regulation, a significant amount of test tracks had been built especially for the evaluation of exterior noise. Although the initial invest usually seems to be a bit lower than for an on-site test bench, the limitations of outdoor testing have to be considered. First, it is highly weather dependent, as measurements can only be conducted on a dry and ice-free test track. Second, the track is usually located in a more isolated environment, as background noise has to be kept low and prototypes should still be kept secret. Hence, there is a huge logistical effort in organizing the measurement campaigns and transporting the vehicles to the test track. Especially during the development process, where modifications are usually being conducted after measurements, transport between work shop and test track seem rather annoying

Figure 1: A test track for outdoor pass-by measurements on the left side. The setup for indoor pass-by on the right

Therefore, the simulated pass-by has been introduced and is widely accepted within the automotive industry [1]. It also underlies strict regulations in order to be comparable to outdoor measurements, but is usually not accepted for type approval. Nevertheless, it is a valuable tool within the development process, as it provides a quite elaborated first guess on the overall level of a vehicle.

Besides the advantage of bringing more efficiency to the actual evaluation of exterior noise, the simulated pass-by also allows for an easy integration of further analysis processes. Considering the exterior noise measurement as standalone application, it provides a predicate on the noise of a vehicle with regard to regulations or any other given target.

In order to localize possible sound sources either inside or outside the vehicle, it seems reasonable to introduce other methods. The stationary indoor setup provides optimal situations for an in-depth analysis. With a set of additional microphones located inside and outside of the test subject, and completed with a set of accelerometers, the Operational Transfer Path Analysis (OTPA), a transmissibility-based approach from the family of Transfer Path Analysis (TPA) [2], can be easily included. In contrast to other methods it does not aim for a physically complete description of a structure, all forces, and the respective transfer paths. It is a valuable troubleshooting tool when it comes to the classification and ranking of possible sources transfer paths respectively. Hence, the additional transducers can be placed close to possible sources, e.g. engine, exhaust, intake, and tires, in order to get a ranking of the contributions in respect to a receiver position – in this case a microphone of the line array.

The basic idea is to compute the transfer functions between indicator positions on or near the sources and the response function. This way a more or less linear correlation between source and response position is computed. In a subsequent step, a ranking of all measured indicator positions can be performed to provide the necessary information at which positions modifications should be made in order to achieve better results.

This White Paper is structured as follows: An overview on both setup and measurement procedure for outdoor and indoor pass-by measurements will be given in section 2. Exemplary setups are provided for both cases. The Operational Transfer Path Analysis will be described in section 3. After a short introduction into the theory of the OTPA and the comparison with other TPA methods in section 3.1, an evaluation in respect to measurement results with the traditional Window Method will be provided in section 3.2, followed by the discussion of the used measurement setup and the acquired measurements results in section 3.3. The work will be concluded by a short conclusion with an outlook into further work in section 4.

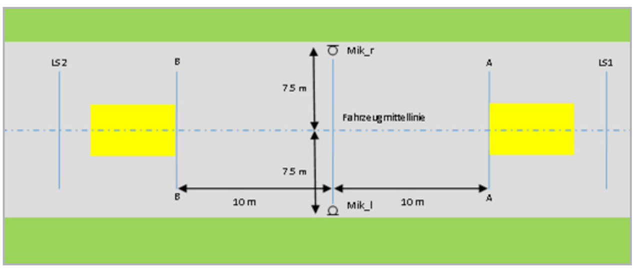

Figure 2: Schematic setup of a real pass-by track with the two microphones on the left and right side of the track, light barriers and the measurement corridor

2. THE SIMULATED PASS-BY FOR EXTERIOUR NOISE MEASUREMENTS

As explained above the simulated pass-by is a widely accepted method for exterior noise measurements. Experience has shown that measurement results inside the chamber and on a real test track are pretty much comparable in case the dimensions of the room, the acoustic properties of the room, and the microphone positions had been designed correctly. Although these measurements are not allowed for type approval, a few test benches had been built in the past, as they provide an efficient and fast way for testing vehicles, comparing modifications, and dramatically enhancing the development process.

2.1 Comparison of Real and Simulated Pass-By Measurement Setups

2.1.1 Real Pass-By Measurements

Test tracks for real pass-by measurements are subject to strict regulations. This includes the type of concrete for the track, the allowed background noise and the environmental conditions. Further, measurements can only be conducted when the weather conditions are suitable. Hence, the location of the track has to be chosen carefully and aligned with the need for short ways for the transport of the vehicles. The measurement setup itself is also subject to strict regulations, such as UN EC 51.02 and 51.03 R, and is illustrated in figure 2. The microphones are located in a distance of 7.5 m from the test track. The region of interest for the measurement is depicted between the AA and BB lines, which are located 10 m in front respectively back of the microphone center. The measurement has to be started as soon as the vehicle crosses the AA line and passes the BB line. In order to trigger the measurement the light barriers LB1 and LB2 are used. Measurements according to the old regulations are performed in different gears with usually the same cycle, meaning entering the AA line at a driving speed of 50 km/h and then performing a full acceleration. Besides the actual noise only the vehicle speed has to be acquired. With the new regulations, the target speed at PP is 50 km/h with a tolerance of ±1 km/h with an acceleration according to the PMR, which is usually in the range of 2 m/s², a_{urban}, and a_{wot}. Further, it is required to acquire the rotational speed of the engine. The driver has not only to keep an eye on the driving speed now, but also on the acceleration which is basically depending on the gear when driving and also having an influence at the entering speed. All these factors increase the complexity, make the highest demands on the test driver's skills, and require a system which is assisting the driver for the task execution.

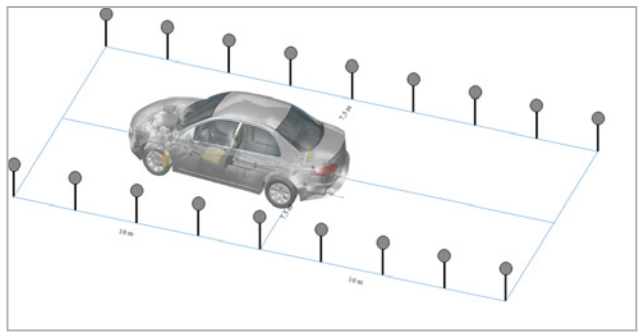

Figure 3: Schematic setup of an exterior noise test bench with two microphone line arrays on each side

2.1.2 Simulated Pass-By Measurements

The measurement procedure for simulated pass-by is basically the same as for real pass-by, with the slight difference that it is conducted on an (all-wheel) dyno in a semi-anechoic chamber. Although a dyno is already installed at most of the test facilities, regulations require a quite sophisticated setup of the test bench, which is illustrated in figure 3. The chamber's dimensions have to represent the measurement corridor of the real pass-by. This results in a width of at least 15 m which is given by the distance of the microphones from the vehicle center line. In order to simulate the approaching and receding of a vehicle on a fixed dyno, microphone line arrays are installed on both sides of the imaginary test track. Consequently the microphones have to be in line with the virtual position of the vehicle, resulting in test benches with a length of usually at least 20 m.

Common setups consist of roughly 36 microphones on each side of the vehicle. In case, the chamber is not as wide as required, a one sided setup is possible, but the vehicle needs to be rotated by 180° to be able to cover both sides. All microphones are captured synchronously and provide a static noise, as the distance between the vehicle and each microphone is constant. In order to be able to hear and measure the effect of the approaching and respectively receding car, an interpolation based on the vehicle speed and time is performed, where basically each microphone is only used for a fraction of time. One could say that just short parts of each microphone are played back after another in the same order as the microphones are aligned. The measurements are now conducted in the same way as for real pass-by with the difference that instead of light barriers usually a kick-down sensor is used to trigger the measurements. Nevertheless, the setup is highly demanding, as quite a lot of microphones are used and have to be checked on a regular base. This requires a monitoring system which guarantees that all microphones are operational and correctly calibrated.

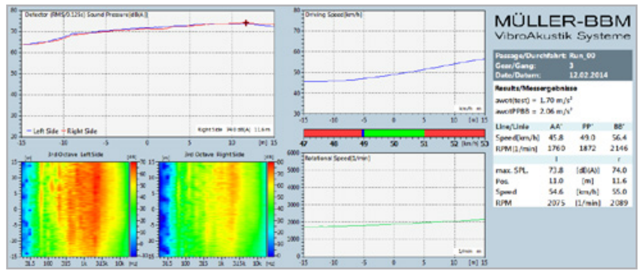

Figure 4: Exemplary result plot of a pass-by measurement with all required data such as SPL, 3rd octaves, etc.

2.2. Measurement Results

No matter whether real or simulated measurements are performed, the results, as exemplary shown in figure 4, are basically the same. In the end the maximum overall level of multiple averaged runs is displayed besides the overall level over the covered distance and an averaged 3rd octave spectrum, as illustrated in figure 4. The driving speed, rotational speed, and some details about the position and speed of the maximum SPL are provided in order to give some further information.

3. OPERATIONAL TRANSFER PATH ANALYSIS

Within the development phase engineers do not only want to know whether the vehicle meets the requirements of the regulations, but also where possible sound sources are located in order to implement possible counter sources. Hence, the idea is to use additional transducers and an advanced method to correlate the excitation and response signals. Structural analysis delivers a wide range of methods for a so-called Transfer Path Analysis [2], where especially the OTPA has been proven to be the method of choice for troubleshooting [3].

3.1. The Operational Transfer Path Analysis

Based on the Cross Talk Cancelation and the Principal Component Analysis (CTC/PCA), the OTPA tries to determine a linearized set of transfer functions which describes the correlation between a given set of excitations and response positions from an operational measurement. Such a system can be basically described as a set of inputs and outputs where $H(j\omega)$ is the transfer function between the input vector $x(j\omega)$ and the output vector $y(j\omega)$.

$$H(j\omega)\, x(j\omega) = y(j\omega) \qquad (1)$$

Usually forces, accelerations and sound pressures are used as input signals, whereas the output can be also one of these quantities, depending on the application. As already described in [4], the reference and response signals are now represented by the synchronous short-term Fourier Transformations (STFTs). In order to solve equation 1 for the transfer function $H(j\omega)$, the inverse matrix of the STFT reference matrix $x(j\omega)$ has to be computed. As the inverse can only be computed in an overdetermined system, the number of reference channels has to be lower than the number of the excitation channels. Therefore, the inverse can be considered as a least square problem, where the solution is given by the singular value decomposition (SVD). As an effect crosstalk is eliminated by a certain degree, which usually appears in case of a sound source influences another one. Neglecting small singular values leads to a rejection of measurement noise, which typically cannot be avoided. The transfer functions can now be used as FIR filters and applied to the original reference signal in order to synthesize the contribution of the observed source. The sum of the computed contributions represents the overall synthesized response signal and can be played back for an auditory evaluation. In case that all sources are included, the overall synthesized signal corresponds to the measured signal.

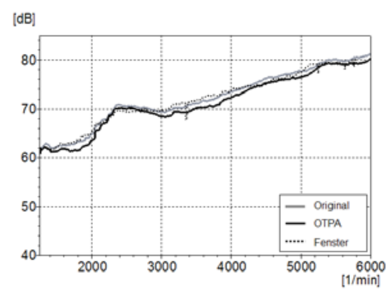

Figure 5: Comparison between window method, OTPA and original measurement

3.2. Evaluation of the Contribution Analysis

As it has been already discussed in [2], the different TPA methods have to be carefully applied as they do not fit to every problem. With the case of exterior noise the contribution analysis has to match the so-called Window Method that has been applied in the past. The general idea was to isolate the individual sources and to measure only their individual noise at the receiver position. This is unfortunately quite laborious, as all sources have to be encapsulated and measured independently. The sum of all measured sources should again result in the overall measured noise.

All measurements have to be conducted at similar loads and temperatures as noise might be depending on a wide range of influences.

Figure 5 illustrates the comparison of the results directly at the receiver position, the window measurement, and the sum of the synthesized contributions computed with the OTPA. At a first glance, the results are comparable in most frequency ranges. Hence, this quite simple and fast approach can be easily used as replacement for the window method.

Figure 6: The measurement setup for the Contribution Analysis during the simulated pass-by measurement with microphones at intake, tires, exhaust, and inside the engine. Accelerometers on the engine and exhaust system provide additional valuable information for statistics

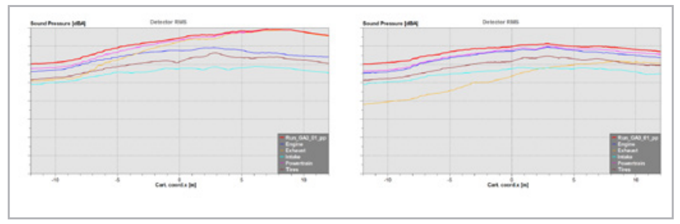

Figure 7: Exemplary contribution analysis results for a vehicle with two different exhausts. While the first implementation was quite dominant, the second one is way quieter. It is observable that the ranking has changed, while values of the other components stayed approximately constant

3.3. Measurement Setup and Results

A possible measurement setup is illustrated in figure 6. Exterior microphone positions are supplemented by positions near possible sources: intake, exhaust, and tires where the front and rear of all four tires are being taken into account. Further, microphones are placed inside the engine. To support the measurement further accelerometers are applied at the engine, on the exhaust system, and on the gear box if required. These accelerometers are often used to compute the matrices of the CA correctly and support a broader statistics.

Following the procedure already described in section 3.1, a network can be set up with the microphone located at the virtual PP line as response position and the following combined excitation positions: intake, powertrain (engine and exhaust combined), and tires. A possible test result for a vehicle with an exhaust variation A is illustrated in figure 8 on the left. It is obvious that tires and intake are almost negligible sources and the powertrain is the most dominant source. It can be stated that all noise is especially caused by the powertrain. In a second network the exhaust system and the engine have been investigated independently, in order to be able to demonstrate where a modification could be performed. The exhaust system is the most dominant source, followed by the engine. Nevertheless, it can be seen that the exhaust is not necessarily dominant all of the time, but is quieter while the vehicle is approaching the PP line and perceived as louder when crossing the PP line. This led to the idea that the overall level could be easily influenced by just modifying the exhaust itself and leaving all other components as they were during the first test. As shown in figure 8 on the right hand side, the overall sound level has been decreased by far and the powertrain is still considered as the dominant source. The astonishing observation is that even with a modified setup the contribution analysis provides almost the same results for the components not being modified. This can be easily shown with the engine, which has almost the same curve in both vehicle setups. With the modified exhaust, the engine is now the most dominant source in the entire system.

4. CONCLUSION AND OUTLOOK

The exterior noise is considered as an important factor in the NVH development cycle – gaining more and more importance with the steadily increasing model palette. It is a common agreement that the simulated or indoor pass-by is an acceptable method and alternative for outdoor testing that can rapidly speed up the entire testing process with quite similar results. One of the main advantages within the development process is the seamless integration of the Contribution Analysis which additionally provides a ranking of possible sound sources and enables engineers to make an elaborated guess where to perform modifications and which components need further attention. In contrast to other TPA based methods, the OTPA can be applied by just using operational measurements which are being performed anyway for the indoor testing.

For future development it seems reasonable to integrate also the Response Modification Analysis (RMA) into the development process of the exterior noise [5]. This allows a modification of the response signal and provides a so-called sensitivity analysis with elaborated assumptions on which paths modifications will lead to better results. With the current development that a common platform is used in the diversification process, meaning applying the same powertrain, tires and chassis for different types of cars, the influence of the visible parts should also be investigated, as this might further speed up the development process.

5. ACKNOWLEDGEMENTS

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