

Methods for Measuring, Analyzing and Predicting the Dynamic Torque of an Electric Drive Used in an Automotive Drivetrain

Albert Albers, Jan Fischer, and Matthias Behrendt
IPEK

Dirk Lieske
Daimler AG

ABSTRACT

The driving comfort is an important factor for buying decisions. For the interior noise of battery electric vehicles (BEV) high frequency tonal orders are characteristic. They can for example be caused by the gearbox or the electric drive and strongly influence the perception and rating of the interior noise by the customer.

In this contribution methods for measuring, analyzing and predicting the excitation by the dynamic torque of the electric drive are presented. The dynamic torque of the electric drive up to 3.5 kHz is measured on a component test bench with the help of high frequency, high precision torque transducer. The analysis of the results for the order of interest shows a good correlation with the acoustic measurements inside the corresponding vehicle. In addition an experimental and numerical modal analysis of the rotor of the electric drive are performed. The torsional resonance modes are put into context of the elevation of the dynamic torque with regard to the frequency. In a further analysis the phase shifts of the torsional excitation of the different rotor segments, caused by the skewing of the stator, are taken into account. The results show a good correlation with the elevation of the dynamic torque as well as the acoustic measurement for the order of interest.

The measurements, as well as the simulation, are integrated in a validation environment in context of the X-in-the-Loop framework. This enables a consistent and thorough validation of BEV interior noise in virtual as well as physical domain.

CITATION: Albers, A., Fischer, J., Behrendt, M., and Lieske, D., "Methods for Measuring, Analyzing and Predicting the Dynamic Torque of an Electric Drive Used in an Automotive Drivetrain," *SAE Int. J. Alt. Power*, 4(2):2015, doi:10.4271/2015-01-2363.

INTRODUCTION

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. For the interior noise of BEV high frequency tonal orders are characteristic. They can for example be caused by the gearbox or the electric drive and strongly influence the perception and rating of the interior noise by the customer. Opposing the importance of the acoustic quality is the lack of knowledge of how to measure, analyze and predict the high frequency tonal noise generated by the dynamic torque of the electric drive.

In [Figure 1](#) a measurement of the interior noise of a BEV can be seen. Here one can see, that the 36th order - being accounted to the electric drive - shows an elevation at about 5000 rpm. This tonal noise at about 50 km/h is clearly audible in the driver cabin and thus influences the acoustic quality of the BEV. The BEV has a central drive topology with a permanent magnet synchronous machine (PMSM) as the electric drive and a one gear two stage transmission.

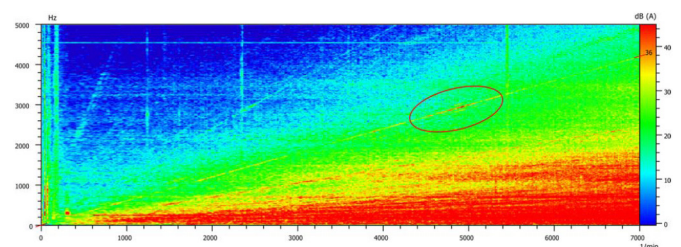


Figure 1. Spectrogram of the acoustic measurement with a binaural head in an electric vehicle [1]

In prior publications the interior noise of the BEV was analyzed with the help of acoustic measurements on the road and on a semi-anechoic roller test bench [2]. As well a transfer path analysis for the airborne sound was performed [2,3]. In further publications the powertrain was analyzed on an anechoic powertrain test bench synchronously measuring electric, mechanic and acoustic quantities [1,4,5]. The results show, that the 36th order tonal noise correlates with the torsional vibration in the rotating system and is excited by the gearbox. The surface velocities of the stator housing show no

significant elevation. A first analysis of the 36th order dynamic torque of the electric drive being the reason for the tonal noise is described in [6]. Overall a high consistency of the measurement results on the different layers of validation can be observed.

The objective of this contribution is to introduce a holistic approach for the measurement, analysis and prediction of the excitation by the dynamic torque of the electric drive in physical as well as virtual domain. New and existing methods are adapted to the phenomenon described above and exemplary results are presented. The dynamic torque of the electric drive up to 3.5 kHz is measured on a component test bench with the help of a high frequency and high precision torque transducer. The analysis of the results for the order of interest shows a good correlation with the acoustic measurements inside the corresponding vehicle. In addition an experimental and numerical modal analysis of the rotor of the PMSM are performed.

The torsional eigenmode is put into context of the elevation of the dynamic torque with regard to the frequency. In a further analysis the phase shift of the torsional excitation of the different rotor segments, caused by the skewing of the stator, are taken into account. The results show a good correlation with the elevation of the dynamic torque as well as the acoustic measurement for the order of interest.

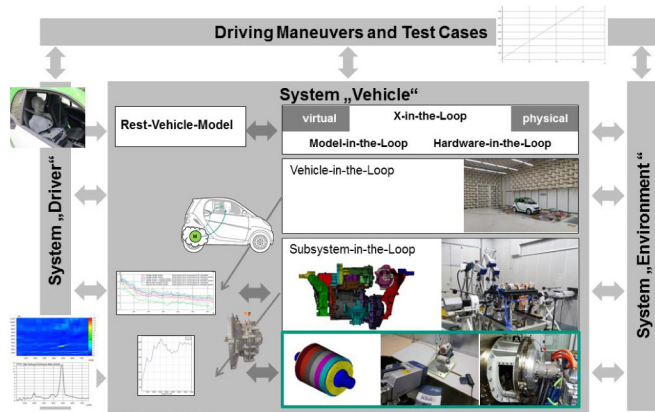


Figure 2. The X-in-the-Loop Framework according to [7,8] for the validation of an electrified powertrain with regard to high frequency tonal acoustic phenomena

The measurements, as well as the simulations, are integrated in a validation environment¹ (VE) in context of the X-in-the-Loop (XiL) framework. An adaption of the general XiL framework to the specific case at hand is depicted in Figure 2. The XiL framework is developed in order to systemize and facilitate the continuous validation of complex products such as vehicles and powertrains throughout the development process. The validation of the system vehicle thereby takes place in context of the systems driver and environment and the relevant driving maneuvers and test cases. This enables a consistent and thorough validation of BEV interior noise in virtual as well as physical domain for the layers vehicle, powertrain and component. In the further course of this contribution the component layer is focused and the specific methods are described.

1. A validation environment (VE) is defined as a manifestation of the operation system used for the validation, with regard to the methods and resources for one or more combinations of a product, a specific point in the product life cycle and a target of validation.

MEASUREMENTS

In this section the measurement of the dynamic torque of the electric drive and the experimental modal analysis of the rotor are described. The measurement setups and the influencing factors are presented and the results are analyzed and compared.

Measuring the Dynamic Torque

In order to measure the high frequency dynamic torque of the electric drive with regard to the excitation of tonal noise a new measurement concept is developed. The dynamic torque is measured on a component test bench using a high frequency and high precision torque transducer. With the help of an asynchronous load machine, the dynamic torque of the electric drive can be measured for the complete speed and load range. The dynamic torque is measured with a high precision, high frequency torque flange installed between the two machines. All measurement quantities - including CAN data - are recorded synchronously using the same vibro-acoustic measurement system used for the measurement on the superior layers of validation. [1,4,6].

Complementary measurement quantities are the torsional vibration measured with the help of an incremental encoder, a rotational vibrometer and the resolver as described in [1,4,6]. As well the surface vibration is measured with three tri-axial vibration sensors. The measurement setup is shown in Figure 3 and a schematic representation is depicted in Figure 4.

Regarding the physical connection special care must be taken for the shaft and the coupling of the test machine and the braking machine with the measurement flange. An ideal solution would be a very stiff connection of the test machine to the measurement flange and a shaft with low stiffness followed by a relatively high inertia forming the connection between the braking machine and the measurement flange [6]. Due to the inline measurement setup of the measurement flange the measurement results necessarily contain the dynamic torque of the load machine as well as the dynamic torque of the test subject. In order to ensure that the order of interest can only be accounted to the test subject further measurements with a different test machine are performed and the results are compared. It can be concluded, that the 36th order can be fully accounted to the electric drive of the BEV [6].

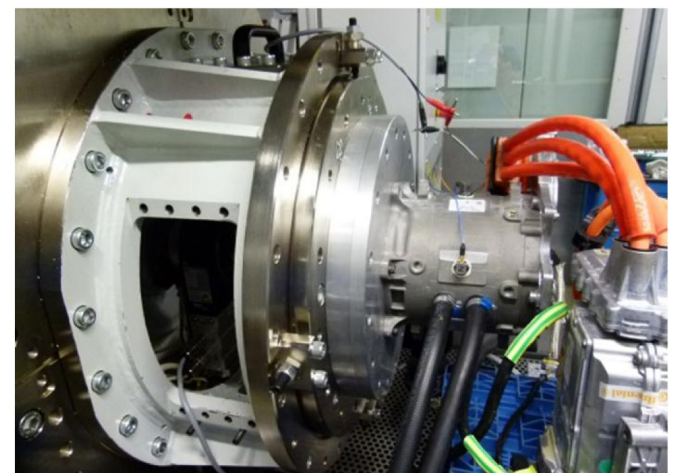


Figure 3. Measurement setup on component test bench for electric drive [6]

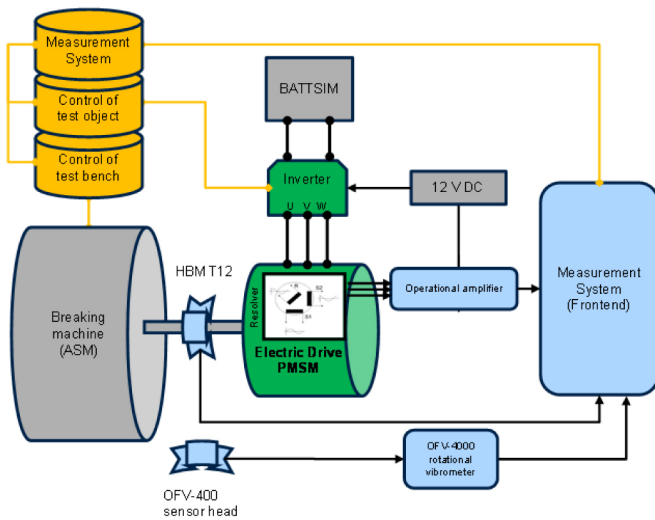


Figure 4. Schematic measurement setup on component test bench for electric drive [6]

The measurement results of dynamic torque are displayed in a Campbell diagram and an order section of the 36th order in Figure 5.

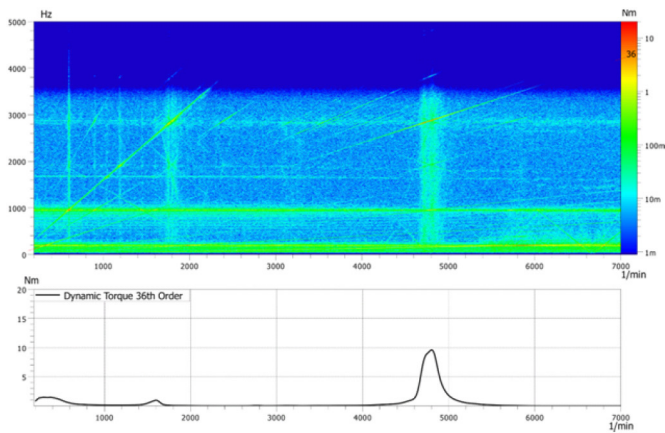


Figure 5. Campbell diagram and order section (36th) of the dynamic torque on a component test bench [6]

The results show that with this configuration it is possible to measure the high frequency dynamic torque like the phenomenon of interest. It can be seen, that the 36th order dynamic torque shows an elevation according to the acoustic phenomenon measured inside the BEV and on the anechoic powertrain test bench [2,4,6]. The measurement results confirm the hypothesis, that the tonal noise is directly related to the 36th order elevation of the dynamic torque of the electric drive.

Experimental Modal Analysis of the Rotor

In a next step an experimental modal analysis is performed in order to investigate the influence of the rotors eigenfrequencies on the dynamic torque, since it is not entirely clear, if the elevation of the dynamic torque at about 5000 rpm can be accounted to an elevation of the electro mechanic excitation or an eigenfrequency of the rotor.

For the experimental modal analysis a 3D scanning vibrometer with an included signal generator is used. The excitation is performed by a shaker system connected to the signal generator as described in

[9,10]. The force eccentrically exciting the rotor is measured by an impedance sensor connected to the stinger of the shaker. The measurement setup is displayed in Figure 6.

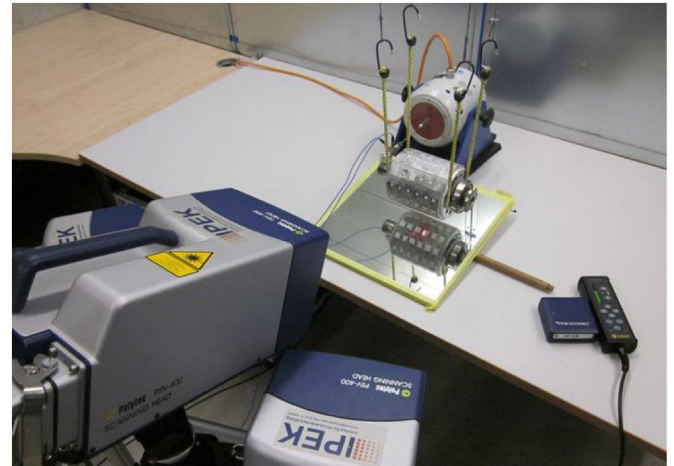


Figure 6. Measurement setup for the experimental modal analysis

Influencing factors regarding the measurement setup are the chosen diameter and length of the stinger as well as the point of excitation and the excitation signal. Measurements are performed for various points of excitation focusing the excitation of the suspected torsional mode being responsible for the elevation of the dynamic torque. The measurements are performed for half of the rotor using a mirror. By looking at half a rotor all modes symmetric to the longitudinal axis can be identified.

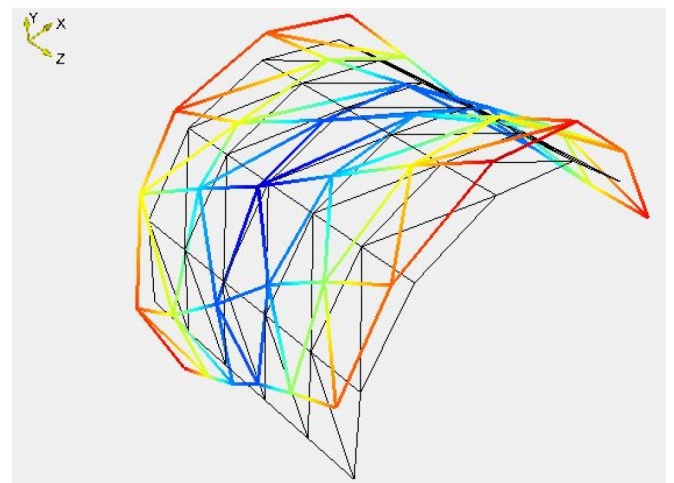


Figure 7. Modal shape of the first torsional resonance

In Figure 7 and 8 a part of the results of the measurements are displayed. In Figure 7 one can see the modal shape of the torsional eigenfrequency at about 3 kHz. In Figure 8 the averaged H1 frequency response function (FRF) from the measured force of excitation to the surface acceleration of the measurement points is displayed.

Hereby the function H1 is defined as the quotient of the cross power spectrum of the measured quantities and the auto power spectrum of the surface accelerations.