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INTERNAL TRANSFER PATH ANALYSIS BASED ON IN-SITU BLOCKED FORCES AND TRANSMISSIBILITY FUNCTIONS

Dennis Zabel, Thomas Alber

Robert Bosch Automotive Steering GmbH, Richard-Bullinger-Strasse 77, 73527 Schwaebisch Gmuend, Germany
email: dennis.zabel@bosch.com

Michael Sturm

Robert Bosch Automotive Steering LLC, 15000 N Haggerty Rd., Plymouth, MI 48170, USA

Andy Moorhouse

University of Salford, Acoustics Research Centre, Salford M5 4WT, UK

Transfer path analysis (TPA) is an established and valuable tool in automotive industry to determine the contributions of structure-borne and airborne sound sources to receiver responses at target positions. The classical TPA approach is based on contact forces at the interface between source and receiver to characterise the dynamic loads induced by the source and frequency response functions (FRFs) to quantify the transfer paths of the sound from the interface locations to the target positions. With knowledge of the determined contributions it is then possible to decide whether source loads or FRFs must be improved to optimise the target quantities. Recently a timesaving improvement to classical TPA has been proposed, where the loads are characterised using the in-situ blocked force method, so that dismantling of source and receiver is not necessary. This method is therefore called in-situ TPA. However, if the contributions of internal structure-borne sound sources to the overall vibro-acoustic behaviour of a product are desired it is of benefit if the target quantities are blocked forces. Thus it would be possible to virtually couple the product with the properties of an overall receiver. Therefore this paper presents a novel TPA approach called blocked force transmissibility TPA. The aim of the presented TPA is to determine the contribution of internal structure-borne sound sources to an overall target quantity of a product. The presented approach uses the vector of blocked forces measured externally at the contact interface of the overall product and a corresponding set of transmissibility functions relating the external coupling degrees of freedom (DOFs) to the internal source DOFs in order to propagate the external blocked forces back to multiple internal blocked forces. To prove the methodology of the presented approach a case study of a beam was carried out experimentally.
Keywords: blocked force, transmissibility, transfer path analysis

1. Introduction

Amongst others, the noise, vibration and harshness (NVH) quality is an important sales argument for vehicles. In order to guarantee high NVH quality transfer path analysis (TPA) is applied in automotive industry to efficiently troubleshoot potential NVH issues of vehicles and its components. Thereby, especially the classical TPA is a well-established tool to analyse the contribution of sources such as vehicle components to the sound characteristic at passive receivers such as vehicles. In order to determine the contribution a kinematic target quantity on the receiver side such as sound pressure is propagated back to dynamic loads at the interface between source and receiver. The drawback of classical TPA is the dependence on the receiver since the dynamic loads generated by the source are characterised by contact forces. As distinct from classical TPA the in-situ TPA approach which was recently proposed characterises the dynamic loads with in-situ blocked forces rather than contact forces [1], [2]. Thus the dynamic loads are characterised independently from the receiver.

Both of the above mentioned approaches yield a meaningful result if the source can be treated as a black box without further interest of the mechanisms within. However, it might be assumed that engineers want to gain insight into the source. Therefore the internal source mechanisms and the transmission of structure-borne sound within the source need to be analysed for further improvement regarding NVH quality. In theory both classical TPA as well as in-situ TPA can be employed to analyse the generation mechanisms and transmission of sound within the source. Nevertheless both aforementioned approaches only provide information about the contribution of the internal source such as a bearing to a kinematic target quantity. This results in the difficulty to use that information for further analysis on vehicle level.

Hence it is obvious to define the target quantity of a TPA within a source such as a vehicle component as a force rather than a kinematic quantity. Therefore a novel TPA approach called blocked force transmissibility transfer path analysis (bfTPA) is introduced which aims to analyse the contribution of the internal source mechanisms to the in-situ blocked forces and moments acting at the interface between source and receiver. To prove the feasibility of the presented TPA approach an experimental case study using a freely suspended steel beam is carried out.

2. Theory of transfer path analysis

The general aim of TPA is to determine the contribution of sound which is generated by a source to a target quantity on a receiver. To fulfil this aim the transfer path problem which is briefly outlined in Section 2.1 is analysed. For this purpose there are different TPA approaches available which are distinguished on the one hand on the characterisation of the generated structure-borne sound and on the other hand on the description of the sound transfer to target locations on the receiver. Section 2.2 and Section 2.3 introduce the most commonly used TPA approaches to the reader since they form the basis of the novel bfTPA approach which is subsequently presented in Section 3. A recent overview of TPA in general can be found in [3].

2.1 Transfer path problem

If a vibrational source (A) is coupled to a receiver (B) sound is induced from the source to the receiver at interface (c) between source and receiver. This is generally known as transfer path problem which is schematically illustrated by Fig. 1.

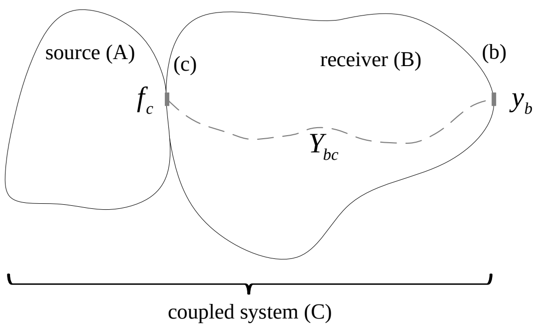

Figure 1: Transfer path problem of sound generated by a vibrational source (A) and subsequently induced at interface (c) to receiver (B).

The induced sound is transmitted via transfer paths to target locations on the receiver side (b). At the extreme the sound which is generated by the source can cause an unpleasant sound characteristic at the target locations on the receiver. For troubleshooting of this problem the aim of TPA is to propagate a vector of kinematic target quantities $\mathbf{y}_b$ on the receiver back to a vector of dynamic loads $\mathbf{f}_c$ at DOFs at interface (c) based on the following equation

$$\mathbf{y}_b = \mathbf{Y}_{bc}\mathbf{f}_c\,. \tag{1}$$

Thereby the transfer paths from DOFs at interface (c) to DOFs at target locations on the receiver (b) are characterised by FRFs which are contained in the FRF matrix $\mathbf{Y}_{bc}$ (see Fig. 1). In the following of this paper matrices are denoted by capital letters and vectors by small letters. With knowledge of both the characteristics of the dynamic loads $\mathbf{f}_c$ and the transfer path behaviour $\mathbf{Y}_{bc}$ it is then possible to determine the contribution of the dynamic loads $\mathbf{f}_c$ to the measured target quantity $\mathbf{y}_b$. Hence it is possible to modify either the source characterised by the dynamic loads $\mathbf{f}_c$ or the transfer paths $\mathbf{Y}_{bc}$ of the induced sound.

2.2 FRF based TPA

Within the conduction of FRF based TPA approaches the characterisation of the generated sound is an important step. This can be achieved by direct measurement of dynamic loads at the interface between source and receiver using transducers. However, since realistic boundary conditions at the sensitive contact interface often cannot be ensured with transducers inverse identification methods are preferred. The idea behind inverse identification is to determine the dynamic loads from observing kinematic quantities at indicator locations on the receiver while the source is in operation. For this purpose a two stage measurement is necessary. The first stage comprises the determination of an FRF matrix $\mathbf{Y}_{bc}$ containing FRFs from indicator locations (b) on the receiver to the interface (c) between source (A) and receiver (B) (see Fig. 1). During the second stage the sound which is generated by the source is observed in form of operational quantities $\mathbf{v}_{op,b}$ at the indicator locations. By multiplying the pseudo inverse of the FRF matrix $\mathbf{Y}_{bc}$ with the vector of operational quantities $\mathbf{v}_{op,b}$ the loads $\mathbf{f}_c$ can be calculated as follows

$$\mathbf{f}_c = \mathbf{Y}_{bc}^{+}\mathbf{v}_{op,b}\,. \tag{2}$$

If the source is not mounted to the receiver while determination of the FRFs the so called contact forces are calculated. In contrast to the determination of contact forces the FRFs which are needed for the calculation of in-situ blocked forces are of the coupled system (see Fig. 1). This is indicated by index C of the FRF matrix $\mathbf{Y}_{C,bc}$. Hence in-situ blocked forces are calculated as follows [4], [5]

$$\mathbf{f}_{bl} = \mathbf{Y}_{C,bc}^{+}\mathbf{v}_{op,b}\,. \tag{3}$$

The most widely used FRF based TPA approach is called classical TPA which was provided by Verheij [6], [7]. For the conduction of classical TPA contact forces at the interface between source and receiver are determined and corresponding FRFs are used to analyse the transfer path problem (see Section 2.1). The drawback of classical TPA is the dismounting of the source from the receiver to determine the dynamic loads. To overcome this drawback the in-situ TPA approach was recently proposed by Elliott et al. [1]. Instead of contact forces in-situ blocked forces are used to characterise the dynamic loads. Since there is no need to dismount the source from the receiver anymore the in-situ TPA is a time saving approach compared to classical TPA.

2.3 Transmissibility based TPA

Both classical and in-situ TPA aim to analyse the transfer path problem based on a physically correct description of the transfer paths. However, this includes the time consuming determination of FRFs and dynamic loads at the interface DOFs between source and receiver. Hence it would be advantageous if this time consuming step could be avoided. Therefore transmissibility based approaches aim to analyse the transfer path problem (see Fig. 1) by observing only operational quantities. The transfer paths are thereby characterised by a matrix $\mathbf{T}_{cb}$ which contains transmissibility functions.

Each transmissibility function is the ratio of kinematic quantities such as velocities $\mathbf{v}_c$ and $\mathbf{v}_b$ near the interface (c) and the target locations (b), respectively. To fully characterise the transfer path behaviour m operational states are needed resulting in the corresponding vectors $\mathbf{v}_b^{(m)}$ and $\mathbf{v}_c^{(m)}$ containing measured velocities near locations (b) and (c), respectively. The requirement for a successful conduction of transmissibility based TPA is that all necessary loads at interface (c) are excited by the *m* operational states. Furthermore it is required that the amount of operational states *m* is equal to or greater than the DOFs at interface (c). The vectors of the response quantities $\mathbf{v}_c^{(m)}$ and $\mathbf{v}_b^{(m)}$ at interface (c) and the target locations (b) as a consequence of the *m* independent operational states are then organized in the matrices $\mathbf{V}_c$ and $\mathbf{V}_b$. Hence the transmissibility matrix $\mathbf{T}_{cb}$ is calculated as follows [8]

$$\mathbf{T}_{cb} = \mathbf{V}_c(\mathbf{V}_b)^+ = (\mathbf{v}_c^{(1)} \quad \mathbf{v}_c^{(2)} \quad \dots \quad \mathbf{v}_c^{(m)})(\mathbf{v}_b^{(1)} \quad \mathbf{v}_b^{(2)} \quad \dots \quad \mathbf{v}_b^{(m)})^+ . \tag{4}$$

In contrast to in-situ TPA the data of transmissibility based TPA cannot be transferred to other assemblies. Furthermore transmissibility based TPA is sensitive to the positioning and amount of the sensors that are used to determine the vectors of responses $\mathbf{v}_b^{(m)}$ and $\mathbf{v}_c^{(m)}$. Nevertheless transmissibility based TPA is a fast and valuable engineering tool.

3. Blocked force transmissibility transfer path analysis

To investigate the structure-borne sound transmission within a source with TPA it is beneficial to define a blocked force as target quantity rather than a kinematic quantity such as velocity, for instance. In the following a novel TPA approach called blocked force transmissibility transfer path analysis or "bfTPA" is introduced which aims to analyse structure-borne sound within a source and propagate the strength of the whole source back to the strength of its internal source mechanisms. Therefore at first in Section 3.1 the internal source-path-receiver model (ISPRM) is introduced which is an extension of the source-path-receiver model of Bolt and Ingard [9]. Subsequently Section 3.2 introduces the methodology of bfTPA based on the introduced ISPRM.

3.1 Internal source path receiver model

The source-path-receiver model is the classical approach to describe the sound transfer from a source to a coupled receiver. The source is thereby conveniently treated as a black box. However the source-path-receiver model is limited when mechanisms of sound generation and the structure-borne sound transfer within a source should be meaningfully analysed. For that reason the ISPRM is proposed which is schematically illustrated by Fig. 2.

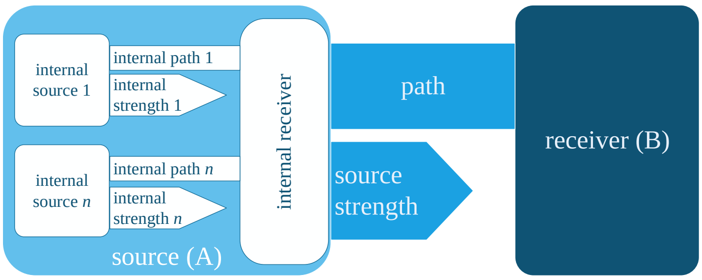

Figure 2: Internal source path receiver model (ISPRM).

To extend the source-path-receiver model the source (A) is subdivided into *n* internal sources which each represents a mechanism of structure-borne sound generation within the source (A). The strength of each of the *n* internal sources is characterised with in-situ blocked forces and moments. Furthermore an internal receiver such as a housing is defined. The structure-borne sound which is generated by the *n* internal sources is transferred via *n* corresponding internal paths to target locations on the internal receiver. These locations are logically chosen to be the interface between source (A) and receiver (B). Hence the target quantity should be chosen as the strength of the source which can be characterised by in-situ blocked forces and moments. By using in-situ blocked forces the source (A) as well as the *n* internal sources are characterised independently. This yields the possibility for further investigation of the paths which relate the strength of source (A) with a kinematic target location on the receiver (B).

3.2 Methodology

The transfer path problem of structure-borne sound within a source (A) that consists of an internal receiver (IB) and multiple internal sources ($IA_1 \ldots IA_n$) is illustrated by Fig. 3. The illustrated problem forms the basis for the conduction of bfTPA.

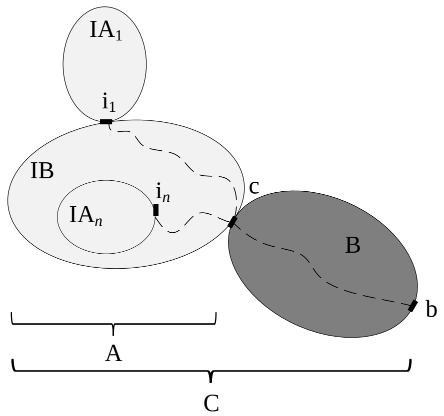

Figure 3: Transfer path problem within a source (A) coupled to a receiver (B)

In contrast to classical and in-situ TPA the target quantity for the analysis of the structure-borne sound within a source (A) is chosen to be a vector of in-situ blocked forces $\mathbf{f}_{bl,c}$ acting at DoFs at interface (c) between source (A) and receiver (B). Furthermore the internal sources ($IA_1 \ldots IA_n$) which induce the structure-borne sound of a source (A) are characterised by a vector of in-situ blocked forces $\mathbf{f}_{bl,i}$ at the corresponding DoFs at the internal interfaces ($i_1 \ldots i_n$) as well. Hence a vector of velocities $\mathbf{v}_c$ at interface (c) between source (A) and receiver (B) can be determined based on the knowledge of the in-situ blocked forces $\mathbf{f}_{bl,i}$ and $\mathbf{f}_{bl,c}$ and corresponding mobilities $\mathbf{Y}_{ci}$ and $\mathbf{Y}_{cc}$ as follows

$$\mathbf{v}_c = \mathbf{Y}_{cc}\mathbf{f}_{bl,c} = \mathbf{Y}_{ci}\mathbf{f}_{bl,i} \,. \tag{5}$$

Based on Eq. (5) the following relation between the in-situ blocked forces $\mathbf{f}_{bl,i}$ at the internal interfaces ($i_1 \ldots i_n$) and the in-situ blocked forces $\mathbf{f}_{bl,c}$ at the external interface (c) can be established

$$\mathbf{f}_{bl,c} = \left(\mathbf{Y}_{cc}\right)^{-1}\mathbf{Y}_{ci}\mathbf{f}_{bl,i} = \mathbf{T}_{C,ci}\mathbf{f}_{bl,i} \,. \tag{6}$$

The matrix $\mathbf{T}_{C,ci}$ which relates the two vectors of internal in-situ blocked forces $\mathbf{f}_{bl,i}$ and external in-situ blocked forces $\mathbf{f}_{bl,c}$ is equal to the transpose of the generalised transmissibility matrix by Ribeiro et al. [10]. Maia et al. [11] proposed an approach to determine the transmissibility based on kinematic quantities only and Moorhouse et al. showed that the generalised transmissibility is invariant to whether the excitation is applied at the interface DOFs or downstream of the interface [5]. Therefore for the determination of the transmissibility matrix $\mathbf{T}_{C,ci}$ the source (A) which is coupled to receiver (B) is excited at multiple locations (b) to yield responses at the internal interfaces ($i_1 \ldots i_n$) and the external interface (c), respectively. A fundamental requirement of this approach is that the number of excitation DOFs o is equal to or greater than the DOFs of dynamic loads at the internal interface ($i_1 \ldots i_n$). The vectors of responses at the internal interfaces ($\mathbf{v}_{C,i}^{(b_1)} \ldots \mathbf{v}_{C,i}^{(b_o)}$) and the external interface ($\mathbf{v}_{C,c}^{(b_1)} \ldots \mathbf{v}_{C,c}^{(b_o)}$) as a consequence of the o excitations are then organised in matrices $\mathbf{V}_{C,i}^{(b)}$ and $\mathbf{V}_{C,c}^{(b)}$. Hence the transmissibility matrix $\mathbf{T}_{C,ci}$ is calculated as follows

$$\mathbf{T}_{C,ci} = \left(\mathbf{V}_{C,c}^{(b)}\right)^{+}\mathbf{V}_{C,i}^{(b)} \,. \tag{7}$$

For stabilisation of the solution to Eq. (7) the amount of excitation o can be greater than the number of DOFs at the internal interfaces. Hence the matrices $\mathbf{V}_{C,i}^{(b)}$ and $\mathbf{V}_{C,c}^{(b)}$ are not square and pseudo inversion of $\mathbf{V}_{C,c}^{(b)}$ is needed. The fundamental equation for bfTPA which forms the basis to analyse the transfer path problem of ISPRM is formulated as follows

$$\mathbf{f}_{bl,c} = \mathbf{T}_{C,ci}\mathbf{f}_{bl,i} \,. \tag{8}$$

Equation (7) and Eq. (8) apply for generalised forces, including moments.

4. Case study steel beam

For the validation of the presented bfTPA a case study is carried out. For that purpose a steel beam is freely suspended on foam and virtually subdivided into three parts representing an internal source, internal receiver and a receiver according to the ISPRM (see Section 3.1), respectively. The aim of the case study is to determine the transmissibility matrix using velocities according to Eq. (7) and compare the entries of the determined matrix with the ratio between blocked forces and moments determined using the in-situ method [4] at the external and internal interface, respectively.

4.1 Test setup

Fig. 4 shows the test setup which is a steel beam that is freely suspended on foam and virtually subdivided into three parts. The green coloured part represents an internal source (IA) that is connected to a blue coloured internal receiver (IB) at the internal interface (i). Both parts (green and blue) together form the source (A) which is coupled to an orange coloured receiver (B). Source and receiver are attached at the external interface (c).

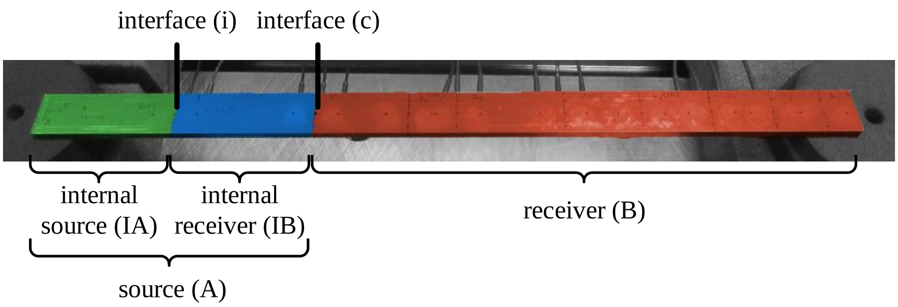

Figure 4: Freely suspended steel beam for the conduction of bfTPA which is virtually subdivided into an internal source (IA), internal receiver (IB) and receiver (B)

The beam is artificially excited in out of plane direction at an arbitrary location on the internal source (IA). This represents an unknown internal source mechanism which can be characterised with in-situ blocked forces and moments at the internal interface (i). Furthermore the artificial excitation generates dynamic loads at the external interface (c) which are characterised by in-situ blocked forces and moments as well. The blocked forces and moments at interface (c) and interface (i) are determined according to the in-situ method. For the determination of the in-situ blocked moments the central difference approach by Elliott is used to yield the necessary moment mobilities [12].

4.2 Results

To prove the methodology of the presented bfTPA the transmissibility matrix according to Eq. (7) is compared against the ratio of the internal and external in-situ blocked forces and moments at interface (i) and (c), respectively. It can be observed from the spectrum of the in-situ blocked forces and moments which are shown by Fig. 5 that the characteristic of the internal and external blocked forces and moments is different hence making them linearly independent. The aforementioned fact is a necessary requirement for the validation of the presented methodology of bfTPA. For a complex product such as a vehicle component it is expected that the internal and external in-situ blocked forces and moments at interface (i) and (c) are linearly independent.

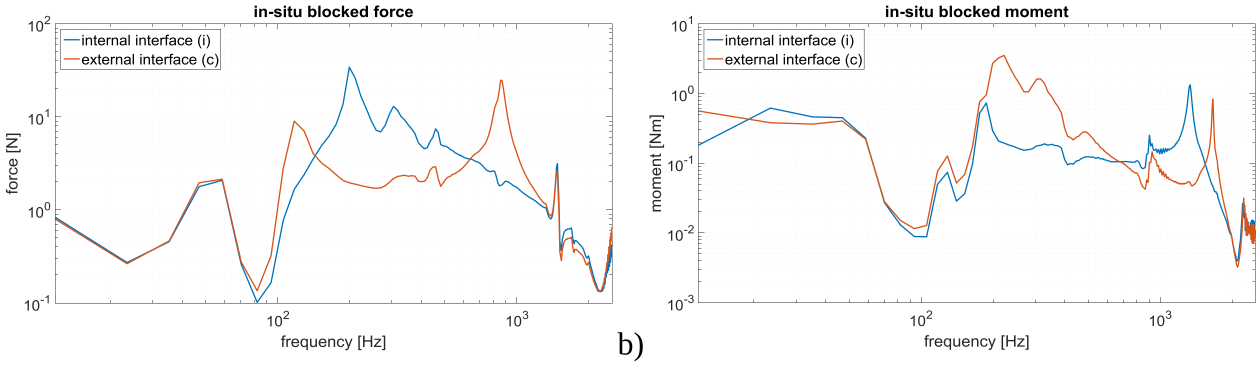

Figure 5: a) in-situ blocked forces, b) in-situ blocked moments at internal (i) and external (c) interface.

The comparison of the transmissibility matrix determined by the ratio of the internal and external in-situ blocked forces and moments and the transmissibility matrix determined by velocities according to Eq. (7) is shown by Fig. 6. It can be observed that both the force and moment based transmissibilities are nearly equal to the corresponding velocity and angular velocity based transmissibilities determined according to Eq. (7).

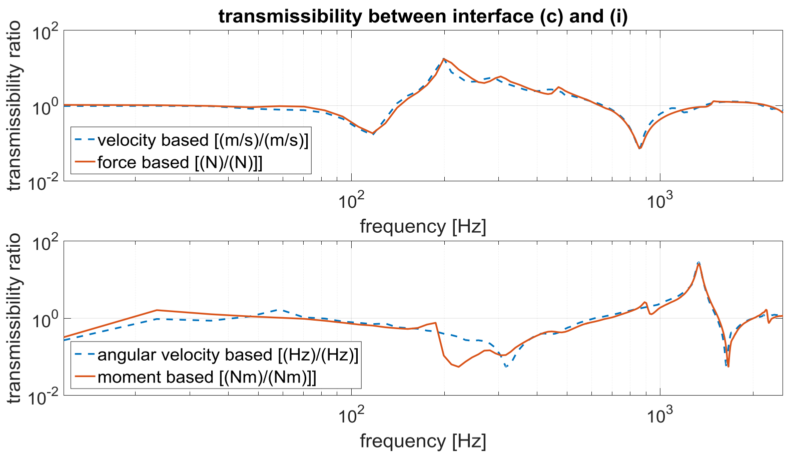

Figure 6: Comparison of transmissibility between external interface (c) and internal interface (i): upper diagram: blocked force transmissibility, lower diagram: blocked moment transmissibility

Based on Eq. (8) the determined in-situ blocked forces and moments at the internal interface (i) can be used in combination with the velocity based transmissibility matrix to predict the in-situ blocked forces and moments at the external interface (c). This shows a potential application of the presented methodology. The result of the prediction of the external in-situ blocked force and moment based on the internal blocked force and moment using the transmissibility matrix determined by velocities and angular velocities is shown by Fig. 7.

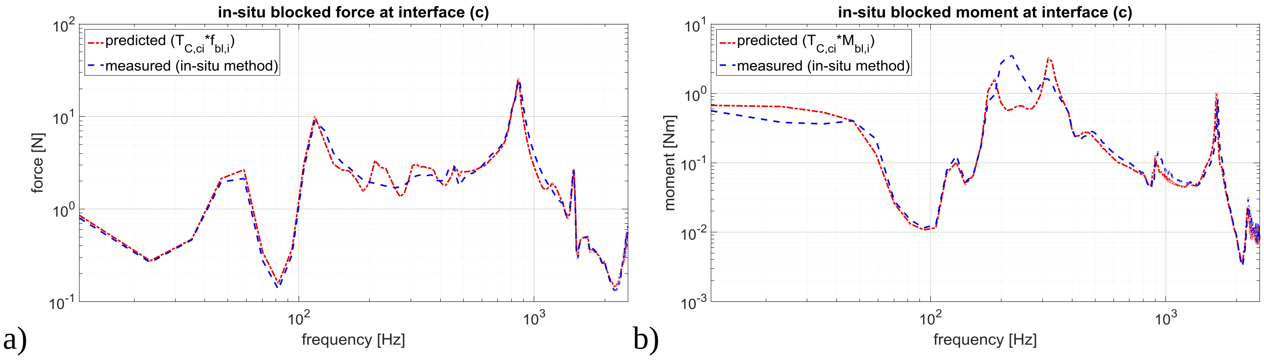

Figure 7: Predicted strength of source (A) at external interface (c) based on transmissibility and source strength of internal source (IA) at internal interface (i): a) in-situ blocked force, b) in-situ blocked moment

It can be seen that the experimentally determined transmissibility matrix according to Eq. (7) is a solid basis to predict in-situ blocked forces and moments at the external interface (c) based on the knowledge of the in-situ blocked forces and moments at the internal interface (i) and vice versa. Therefore the internal source mechanisms can be easily observed from the external in-situ blocked forces and moments if the transmissibility matrix can be experimentally determined using accelerometers, for instance.

5. Concluding remarks

A novel TPA approach called bfTPA is presented which aims to analyse the transfer path problem for the introduced internal source-path-receiver model. Therefore the in-situ blocked forces and moments of a source are propagated back to the in-situ blocked forces and moments which characterise the internal source mechanisms at the interface with an internal receiver such as a housing for example. By carrying out a case study of a freely suspended steel beam the methodology of the introduced bfTPA is validated for a multiple degree of freedom system.

It was shown that the transmissibility functions can be determined by measuring only operational kinematic quantities such as velocity or angular velocity at the internal and external interfaces. Thereby the transmissibility can be conveniently determined while the source is passive and artificial excitation at the receiver is applied hence making it possible to determine the necessary transmissibility functions using an impact hammer, for instance. Furthermore an application of bfTPA was outlined by predicting the in-situ blocked forces and moments of a source based on the knowledge of the in-situ blocked forces and moments of the internal source as for instance a bearing and corresponding transmissibility functions between the internal and external interface. Furthermore the presented methodology of bfTPA allows to determine the in-situ blocked forces and moments at internal interfaces based on the knowledge of the in-situ blocked forces and moments at the external interface and corresponding velocity based transmissibility functions.

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