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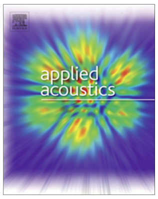

A system response prediction approach based on global transmissibilities and its relation with transfer path analysis methods

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ABSTRACT

In this paper, a response prediction approach based on global transmissibilities is proposed to improve transfer path analysis (TPA) methods. The method allows predicting the system response when a subsystem becomes connected to the ground using easily measured variables of the original system. It avoids the necessity to perform demounting tests and to measure, or indirectly determine operational forces. The mathematical relationships between the proposed method and TPA methods are derived. Four TPA relations are discussed: the classical TPA relation, the OPA relation, the Advanced TPA relation and the Component-based TPA relation. The advantage of this method is that it estimates the properties of a mechanical system or subsystems using in-situ measurements. These properties are the transmissibility between two sets of responses, the coupled and uncoupled transfer functions between responses and forces. The TPA relationships are validated by numerical and experimental case studies.

1. Introduction

Transfer path analysis (TPA) method has been a common and powerful tool for studying the NVH behavior of mechanical systems. It is particularly well suited to solving complex vibro-acoustic problems, as it allows the mechanical system to be separated into a source represented by forces and transfer paths. The TPA family members can be mainly classified as the classical TPA (the matrix-inverse and mount-stiffness methods) [1–3], Operational TPA (OPA) [4–6], Operational path analysis with exogenous inputs (OPAX) [7], Component-based TPA [8–10] and Global Transfer Direct Transfer (GTDT) method [11–13]. A recent review of TPA methods can be found in [14].

The family of classical TPA has nowadays become standard practice in an NVH field, since it is a widely implemented and well-known method. The main idea of the classical TPA is based on a source-path-receiver model, whose basic assumption is to divide the global system into two parts: an active part containing load sources and a passive part containing the receiver points. Each interface degree of freedom (DOF) between the active part and the passive part stands for a transfer path. Basically, two steps are needed to build a classical TPA model: an indirect measurement procedure for estimating interface loads during in-operation tests and the direct or reciprocal measurement of frequency response functions (FRFs) between response in points of interest and points where these forces act [4]. The main drawbacks of classical TPA are related to measurement issues, namely the problem of having to remove the active part when conducting FRF measurements, and the difficulties associated with the measurement or indirect determination of operational forces [13]. Despite having become a well-established and reliable technique for addressing NVH problems, the classical TPA remains a time consuming and complex procedure, which limits its wider industrial application [4]. Besides, the obtained transfer path contributions using classical TPA are valid only for existing designs or measured assembly. If a component or a connector between components is modified, it cannot predict the dynamical behavior of the new modified system since in that case the interface forces and vibration transmission are changing according to the overall interaction between components [10].

In order to cope with the evolving demands, TPA methods have been under continuous development and a large number of members have been proposed to be, at least, free of some of classical TPA measurement difficulties or to solve specific cases. These TPA methods aim at giving as good prediction of target response and as reliable path contributions in a mechanical system as the classical TPA, whilst reducing the measurement time and complexity. A dominant class of these new approaches is the OPA method,

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which only uses operational data of path references and targets in conjunction with the application of the transmissibility concept for TPA. The use of transmissibility indeed offers a possibility for a significant reduction in measurement time and complexity. The transmissibility is inherently different from FRF. Essentially, when dealing with the transmissibility it leads to a co-existence relationship between the target responses and the input path responses, not a causality relationship [15]. It means that the transmissibility matrix concept should be used with special care during the path contribution analysis. One of the difficulties in OPA is that it can be difficult to obtain a full rank transmissibility matrix. In order to enable a successful identification of the transmissibility matrix, a data set containing a number of different conditions whose number at least equals the number of transfer paths is required. In Ref. [15], a new measurement procedure on the use of artificial excitation was proposed to obtain the transmissibility, which was proved to be of a better quality as compared with the conventional one. It requires less data set to obtain a full rank compared to conventional OPA. To reduce the noise influence on the transmissibility matrix estimation, the possibility of using H_s estimator was presented for the experimental assessment of transmissibility matrices in Ref. [16].

In Ref. [7], the OPAX method is also considered as Transmissibility-based TPA. Actually, it still keeps the classical TPA model. OPAX uses the parametric model to identify the operational loads, providing a good compromise between path accuracy and measurement time. In this paper, OPAX is classified as a member of the classical TPA family.

The GTDT method, also called Advanced TPA, is a variant of TPA. Despite also using transmissibility concept to carry out TPA, GTDT was developed independently and is totally different from OPA. On the one hand, definitions of the term transmissibility of these two methods are different. On the other hand, the path contribution in these two methods is computed by different ways. Like all other TPA methods, OPA aims at finding the contributions of various transfer paths to the target response, which can be characterized as absolute path measures. However, GTDT focuses on quantifying and ranking the transmission paths between subsystems or DOFs, allowing the determination of relative contributions of the selected transmission paths [11]. GTDT does not require force determination. It provides an alternative way to deal with NVH problems and complements current TPA methods.

Another fundamentally different family of TPA is that of Component-based TPA. It includes in situ TPA, blocked force approach, free velocity approach, hybrid interface approach and pseudo force method. These methods are equivalent to each other. The Component-based TPA uses measurements of the vibration source conducted on a component test setup, as well as a measurement of the entire system's FRFs [10]. The vibration source is uniquely characterized by the blocked force and the free displacement on its interface. Once the blocked force is determined from a measurement of the stand-alone subcomponent on a test bench, it can be used combined with the system FRFs to predict the target response and rank ordering of transfer paths. Therefore the Component-based TPA avoids the need to disassemble the system, reducing test time. Furthermore, it can predict the dynamics of the system in a modified situation where an interface or a receiver part connected to the active part is modified.

During the past decades, these TPA methods are developed simultaneously and largely independent of each other, all having their specific advantages and disadvantages. These methods have their own uses and the extent to which they are used has no bearing on each other. The review of TPA methods from different perspectives has been given in literature [14]. To some extent, it can be roughly said that the more advanced a TPA method is, the less experimental effort the method requires and the more intricate its data post processing is. Advanced algorithms in post processing of these methods can be free of some experimental measurements, whilst giving reliable and accurate path contributions, and even predicting response for a modified system. As opposite, classical TPA accounts for more cumbersome measurements but easier post processing.

In this article, a response prediction method using the global transmissibility concept is derived. The proposed method uses much simpler measurements of the original system to calculate the new system response because no force determination is required. Consequently the data post processing is more intricate. It has significant potential advantages in improving TPA methods, such as avoiding the experimental measurements of FRFs or operational forces. Hence, the aim of the paper is to derive the mathematical relationships between the proposed method and the above TPA methods and investigate their potential application in improving TPA methods.

For the sake of completeness, it must be mentioned that there are some other approaches already reported in literature to address structural modification issues, such as structural modification or reanalysis methods [17–21]. In essence, the proposed method is equivalent to the one in Ref. [17] since the global transmissibility can be expressed in terms of FRFs.

The advantages of the proposed method when conducting TPA are summarized as follows:

- The response prediction method can predict the new system response when a subsystem becomes connected to the ground using measurements of global transmissibilities and operational responses of the original system, as well as a measurement of the diagonal terms of the FRF matrix.
- Only subsystems of interest are taken into consideration.
- It doesn't require knowing the situation of operational forces when applying the response prediction method. That is no force determination is required.

The following sections are organized as follows. First the basic theory of the global transmissibility based response prediction method is introduced. Then, the relationships between the response prediction method and TPA methods are discussed in detail and finally, they are analyzed and validated by numerical and experimental case studies.

2. A system response prediction approach based on global transmissibilities

Let us consider a mechanical system as schematically depicted in Fig. 1(a). The system can be divided into two parts: an active part containing an excitation and a passive part comprising the target response at point *t*. In the mechanical system, DOFs *j* and *s* are connected directly, and the dynamic stiffness of the link is K_{js} (for simplicity the link is assumed to be elastic, similarly hereinafter). DOFs *i* and *n* are the reference DOFs. Assume that the five DOFs are of interest. $\mathbf{F}^{\mathrm{op}}$ is the operational force vector and $\mathbf{X}^{\mathrm{op}}$ the operational response vector. There is the following relationship between operational forces and operational responses:

$$\mathbf{X}^{\mathrm{op}}(\omega) = \mathbf{H}_{\mathrm{ori}}(\omega)\mathbf{F}^{\mathrm{op}}(\omega) \tag{1}$$

where $\mathbf{H}_{\mathrm{ori}}(\omega)$ is the transfer function matrix between DOFs of interest and operational forces. From here on the dependence on frequency is omitted for clarity, and the term subsystem is identified with a DOF. The follow-up variables with these five indices are associated with these five DOFs.

The above mechanical system can be schematically modelled by a linear network, which is shown in Fig. 1(b). The solid line repre-