Journal of Sound and Vibration 437 (2018) 242–263

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Advanced component transmission path analysis based on transmissibility matrices and blocked displacements

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A R T I C L E I N F O

Article history:
Received 17 March 2018
Received in revised form 5 September 2018
Accepted 9 September 2018
Available online 12 September 2018
Handling Editor: S. Ilanko

Keywords:
Advanced component transmission path analysis
Coupled structures
Response prediction
Blocked displacements
Transmissibility matrices

A B S T R A C T

In component transmission path analysis (TPA), the blocked forces of subsystems and the frequency response functions (FRFs) of the total system need to be measured, which are always not easy to implement. In this paper, an advanced component TPA procedure is proposed. The method allows one to predict the vibroacoustic responses of coupled systems according to the dynamical properties of the subsystems. More specifically, it is based on the knowledge of the displacements of blocked subsystems and the transmissibility matrices between subsystems. The physical meanings of blocked displacements and transmissibility matrices are discussed in detail. It is proved that the transmissibility matrices in this method can be measured independently by suppliers of various components, which is important for complicated products' vibroacoustic response syntheses. Furthermore, an interpretation of this method's physical meaning is given in terms of the Neumann series. The response of a coupled system can be regarded as the result of the superposition of infinite transmissions. This highlights the transmission mechanism of vibration and makes the method more perceivable. The method is illustrated and validated by a numerical model and a finite element (FE) model.

1. Introduction

Modern industry is becoming more and more complicated and specialized. Usually an industrial product is assembled with a large number of components produced by different manufacturers. All components interact with each other and affect the noise, vibration and harshness (NVH) performance of the final product, since they are coupled. A straight-forward and accurate way to acquire the responses of coupled structures is to measure them on the assemblies directly. However, it is impossible to make a prototype for each of the improved designs in the early design phase. Therefore, it is very important to predict the vibroacoustic characteristics of coupled structures in modern industry.

The most widely used method to obtain coupled structures' properties is dynamic substructuring (DS) [1–4]. In DS, a structure is first divided into substructures. Then, each substructure's dynamical properties are obtained by numerical or experimental means. Finally, the dynamical properties of the coupled system can be obtained by combining all substructures'

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https://doi.org/10.1016/j.jsv.2018.09.024
0022-460X/

dynamical properties. DS methods are very useful in obtaining coupled structures' dynamical properties typically characterized by modal parameters or frequency response functions (FRFs). However, without the knowledge of the vibroacoustic sources, it is impossible to predict the responses of coupled structures.

Transmission path analysis (TPA) methods are also commonly used in practice to analyze or predict vibroacoustic responses [5–7]. In classical TPA, the response of the target point is considered as the sum of the contributions of all transmission paths. In practice, the classical TPA consists of a two-step procedure in which FRFs are measured in a first step, with the system being non-operative, and then operational loads (mechanical forces and/or volume velocities) get recorded in a second step. It is well-known that the classical TPA method has two major shortcomings: one is time-consuming due to the necessity to remove the active part when measuring the FRFs of the passive part, the other is the difficulty to obtain operational forces.

In the past decades, the TPA methods have been greatly developed. So far, a number of TPA methods have been developed, such as operational transmission path analysis (OTPA) [8,9], operational path analysis with exogenous inputs (OPAX) [10], component TPA [11,12] etc. Among them, the component TPA is rather special because it is more focused on the response prediction of assembled structures. Component-based TPA tries to characterize the source excitation by a set of equivalent forces which in fact are the so-called blocked forces. After the measurements of the blocked forces, applying the equivalent forces to the junctions of the coupled system will obtain equivalent responses in the passive side. The component TPA method is also called the blocked-force method because blocked forces need to be measured for applying this method. An obvious advantage of this method is to avoid measuring the inaccessible excitation forces. Though the responses of coupled structures can be predicted well by the component TPA method, two shortcomings of this method hinder its applications. One is the difficulty due to the measurement of the blocked forces. The other is that the dynamical properties of coupled structures are still required to be known. Of course, one can obtain the coupled structure's dynamical properties by using methods such as DS. However, it will make the component TPA method a more complex procedure.

To avoid the difficulty of measuring forces, the concept of transmissibility was developed and widely used [13–15]. In Refs. [13,16], the basis of the global transmissibility direct transmissibility (GTDT) approach to TPA was established. The GTDT method factorizes the responses of target points in terms of the responses of reference points, instead of in terms of path forces. Direct transmissibilities play a central role in the GTDT method. In Refs. [16,17], direct transmissibilities are computed from standard measured transmissibilities (global transmissibilities). The direct transmissibility represents a relationship of the responses of two different degree of freedoms (DOFs). In Ref. [18], the direct transmissibility between two DOFs is generalized to the transmissibility matrix between subsets of DOFs. Obviously, the transmissibility matrix can be naturally applied to express the relationships of the responses between coupled substructures.

In this paper we propose a novel method to predict the vibroacoustic responses of coupled systems according to each component's dynamical properties which can be obtained by each part manufacturer individually, through measuring or computer simulation. The method expresses the responses in terms of transmissibility matrices and blocked displacements. Compared with classical component TPA, the proposed method only needs to measure the blocked displacements, rather than the measurement of the blocked forces. Furthermore, the dynamical properties of coupled structures do not need to be known. In consideration of the above advantages, the proposed method in this paper is called the advanced component TPA.

Coupling problems are very often not easy to visualise and understand. The concept of vibration transmission helps to understand this problem better. In this paper, the problem of vibration transmission is also addressed in detail. The Neumann series is applied to explain the process of vibration transmission. The use of the Neumann series has two obvious advantages. One is that the incomprehensible vibration transmission mechanism of coupled systems can be well explained. The other is that the procedure of matrix inversion can be avoided. The most relevant literature of the research is [19] in which the Neumann series is also used to describe the problem of vibration transmission path. The physical meaning of the Neumann Series in this article is similar to but clearer than that in Ref. [19].

Generally, this research provides a new idea for the response predictions of coupled structures. The goals and achievements of this research are as follows:

- To derive a novel and effective method to calculate the vibroacoustic responses of coupled structures according to all components' dynamical properties.
- To give a complete physical interpretation of the method. The concepts of transmissibility matrices and blocked displacements are introduced and used in response predictions.
- To provide a new insight of the vibration transmission mechanism of coupled systems according to the Neumann series. The vibroacoustic responses of coupled structures are interpreted as the results of infinite vibration transmissions.
- To provide a detailed explanation of the application aspect of the proposed method.
- To illustrate and validate the proposed method with an analytical example and a finite element (FE) model.

The remainder of this paper is organized as follows. The theoretical fundamental of the research is presented in Section 2. The formula for calculating the responses of coupled systems is derived. The physical meaning of this formula is explained in detail in Section 3. In this section, the physical meaning of each term in the formula is interpreted first and then the vibration transmission mechanism of coupled systems is explored by means of the Neumann series. In Section 4, the transmissibility