An Integrated Approach for Exterior Noise Development

AUTHORS

Dr.-Ing. Dejan Arsić
is Key Account Manager at Müller-BBM VibroAkustik Systeme GmbH in Munich (Germany).

M.Sc. Florian Bock
is Acoustic Development Engineer at Audi AG in Ingolstadt (Germany).

This article presents a framework which can be used as an iterative process in the development and design phase of the exterior noise. It describes how measurements and analysis results can be easily compared to previous measurements. This process is more cost-efficient and speeds up the entire vehicle development.

INTRODUCTION

Exterior noise has been one of the key factors in acoustic development in recent years. While each vehicle is supposed to contain a certain image, whether it be sporty or comfortable, regulations regarding emitted noise still have to be met worldwide. Unfortunately, these regulations are not quite the same in all regions. The ever-increasing model palette at most OEMs and their international business indicate that more and more measurements have to be performed in shorter times. These not only include type approval and the conformity of production, but also the research and development cycle, as the requirements have to be taken into account at an early stage. Real pass-by measurements have been optimised in the past for a rapid workflow, thus saving as much time as possible, maximising reproducibility and enhancing the track's capacity. However, the measurements require huge organisational effort, as vehicles must be transported to the test facilities, the weather has to be good and drivers have to be perfectly trained to be at the precise point for the measurements. Moreover, it is usually difficult to perform modifications to the vehicle or the measurement set-up on-site. Hence, it makes sense to build specialised test benches for the simulation of pass-by measurements. This approach also allows for further investigation in the field of NVH during the research and development phase.

SIMULATED PASS-BY MEASUREMENTS

The basis of a simulated pass-by test bench is usually an all-wheel dyno in a semi anechoic chamber [1]. In contrast to the real application, multiple microphones, not only two microphones, are lined up along the imaginary track. This allows the distance of the approaching or receding vehicle to be simulated on the dyno. As the regulations require measurements to start and end at a distance of ±10 m from the zero line, a 20 m stretch is regarded as the minimum size for the line array. Furthermore, reflective and absorption properties of the chamber have to be taken into account, resulting in a common minimum length of 30 m. The width is defined by the minimum microphone distance of 7.5 m from the middle of the track, thus resulting in a width of at least 15 m.

Depending on the requirements, each side of the test bench should be equipped with 36 microphones, which are all synchronised with the driving speed and the rotational speed measured in the vehicle. During subsequent post-processing, taking the propagation of sound into account, the individual microphone signals are combined into one signal, which is then used for the analysis of the exterior noise and processed according to the respective regulation. An interpolation applied between the microphones in the time domain allows the synthesis of an audio signal. This can either be listened to, thus sounding quite like a real pass-by measurement, or used for further investigations.

Although the measurement set-up seems quite straightforward and is also fixed, various factors have to be taken into account. The microphones need to be calibrated and checked regularly. A smart data acquisition system now allows the calibration of the sensors with a smart device directly on location, without the need for direct interaction with the control system. All microphone signals can therefore be checked for plausibility and calibrated in a row. Prior to the analysis and the finalisation of the measurements, each run performed has to be validated, as acceleration and driving speed have to be in a defined corridor. The analysis is averaged within the same gear. In the past, this task was performed by the operator of the test bench.

Thanks to intelligent signal processing, all data is checked for validity immediately. Gears can be detected according to the current rotational speed and the gear ratio. All measurements are classified and sorted directly. As soon as a measurement is considered valid, the intermediate results are updated right away and feedback is given to the operator. Furthermore, measurements can be manually set to either a valid or invalid state. As the analysis only requires the two interpolated signals, not all of the real signals are necessarily stored and displayed on the screen. Nevertheless, it seems reasonable to have an easy-to-handle scope mode in order to check the signal quality and to see whether or not any disturbing noises are present. It is inevitable that this information is received continuously, even in between the runs, as each run should be valid and of a high signal quality. Therefore, it is essential to check the data prior to the measurement.

The scope mode is consequently an independent process and operates continuously without interfering with the actual measurement. If all required runs are considered valid, all the necessary information is presented to the operator, **FIGURE 1**. According to the selected regulation, e.g. UN ECE R 51.02/3 and/or ASEP, not only the overall level but also the velocity, rotational speed and acceleration are displayed, thus providing quite an extensive overview of the measurement procedure.

DATA ACQUISITION AT THE EXTERIOR NOISE TEST BENCH

Most of the engineers involved tend to lack interest in acquiring and storing all the data of all transducers connected.

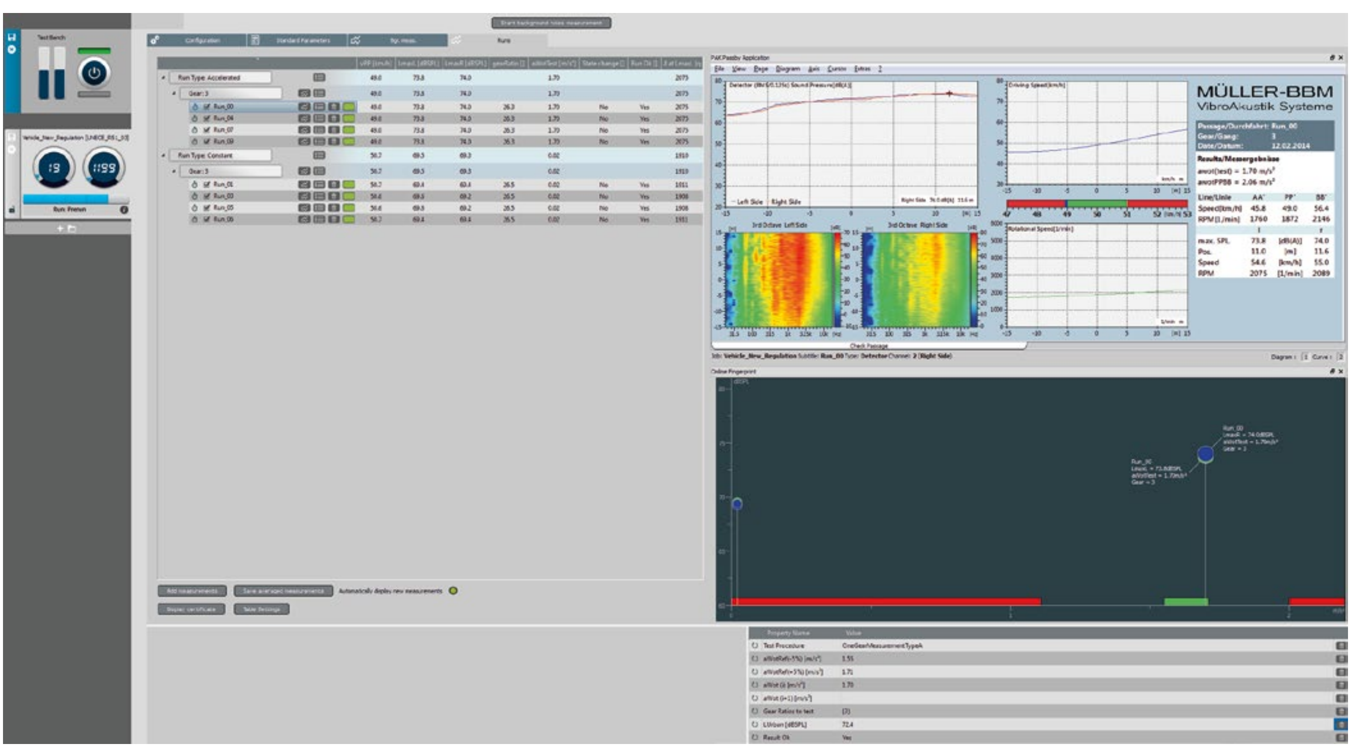

FIGURE 1 Examples of measurement results for simulated pass-by (© Audi)

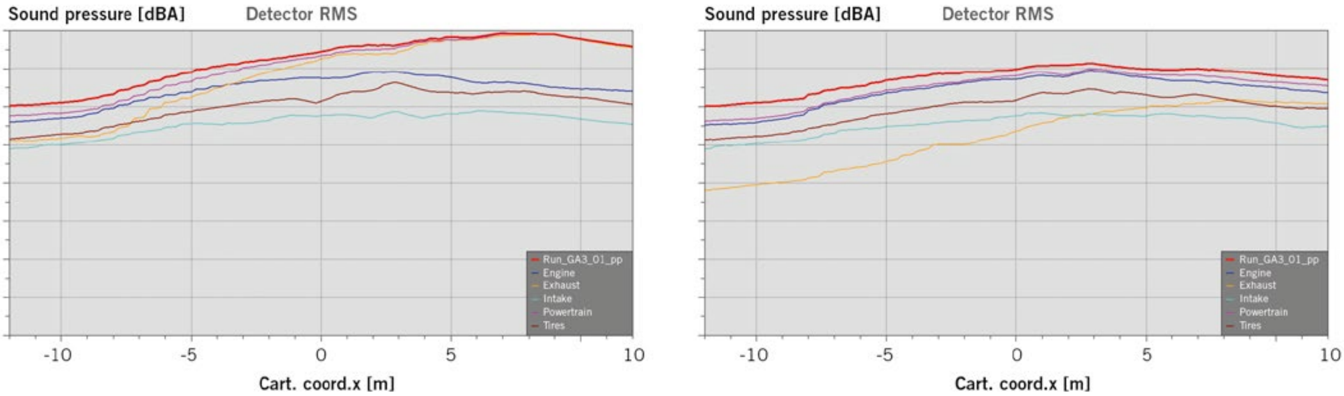

FIGURE 2 Contribution Analysis results before (left) and after the modification of the exhaust (right) (© Audi)

The pass-by result requires only the data of the interpolated signal, the Contribution Analysis (CA) needs one microphone at a distance of 7.5 m and the additional sensors near or in the vehicle, and sound localisation needs only the data from the line array. The wide range of possible tasks requires smart and fast data acquisition, because all the experts involved should receive only the data of interest at the time at which they are interested in it.

The PAK live technology allows each dedicated expert to capture the data of interest in parallel to others without interfering. Moreover, it is seldom possible to equip the test bench for every possible experimental set-up, as the sensor types and positions are not necessarily known during the planning phase. Additional data acquisition systems can easily be seamlessly integrated and synchronised with the central system by simply using a network cable. The data from the additional sensors is then automatically added to the data stream, and each user can decide whether or not they want to analyse the data.

ADDITIONAL ANALYSIS

The application of the simulated pass-by not only enhances measurement times, reproducibility and organisational effort, but also allows additional analysis to be performed during the development process of new vehicles. Measurement results can be compared with regulations or internally set goals. Besides providing the opportunity to simulate modifications and combinations of components, it also makes it possible to investigate why the vehicle does not meet the goals or localise possible sources of disturbances, whether they are airborne or structure-borne. Performing the measurements with slicks now allows the simulation result to be obtained with different types of tyres, as these usually influence the overall level. This influence is increasing due to new regulations.

As is commonly agreed, the contribution of slicks is considered rather low or even negligible. Therefore, the acoustic

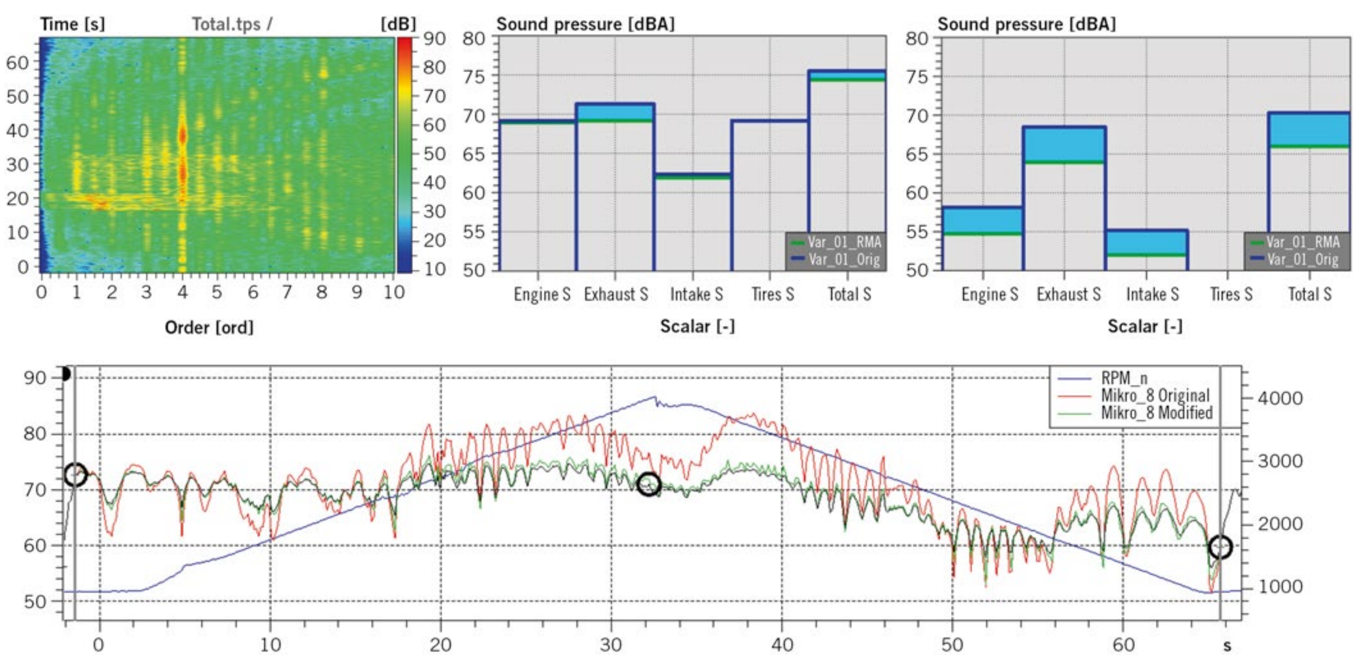

FIGURE 3 Results of the RMA for the 4th order, where the exhaust is identified as most dominant (© Audi)

measurements of tyres, either conducted on the road, applied in an electric car or on a specially constructed trailer, or in special test benches, can be used in order to simulate the result with different kinds of tyres without the need to actually change the tyres themselves and perform further test runs. The original measurement can now be combined with a wide range of tyre measurements by mixing the acoustic signals. This dramatically speeds up the test procedure, including engineering effort.

Probably the most obvious solution would be to actually use all of the already installed microphones for further analysis, instead of simply using the resulting signal at the imaginary zero line. It is now possible to conduct sound localisation by using the phase differences and run-time differences of the microphones. Assuming that the microphones form a simple line array, disturbing noises and frequencies can be roughly localised and the possible sources can be narrowed down quite well.

If this rough estimate is not sufficient, an in-depth investigation can be performed by applying additional transducers, such as near-field microphones, accelerometers, etc. inside and outside the vehicle. This now allows the determination of correlations between the microphone signal along the test track and the signals near to and inside the vehicle, respectively. Although the correlation between the signals gives a first indication of possible sources, this method does not take the transfer paths and contributions into account. Consequently, it makes sense to include a Contribution Analysis (CA) or Operational Transfer Path Analysis (OTPA) [2] into the development process, which computes the contributions of each individual source to the overall signal perceived at the desired response position. This may be one of the microphones outside or even a microphone or accelerometer inside the vehicle, and could be used for investigating acoustic comfort inside the cabin.

The basic idea is to compute a transfer function matrix, linking the input signals to the output signals. While classical transfer path analysis is basically limited to forces as inputs [2], contribution analysis can deal with airborne and structure-borne sources, and can also cope with operational measurements [3,4], which is the case for simulated pass-by. The contribution of all excitation sources $Y(\omega)$ to the observed signals $X(\omega)$ at the desired response positions can now be determined by solving the equation system $X(\omega)\ H(\omega) = Y(\omega)$ for the matrix $H(\omega)$ [5].

Applying the computed transfer functions as a FIR filter on the time raw data at the excitation positions will result in the contribution of the indicator position in respect to the response signal. Consequently, this allows a ranking of all observed excitations, which indicates whether the engine, tyres, exhaust or other components may be the dominant sound source and thus mainly responsible for a high overall noise level. The sum of all contributions usually corresponds to the observation at the response position. This approach makes it easy to rank the individual components, such as the powertrain, tyres, etc. These results could also be used for simulating the changes in the individual components if the transfer functions between an isolated measurement and integrated measurement are known. **FIGURE 2** illustrates the results of a rather sporty vehicle on the left. It shows that the exhaust is considered quite dominant, followed by the engine. After replacing the exhaust with a modified version, the overall level is obviously far lower, **FIGURE 2** right, and the exhaust is not as dominant as before. It is quite remarkable to see that the other contributions remain the same.

In a subsequent step, the Response Modification Analysis (RMA) can be included in the R&D process. While the CA computes the contribution of each individual observed indicator position, it does not take the sensitivity of each path into account. Modifying a source with a large contribution does not necessarily provide the desired results, as the component might be insensitive to changes [6]. Hence, the RMA is integrated into the process in order to cope with this weakness. The algorithm can be briefly described as follows: the signal at the response position is altered in the time domain, for example at a position with a peak in the signal, and the RMA now computes the sensitivity of all excitation positions, providing information about which of the observations should be altered, for instance by damping, in order to receive the desired output signal.

It is quite exciting that not only the overall level can be altered, but also individual parts of the signal. As **FIGURE 3** shows, it is now possible to look closely at the 4^{th} order, extract the order, modify the curve and then feed the network of the Contribution Analysis. One would usually assume that the rotating powertrain creates the dominant orders, but this is obviously not the case, **FIGURE 3**. The RMA now indicates that the modification of the exhaust system will not only result in a lower overall signal, but also in a far lower 4^{th} order.

SUMMARY

The presented framework can now be used as an iterative process in the development and design phase of the exterior noise. After the measurements have been performed and analysed, the conclusions drawn on the basis of either the Contribution Analysis or the Response Modification Analysis can be implemented for the test subject. The new measurements and analysis results can now be easily compared to previous measurements in order to qualify the modifications. This process speeds up the entire development process and thus leads to a more cost-efficient and valuable product for the customers.

REFERENCES

[1] H. Finsterhölzl, V. Caldiero, J. Hobelsberger, W. Baumann and F. Daiber: A New Exterior Noise Testing Facility in the Development Process at BMW. In: ATZ Worldwide, 108 (4), 2-5. 2006

[2] M. V. van der Seijs, D. de Klerk, D. J. Rixen, General framework for transfer path analysis: History, theory and classification of techniques, Mechanical Systems and Signal Processing, Volumes 68–69, February 2016, Pages 217-244, ISSN 0888-3270

[3] D. De Klerk, and A. Ossipov, Operational transfer path analysis: Theory, guidelines and tire noise application, Mechanical Systems and Signal Processing 24.7 (2010): 1950-1962.

[4] K. Noumura, J. Yoshida: Method of transfer path analysis for vehicle interior sound with no excitation experiment. Proc. of the FISITA 2006 World Automotive Congress, Yokohama, Japan

[5] J. Putner, M. Lohrmann, H. Fastl: Contribution analysis of vehicle exterior noise with operational transfer path analysis. In: Proceedings of Meetings on Acoustics, 19,040035, 2013, Acoustical Society of America

[6] J. Scheuren and M. Lohrmann: Transfer Path Analysis – Experiences, Expectations and Perspectives, SAE Technical Paper 2014-36-0803, 2014