Mechanical Systems and Signal Processing 79 (2016) 254–270

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Substructuring of multibody systems for numerical transfer path analysis in internal combustion engines

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ARTICLE INFO

Article history:
Received 16 February 2016
Accepted 23 February 2016
Available online 5 March 2016

Keywords:
Vibro-acoustics
Numerical TPA
DS
Noise source identification
Engine vibrations
WBM

ABSTRACT

Noise legislations and the increasing customer demands determine the Noise Vibration and Harshness (NVH) development of modern commercial vehicles. In order to meet the stringent legislative requirements for the vehicle noise emission, exact knowledge of all vehicle noise sources and their acoustic behavior is required.

Transfer path analysis (TPA) is a fairly well established technique for estimating and ranking individual low-frequency noise or vibration contributions via the different transmission paths. Transmission paths from different sources to target points of interest and their contributions can be analyzed by applying TPA. This technique is applied on test measurements, which can only be available on prototypes, at the end of the designing process.

In order to overcome the limits of TPA, a numerical transfer path analysis methodology based on the substructuring of a multibody system is proposed in this paper. Being based on numerical simulation, this methodology can be performed starting from the first steps of the designing process. The main target of the proposed methodology is to get information of noise sources contributions of a dynamic system considering the possibility to have multiple forces contemporary acting on the system. The contributions of these forces are investigated with particular focus on distribute or moving forces.

In this paper, the mathematical basics of the proposed methodology and its advantages in comparison with TPA will be discussed. Then, a dynamic system is investigated with a combination of two methods. Being based on the dynamic substructuring (DS) of the investigated model, the methodology proposed requires the evaluation of the contact forces at interfaces, which are computed with a flexible multi-body dynamic (FMBD) simulation. Then, the structure-borne noise paths are computed with the wave based method (WBM).

As an example application a 4-cylinder engine is investigated and the proposed methodology is applied on the engine block. The aim is to get accurate and clear relationships between excitations and responses of the simulated dynamic system, analyzing the noise and vibrational sources inside a car engine, showing the main advantages of a numerical methodology.

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http://dx.doi.org/10.1016/j.ymssp.2016.02.034
0888-3270/

1. Introduction

TPA is a test-based method, which allows to trace the flow of vibro-acoustic energy from a source, through a set of known structure- and air borne pathways, to a given receiver location. It is commonly implemented for the analysis of vibrating active systems and the transmission of these vibrations to connected passive structures. In recent years TPA tends to be particularly associated with noise, vibration and harshness (NVH) engineering, with particular interest in the automotive industry driven by the increasing customer expectations on acoustic comfort [1–5]. TPA technique is adopted in automotive industry since 1970s and so far it is still a useful tool for the NVH assessment of vehicles and mechanical structures. It is commonly applied for the analysis of interior and radiated noise and the identification of different noise paths in vehicles.

Although TPA is useful for the identification of vehicle noise sources, it is difficult to perform substantial modifications to the system by using experiments for the reduction of the vibration and noise. Moreover, TPA can only be applied at the end of the engine and vehicle development process, because a prototype is needed for the experimental measurements, and this represents a limitation in terms of troubleshooting time. This paper introduces a numerical transfer path analysis methodology, based on substructuring of a multibody system, which is able to give information on the vibration paths and noise contributions with the advantage of being entirely based on numerical simulations. This proposed method investigates a substructure of the whole dynamic system. The difference between this methodology and TPA is that in the former it is not necessary to evaluate the vibro-acoustic transfer functions between excitations and responses of the investigated substructure. Compared with TPA, the proposed methodology can be applied already during the first steps of the designing process. Moreover, with a numerical methodology it is possible to overcome some of the obvious limitation related to an experimental methodology, such as the identification of the operating forces (especially when are moving or distributed forces) and the reduction of the measurement based error, as described in [6–11].

In order to introduce both methods, an historical overview of TPA is presented in Section 2 and a theoretical introduction will be presented in Section 3. In Section 4 the two methodologies will be compared with a simple test case and the main advantages of the proposed method will be discussed. Finally, in the last two sections, the proposed methodology is used to analyze the structural velocities and structure-borne noise paths of a numerical model of an engine, with particular focus on the engine block, which represents a structure excited from both direct excitations (combustion forces) and interface forces (contact with other engine components like crankshaft or pistons). The identification of noise sources in internal combustion engines is a challenging task required for the purpose of effective noise reduction. Experimental analysis of noise sources and their transfer paths can be found in literature. In [12,13], the contributions of different structural vibration sources are investigated with the coherence method, focusing mainly on combustion and piston slap noise. In both cases the predominant low frequency vibrational source of the investigated engines is combustion, even though it is highlighted that, due to physical limitations, it is not easy to clearly distinguish the different sources in an experimental analysis. As concerns the acoustic radiation, in [13,14], some analyses were performed with the aim of ranking the different radiating surfaces of the engine in terms of sound intensity and sound power.

2. Historical overview

TPA has been developed mostly during the second half of the XX century. Bendat and Piersol between 1971 and 1981 presented solutions for the derivation of general multiple input/output problems involving any number of stationary random processes having any arbitrary spectral density matrix [15–18]. These publications have empowered multiple-input/multiple-output (MIMO) measurement techniques, giving the chance to analyze vibration problems in their full complexity instead of simplified or analytical descriptions.

The first examples of techniques nowadays denoted as *classical TPA* are often attributed to the work of Verheij around 1980s who studied the transmission of ship machinery vibrations through resilient mounts [19,20]. In 1981 Magran studied the transmissibility between terminals in a network [21]. The so called Global Transfer Direct Transfer (GTDT) method, further investigated by Guasch [22–24], was put into practice as the *advanced TPA* [25]. Independently, Liu and Ewins [26] and Varoto and McConnell [27] explored properties of transmissibility matrices for structural vibration problems, followed by Ribeiro, Maia, Silva and Fontul [28–31]. The transmissibility based method known as *Operational TPA*, developed to overcome the disadvantage of having individual measure of each single path from a source to a receiver, was developed by Noumura and Yoshida [32]; further reviews and benchmark studies can be found in [33–36].

A different approach is the one proposed by Mondot and Petersson in 1987, in which the vibration transfer problem is investigated using the characteristic power of the source and a coupling function accounting for the dynamics of the receiving structure [37]. This methodology led to the characterization of the source by means of blocked forces or free velocities [38–40], to the *in situ* method [41,42] and the *pseudo-forces* method [43,44].

Recent applications combine TPA methodology with the novelty of numerical simulations. Kim and Lee in 2008 proposed a Hybrid TPA formulation (HTPA) that uses simulated excitation forces as input for TPA analysis, where the vibro-acoustic transfer functions are measured [45].

In practical applications, TPA often requires the decomposition of the investigated system by means of DS, in order to investigate a system considering its substructures [46]. The first DS were developed as reduction techniques by Hurty in