Mechanical Systems and Signal Processing 95 (2017) 122–137

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Analytical transmissibility based transfer path analysis for multi-energy-domain systems using four-pole parameter theory

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ARTICLE INFO

Article history:
Received 7 March 2016
Received in revised form 12 March 2017
Accepted 17 March 2017

Keywords:
Transfer path analysis
TPA
OPA
Bond graph
Transmissibility
Multi-energy-domain

ABSTRACT

The increasing demand to minimize undesired vibration and noise levels in several high-tech industries has generated a renewed interest in vibration transfer path analysis. Analyzing vibration transfer paths within a system is of crucial importance in designing an effective vibration isolation strategy. Most of the existing vibration transfer path analysis techniques are empirical which are suitable for diagnosis and troubleshooting purpose. The lack of an analytical transfer path analysis to be used in the design stage is the main motivation behind this research. In this paper an analytical transfer path analysis based on the four-pole theory is proposed for multi-energy-domain systems. Bond graph modeling technique which is an effective approach to model multi-energy-domain systems is used to develop the system model. In this paper an electro-mechanical system is used as a benchmark example to elucidate the effectiveness of the proposed technique. An algorithm to obtain the equivalent four-pole representation of a dynamical systems based on the corresponding bond graph model is also presented in this paper.

1. Introduction

The increasing demand to minimize undesired vibration and acoustic pressure levels in several high-tech industries as well as the desire to improve product lifetime and comfort has generated a renewed interest in vibration transfer path analysis techniques.

There is a rich body of literature on transfer path analysis. The classical transfer path analysis technique which is used to identify and rank major transfer paths within a system is to disconnect the vibrations paths one by one and measuring the target output signal under operational loads. Apart from being costly and even impractical in many situations this technique can yield inaccurate data as the results would depend on the boundary and interface connections which may vary from one experiment to the other.

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http://dx.doi.org/10.1016/j.ymssp.2017.03.022
0888-3270/

From the vibration transfer path point of view, a typical dynamical system is composed of three main subsystems [1–4], namely: active sub-system; generating noise and vibration, mechanical and airborne transfer paths and passive subsystem; receiving the noise and vibration.

Transfer Path Analysis (TPA) methods can play an important role in designing an effective vibration reduction scheme. The original idea of TPA which is primarily an experimental technique, dates back to 80s' [2]. This method can be used to rank the contribution of different transfer paths to the noise level at the target point (e.g the pilot seat in an airplane). TPA can also provide useful information about how the modification of a specific component within a specific path can contribute to the vibration level at the target point [5]. The experimental TPA approach consists of two steps, namely: operational forces or accelerations measurement and obtaining the uncoupled FRFs, after dismounting the active subsystems.

The accuracy of the measured operational data is one of the major challenges of classical TPA techniques [6–8,4]. The main drawback of classical TPA algorithms is the large amount of data measurement requirement. Nevertheless, due to the simple theory behind this method, TPA has been in practice in several industries over the years. However due to the cost and reliability issues of the existing TPA techniques, the importance of developing a more straightforward and faster algorithm for industrial applications is evident.

Some approaches based on multiple as well as partial coherence analysis which were introduced in 1970s can be used to improve the efficiency of the TPA methods [9–12]. These approaches rely only on the operational measurements and therefore are called Operational Transfer Path Analysis (OPA or OTPA) methods [13,14]. The original idea of the OPA method was introduced by Bendat et al. [10,11]. OPA methods would eliminate the necessity of dismounting system components and hence reduce the cost significantly [4]. Janssens et al. [15] have conducted a critical analysis on the OPA technique. They have shown that this method is very time-efficient compared to the classical TPA method but it suffers from accuracy issues.

The transmissibility principle gained a renewed interest in recent years, specially due to its application in OPA approaches, structural monitoring and operational modal analysis [16]. The transmissibility principle can be used to replace the costly Frequency-Response-Functions (FRFs) required by both OPA and TPA methods [17,18].

The transmissibility principle can also serve as a means to factorize the vibration at a target point in terms of the contribution of different paths. This type of signal factorization can be obtained for example by the Global Transfer-Direct Transfer (GTDT) approach [1,19–23] or by path blocking techniques [24].

The GTDT method applied to a system composed of lumped masses, springs and dampers is studied by Guasch [25]. The predictive capabilities of the GTDT approach particularly when a certain path is blocked is also studied. The simplicity of examples used in [25] is very useful to study and compare different methods. Many of the real world complex systems can be simplified to a lumped model for a fast primary analysis.

There are several major contributions to the field of transmissibility analysis, motivated and influenced by electrical network principles, such as the Kirchhoff laws [26] as well as the electrical domain concepts such as impedance and admittance [27]. The principles introduced by Thevenin in 1885 [28] and Norton in 1926 [29] allowed modeling complex systems composed of active and passive subsystems by an equivalent Impedance. These developments led to a better understanding of complex electrical systems, by modeling them as a set of lumped subsystems, characterized by frequency dependent admittance or impedance.

The admittance and impedance concepts developed in the electrical domain has inspired theories of mechanical mobility and impedance. Gardonio and Brennan [30] described direct and inverse electromechanical analogies together with the impedance and mobility formulation for mechanical systems.

In this paper it is shown that mobility and impedance principles can be used to develop the transmissibility matrix of a dynamical system. An extended transmissibility theory for multi-energy-domain dynamical systems is presented in this paper based on the general form of impedance and mobility concepts.

The four-pole parameter theory which is based on the mobility and impedance concepts can be used to describe the input-output relation of a dynamical system [31]. This theory is used to obtain closed form expressions for the transmissibility matrix of multi-energy-domain systems in this paper.

Multi-energy-domain systems are ubiquitous in high-tech industries. Obtaining the transmissibility matrix for such systems could be cumbersome. Bond Graph modeling technique which is a powerful tool to model multi-energy-domain systems is used in this paper [32,33]. The bond graph model of a system represents power flow between different elements. This technique has been used to study mechatronic systems [34], however to the best of authors' knowledge it has never been used in transmissibility analysis.

Most of the existing TPA algorithms are empirical and are suitable for system diagnosis and troubleshooting but not the best option for design purposes. The lack of an efficient analytical TPA approach for modern multi-energy-domain systems is the main motivation behind this research. The proposed technique which can be used to obtain closed form transmissibility functions between inertia elements of a dynamical system is based on the four-pole parameter theory and is extended to cover multi-energy-domain systems. The proposed technique can be used at the design stage and hence reduces the cost of troubleshooting significantly. A systematic approach for obtaining the four-pole representation of a bond graph model is also presented in this paper. A lumped parameter electro-mechanical system is used as a comprehensive and yet simple enough example to elaborate on the proposed algorithm.

This paper is structured as follows: An introduction to the four-pole theory is presented in Section 2. Section 3 describes a systematic approach for obtaining the four-pole representation of a dynamical system based on its bond graph model. The