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Validation of the blocked force method for various boundary conditions for automotive source characterization

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ABSTRACT

Vibro-acoustic source characterization is an essential task in vehicle development to enable prediction of receiver response. For structure-borne noise, the interface forces in multiple degrees of freedom due to internal loads are often quantified for root cause analyses in a single system assembly, as in transfer path analysis (TPA). However, for a reliable prognosis of the acoustic performance of a known component such as a motor or pump, a receiver-independent source characterization is required, and the method of acquiring blocked forces from in-situ measurements has been shown to be a preferred technique for such purposes. The benefits of the method are the characterization of the intrinsic properties of the source and the possibilities of measuring the component attached to receivers with varying dynamic properties.

There is to date a limited number of validation cases where blocked forces from in-situ measurements are acquired for automotive source–receiver assemblies. In this study the blocked forces of a vacuum pump in nine degrees of freedom were determined when connected to a bracket whose boundary conditions were modified in order to achieve four assemblies with different source/receiver dynamic properties. The results show that the blocked forces are transferable, i.e. the receiver response in one assembly was predicted in a wide frequency range by combining source–receiver transfer functions of that assembly with blocked forces estimated in another assembly. Furthermore, an in-situ blocked force TPA was applied to a double-isolated complete vehicle source–receiver case of an electric rear axle drive with interior compartment sound pressure as target. The reconstructed magnetic tonal harmonics agreed with the measured target response in the frequency range 50–500 Hz, which further motivates the use of the blocked force principles for TPA and source requirements specifications.

1. Introduction

In automotive development, tools and methods for structure borne noise diagnosis and prognosis are essential. The structure-borne receiver response (e.g. sound pressure, vibration velocity) due to a vibrating source is caused by its internal forces and the transfer functions relating source and receiver. The internal forces are often difficult to model or measure, so instead, equivalent operational *interface forces* are typically used. In most situations, direct load determination by force transducers mounted at the connection interfaces is practically difficult. Indirect determination of loads in multiple degrees of freedom are often performed by inverse methods which are widely used in transfer path analysis (TPA), a diagnosis tool which enables separation of partial path contribution from the total sum. Each partial contribution can further be broken down into source strength (force) and system sensitivity (transfer functions), providing useful underlying information about a noise issue. Comparing the reconstructed response resulting from the partial contributions of all accounted transfer paths with a measured response is a common method for judging the quality of a classical TPA-model. One major disadvantage associated with classical TPA based upon inverse force synthesis is that the source needs to be mechanically decoupled from the receiving structure when measuring transfer functions between the interface and receiver. In many cases, this operation is time-consuming and can induce errors related to the decoupling stage. Also, and very important, is that the interface forces derived from classical TPA are not valid for predicting the response when the same source is assembled to a dynamically different receiver. For such a prognosis, an independent source characterization is required.

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Elliot and Moorhouse et al. [1–5] have in recent years illuminated the *blocked force* as being beneficial for intrinsic source characterization. The blocked force is analogous to the open-loop voltage in electrical networks and can be estimated in-situ from e.g. operational velocity and mobility. This approach is often more practically realizable compared to direct measurements of the blocked force which requires blocking of all interface degrees of freedom (DoF). In [1], the blocked force was validated in-situ for two source–receiver assemblies consisting of beams with two rigid connections, and with force excitation in one single DoF. It was also shown that the interface forces varied while the blocked forces remained the same for the two different assemblies. In [2], the in-situ method for acquiring blocked forces was experimentally carried out on wind turbine prototype assemblies with different receiver poles. The validation of the independent source properties were in the two studies above mentioned performed through the following steps: first, the blocked forces for one source–receiver assembly is derived. Then, those forces are applied to a dynamically different receiver and the velocity response is calculated. Finally, the reconstructed velocity on the second receiver is compared to the directly measured response on the second receiver. This is an elegant way of verifying that the blocked force estimates are unaltered instead of comparing them directly especially in the case of multiple interface DoF.

There are apparently major potential benefits associated with the blocked force methods. Besides the advantages of reducing the time effort and avoiding potential errors thanks to the possibility of working in the source/receiver coupled state, the outcome of a TPA can be further utilized for making reliable prognoses. For instance, the same blocked forces can be re-used in calculations where the receiver is modified/improved. Another advantage is that the blocked forces of a source may be determined for receivers with various boundary conditions. The alternatives to in-situ conditions (for automotive applications meaning a prototype or production vehicle) as in the case of TPA, are quasi-free boundary conditions (the free velocity approach is standardized in ISO 9611:1996) [3] or in a test bed or other fixture with no particular stiffness requirements. Finally, the blocked forces can also be obtained directly by force transducers if the receiver structure can be made perfectly rigid.

There are only a limited number of case studies on more complex assemblies available to date. One exception is [6], where a blocked force tensor for a rigidly mounted oil pump connected to a truck engine proved to be successful. Also, Elliott et al. [5] showed that TPA based upon blocked forces obtained from in-situ measurements provided at least as good results as the classical inverse force synthesis method for structure-borne road noise, with the added value of reducing the time effort by 50%.

In this work, we wish to highlight practical aspects related to in-situ measurements of blocked forces for automotive engineering applications. The objective of the paper was to investigate the following:

1. By what accuracy can the response for one source/receiver assembly be reconstructed from blocked forces obtained from measurements of the same source but being attached to other receivers, yielding dynamically different assemblies?
2. By what accuracy can the structure borne sound from an electric motor transmitted into the cabin of a car be estimated by contribution analysis based on blocked forces obtained with the in-situ method?

The results provide information on the expected accuracy of the in-situ blocked force method when used in automotive applications. First the findings from measurements on a vacuum pump for brake pressure attached in three connection points to a rig-mounted bracket, which boundary conditions were altered, are presented. The operational excitation included both lateral as well as in plane forces acting on the receiver. Secondly, a blocked force TPA case-study concerning electromagnetically induced structure-borne tonal vibration and noise from a double-isolated electric rear axle drive (ERAD) installed in a passenger car is described. Limitations and applicability related to the two cases are discussed.

2. Theory

In many structure-borne noise applications related to automotive NVH, the problem to be solved can be illustrated by the sketch shown in Fig. 2.1. The source A is connected to a receiver B, either rigidly or through vibration isolators, therefore forming the coupled assembly C.

Examples of source A can be a cooling fan, a pump, a compressor, or an electric motor. The receiver B can typically be the vehicle chassis or body. A and B are connected at the interface (c), involving several contact points and coupling directions. For the case of A and B being connected through vibration isolators, it is convenient to include the isolators in the receiving structure B, but its dynamic properties can still be identifiable in the equations if a parameter study on the isolator's stiffness is planned. Assembly C has a vibro-acoustic response due to internal forces located at (a) which cannot be measured or accessed. This vibro-acoustic response could either be a velocity response, $\mathbf{v}_{\mathbf{C},\mathbf{b}}$, on the receiver B at (b) or a sound pressure level, $\mathbf{p}_{\mathbf{C},\mathbf{d}}$, when receiver B is coupled to source A.

2.1. The blocked force method and its' applicability

If a source A is to be characterized, the free velocity $\mathbf{v_{fs}}$ can be measured at the likely contact points between A and B. $\mathbf{v_{fs}}$ is the velocity of structure A hanging free and running at the assumed operating conditions. A better way to characterize the source is to derive its blocked force, $\mathbf{f_{bl}}$, which is the force applied at the contact points to neutralize $\mathbf{v_{fs}}$. $\mathbf{f_{bl}}$ reads [7,1]

$$\mathbf{f_{bl}} = [\mathbf{Y}_{\mathbf{A},\mathbf{cc}}]^{-1}\mathbf{v_{fs}} \tag{2.1}$$

$\mathbf{Y}_{\mathbf{A},\mathbf{cc}}$ is a 9 * 9 square matrix for each frequency in the case of three contact points with three DoF each. $\mathbf{Y}_{\mathbf{A},\mathbf{cc}}$ is the mobility at (c) when excited at (c) on structure A alone.

In many cases, it is practically not possible to operate the source in free conditions or it is suspected that the internal forces of the source can be influenced by the large installation difference

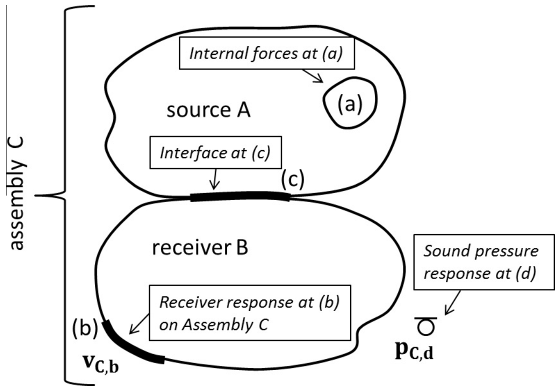

Fig. 2.1. Sketch illustrating a source A connected to a receiver B. The coupled structure is denoted as assembly C. (a) is the location of the internal forces, (b) represents the location of the receiver response positions on assembly C and (c) is the interface between source A and receiver B. $\mathbf{p}_{\mathbf{C},\mathbf{d}}$ denotes the sound pressure caused by the assembly, for instance the interior noise in a vehicle.