Independent characterization of structure-borne sound sources using the in-situ blocked force method

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ABSTRACT

The vibro-acoustic behavior of systems and components in modern vehicles play an increasingly important role in the development process of high quality products in automotive industry. In order to characterize the numerous mechanical, electrical and mechatronic systems, many of which embody significant sources of structure-borne sound and vibration, advanced measurement techniques are required. Ideally, such characterization techniques should allow specifying supplier components on a test rig without the necessity of conducting vehicle measurements to allow a better understanding of the NVH behavior at an early stage in the development process.

This paper investigates the applicability of the in-situ blocked force method as a receiver-independent approach for the characterization of an electrical steering system. First, blocked forces are obtained from test bench measurements to characterize the system at its multiple connection points. In a second step, the blocked forces are transferred to a second structure to predict the receiver response in a different installation. The accuracy of the in-situ blocked force approach is investigated by comparing the predicted response with actual measurements. Finally, the usability of the obtained data for a virtual prediction of the interior sound pressure is discussed.

Keywords: source characterization, blocked forces, TPA, Virtual Acoustic Prototyping
I-INCE Classification of Subjects Numbers: 11.1.4, 11.1.8, 11.5.1, 13.2, 74.5

1. INTRODUCTION

In automotive industry a major task in the development process of vehicle components is achieving a satisfying NVH performance of the component on a vehicle level. In accomplishing this task, it is necessary to consider the source of the noise on system level as well as the transfer behavior of the vehicle, as both contributions result in the NVH impression the customer experiences in the passenger cabin. Hence, as for other applications in the field of acoustics, one must follow the typical source-path-receiver sequence to obtain full understanding of the physical process. The emphasis of this paper is on the source and its characterization.

While for airborne sound contribution straightforward methods for source characterization on a power basis exist [1], invariant classification methods for structure-borne contributors are rare. However, precise characterization of structure-borne sound sources, i.e. structures with some form of internal excitation, is crucial for predicting sound and vibration in assembled structures like the vehicle. Therefore, this paper deals with an approach to accomplish this objective for steering systems, which can also be used for other structure-borne sound sources. In automotive industry this approach is explicitly useful as it allows separation of contributions from the source from effects caused by the vehicle structure, which can be examined using transfer path analysis.

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Once invariant source descriptors and the transfer behavior of the vehicle are available, the resulting sound pressure in the cabin can be predicted for any given combination of source and receiver without the necessity of having a physical assembly. This approach is called Virtual Acoustic Prototyping [2] and will be addressed towards the end of this paper.

2. Electric steering systems

Due to their numerous advantages, electrically operated power steering systems (EPS) have become increasingly widespread in all vehicle classes in recent years. These systems allow fuel savings up to 0.8 liters per 100 kilometers, solely by the use of an EPS system [3]. The general design of an EPS-system uses an electric motor to generate the required power for steering assistance as shown in Figure 1. The electric motor obtains its power from the onboard supply system of the vehicle and is controlled by an electronic control unit (ECU). The steering command from the driver is obtained by a torque sensor measuring the twist of the torsion bar, which is linked to the steering wheel by the steering column and intermediate shaft. This torque and the vehicle velocity serve as inputs to the ECU for calculation of requested power assist.

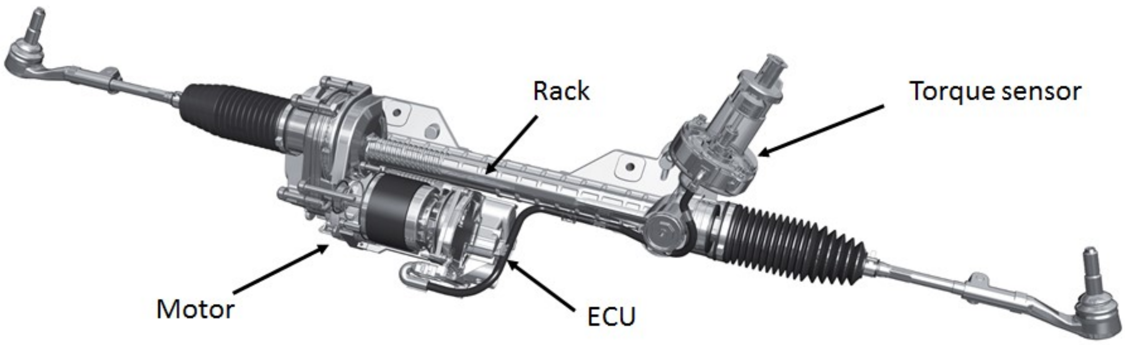

Figure 1 – General setup EPSapa-system

The rotational power of the motor is converted to a translational movement of the steering rack via a steering power gear. The specific steering system under investigation belongs to the group of EPSapa-systems, which have the physical attribute that the motor shaft is mounted axis-parallel to the steering rack. For such systems, the rotational movement of the motor shaft is transmitted to the steering rack by a toothed-belt and a recirculating ball gear as shown in Figure 2.

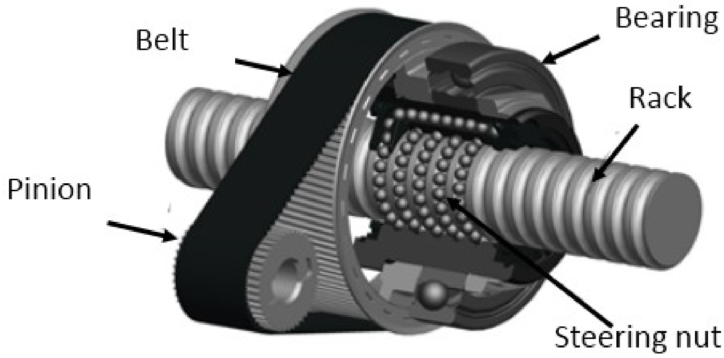

Figure 2 – Ball and nut gear in EPSapa-system

The recirculating ball gear consists of a ball screw, an endless ball chain, and a ball screw nut. The ball and nut gear are driven by a toothed belt and pulley. The steering nut rotates around the steering rack and the interposed ball chain converts the rotating motion into a linear motion of the steering rack.

Regarding the NVH-behavior of EPSapa-systems, the main contributors during normal operation are noise induced by the active meshing of the toothed-belt and electrically induced noise from the power pack.

3. Methods for source characterization based on forces

For characterization of structure-borne sound sources, dynamic forces, acting at the interface between the vibration source and a passive receiver structure, are of major interest. At each of these coupling points, where source and receiver are connected, there can exist up to three orthogonal forces and three moments about the orthogonal axes. Since source modelling is still not sufficiently developed to handle most active technical components, the 'activity' of such vibration sources have to be determined by measurement. In the following paragraphs different approaches for obtaining the dynamic forces are presented and discussed regarding applicability for the investigated case of an electric steering system.

For reasons of clarity the chapter is split up into direct methods, which include techniques, where the forces are measured directly via force sensors and indirect methods, which abstain from using force cells in the path of force flux. Besides that distinction, the different measurement approaches can be divided into two substantial classes, some providing contact forces, while the others allow acquiring blocked forces. While contact forces represent the dynamic input of a certain source into a certain receiver structure, blocked forces provide an invariant description of the source, as they are not altered when using a different receiver structure, but represent a pure source characterization.

3.1 Direct methods

A trivial solution to the task of obtaining dynamic forces, is to measure the desired interfacial quantities directly by placing force sensors amid source and receiver. However, in many technical applications, nonreactive implementation of the transducers is impracticable due to constraints caused by the physical design or potential alterations of the source-receiver interface [4]-[5].

Nevertheless, in the following two direct methods to obtain the force contribution of a source are presented, which are the direct contact force as well as the direct blocked force method according to Figure 3:

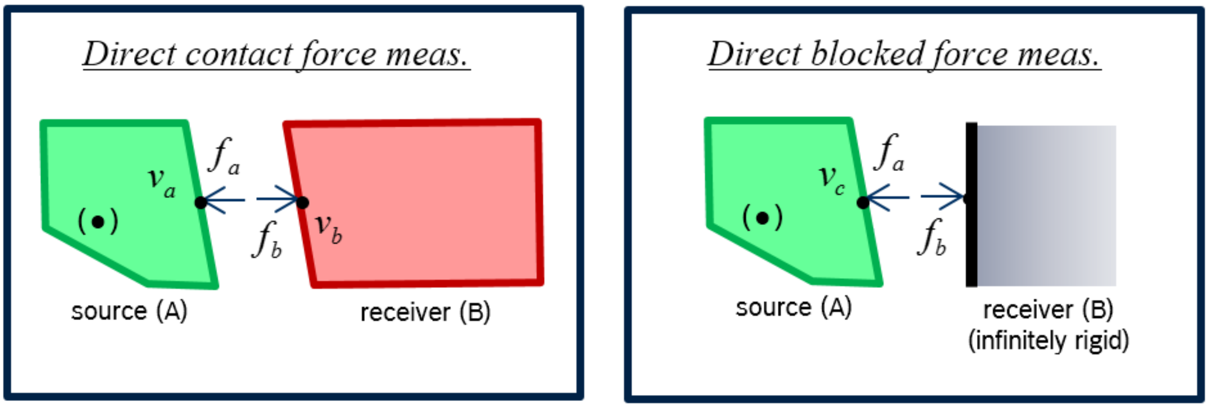

Figure 3 – Direct methods for force identification

3.1.1 Direct contact force

The source contribution of a source (A) into a receiver (B) is controlled by the transmission process at the coupling points (a/b).

$$\{f_c\} = \{f_b\} = -\{f_a\} \Big|_{(\{v_a\}-\{v_b\})=0} \tag{1}$$

Therefore contact forces can be seen as a measure for the source activity, which strongly depend on the investigated source-receiver installation, therefore the operational forces are not suitable for prediction of the response, when the passive receiver structure differs in its properties or is even changed by another set-up. Hence, this approach is not useable for Virtual Acoustics Prototyping.

3.1.2 Direct blocked force

The blocked force is defined as the force that is required to counter the operational source velocity at the interface at which the source is connected to a receiver to zero.

$$\{f_{bl}\} = -\{f_a\}\Big|_{\{v_c\}=0} \tag{2}$$

In theory, true blocked terminations ($v_c = 0$) can theoretically be achieved by connecting the source to an infinite rigid receiver structure. In practice these conditions can only be approximated over a limited frequency range requiring bulky, rigid test rigs [6], which are not feasible for electric steering systems, among other things, due to a wide variety of possible positions of the mounting locations.

3.2 Inverse methods

Due to the shortcomings of the previously mentioned methods of direct source characterization for many technical components, this section is about inverse methods relinquishing on direct measurement of forces using force transducers.

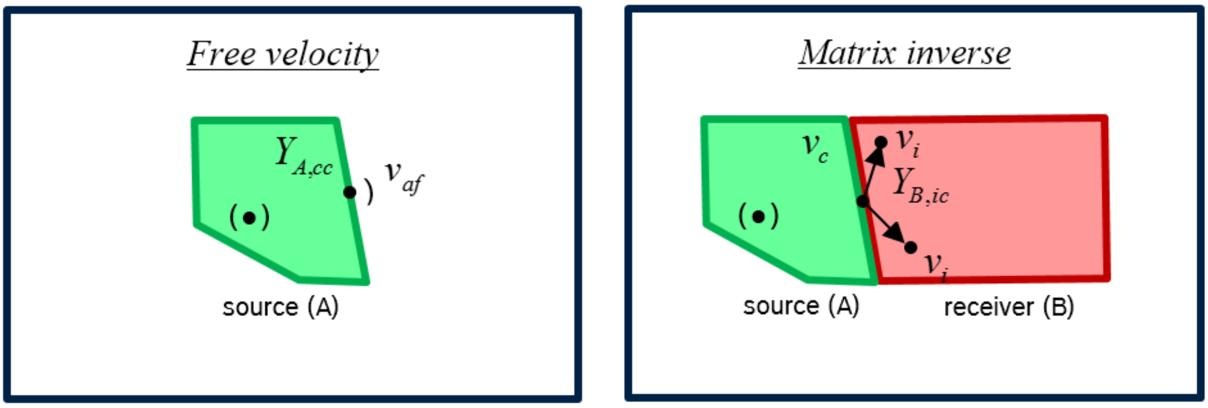

Figure 4 – Inverse methods for force identification. Free velocity (left); Matrix-inverse method (right).

3.2.1 Matrix-inverse method (classic TPA)

Inverse methods have been widely and successfully applied, particularly in transfer paths analysis (TPA) [7]. The basic idea is to obtain the required forces from structural responses observed at several remote positions on the receiver structure, while applying a known force at the force input points of the separated receiver structure or vice versa. Conventionally, these responses are used as quantities to calculate the FRF-Matrix $Y_{B,ic}$. Besides the passive measurement of receiver properties with dismounted source, it is required to measure the source in operation using the resulting velocities at the previously chosen positions on the receiver structure yielding the velocity vector $\{v_i\}$. The blocked forces can then be calculated using matrix inversion of the FRF matrix:

$$\{f_c\} = [Y_{B,ic}]^{+}\{v_i\} \tag{3}$$

Again, the main drawback of this approach is the lack of invariant source data, as it delivers contact forces for the interfaces that cannot be used for Virtual Acoustic Prototyping.

3.2.2 Free velocity

The free velocity method can be seen as a counterpart to the previously explained direct blocked force method. While the blocked force method requires a significantly lower mobility of the receiver compared to the source mobility, requirements of free velocity are the reverse.

$$\{f_{bl}\} = [Y_{A,cc}]^{-1}\{v_{af}\}\Big|_{\{f_a\}=0} \tag{4}$$

The boundary condition f_a=0 is a constraint to the method allowing only situations where (i) a constant velocity source idealization can be assumed or (ii) the source can be completely separated from the receiver and operated freely suspended to yield the free velocity vector $\{v_{af}\}$. When considering the dynamic behavior of the source $Y_{A,cc}$, the free velocity can be transferred into its opponent, the blocked force, using equation (4).

Although the essential conditions can be met for many technical applications like fans or pumps and the method is widely accepted even to the extent that it has been standardized [8], the main shortcoming of the concept results from the need to separate the source from any rigid support, which is unfeasible for many machines and active components that require a certain load to represent real-life operation conditions like appropriate forces on the rack of the steering systems.

3.3 In-situ blocked force

A relatively new approach, known as the in-situ blocked force method, has the advantage that blocked forces can be obtained from a two-stage measurement conducted in-situ, i.e. when the source is connected to a receiver, thus facilitating independent source characterization, while the source is operated under realistic conditions [9].

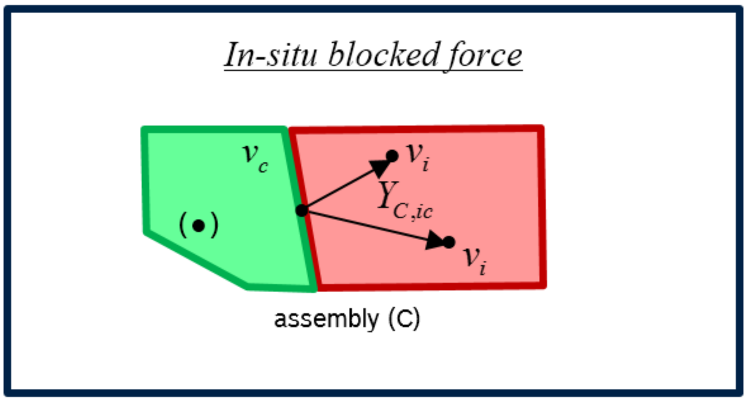

Figure 5 – In-situ blocked force method

In a first step, frequency response functions between the source-receiver interface (c) and remote points (i) on the passive receiver structure are measured on the coupled assembly C, yielding the generalised transfer mobility matrix $Y_{C,ic}$. In a second phase, the vibration source is operated and the vector of operational velocity responses $\{v_i\}$ is measured on the receiver interface at the previously defined remote points. The vector of in-situ blocked forces f_{bl} can eventually be obtained using matrix inversion similar to the classic TPA-approach with:

$$\{f_{bl}\} = [Y_{C,ic}]^{+} \{v_i\} \tag{5}$$

Considering this method, it is obvious that the obtained data is an invariant source characterization that can be used for Virtual Acoustic Prototyping without the major drawback of the direct blocked force method of requiring an infinite rigid receiver. Furthermore the approach is appealing in the automotive industry, because source characterization can be done either in-situ without dismounting the source from the vehicle if needed on a test-rig representing the receiver structure. The application of this method will be discussed in section 4.

3.4 On-board validation

To meet the requirements of testing quality in automotive NVH it is necessary to have confidence in predicted sound pressures based on the blocked forces like in a Virtual Acoustic prototype. Therefore some form of validation for the obtained blocked forces is crucial. The so-called on-board validation (OBV) has become popular in recent years as tool to ensure such quality of measured blocked forces and cross check the obtained results [10].

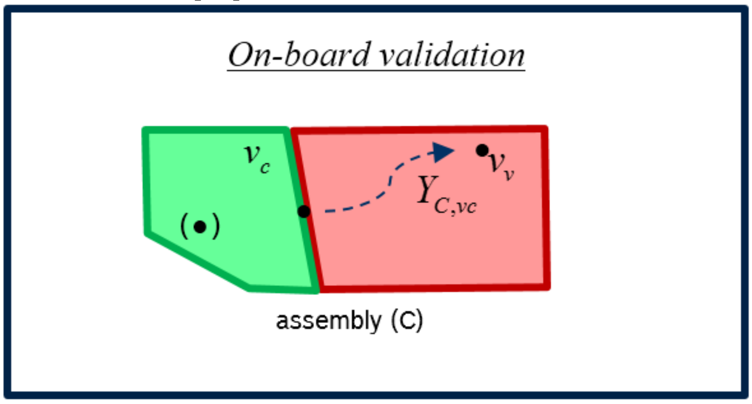

Figure 6 – On-board validation

It requires to define a validation point (v) on the receiver structure to obtain the velocity v_v at this position during the operational measurement, which is not part of the operational velocity vector v_i and is therefore not employed to calculate the blocked force according to equation (5). During the measurement of the passive properties of the receiver structure $Y_{C,ic}$, the on-board validation approach requires to measure the transfer mobilities between the coupling points of source / receiver (c) and the validation point to obtain $Y_{C,vc}$. With this data the velocity at the validation point can be calculated:

$$\{v_{v,calc}\} = [Y_{C,vc}] \cdot \{f_{bl}\} \tag{6}$$

One advantage of the on-board validation is the fact, that it is not necessary to move the source to another receiver structure, which would involve possible problems due to remounting, but on the other hand would be the more consistent procedure, as it is similar to what is done in practice, when taking results from the test rig to predict sound pressure in a vehicle. Therefore in this report an additional validation approach is employed, where the subframe is the same, but its structural behavior is modified for validation by changing the clamping condition of the carrier to yield a significant change in the structural behavior. This technique is called modified on-board validation (MOBV) throughout this paper.

4. Measurement results

4.1 Measurement setup

In the presented case the blocked forces of an EPSapa electric steering system have been measured. In general the receiver should comprise a sufficiently high mobility to provide adequate SN-ratio even for low steering speeds like 100°/s. Therefore the original subframe from the vehicle was mounted on a rigid test bed as shown in the overview of Figure 7 to act as receiver structure.

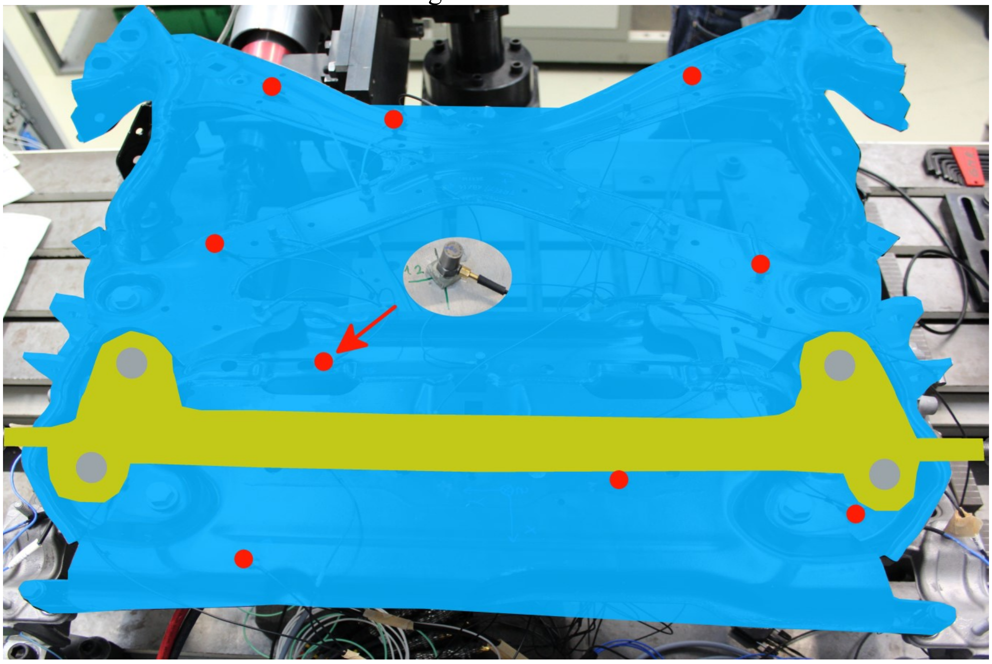

Figure 7 – Subframe (blue) mounted on test bed with steering system (yellow)

The investigated steering system comprises four coupling points with the subframe, which have been considered as force inputs in this study. It is a common understanding of many authors in the field of inverse force determination to consider twice as many degrees of freedom for the calculation of input forces than there are coupling DOF’s to yield a factor 2 for over-determination. In this study three translational force inputs (x,y,z) at each coupling position were considered, leading to 12 force input DOF for the four coupling points, so that 24 single-axis accelerometers have been attached to the subframe to obtain the operational response of the steering system. The mobility matrix $Y_{C,vc}$ has been obtained by exciting the remote points (some exemplary shown as red dots in Figure 7) using an instrumented hammer and measuring the response with 3D-accelerometers at the coupling points of the steering system. A direct measurement of the mobility matrix is also possible in a general sense, but was circumvented due to poor accessibility of these positions in the investigated application.

The rack of the steering system is connected to force cylinders of the test rig via tie rod adapters, which provide the necessary counter force on the steering system’s rack bar to represent the load on the system. A steering angle drive unit provides the artificial steering maneuver.

A prerequisite to measure blocked force is sufficient SN-ratio during the operational measurement. Therefore the SN-ratio for the 24 remote positions was checked for the lowest steering speed of interest (100°/s). Results are shown in the following figure, where a SN-ratio >10dB is in green color.

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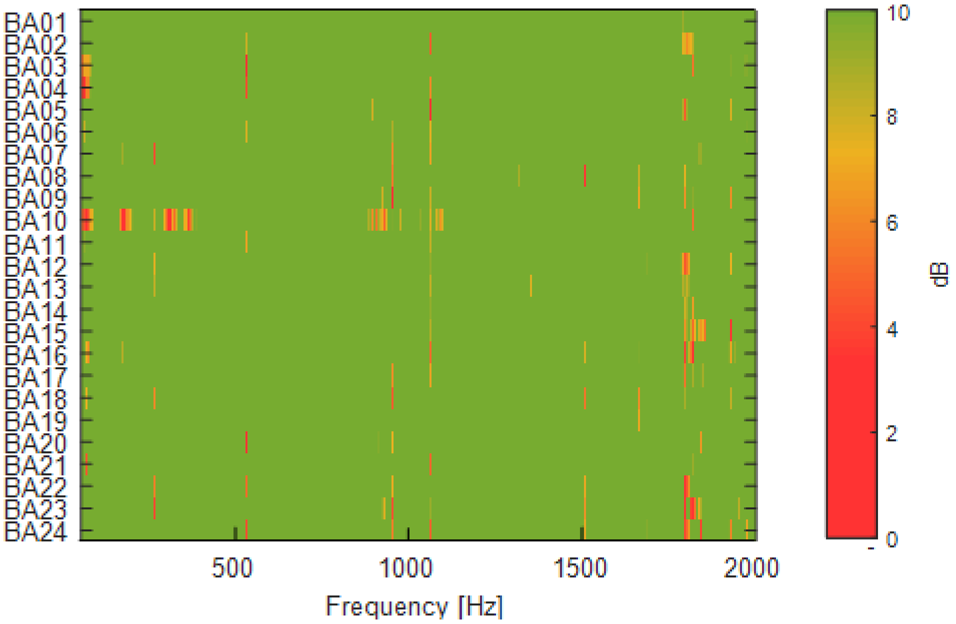

Figure 8 – SN-Ratio at remote points for lowest steering speed 100°/s

The SN-ratio for all 24 remote points is sufficient in the frequency range of interest. This is also true regarding the SN-ratio of the FRF data. At some, distinct small frequencies SN is less than 7 dB at numerous positions, which is due to excitation contributed by the load unit providing the rack force. The worst result can be seen for accelerometer BA10 for low frequencies. This is caused by anti-resonances at this position in the correspondent frequencies as shown in the spectra below:

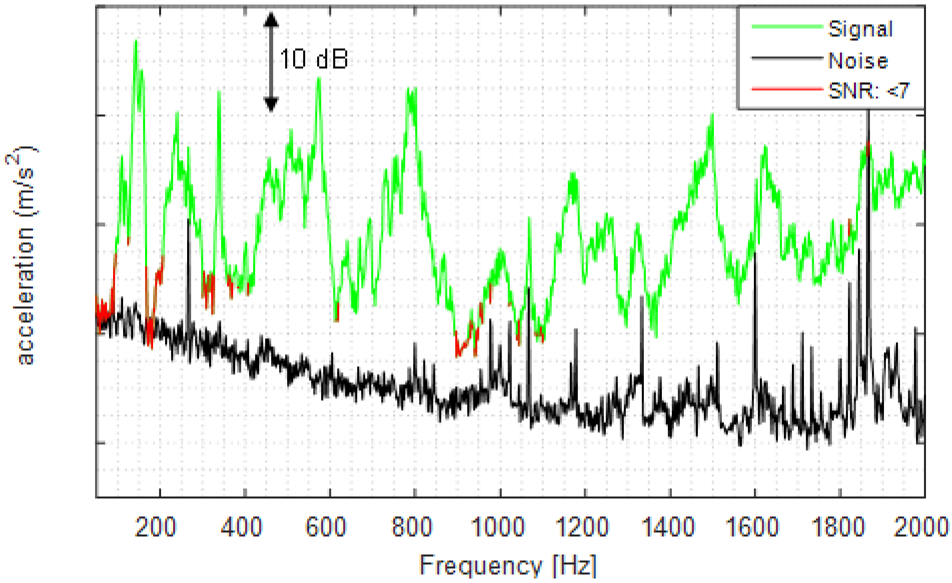

Figure 9 – SN-Ratio at remote position BA 10 for lowest steering speed 100°/s

It can be summarized that the chosen test-rig is useable for in-situ blocked fore measurements, as only at frequencies with very low force input from the EPS and at low steering speeds, which are of minor interest, when predicting the interior sound, low SN-ratios exist for discrete frequencies.

4.2 Operational conditions

4.2.1 Artificial excitation

In a first step a simplified, well-controlled operating condition of the steering system was employed. The excitation in this case consists of impulse hammer blows introduced via a triangular, aluminum plate glued to the steering housing to excite all translational directions simultaneously. These hammer blows represent an excitation of the steering system. In the case of modified on-board validation (MOBV), it is required to operate the source on a different receiver and therefore to ensure consistent excitation between in-situ blocked force measurement and MOBV. While for a steering maneuver this can be considered by using the same operating condition for each measurement, the artificial excitation approach requires a normalization to account for differences between different test runs using following equation, where the operational velocities are normalized to the input force of the impulse hammer f_{IH}:

$$f_{bl,n} = \frac{f_{bl}}{f_{IH}} = \left[Y_{C,ic}\right]^{+} \frac{\{v_i\}}{f_{IH}} \tag{7}$$

With this procedure good reproducibility between different operational measurements is achieved.

4.2.2 Steering maneuver

For the operational measurement a standard test maneuver has been conducted, which consists of steering from end lock to end lock at a constant steering speed in both steering directions (direction A and B) starting at 100°/s. Afterwards the steering speed is increased to a higher level for the following sequence. This procedure is continued until the highest steering speed of interest is reached (here: 600°/s). The required data (steering wheel angle and tie rod force) has been recorded during a vehicle measurement and is used as input for the steering angle drive and the force cylinders as load, respectively. In the next sections results are shown for one steering speed and direction for reasons of simplification.

4.3 Results and validation

4.3.1 Artificial excitation

In Figure 10 the on-board validation for the case of artificial excitation is shown for the validation point v, where the calculated response $v_{v,calc}$ obtained from measured blocked forces according to equation 6 is compared to the measured response $v_{v,meas}$.

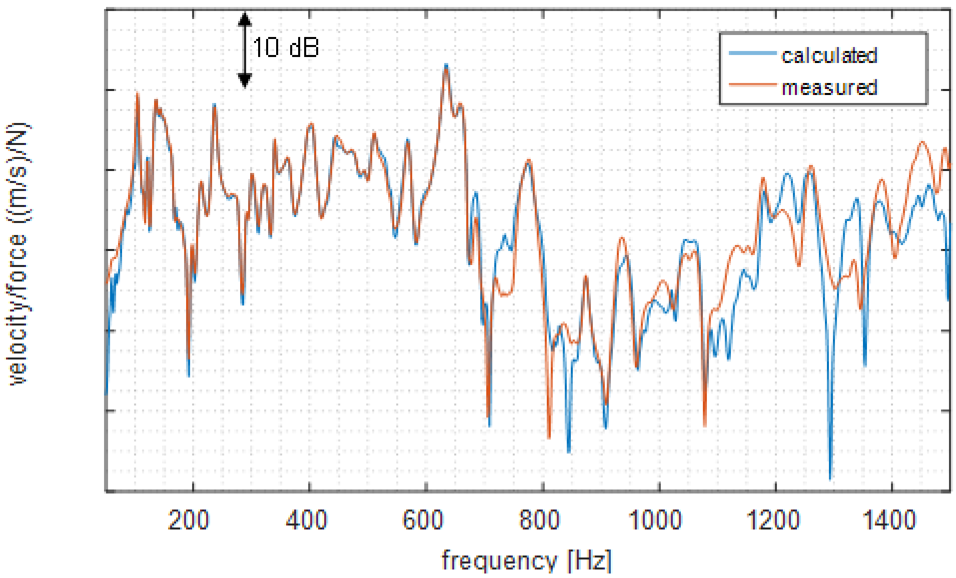

Figure 10 – On-board validation for artificial excitation

The result is very promising with very good agreement for frequencies below 700 Hz, especially considering the fact that calculations in this paper have been conducted without using any form of regularization. Differences increase with frequency, but in general the major peaks in the frequency spectra show matching between measured and predicted results.

In the following figure the modified on-board validation (MOBV) for the validation point is shown in the frequency range from 100-1500 Hz, where the subframe was structurally changed by adding mass and stiffness to obtain a different receiver structure.

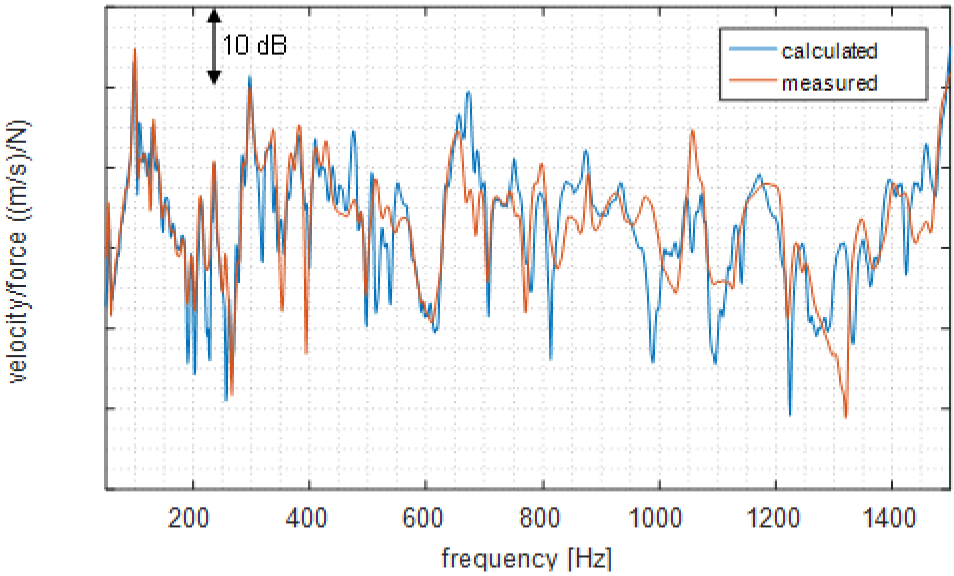

Figure 11 – Modified on-board validation for artificial excitation

Compliance between measured and calculated velocity at the validation point is reduced in that case, which could be expected due to the mechanical changes on the structure yielding an increased complexity of the procedure. But still agreement for frequencies below 500 Hz is very good, showing the invariance of in-situ blocked forces.

4.3.2 **Steering maneuver**

In the following figure the on-board validation for the actual steering maneuver is presented. For the calculation one steering direction and a constant steering speed was used to ensure clarity. The validation point was chosen at the same position as before for artificial excitation.

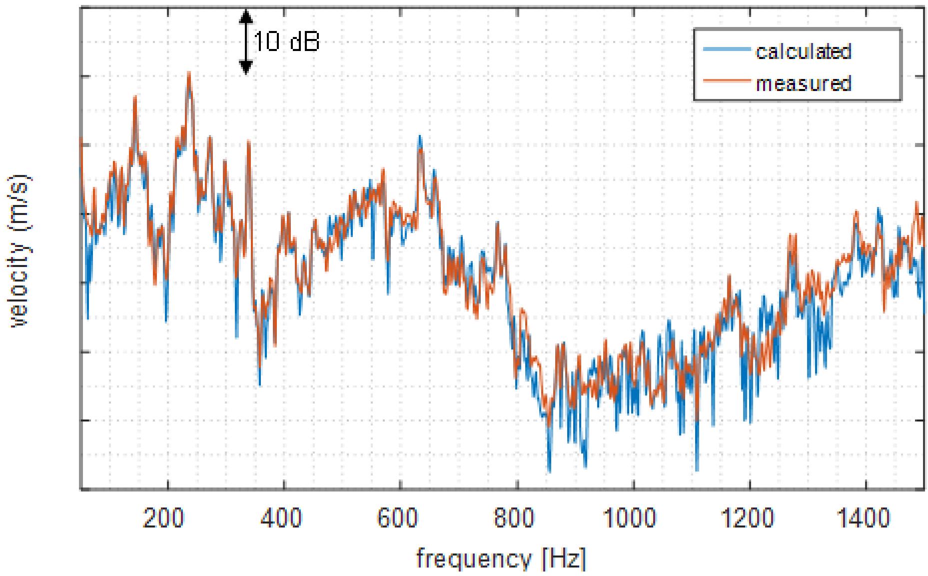

Figure 12 – On-board validation for steering maneuver (single direction, constant speed)

The agreement between measurement and prediction is very strong in the frequency range up to 1 kHz and even above there is strong comparability even in the presented narrow-band data. Consistency exceeds the level of compliance in the artificial excitation shown before. The reason for this improved agreement in the realistic case of a steering maneuver is most likely caused by the influence of moments, aroused by exciting the steering system via a triangular-shaped plate for the artificial excitation, as moments were not included in the calculation of blocked force.

It can be concluded, that in-situ blocked forces can be used as an invariant source descriptor for steering systems. This serves as a first indicator that results can be used for the prediction of interior sound pressure, once good-quality transfer functions of the vehicle are available. In the following chapter the application of blocked forces for predicting interior sound caused by a steering system or any other automotive component is discussed.

5. Prediction of interior sound pressure in the vehicle

5.1 In-situ transfer path analysis

The in-situ TPA is an inventive technique to predict the sound pressure level of a source, like an electric steering system, mounted in a vehicle based on blocked forces obtained from test rig or vehicle measurements [2]. The major difference compared to conventional TPA is the use of in-situ data for the vehicle. This means, source and receiver remain assembled for the measurement of the vibro-acoustic transfer function matrix $Y_{C,V}$ of the vehicle. Hence, the approach is very appealing in industry, where time is a major factor. The transfer behavior of the vehicle can either be obtained using the direct method by excitation at the coupling points of the steering system using an instrumented hammer or shaker and measurement of the response as sound pressure at the interesting position(s) in the interior of the vehicle or reciprocally using a loudspeaker excitation with known volume velocity in the cabin and measurement of response velocities at the coupling points using accelerometers [4].

The successional prediction is based on the following calculation approach, which is formulated in frequency domain:

$$\{p_{calc}\} = \lfloor Y_{C,V} \rfloor \cdot \{f_{bl}\} \tag{8}$$

The sound pressure is calculated using the in-situ vibro-acoustic transfer functions from vehicle measurement, which could also be results obtained from simulation. The blocked forces are acquired on the test-rig as discussed in the previous chapter, so that the presented approach fulfills the requirements for Virtual Acoustic Prototyping or it can be obtained by measurements in the vehicle if understanding the root-cause of a noise complaint is in focus.

Finally, the next section describes an approach, where the interior sound pressure is calculated in the time domain to offer the possibility of auralization for predicted sound pressures e.g. for jury testing.

5.2 Prediction of interior sound pressure in time domain

In time domain prediction of interior vehicle sound, the validated impedance matrix $[Y_{C,ic}]$ (see equation 5), after on-board validation according to eq. 6, is used as finite impulse response filter using the approach of Powell and Seering [11]. A convolution of the impedance FIR filters with the time domain operational velocity data $\{v_i\}$ yields the blocked forces in time domain. In the next step, the blocked force vector $\{f_{bl}\}$ serves as operational data for the prediction of the interior sound pressure in the vehicle by convolution with the in-situ transfer functions FIR filters of the vehicle like in classic Time-Domain-TPA, yielding predicted interior sound pressures in time domain [12]. In the end this data can be taken for auralization and hence subjective rating or jury testing of steering noise caused by arbitrary source/receiver combinations without the requirement of having a physical assembly of the different combinations according to the aim of Virtual Acoustic Prototyping.

6. CONCLUSIONS

In this paper the applicability of the in-situ blocked force method was investigated for electric steering systems. The method is preferable compared to other source characterization techniques, which require special test-rigs or do not allow loads on the source under test, because in-situ blocked forces can be either obtained in the usual installation environment, e.g. the vehicle, or on standard test rigs. The validation of measured blocked forces indicated, that they are an invariant source descriptor revealing a good basis for understanding excitation mechanisms of technical components as well as for the prediction of interior sound pressure in the vehicle even to the extent of auralization at an early stage in the development process.

Considering the consecutive steps from obtaining the blocked forces on a test rig or in the vehicle to the prediction of the interior sound pressure discussed in this paper, it can be concluded, that the presented procedure has significant value in the development process of a vehicle. In the test-rig stage it is possible to compare different steering systems regarding their acoustical performance based on sole source quantities. On vehicle level, engineers are able to obtain blocked forces and transfer functions of the vehicle without the necessity of dismounting the steering system and separate the contribution the steering system and the vehicle. Regarding Virtual Acoustic Prototyping the approach allows prediction of the resulting interior sound pressure for any given source/receiver combination offering an important tool in the early development stage.

Methods presented here, were applied for electric steering systems, but can also be used for many other technical applications.

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