Chapter 11
Using Blocked Force Data for Vibro-Acoustic Prediction and Simulation

A.T. Moorhouse, A.S. Elliott, and J.W.R. Meggitt

Abstract The context of the paper is the need across many industries for prediction and simulation of vibro-acoustic response of assembled structures. One of the main areas of difficulty is to know the excitation forces. The blocked force method allows vibration sources to be characterised independently using conventional measurements similar to those used in Transfer Path Analysis (TPA). A major advantage is that the blocked force data remains valid when for example the same vibration source is attached to different receiver structures. It is shown how measured blocked forces can be validated using an 'on board validation' procedure. Progress in the standardisation of the blocked force method is also described. The question is then considered of how this blocked force data can be fed into vibro-acoustic models to provide realistic excitation and response prediction. It is shown that a substucturing step is needed in which the passive properties of the source and receiver structures are combined. Examples are presented to demonstrate that this substructuring step can be a source of significant error and ways of minimising the errors are discussed.

Keywords Blocked force • Source characterisation • Transfer path analysis • Vibro-acoustic simulation • Excitation forces

11.1 Introduction

The context of the paper is the need across many industries for prediction and simulation of vibro-acoustic response of assembled structures. The lack of data to describe excitation by active components is arguably one of the biggest limitations of numerical models in vibro-acoustics; models typically produce unscaled responses due to arbitrary unit force excitation. In this paper we consider how experimental blocked force data can be combined with measured or modelled FRF data so as to allow prediction of vibro-acoustic response in an assembly.

11.2 Contact Forces and Blocked Forces

Consider a source substructure installed on a receiver structure (see Fig. 11.1). The source substructure is excited by internal forces when operational. The effect of the source on the receiver can be represented simply in terms of the contact forces at the interface, as in Fig. 11.1b. This free body diagram approach is so well known that it hardly needs any justification. Less well known is the second equivalent system, shown in Fig. 11.1c. Here the passive assembly of source and receiver is excited at the interface by a set of forces which reproduce the identical response field in the receiver. It turns out that these forces are equal to the blocked forces of the source, i.e. the forces which the operational source would exert on a perfectly rigid receiver [1, 2]. Thus, the response field in the receiver can be represented in two equivalent forms:

$$\mathbf{a_R} = \mathbf{A_R f} = \mathbf{A_C \bar{f}}$$

where $\mathbf{a_R}$ is the vector of the response field in the receiver, $\mathbf{A_R}$, $\mathbf{A_C}$ are the receiver FRF and coupled FRF of the assembly and $\mathbf{f}$, $\bar{\mathbf{f}}$ are the force and blocked force vector respectively. The first form on the rhs of Eq. 1 corresponds to Fig. 11.1b and

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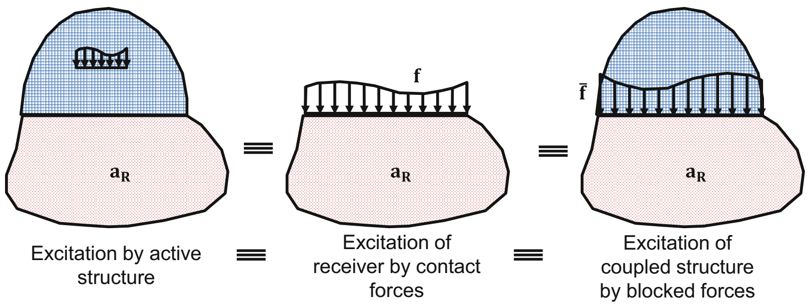

Fig. 11.1 (**a**) Operating source on receiver (**b**) free body diagram of receiver (**c**) equivalent blocked force excitation

the second form to Fig. 11.1c. The major potential advantage of the second formulation is that, whereas the contact forces applied by a source are a function of the receiver and therefore vary from one installation to the next, the blocked forces on the other hand are theoretically an invariant property of the source and can therefore be transferred from one installation to another, for example from a test bench to a real installation. Eq. 1 provides the theoretical basis for obtaining the blocked forces by inverse methods as will be described in the following section.

11.3 Blocked Forces in Transfer Path Analysis

The first form of eq. 1a is the basis for the classical form of transfer path analysis (TPA). A two-stage measurement method is employed: in the operational stage, the receiver responses are measured, normally using accelerometers close to the source-receiver interface; in the passive stage the FRFs are measured, typically using a hammer or shaker. Note that in order to obtain contact forces, the source and receiver substructures must be physically separated so as to allow $\mathbf{Y_R}$ to be measured. With knowledge of the FRFs and the response field, one can obtain an estimate of the contact forces by inverting Eq. 1b. Knowing the contact forces, a forward calculation can be carried out to predict the response at a point of interest, such as a driver's ear, using $\mathbf{a_p} = \mathbf{H_{pf}f}$ where$\mathbf{a_p}$is the response and $\mathbf{H_{pf}}$ the FRF connecting these points with the source-receiver interface. The contributions of the individual forces in $\mathbf{f}$ to $\mathbf{a_p}$ provide a rank-ordering which is useful for diagnosis and redesign.

One can perform a 'blocked force TPA' (also known as component TPA [3] or in situ TPA [4]) by following the same steps as for a classical TPA but with the sole difference that the source and receiver substructures are not separated prior to FRF measurement. Leaving the assembly intact may sometimes provide practical advantages - it saves time and avoids any need to remove and replace accelerometers which can be a cause of inconsistency and errors. In other situations it may be disadvantageous, for instance if removing the source allows better access to measurement points. However, aside from practical details, blocked forces have a major advantage over contact forces in that the data remains valid when the source is transferred to a new receiver. Blocked force data can therefore potentially provide realistic excitation data for vibro-acoustic simulations in a new assembly.

Before going on to consider a simulation example, we note that considerable care is required to avoid potentially large errors during inversion. This topic is too large to be covered here except for two remarks. First, it is the authors' experience that many problems are caused by poor quality or erroneous input data and that the overriding consideration is therefore to obtain the best quality measurement data possible. Secondly, we would highlight the advantages of cross checking the blocked forces (or contact forces) using an 'on board validation' step. The latter is achieved by predicting the response at a spare receiver location (not used in the inverse calculation) and comparing with the directly measured value. This is not a fool proof independent validation but is likely to show up inversion errors which are the main source of poor results.

11.4 Blocked Forces in Simulation

As mentioned above, the use of blocked forces, rather than contact forces, potentially opens up important possibilities for prediction and simulation of sound and vibration. However, the application of blocked force data in prediction is not necessarily straightforward. Consider that the response in a new receiver is given by:

$$\mathbf{a}_{\mathbf{R},\mathbf{new}} = \mathbf{A}_{\mathbf{C},\mathbf{new}}\bar{\mathbf{f}}$$

where $\mathbf{a}_{\mathbf{R}\,,\,\mathbf{new}}$ is the response to be predicted and $\mathbf{A}_{\mathbf{R}\,,\,\mathbf{new}}$ is the coupled FRF of the new assembly. Irrespective of whether the assembly FRF is to be obtained from measured or modelled data, a substructuring step is required to calculate $\mathbf{A}_{\mathbf{C}\,,\,\mathbf{new}}$.the challenges of which are well known e.g. [5]. The only situation in which substructuring can be avoided is when the assembly already exists so that $\mathbf{A}_{\mathbf{C}\,,\,\mathbf{new}}$ can be measured directly. However, if this is the case then it is unlikely that prediction will be required since the receiver response could be measured directly.

We now go on to describe a case study of predicted vibration response using blocked force data. The case study presented here concerns the construction of a 'virtual assembly' whereby a four footed electric pump is resiliently mounted to a Perspex receiver plate. This study is a realistic but relatively simple example in that the resilient couplings allow degrees of freedom other than the vertical to be neglected.

The construction of the virtual assembly first required the determination of the coupled assembly's FRF matrix. This was achieved through a sub-structuring procedure whereby FRFs of each sub-structure were determined by measurement and they were then coupled computationally. Source and receiver sub-structures were characterised by their free FRF, whilst the resilient coupling elements where characterised via an in-situ approach [6]. It should be noted that whilst characterising the receiver sub-structure an additional remote measurement position was included to so as to provide an on board validation.

Having acquired the assembly's FRF matrix, the blocked force of the source sub-structure was determined whilst installed on a different resiliently mounted assembly. These blocked forces were subsequently injected into the initial assembly's sub-structured mobility matrix and a prediction made for the remote receiver position.

For comparative purposes the same assembly was physically constructed. Shown in Fig. 11.2 are the narrow band velocity spectra for the virtual assembly (i.e. blocked forces injected into a sub-structured mobility matrix) and the physical assembly. It can be seen that a reasonable prediction is achieved across the majority of the frequency range. Noticeable errors can be observed at low and high frequencies. These are believed to be due to neglected co-ordinate DoFs (i.e. rotational), and noisy resilient element data, respectively. Regardless of these errors, the agreement in the prediction clearly demonstrates the potential of the blocked forces as a source characterisation for use in vibro-acoustic simulation.

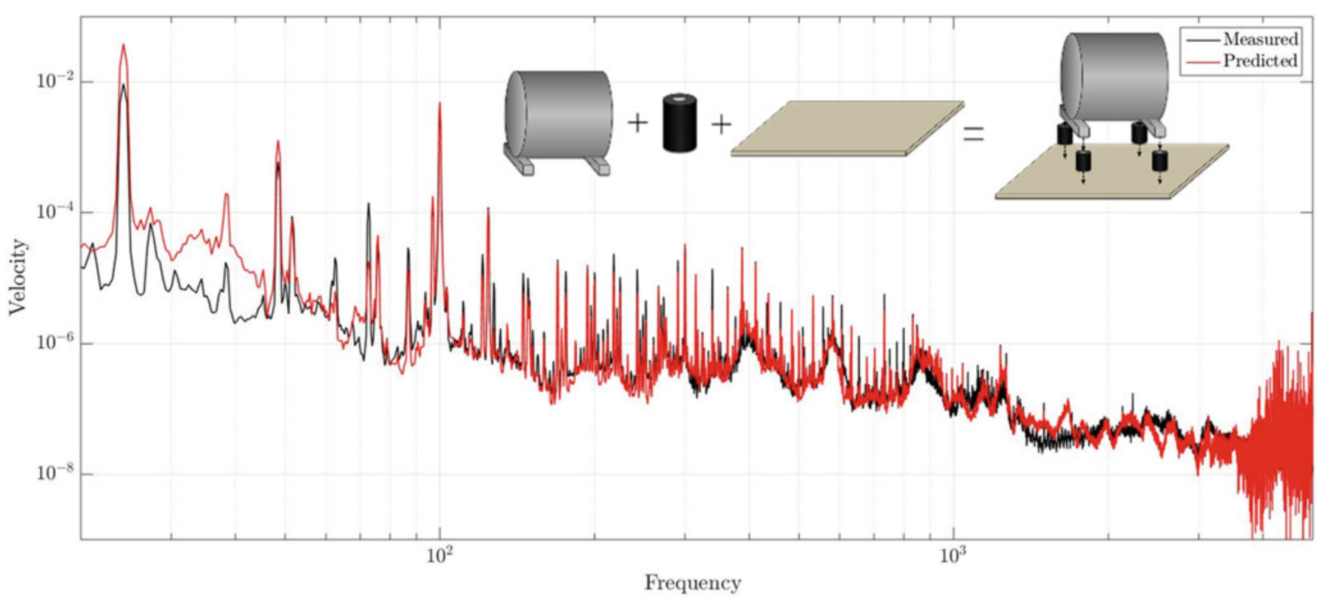

Fig. 11.2 Predicted response of the assembly obtained from blocked forces and substructured FRFs compared with measurement

11.5 Conclusions

It has been argued that blocked forces have a major potential advantage over contact forces in that the data is transferrable and can therefore be used for prediction of sound and vibration in addition to its use in TPA. Reliable solution of the inverse problem represents a difficulty, but there is an increasing number of case studies to demonstrate that, with adequate care, good results can be obtained [7]. An additional difficulty for prediction is that a substructuring step is required and this fact has so far not been widely addressed in the literature. The somewhat simplified but realistic example presented here of a pump on resilient isolators has shown good results but there is much work to do before blocked forces achieve their full potential.

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