A generalized methodology for a compensation of test-bench specific influences of a simulated pass-by compared to real outdoor measurements

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ABSTRACT

Due to new regulations regarding exterior noise of vehicles, requiring a more complex measurement procedure, and the increasing number of models and vehicle derivatives, the demand of pass-by measurements is increasing. Under these intensified conditions and while keeping organizational efforts low, the simulated pass-by has been widely accepted as an engineering alternative for measurements on real test tracks. Although the ISO 362-3 exactly depicts the setup of the indoor-testing of pass-by noise, some differences between outdoor and indoor measurements can be observed. These are usually caused by the semi-anechoic room itself and the dyno, which doesn’t necessarily represent the real tire-road contact. While the entire development process can be efficiently conducted in the indoor test-bench, type approval has to be performed outdoors. Even small deviations in the indoor measurement results may cause the developed vehicle to fail the type approval. Hence, we suggest a new method for a prognosis of the exterior noise on real test tracks based on indoor measurements. Therefore we have tested a wide range of current vehicles both indoors and outdoors in order to define a transfer function between both test methodologies either for individual vehicles or as a generalized model for test-benches.

1. INTRODUCTION

The importance of the exterior noise in the acoustic development process has grown in recent years. While each vehicle is supposed to deliver a certain image, from comfortable to sportive, regulations regarding emitted noise have still to be met worldwide. Unfortunately, these regulations are not quite the same in all regions. The ever-increasing diversification at most OEMS and their international business indicate that more and more measurements have to be performed. These not only include the conformity of production and type approval but also the research and development cycle, as the requirements have to be taken into account in an early stage for maximum cost-efficiency. Real pass-by measurements have been optimized in the past for a rapid workflow, saving as much time as possible and enhancing the track’s capacity. Yet, the measurements require a huge organizational effort, because vehicles must be transported to the test facilities, the weather has to be good, and drivers have to be perfectly trained to be on point for the measurements. Moreover, it is usually difficult to perform modifications to the vehicle or the measurement setup on site. Hence, it is reasonable to build specialized test benches for the simulation of pass-by measurements [1]. This approach also allows for further investigation in the field of NVH during the research and development phase. Both outdoor and indoor pass-by are exemplary shown in figure 1.

The base of a simulated pass-by test bench is usually an all-wheel dyno in a semi anechoic chamber. 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 respectively receding vehicle to be simulated on the dyno. Depending on the requirements, each side of the test bench is equipped with 36 microphones, which are all acquired synchronously to the driving speed and the rotational speed measured in the vehicle. With a subsequent post-processing, taking the propagation of sound into
account, the individual microphone signals are combined into one signal. This resulting virtual signal 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, further allows the synthesis of an audio signal, which can easily be monitored and analyzed subjectively.

With a well-designed test-bench and a thorough microphone setup the measurement results of indoor and outdoor measurements can be considered as almost congruent with little difference, especially considering the old regulations. Unfortunately it is not always possible to build a perfect test-bench meeting all the desired requirements, especially regarding size and lower cut-off frequency. Further, the microphone positioning is not always as detailed as necessary, resulting in a suboptimal spatial resolution. Hence, measurement results can differ quite drastically. As illustrated in figure 2, the measurements of a vehicle with a 12 cylinder engine can be considered as equal for indoor and outdoor measurements with the new regulations. Nevertheless, the same measurement with a 3 cylinder engine showed quite large differences between indoor and outdoor testing, as illustrated on the right hand side of figure 2. Consequently it is necessary to investigate on the reasons why such a huge difference could be observed. Therefore, both the acoustic properties of the semi-anechoic chamber and of the powertrain noise have been thoroughly analyzed.

Although there are strict regulations regarding exterior noise measurements and the design of the semi-anechoic chamber, it is not always possible to design the semi-anechoic chamber in an almost perfect fashion. Drawbacks are usually made regarding size and number of microphones, which consequently influences the acoustic properties. The desired lower cut-off frequency of the chamber hence cannot always be guaranteed. Considering this and the first mode of the room, it seems reasonable to investigate especially lower frequencies. Taking this and the results from the Contribution Analysis [5], which is based on the fundamentals of the transfer path analysis [2],[3], into account, usually the exhaust system and the engine are the dominant sources. Consequently, in an idealized model it could be possible to neglect the tires. Nevertheless we have decided to align both measurements with a tire noise simulation in the first place, and if necessary eliminating the influence entirely by the means of the operational transfer path analysis. Applying this knowledge, we investigated exhaust and engine noise rather thoroughly, where especially the order analysis came in handy, showing a correlation between measurement error, rotational speed and number of cylinders. This way it has been possible to create an engine specific transfer function between indoor and outdoor measurements, based on engine type and rotational speed.
2. A METHODOLOGY FOR COMPENSATING TEST-BENCH SPECIFIC INFLUENCES ON SIMULATED PASS-BY COMPARED TO REAL PASS-BY

2.1 Experimental setup

In order to be able to conduct a fair comparison we have measured a wide range of different vehicles in various configurations both in the semi-anechoic room and on the test track, where it has been taken care that exactly the same vehicle without any differences has been used. The aim was to avoid any possible difference, such as tires or other modifications, to receive reliable results. Outdoor tests have been conducted on the Audi test track in Neustadt, Germany, by experienced drivers using the PAK pass-by application. This has also been used for the indoor measurements, guaranteeing the exactly same analysis procedures and yet avoiding errors in the signal processing chain. In contrast to the outdoor measurement, instead of a test driver a robot has been used for all the runs. Rotational speed has been measured using the CAN interface in both setups, whereas velocity has been measured with radar outside and been provided by the test bench indoors.

We have tested a total of 16 vehicles from the various classes of Sedan, Avant, SUV, sports car, and coupe. If possible all engine variations have been tested resulting in tests with one 3 cylinder, seven 4 cylinder, one 5 cylinder, three 6 and 8 cylinder, and one 10 and 12 cylinder vehicles. Hence, the influence of different engine types and the exterior shape of the vehicle could be taken into account.

2.2 Powertrain noise measurements

One of the main questions raised prior to the analysis itself has been which sound sources are actually contributing to the overall level of the exterior noise. Previous experiments within the test-bench applying a contribution analysis, have shown that engine and exhaust system are usually the dominant sources, whereas tires and intake are negligible [5]. Adding all these individual contributions usually results in approximately the measured overall level. Therefore it seems reasonable to take care that all of these sources can be captured as similar as possible. Engine noise, exhaust and intake are not really affected and therefore considered as valid. Nevertheless, tire noise, which might be neglected, might show huge differences. The first difference is the contact between dyno and tire and road and tire. Depending on the dyno’s design the effective load on the surface might differ. Further, the surface is not necessarily comparable, so that even with the same tires noticeable differences might appear. Therefore it has been decided to remove this uncertainty and concentrate on the powertrain itself.

In order to accomplish this goal the used tires have been acoustically investigated with two different setups. Tire noise measurements have been performed on the test track with a customized quiet car. This way only the tire noise could be recorded while cancelling all other sources. For further

Figure 2: The diagram on the left side shows the results of indoor and outdoor pass-by measurements for a 12 cylinder engine. The difference is considered as negligible in contrast to the difference with a measurement of a 3 cylinder engine, where a difference of apx. 3 dB has been observed between indoor and outdoor measurement.
trials pass-by measurements have been conducted using an electric vehicle, assuming that the tire noise is dominant and all other sources can be neglected. Applying a logarithmic regression analysis along the test track, it is now possible to compute the share of the load and the rolling noise of each tire. Performing the measurements with different speed and acceleration both shares can be determined for each observed point along the test track according to the current speed. Figure 6 exemplary shows the portions of rolling and load for a tire measurement and the comparison of tire noise to overall noise. Applying the tire profiles allows to eliminate the tire noise from the outdoor measurements, resulting in more similar results to measurements performed indoor with slicks. The same can be done for the indoor measurements. Consequently it is now possible to either eliminate the tire noise or even simulate other tire/road constellations, which allows a direct comparison. Nevertheless we decided to eliminate the tire noise on concentrate on the power train.

2.3 Comparison of indoor and outdoor measurements

As previously described, the quantitative results of simulated pass-by measurements have been considered as valid in the past and provided reliable results in well-designed and planned test benches. As this is not always the case, it has been decided to investigate especially the scenarios where the results did not meet the expectations and a rather huge deviation appeared. Figure 2 illustrates measurement results for a 3 and a 12 cylinder engine, where the 12 cylinder engine shows almost no difference. Therefore we have decided to take a closer look into these two engines at first and investigate the differences for different runs, resulting in different gears, rotational speeds and overall levels. The results for the two observed engines are illustrated in figure 7 and 8. The 12 cylinder engine shows almost no difference between in- and outdoor testing in different gears and consequently different rotational speeds. The 3 cylinder appears to show a by far larger difference for higher gears and lower RPM respectively. While the measurements in the 2nd gear provided reliable results, a huge difference has been observed in the 3rd and 4th gear at low rotational speeds. This phenomenon has been observed for all vehicles with 3, 4 and 5 cylinders based engines, whereas 8 and 12 cylinder engines did not show such large differences. Hence, it seems reasonable to investigate the influence of the engine further.
Figure 7: Comparison of real and simulated pass-by measurements with a vehicle equipped with a 12 cylinder engine in 3rd, 4th and 5th gear. Only a little difference is being observed at lower RPM.

Figure 8: Comparison of real and simulated pass-by measurements with a vehicle equipped with a 3 cylinder engine in 2nd, 3rd and 4th gear. The difference between indoor and outdoor measurement is obviously rising with lower RPM.
The previously made observations led to the assumption to further investigate the engine noise itself, as there seems to be a correlation between rotational speed and sound pressure level. A rather common analysis method of rotating systems, such as a power train, is the so-called order analysis [6]. With the known acoustic properties of the engine, it is now possible to see whether the observed signal at one of the exterior noise microphones corresponds to the expected distribution. Knowing the engine type it is now quite simple to predict the dominant orders. As figure 9 illustrates, the 12 cylinder engine shows a quite distinct line at the 6th order and this hence meets the expectations. A further analysis of the signal showed that especially the 6th order has a huge contribution to the overall engine sound.

<table>
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<th>rpm 3rd gear</th>
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Table 1: Rotational speeds, dominant orders and the frequency of the dominant order for different engines in different gear constellations. Lower rpms at higher gears lead to lower dominant frequencies, which consequently lead to higher errors. The suspicious results are indicated in red.

### 2.4 Order Analysis and RPM based correction of the sound pressure level

The previously made observations led to the assumption to further investigate the engine noise itself, as there seems to be a correlation between rotational speed and sound pressure level. A rather common analysis method of rotating systems, such as a power train, is the so-called order analysis [6]. With the known acoustic properties of the engine, it is now possible to see whether the observed signal at one of the exterior noise microphones corresponds to the expected distribution. Knowing the engine type it is now quite simple to predict the dominant orders. As figure 9 illustrates, the 12 cylinder engine shows a quite distinct line at the 6th order and this hence meets the expectations. A further analysis of the signal showed that especially the 6th order has a huge contribution to the overall engine sound.

Figure 9: Comparison of the order analysis of a 3-cylinder and a 12-cylinder engine inside the exterior noise test-bench. The lack of low orders is quite obvious for both measurements. The 6th order of the 12-cylinder engine is picked up as domain, which has been expected, while the 1.5th order of the 3-cylinder engine is being absorbed.
Engines with three or four cylinders are expected to show a dominant 1.5\textsuperscript{th} or 2\textsuperscript{nd} order. Unfortunately figure 9 shows that the 1.5\textsuperscript{th} order is almost not visible in the 3D order APS, although it should be rather dominant. In comparison to the 12 cylinder engine it seems that lower orders are not even present, although the dynamic range for both diagrams has been set to the same levels. Hence, it needs to be investigated why these orders are not appearing. In a first step the base frequency for each observed order, gear and rpm constellation has been computed, as illustrated in table 1. It is quite obvious that the rotational speed is low for high gears and consequently resulting in low frequencies for the observed orders. Correlating this information with the acoustic properties of the exterior noise test-bench, led to the conclusion that the dominant frequencies are obviously damped by the room, which as a rather high lower cut-off frequency and 1\textsuperscript{st} mode.

This observation has been valid for all vehicles with similar engines and could be repeatedly confirmed. The shift in the SPL level has been almost constant for all 3 cylinder and 4 cylinder vehicles and only depending on the rotational speed of the engine. In a subsequent step we have correlated the rotational speed and difference between indoor and outdoor measurement. The scatter plot of the deviation in dB correlated to the rpm is illustrated in figure 10. It is quite obvious that the deviation for different rotational speeds is rather low and within a 0.5dB range both for accelerated and constant velocity measurements. Furthermore, a clear trend is visible. Moreover, experiments have shown that the SPL shift has been constant over the entire distance, resulting in a parallel shift of the curves. Consequently a RPM based lookup table could be designed for each engine type based on the regression curve shown in figure 9. Nevertheless it has to be noted, that these correction factors have been determined for one specific room and are not transferrable to other chambers.

3. 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 portfolio and the decreasing limits of worldwide regulations. 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. Nevertheless, results are highly depending on an optimal design of the semi-anechoic chamber. Measuring different gear constellations in different RPM ranges led to deviations up to 4 dB, which were caused by absorption of the dominant orders in the low frequency range. Hence, it is suggested to perform a RPM and dominant order based correction by just adding an RPM and room specific factor to the overall result. Due to the parallel shift of the curves reliable results have been achieved and a quite good prognosis can be made after conducting indoor measurements in a non-ideal chamber. Furthermore it is now possible to compensate test bench specific influences on the exterior noise, leading to an acceleration of the development process and therefore an improvement of the final product.
REFERENCES


