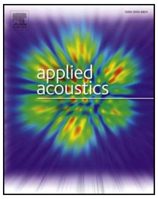
Applied Acoustics 136 (2018) 102–112

Contents lists available at ScienceDirect

Applied Acoustics

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



The transfer path analysis method on the use of artificial excitation: Numerical and experimental studies

Ping Zhu[a,b,*], Zengwei Wang[a,b], Zhiwei Qin[a,b], Yang Shen[c]

[a] State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, Shanghai 200240, PR China
[b] Shanghai Key Laboratory of Digital Manufacture for Thin-walled Structures, Shanghai Jiao Tong University, Shanghai 200240, PR China
[c] SAIC-GM-Wuling Automobile CO., LTD, Liuzhou, Guangxi 545000, PR China

ARTICLE INFO

Keywords:
Transfer path analysis
Frequency response function
Artificial excitation
Mechanicalvibrations
Transmissibility

ABSTRACT

Transfer path analysis (TPA) method is a powerful tool used to study the noise, vibration and harshness (NVH) behavior of mechanical systems. With the development of detecting and testing technology, more powerful and accurate tools for vibration and noise troubleshooting are required. The classical TPA works as the system is disassembled, and thus it is very time-consuming and the boundary conditions are not correct anymore. These topics makes classical TPA still an active research area.

In this paper, a TPA method on the use of artificial excitation is presented. In the method artificial excitation is applied on the active part for providing sufficient incoherent forces to improve the estimation. The known force is applied on the passive part for establishing a relationship between the responses and loads. The advantages of this method are that it estimates the uncoupled transfer function of the passive part on the basis of in-situ measurements, without disassembling the system. The proposed method is validated by numerical and experimental case studies. Some remarks and practical aspects are discussed.

1. Introduction

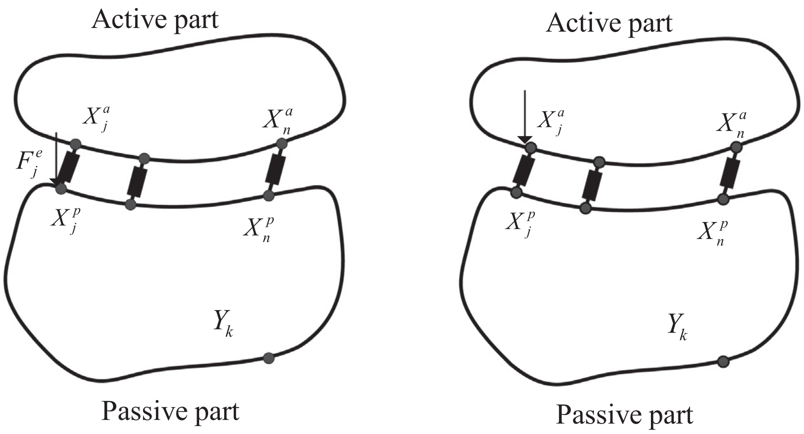
Transfer path analysis (TPA) method has been around for many years to improve noise, vibration and harshness (NVH) problems in automotive engineering by identifying sources and calculating the contribution of each source [1]. It helps engineers detect root causes of noise problems, set performance targets for each critical component as well as quickly evaluate design improvements [2], and is widely used in various engineering fields, such as automobiles and trains [3–6].

The classical TPA is based on a source-path-receiver model, which was developed for solving univariate noise and vibration problems. The basic assumption of this model is that it divides the global system into two parts: an active part containing the load sources and a passive part the receiver points. Each degree of freedom (DOF) acting at the interface points between the active part and the passive part stands for a transfer path. Energy generated by the structural or the acoustic loads of the active part propagates through mount connections or the airborne paths to the receiver points of the passive part. The responses at the receiver point are expressed as a sum of contributions due to individual path, and each path contribution is considered as the result of the individual load acting on the localized interface [7]. Basically, two steps have to be determined to build the classical TPA model: estimation of decoupled frequency response functions (FRFs) and identification of operational forces. First, the FRFs are estimated from experimental tests by use of an impact hammer or shaker for the structural loads, with the system disassembled. Usually, the decoupled FRFs are measured using reciprocity techniques. Second, several operational measurements during engine run-up or run down at different conditions (e.g. for various throttles, gears) are conducted to identify the operational interface loads. The synthesized responses at the receiver points are thereafter obtained, at the same time determining the contribution of each transfer path, by combining the interface loads with the corresponding FRFs. Three measurement methods are usually used for the identification of the interface force. The first method obtains the interface force in a direct way by using force transducer. In the majority of cases, it is not possible to apply a direct measurement of interface loads as the load cells require space and well-defined support surfaces, which often makes application impractical or even impossible without distorting the natural mounting situation [7]. The second method calculates operational interface force with the relative displacement and the mount dynamic stiffness. This method needs priori dynamic stiffness of the mount. The third method identifies the interface forces by combining the operational accelerations of the attachment points with the corresponding acceleration matrix. Because of the

---

[*] Corresponding author at: Room 607, Building A, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China.
E-mail address: pzhu@sjtu.edu.cn (P. Zhu).

https://doi.org/10.1016/j.apacoust.2018.02.007
Received 7 July 2017; Received in revised form 27 January 2018; Accepted 7 February 2018



(a) The known force applied on the passive-side (b) The unknown force applied on the active-side

Fig. 1. The OPAF model.

large number of measurements this method costs a lot of time.

The classical TPA has been proved to be an efficient technique to study the vibro-acoustic behavior of complicated structures, and become standard practice in an NVH field. The main drawbacks of the classical TPA are related to measurement issues, namely the problem of having to remove the active part for FRF measurements, and the difficulties associated with the determination of operational forces [8]. Despite being widely implemented, the classical TPA remains a time consuming and complex procedure, since it needs disassembling the system to measure the decoupled FRFs, which limits its wider industrial application [9]. With the continuous development of TPA methods, a large number of TPA family members have been proposed in literature. It mainly includes the Operational TPA (OPA) [10–12], OPAX [13], Component-based TPA [14–16] and Global Transfer Direct Transfer (GTDT) method [17–19]. A recent review of TPA methods can be found in [20]. In Ref. [21,22], a response prediction approach based on global transmissibilities is proposed to improve TPA method. These TPA methods aim at giving as good prediction of target response and as reliable path contribution as the classical TPA, whilst reducing the measurement time and complexity. In particular, the OPAX and the TPA method described in Ref. [11] are developed on the basis of the classical TPA theory frame. OPAX identifies the operational loads in a parametric way from the operational data of path references, and is considered as a compromise between path accuracy and measurement time [13]. The main drawback of OPAX is that it still needs disassembling the system for experimental FRF measurements. As described in [11], disassembling is very time-consuming and the boundary conditions are not correct anymore. The second method is proposed for the in-situ estimation of the FRFs using the measured operational data with a known external force. Although this method is called OPA, it is different from the common known transmissibility-based OPA. This is because this method still keeps the classical TPA model. Therefore a term OPA with known forces (OPAF) is temporarily used in this paper [11] to differentiate this method from the transmissibility-based OPA. Theoretically speaking this method gives a quite good combination of the accuracy and efficiency, since it doesn't need disassembling the system but gives causality analysis. However requirements of the known force acting on the passive part and the large number of uncorrelated forces acting on the active part during operation make it difficult and even impossible for practical mechanical systems. In spite of this, the method using in-situ measurements shows a lot of promise. Besides, although formulated several years ago, no detailed and controlled experimental test that could help to understand as well as assess the OPAF validity has been published to date.

The aim of this paper is to further develop the OPAF method overcoming limitations related to strict measurement conditions and cover this lack of controlled experimental results on assessing the validity. The novelty of the paper is that a new measurement procedure to obtain transfer and transmissibility functions for application in a two-step transfer path analysis is presented. In the proposed method the external excitation is used to bring the structure into vibration. The external excitation is divided into known and unknown excitation. The unknown artificial excitation, for instance by means of a non-instrumented hammer, is applied on the active part for providing sufficient incoherent forces to improve the estimation. The known artificial excitation, for instance by means of an instrumented hammer, is applied on the passive part for establishing a relationship between the responses and loads. The external excitation is applied in turn, with the machine not in operation. The resulting response and the known forces are then used to estimate the transfer and transmissibility functions. That is the transfer and transmissibility functions are solely computed from a set of responses resulting from the artificial excitation only. Such measurements can be performed relatively easy whilst the experimental effort is relatively low compared to the classical OPAF. Subsequently, a transfer path analysis is carried out using the thus measured transfer and transmissibility functions. Compared to conventional OPAF it is believed that the proposed method is advantageous, since when a structure is excited by hammer strokes, its responses are largely independent from each other, whilst vibrations induced by machine operation are in general not [12].

This paper is organized as follows. First the basic theory of OPAF combined with the artificial excitation is outlined in Section 2. In Section 3, a numerical example of the nine degree-of-freedom (DOF) system is used to illustrate the proposed method, and some properties and the effects of practical factors are investigated. In Section 4, an experimental analysis of a car mock-up is conducted. The article is concluded with a summary in Section 5.

2. Theory

The OPAF method tries to introduce a known force to establish the relationship between the system responses and the interface forces. This can be seen from Fig. 1(a). The known force is applied on the passive-side point of the mount connection. The response of receiver point can be expressed as

$$Y_k(\omega) = \sum_{i=1}^{n} H_{ki}(\omega)F_i(\omega) + H_{kj}(\omega)F_j^e(\omega) \tag{1}$$

where $F_j^e(\omega)$ is the known force, and

$$F_i(\omega) = K_i(\omega)(X_i^a(\omega) - X_i^p(\omega)) \tag{2}$$

From here on the dependency on frequency is omitted for clarity. Eq.