



Measurement and analysis of the interior noise and the transfer path of acoustic phenomena into the driver cabin of a battery electric vehicle

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ABSTRACT

Driving comfort is an important factor for buying decisions. This is especially apparent in battery electric vehicles (BEV) where the acoustic quality is an elementary distinguishing feature, since the masking of an internal combustion engine (ICE) is no longer present. Despite the importance of the acoustic quality, there is a general 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.

In this contribution, the measurement results of the interior noise of a battery electric vehicle are analyzed. Specific methods for determining the torsional vibration of the powertrain as reference value are also presented. Furthermore, 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.

The measurements are performed in the context of the IPEK-X-in-the-Loop Framework on a roller test bench in a semi-anechoic chamber.

Keywords: Interior noise, transfer path

I-INCE Classification of Subjects Number(s): 11.5.1, 13.2.1

1. INTRODUCTION

Driving comfort is a factor of importance for buying decisions, especially for electric vehicles where acoustic quality is an elementary distinguishing feature, since the masking of an internal combustion engine (ICE) is no longer present (1). Despite the importance of the acoustic quality, there is a general lack of knowledge of how to measure, interpret, and rate the high frequency noise generated by an electric powertrain (2).

When facing the challenge of validating the interior noise of battery electric vehicles (BEV), a few general obstacles must be understood and overcome. First of all, the lack of masking by the ICE has to be considered when looking at the contribution of the main sources to the overall sound pressure. Figure 1 depicts the contribution of the different sound sources depending on the vehicle speed for a conventional vehicle and a BEV. Especially for lower vehicle speeds, electric vehicles lack the accustomed masking of the ICE, making room for the noise of auxiliary components as well as the noise of the electric powertrain, which in general is much quieter than the ICE (2). Further challenges arise when looking at the general characteristics of the interior noise of BEV, which are displayed in Figure 2. These are – depending on the topology – mainly the higher rotational speed of the electric drive and the higher excitation orders in comparison to ICEs, thus causing higher frequency content in the vehicle interior noise. This leads to new acoustic phenomena, resulting in new challenges regarding the validation of the vehicle interior noise (3,4).

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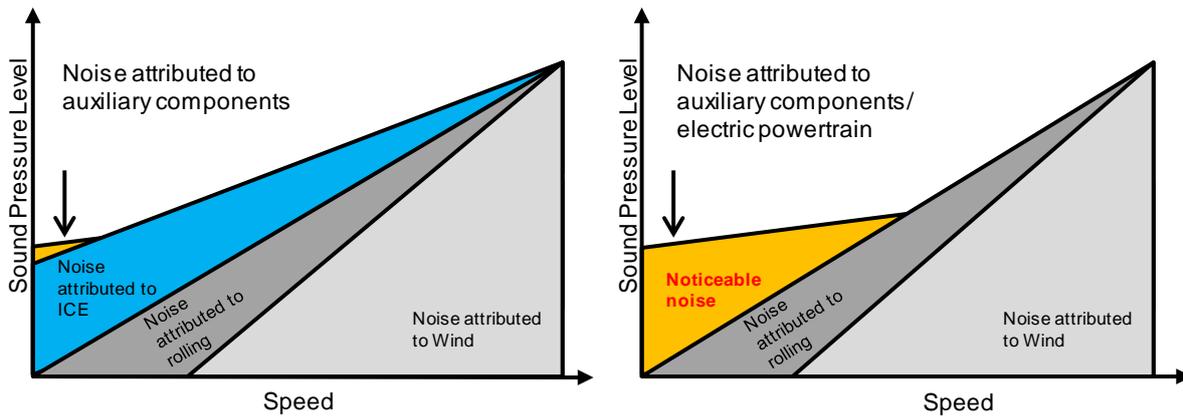


Figure 1 – Lack of masking in BEV (2)

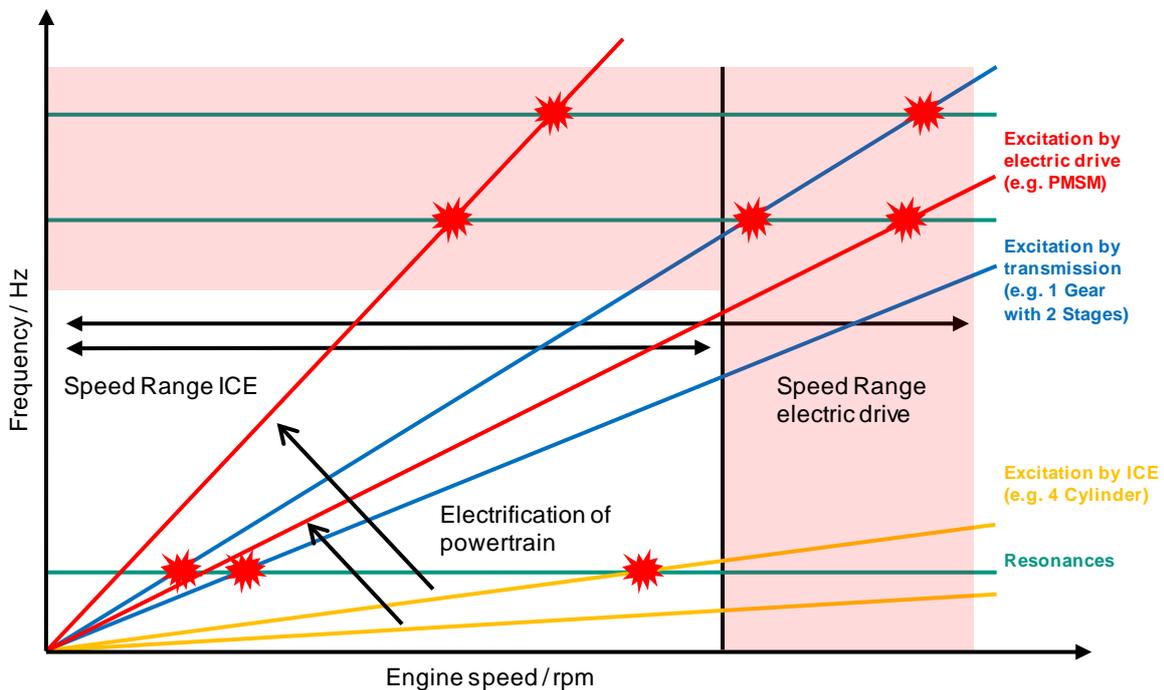


Figure 2 – Challenges regarding NVH of BEV (2)

2. Validation of the interior noise in context of the XiL framework

Due to the increasing complexity of modern powertrain design, validation – being the task of answering the question if the right system for the customer is developed – can only be accomplished using a holistic approach considering every component of the powertrain, as well as the customer, the relevant driving maneuvers and test cases, and the environment of this sociotechnical system.

At IPEK - Institute of Product Engineering at KIT, the X-in-the-Loop (XiL) framework is developed in order to enable engineers to continuously validate complex products – mainly, but not exclusively, vehicles and drive systems – in every stage throughout the product development process (5–7). Thus, the XiL framework is used to systematically develop validation environments. When looking at the validation of the electrified powertrain regarding interior noise, an exemplary validation environment for the assessment of the tonal noise caused by the torsional vibration of the electric drive is shown in Figure 3. Here, the validation of the system vehicle is performed on the complete vehicle level, the powertrain level, and the component level. Each level can be addressed in the virtual domain and the physical domain. The validation of the subordinate level is performed using suitable rest vehicle models, which are derived from the superior level, or in case of an evolutionary product development process, can be derived from the predecessor (5).

In this contribution, the measurement setup and results for the complete vehicle and the analysis of the airborne noise transfer path from the motor compartment into the driver cabin are presented.

In previous publications, the investigation of the physical powertrain on an anechoic powertrain test bench (2,8–10), the simulation of the virtual powertrain (10), and the investigation of the electric drive on a component test bench (5) were presented. The results, among others, include the analysis of the system's torsional vibration and the torsional excitation by the electric drive, as well as the analysis of the structural vibration and surface velocities of the powertrain.

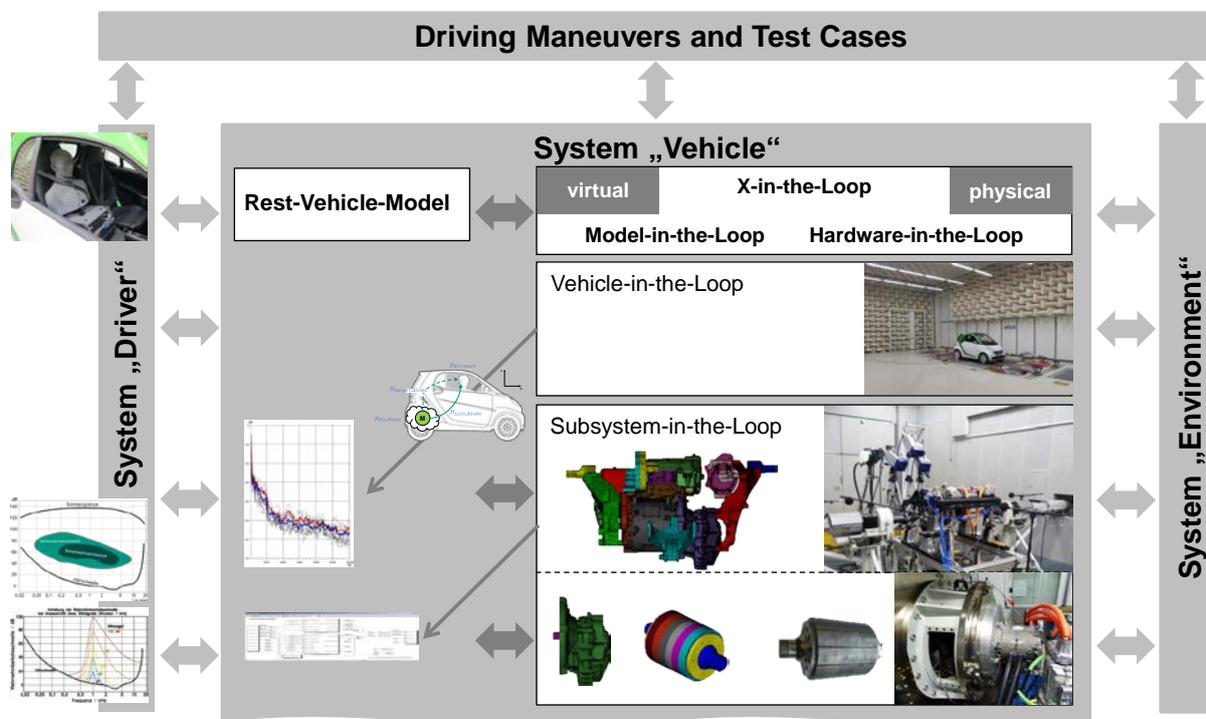


Figure 3 – Validation of interior noise of BEV in context of XiL (11)

3. Measurement setup for a semi-anechoic roller test bench

In this section, the measurement setup for the operational measurement of the complete vehicle on the semi-anechoic roller test bench and the measurement setup for an airborne noise transfer path analysis are introduced. To facilitate the comparison of the measurement results from previous publications (2,8,9), the same measurement system is used for all measurements.

3.1 Operational measurement

In order to guarantee consistent and comparable results for the operational measurement of the BEVs interior noise, the powertrain from (2,8,9), including the electric drive used in (5), are physically integrated into the vehicle. The measurement of the vehicle interior noise is performed on the semi-anechoic roller test bench of the IPEK-Institute of Product Engineering at the Karlsruhe Institute of Technology.

The measurement setup includes a binaural head on the front passenger seat and six microphones surrounding both ear positions in a statistically random pattern as displayed in Figure 4. The microphones are used to control the results regarding variations of the sound pressure due to position and frequency dependent local maxima and minima. Especially for higher frequencies, this can be problematic since the wavelength is inversely related to the frequency. In addition to the microphones and the binaural head in the passenger compartment, six microphones are installed inside the motor compartment surrounding the powertrain in a star-like pattern relating to the powertrain measurements in (2,8,9). In addition to the acoustic sensors, vibration sensors are installed before and after the motor mount and on the surface of the powertrain, in order to quantify the transfer of structural vibration into the vehicle body and to assess the radiation of acoustic power by the powertrain.

For the quantification of the 36th order torsional vibration, the resolver signals are recorded and analyzed as described in (2). Due to the similar layout, the results can be compared to the measurements presented in (2,8,9).

The driving maneuvers and test cases, as described in the context of the XiL framework, for one thing are ramps of vehicle velocity with a constant accelerator pedal position and slope. The different load cases are realized very consistently by applying a defined voltage to the electric accelerator pedal. Due to the fact that the gearbox only has one gear, the vehicle velocity is directly linked to the rotational speed of the electric drive. Nevertheless, a precise measurement of the rotational speed of the electric drive is necessary for the order based analysis of the recorded time data (12). This is realized by using the resolver signals to calculate the rotational speed of the electric drive. The other test cases are ramps of load for a given rotational speed of the electric drive in the range of interest. Here, the vehicle speed is controlled by the roller test bench and the accelerator pedal position is consistently increased via the voltage with a constant slope. For both general test cases, the electric drive's possibility of recuperation and thus negative loads are regarded.

In order to control the overall vehicle conditions such as temperature and state of charge (SOC), influencing for example the recuperation, the CAN data is continuously monitored and recorded on the measurement system during the maneuvers.

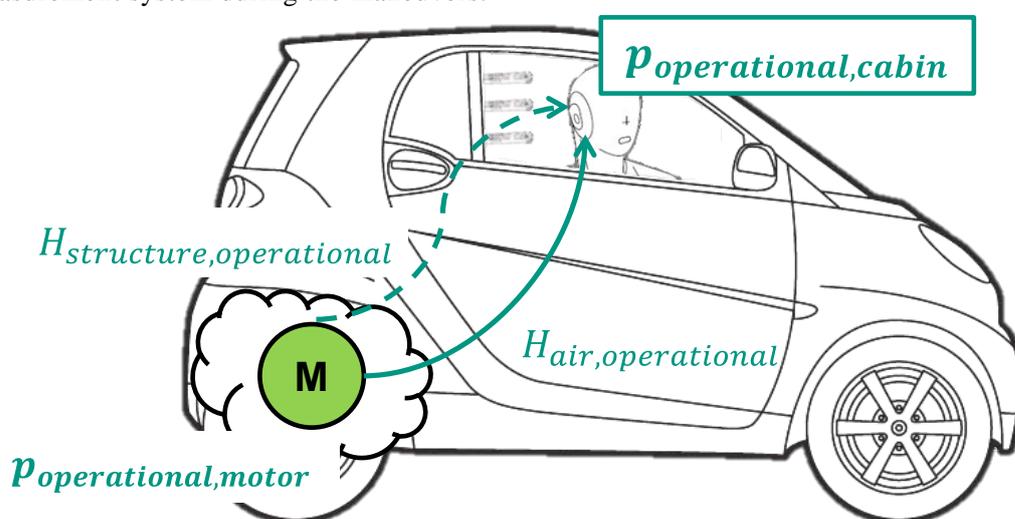


Figure 4 – Measurement setup for operational measurement (11)

3.2 Reciprocal measurement setup

In general, the part of the interior noise that can be accounted to the powertrain is dependent on the transfer paths transmitting and transforming the excitations by the powertrain into the interior. Here, two main paths can be differentiated: first, the structure borne transfer path regarding the vibrations introduced into the vehicle body over the motor mountings and other connections; second, the airborne transfer path accounting for the transmission characteristic of the airborne noise from the motor compartment into the driver cabin. Prior investigations (9) showed that, for the focused example, the structure borne transfer path can be neglected due to the dominance of the airborne transfer path.

In order to determine the transfer function of the airborne noise from the motor compartment into the driver cabin, various techniques can be applied. First of all, a thorough analysis of the operational measurements, using the signals of the microphones inside the motor compartment and the driver cabin, can lead to important insights. A problem with the use of the operational measurements however, is the determination and separation of the structure borne and airborne noise. Referring to the hypothesis that only the airborne transfer path is relevant for the focused example, an isolated analysis of the 36th order transfer function can lead to good results.

Other possibilities to determine the airborne noise transfer path are direct and reciprocal measurements, using artificial sound sources as described in (11) utilizing a dodecahedron. In this contribution, a specialized volume source with an encapsulated loudspeaker connected to a rigid tube is used. The volume velocity at the end of the tube can be determined using two microphones for the frequency range in which the sound can be described by a plane wave (13). The signal generated by a signal generator and applied to the volume source is band-limited white noise in the frequency range from 96 to 6400 Hz.

The frequency response function (FRF) is measured reciprocally using seven different positions for the point of excitation, in order to control the results regarding variations due to position and frequency dependent local maxima and minima (14,15). Additionally, three direct measurement positions inside the motor compartment are used to control the results. The sound pressure is measured with six microphones inside the passenger cabin and on twelve different positions inside the motor compartment. The measured quantities can be used to determine the FRF between either two sets of pressure microphones or between the calculated volume velocity of the source and the sound pressure in the motor compartment (14).

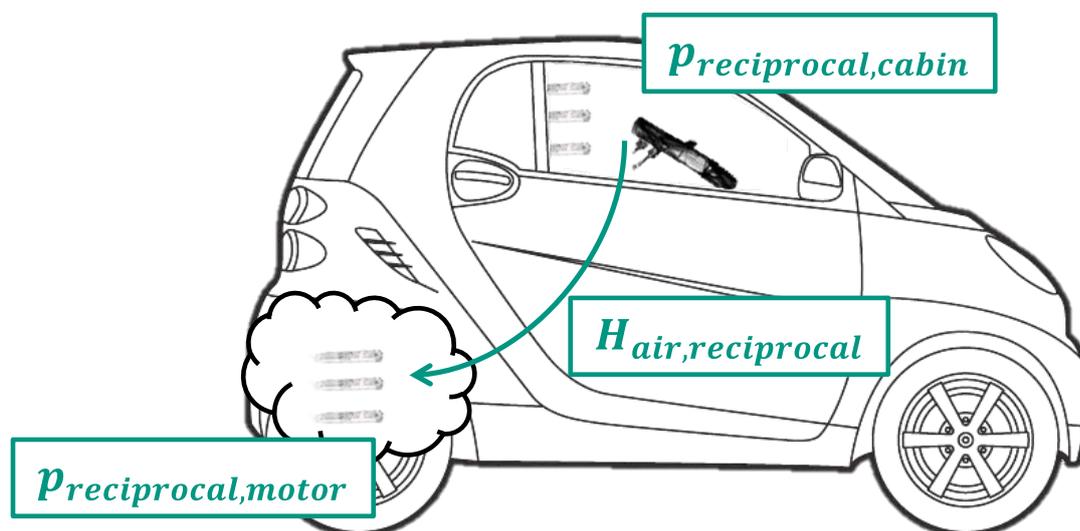


Figure 5 – Measurement setup for reciprocal measurement (11)

4. Measurement results for semi-anechoic roller test bench

In this section, the measurement results for the operational measurement of the BEV and the reciprocal quantification of the airborne noise transfer path are presented.

4.1 Operational measurement results

Figure 6 shows a spectrogram of an acoustic measurement in the driver cabin of the BEV for a linear variation of velocity for a constant accelerator pedal position of 80 percent, measured on an acoustic roller test bench. The measurements are realized using six microphones positioned around the artificial binaural head on the front passenger seat. The figure displays the energetic average of the six microphones, thus stabilizing the results with regard to position dependent variations.

It can be seen that the 36th order, related to the electric drive, shows an elevation of about 5000 rpm, thus indicating resonant frequencies respectively an elevation of the excitation as described in (2,5,8). The powertrain at hand consists of a permanent magnet synchronous machine (PMSM) as a central drive and a two-stage transmission with one gear. With an approximate gear ratio of about ten and a tire radius of about 0.28 m, the velocity corresponding with the acoustic phenomenon is close to 50 km/h and thus in the region of interest regarding the masking according to Figure 1 (2).

Due to the measurement on an acoustic roller test bench, the interior noise lacks wind noise entirely and the rolling noise is altered by the different surface of the roller and contact conditions, which leads to the differences in the results when compared to the road measurements displayed in Figure 7. Other differences result from the impulsive disturbances induced by the road surface during the road measurement, and the fact that the slope of the increasing vehicle velocity can only be controlled on the roller test bench. Thus, vehicle conditions cannot be controlled as effectively, and signal analysis and comparison of different vehicles and components is aggravated. In contrary, the realistic evaluation of the vehicle interior noise is only possible using road measurements since the wind and tire noise in general cannot be neglected in terms of masking. Another solution to overcome these obstacles is to simulate the contribution of the wind and tire noise, creating a mixed physical and virtual validation environment in the context of the XiL framework.

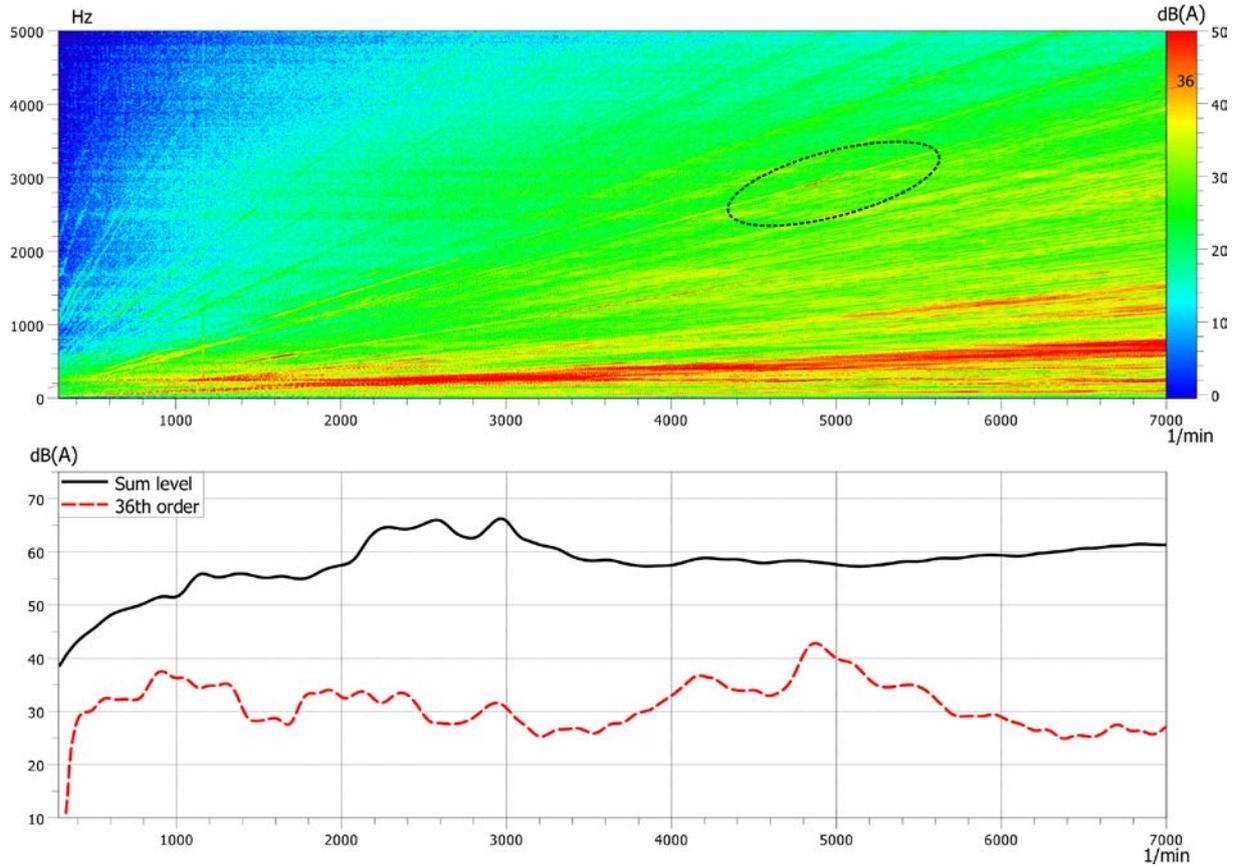


Figure 6 – Interior noise for 80 % accelerator pedal position measured on roller test bench

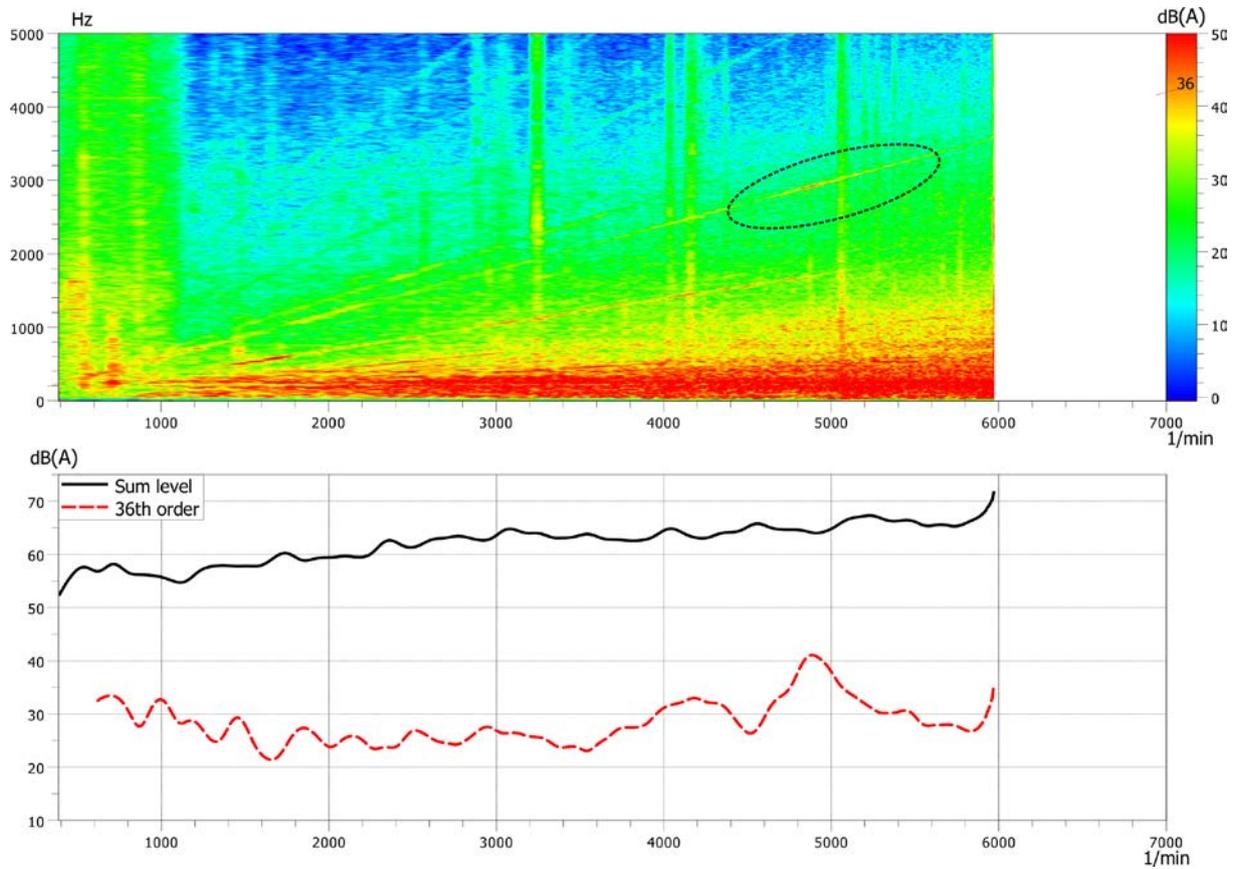


Figure 7 – Interior noise for 100 % accelerator pedal position measured on test site

In Figure 8, the torsional vibration for the measurements on the component, powertrain, and complete vehicle level are displayed. The torsional vibrations in the drivetrain of the acoustically relevant 36th order are measured with different methods. On each level of validation, the torsional vibrations on the backside of the electric drive are analyzed using the recorded resolver signals as described in (2). On the component level, these results are compared to measurements with an incremental disk with 360 increments on the front side of the electric drive (5). On the powertrain level, the torsional vibration in addition to the analysis of the resolver signals is measured using a rotational vibrometer on the input shaft and the intermediate shaft of a specially prepared gearbox as described in (8). The measurement of the torsional vibration on each level of validation shows consistent and comparable results across the levels and different measurement methods. It can be noted that each methods has its limits, like the decreasing signal-to-noise ratio of the incremental disk for higher rotational speeds (5), the difficulty in stabilizing the measurement with the rotational vibrometer (8), and the electric disturbances influencing the analysis of the resolver signals (2). Nevertheless, the torsional vibration can be used for a comparison of the acoustic quality on different levels since there is a good correlation of the 36th order interior noise and the 36th order torsional vibration (2).

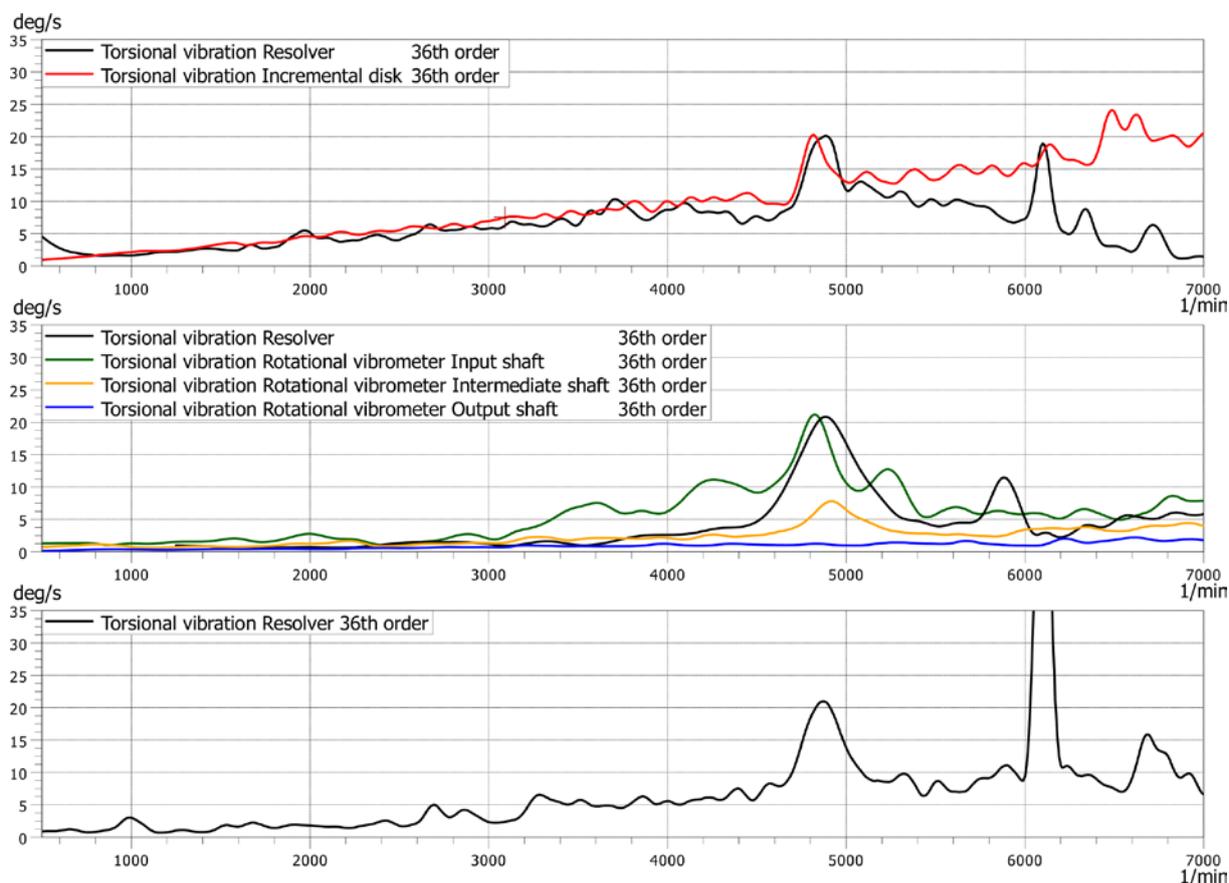


Figure 8 – Torsional vibration of the rotating system on component, powertrain, and vehicle level (2,5,8)

4.2 Reciprocal measurement results

In Figure 9, the analysis of the reciprocal measurement in the form of the FRFs of the sound pressure inside the driver cabin (measured at six different positions) and the sound pressure in the motor compartment (measured at twelve different positions) are displayed. The excitation is realized with the help of the source described in paragraph 3.2. Seven different positions corresponding with the microphone positions and the binaural head inside the driver cabin are used. The measurement time is five seconds for each different source position. When calculating the transfer functions the microphone next to the position of the sound source is not considered because they are too close.

As previously proposed, an excitation position dependent variance of the FRFs can be observed based on the curves in Figure 9 in the top diagram, and looking at the standard deviation displayed in Figure 9 in the bottom diagram.

For the overall evaluation and further utilization, the average of those transfer functions is calculated and displayed in Figure 9 at the bottom. The trend of the curve is – as expected – a flattening decrease over the frequency range that can generally be described using an estimation function of the form $y=a+b*x+c*\sqrt{x}$, starting at about 200 Hz as depicted in Figure 9 in the bottom diagram.

The evaluation of the average transfer function and its standard deviation is influenced by the frequency resolution and the sample rate, the averaging over time and the different measurement positions and repetitions. Further influencing factors are the estimator of the transfer function and the either linear or quadratic averaging of the complex value or the magnitude of the pressure or transfer function (16–20).

In this example the auto power spectrums (magnitude of the FFT) are linearly averaged over the measurement time and the microphone positions in the driver cabin and the motor compartment for each reciprocal excitation position. Afterwards the transfer function is determined as the quotient of these real-valued functions. Those transfer functions - displayed in Figure 9 in the top diagram - representing the different excitation positions are linearly averaged and the standard deviation is calculated. Those results are displayed in Figure 9 at the bottom.

The transfer function can, for example, be used to virtually transfer the 36th order from the measurement of the powertrain in an anechoic chamber to the vehicle level and possibly auralize the results, thus enabling an early assessment of the powertrain and its components by either subjective or objectified ratings.

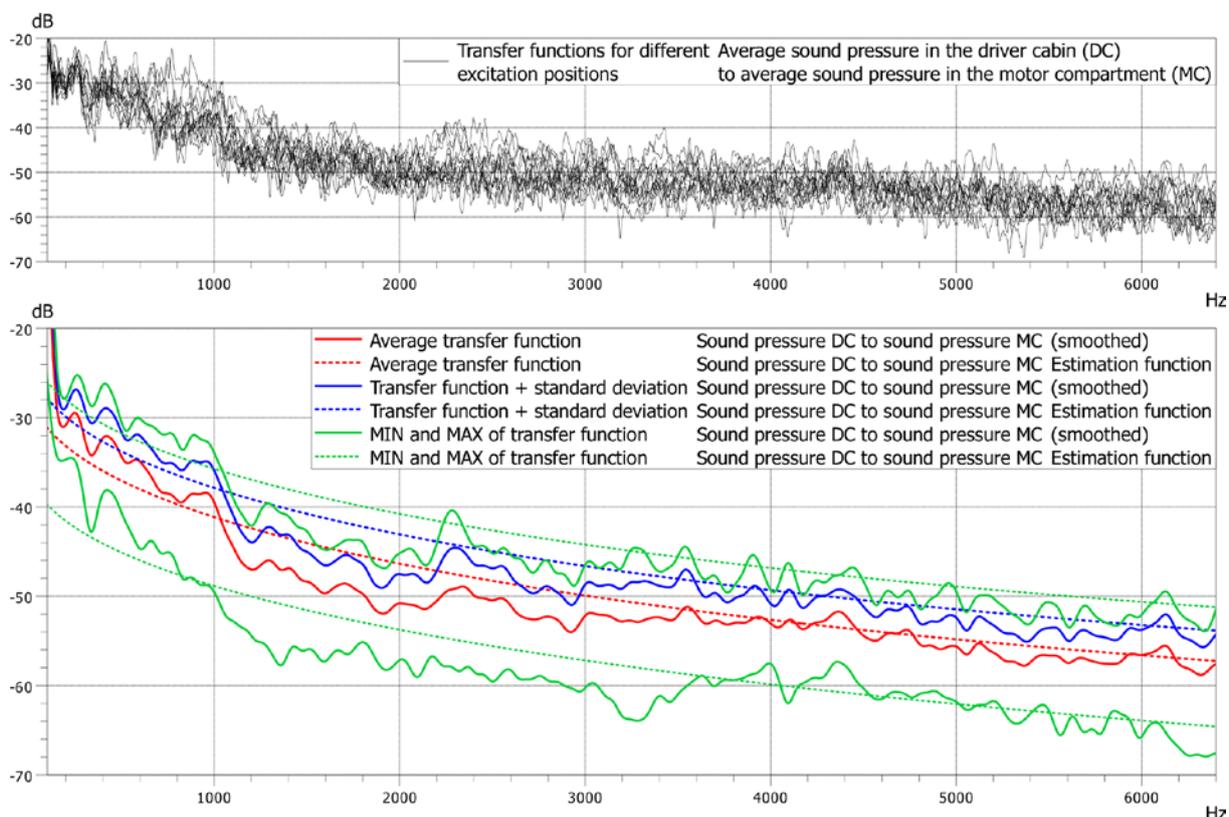


Figure 9 – Airborne noise transfer function from the motor compartment into the driver cabin

5. CONCLUSIONS

In this contribution, the motivation and goals for a holistic approach to the validation of the (battery electric) vehicle interior noise on the vehicle, powertrain, and component levels are presented with the example of the 36th order torsional excitation by the electric drive. The validation environment is developed in the context of the X-in-the-Loop framework regarding the systems driver and environment with respect to the relevant maneuvers and test cases.

The measurement setup for the validation of the complete vehicle on a semi-anechoic roller test is explained. The results are presented and compared with the analysis of the powertrain and component level in previous publications. The torsional vibration and various methods for its measurement are introduced as a comprehensive physical value with good coherence to the 36th order interior noise in the focused battery electric vehicle.

Additionally, the measurement setup for the determination of the airborne noise transfer path from the motor compartment into the driver cabin is shown. The airborne noise transfer path - described by the transfer function of the sound pressure in the motor compartment with respect to the sound pressure in the driver cabin - shows position dependent variations. Multiple transfer functions are averaged and approximated by a simple mathematic function. Further investigations should focus on the systematic evaluation of the influences on estimating and averaging airborne noise transfer functions, as well as the position dependent variations.

Additional research will focus on the quantification of the volume source, calculating the volume velocity in order to determine the transfer path between the calculated volume velocity of the source and the sound pressure in the motor compartment.

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