

Method for Measuring and Analyzing the Transfer Path of Acoustic Phenomena into the Driver Cabin of a Battery Electric Vehicle

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ABSTRACT

The driving comfort is an important factor for buying decisions. Especially for battery electric vehicles (BEV) the acoustic quality is an elementary distinguishing feature, since the masking of an internal combustion engine (ICE) is no longer present. Opposing the importance of the acoustic quality is the lack of knowledge of how to measure and interpret the high frequency noise generated by an electric powertrain with respect to the NVH behavior influencing the passengers [1, 2].

In this contribution a method for measuring and interpreting the transfer path of acoustic phenomena from the drivetrain of a battery electric vehicle into the passenger cabin is presented. Due to the lack of masking by the ICE in case of BEV, high frequency phenomena must be considered as well.

In order to determine the airborne transfer function from the electric powertrain to the driver cabin, a dodecahedral speaker is used for reciprocal measurements. Therefore in a first step, the sound power and the emission characteristic of the dodecahedron is investigated in a novel approach by laser scanning vibrometry and by measurements according to DIN EN ISO 3745:2012 [3].

The results of the reciprocal measurements are validated by calculating the direct transfer path with the help of an order section analysis and comparing those results to measurements on the semi-anechoic roller test bench.

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INTRODUCTION

The driving comfort is an important factor for buying decisions. Especially for battery electric vehicles (BEV) the quality of the vehicle interior sound is an elementary distinguishing feature, since the masking of an internal combustion engine (ICE) is no longer present. Opposing the importance of the acoustic quality is the lack of knowledge of how to measure and interpret the high frequency noise generated by an electric powertrain with respect to the NVH behavior influencing the passengers [1, 2].

Regarding the acoustic quality of electrified powertrains various new effects and sound sources have to be accounted for. In [Figure 1](#) one can see a main challenge regarding the electrification of the automotive powertrain. In course of the electrification of the powertrain vehicles lose the internal combustion engine and thus one of their main characteristic sound sources. This leads to the fact, that electric vehicles lack the masking of the ICE and the noise of auxiliary components and the electrified powertrain are thus audible.

Along with the lack of masking arouse other challenges depicted in [Figure 2](#). In [Figure 2](#) a schematic representation of a Campbell-Diagram is shown. The horizontal lines are the resonant frequencies of the system and the lines originating from zero, which are called orders, are the harmonic excitations of the system depending on the engine speed. For electrified powertrains orders related to the excitations by the electric drive are in general higher than those in accounted to ICE. The main excitation of a permanent magnet synchronous machine with 36 slots and 6 pole pairs is for example the 36th. In comparison the main excitation orders of a four cylinder ICE are the 2nd and the 4th. As well the speed range of the electric drive may - depending on the topology - well be above of the speed range of an ICE. These effects result in the fact that regarding the acoustic quality of electrified powertrains acoustic phenomena in higher frequency regions have to be accounted for.

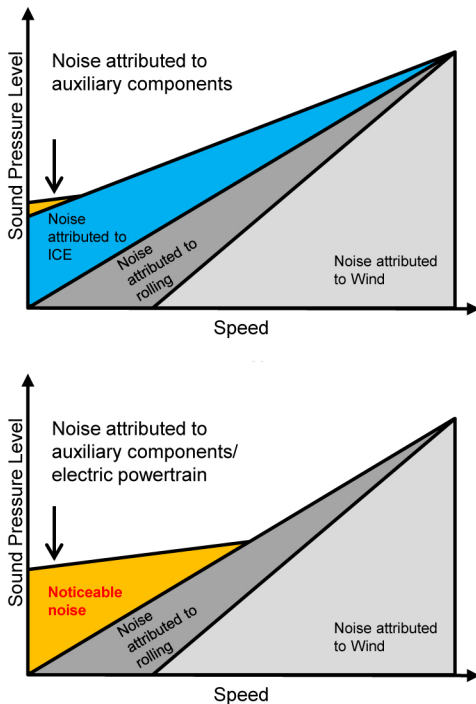


Figure 1. Lack of masking by the ICE in electrified powertrains [1]

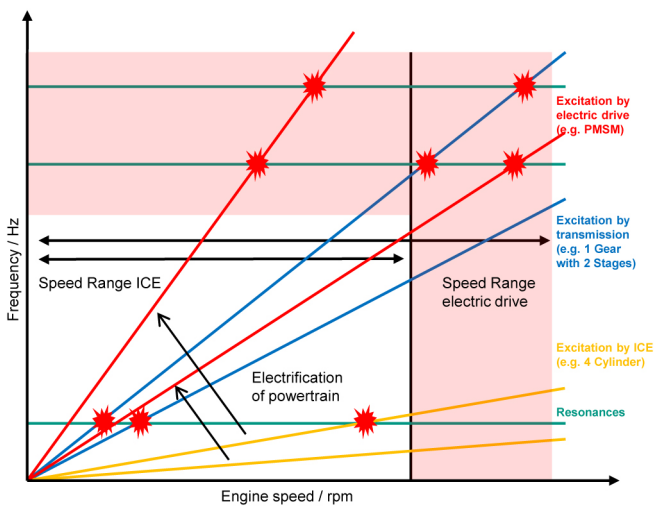


Figure 2. Challenges regarding acoustic phenomena in BEV [1]

The before mentioned challenges can be exemplarily demonstrated looking at the interior acoustic measurement of a BEV in [Figure 3](#). The measurements are performed using a binaural head positioned on the front passenger seat. The powertrain of the BEV mainly consists of a PMSM with 36 slots and 6 pole pairs and a gearbox with one gear and two stages leading to characteristic orders.

In prior publications [2, 4, 5] these measurements and measurements on an anechoic powertrain test bench were analyzed regarding whine phenomena originating from the electric drive.

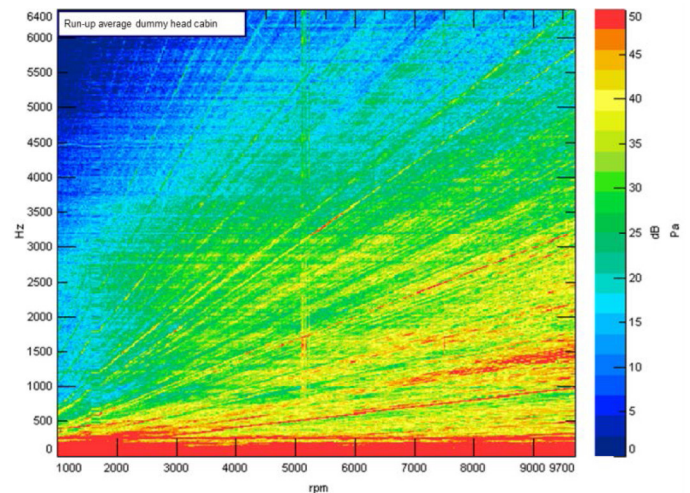


Figure 3. Actual Sound-Pressure-Levels in the driver cabin during the Run-Up measured with an artificial head microphone

Looking at the tendency towards increasing complexity of modern powertrain design and the distributed development of the components it becomes obvious, that new methods for the early validation of the interior acoustic quality of BEV must be adapted, developed and tested. Since most acoustic phenomena can only be described using a holistic approach considering every component of the powertrain the IPEK X-in-the-Loop-Framework (XiL) is used as a basis to develop a method for the validation of the interior sound quality [6]

The XiL framework, shown in [Figure 4](#), is developed at IPEK in order to support and structure the validation of technical products - mainly with the focus on vehicles - throughout the product development process. The X represents the System under Development (SUD), which can either be virtual or physical. The SUD is completed by the rest system forming the technical system to be validated in context of the System "Environment", the system "Driver" and the "Maneuvers and Test Cases".

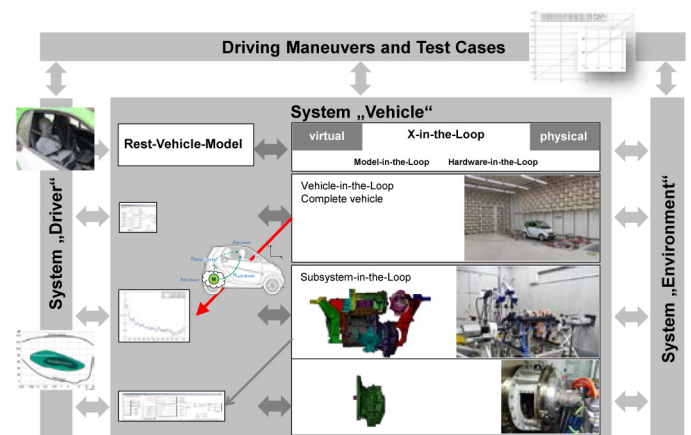


Figure 4. X-in-the-Loop-Framework used for the validation of acoustic phenomena [6]

Hereby a validation on the different levels - component, powertrain and vehicle - is only possible using rest vehicle models. Thus it is of crucial importance to determine valid vibroacoustic rest vehicle models with regard to the focused whine phenomena at hand.

In this contribution the rest vehicle model for the powertrain is derived looking at the complete vehicle using transfer path analysis. Regarding [4], in a first step only the transfer path of the airborne sound into the vehicle is considered and quantified. The transfer path of the airborne sound could for example be used to virtually transfer the measurement results from the powertrain test bench into the vehicle and thus validate the interior noise with respect to the whine phenomenon at hand.

In order to determine the transfer path using Rayleigh's reciprocity principle first the sound source, a dodecahedron, is quantified and then used for the reciprocal excitation. Then the transfer path from the engine compartment into the driver cabin is calculated and compared to the direct measurement results.

Finally a summary of the achieved results is presented and further research potential is identified.

MEASUREMENTS

In the following chapter, the different series of measurements, necessary to obtain the airborne transfer function from the engine compartment into the driver cabin are demonstrated.

Emission Characteristic of the Dodecahedral Speaker

One important criterion for the application of the reciprocity principle on acoustic measurements according to Fahy [7] is an omnidirectional radiation of the sound source.

In preparation for the reciprocal transfer path analysis, the directivity of the dodecahedral speaker is investigated, by a measurement setup according to DIN EN ISO 140-4 [8].

The dodecahedron is placed in the center of a full circle with a radius of 1.5 m. Twelve microphones are positioned at a height of 0.75 m in 30°-intervals on the circle. As an input signal, white noise is applied to the speaker. The setup is illustrated in Figure 5.

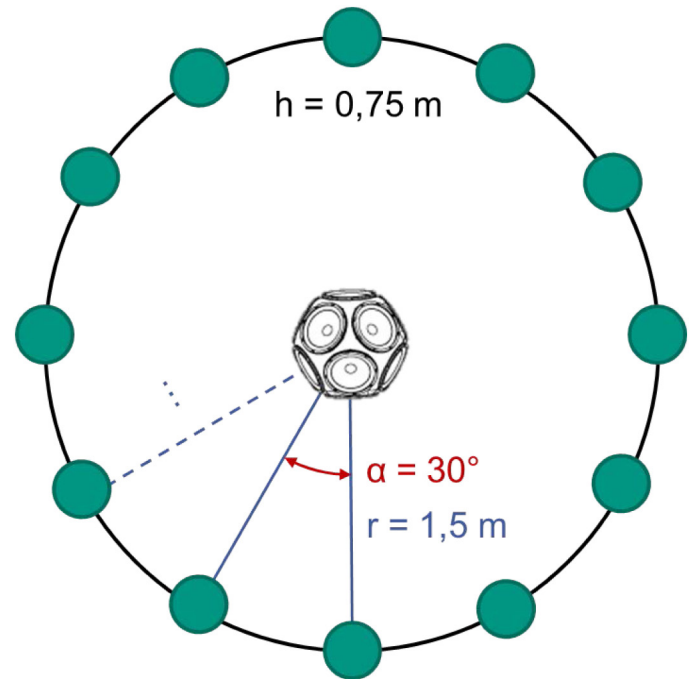


Figure 5. Measurement setup for the determination of the radiation characteristic according to DIN EN ISO 140-4 [8]

An energy average of the sound pressure levels of the 12 microphones is calculated by the formula

$$L_{360} = 10 \log \left[\frac{\sum_{i=1}^{N_M} 10^{0,1L_{30,i}}}{N_M} \right] \text{ dB} \quad (1)$$

The deviation of the energy average (L_{360}) and the sound pressure level of the equivalent position ($L_{30,i}$) indicate the corresponding directivity. Both are demonstrated in Figure 6, in addition with the upper and lower limits according to DIN EN ISO 140-4. Those are not obligatory values for an omnidirectional radiation with regard to reciprocal measurements, but give a good impression of the radiation characteristic.

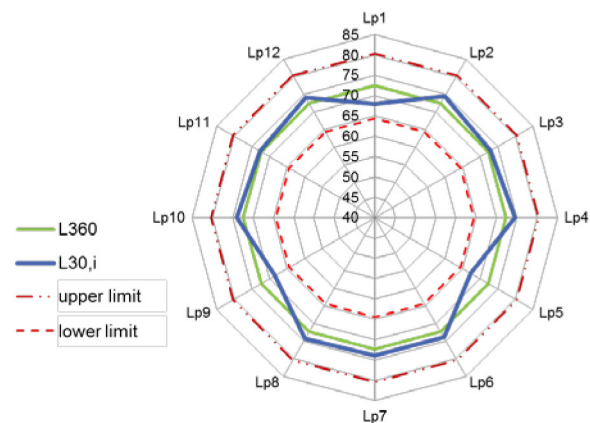


Figure 6. Radiation characteristic of the dodecahedral speaker