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Transfer path analysis: Current practice, trade-offs and consideration of damping

Akın Oktav*, Çetin Yılmaz, Günay Anlaş

Department of Mechanical Engineering, Boğaziçi University, Bebek 34342, İstanbul, Turkey

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ABSTRACT

Current practice of experimental transfer path analysis is discussed in the context of trade-offs between accuracy and time cost. An overview of methods, which propose solutions for structure borne noise, is given, where assumptions, drawbacks and advantages of methods are stated theoretically. Applicability of methods is also investigated, where an engine induced structure borne noise of an automobile is taken as a reference problem. Depending on this particular problem, sources of measurement errors, processing operations that affect results and physical obstacles faced in the application are analysed. While an operational measurement is common in all stated methods, when it comes to removal of source, or the need for an external excitation, discrepancies are present. Depending on the chosen method, promised outcomes like independent characterisation of the source, or getting information about mounts also differ. Although many aspects of the problem are reported in the literature, damping and its effects are not considered. Damping effect is embedded in the measured complex frequency response functions, and it is needed to be analysed in the post processing step. Effects of damping, reasons and methods to analyse them are discussed in detail. In this regard, a new procedure, which increases the accuracy of results, is also proposed.

1. Introduction

Transfer path analysis (TPA) describes a noise or vibration response at a selected target, as a superposition of vectorial contributions from a defined set of force inputs that excite the structure, through a chosen set of connections [1,2]. To express the problem in this way gives an insight and a capability in the attenuation of response at the source and/or on the structure, using various techniques of active, or passive vibration control [3]. In the widespread practice, TPA is a two-step experimental procedure: first step is the identification of forces and the second one is to relate identified forces to target receivers through assumed paths. The first step, identification of forces, is mostly the main problem that affects results and developed solutions, accordingly. Operational forces that excite a structure are generated by a single coherent source, or multiple partially-correlated sources [4–6]. In the context of vehicle acoustics, typical examples for single and multiple coherent sources are engine and road inputs, respectively, where the former is addressed in this work.

The method chosen to identify operational forces shapes the procedure of transfer path analysis. To measure operational forces directly is generally hard, since force transducers are required to be located between the structure and source, where vibration isolators or mounts are present. These non-linear isolators respond differently in the presence of transducers, since local stiffness changes significantly [7]. Direct force measurement often gives unreliable results [8]; instead, indirect force estimation techniques are widely used. Mount stiffness and matrix inversion methods are the tools in identifying operational forces [2,8]. These indirect

* Corresponding author.
E-mail address: akin.oktav@boun.edu.tr (A. Oktav).

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methods have their own advantages and drawbacks. Mount stiffness method requires precise mount data, which are seldom available, while matrix inversion method requires accelerance matrix data, which can be obtained by a troublesome and time consuming experimental campaign. Even when mount data are available, they are sensitive to excitation amplitude due to the non-linear nature of the material. Matrix inversion method requires removal of source to achieve both frequency response function (FRF) and noise transfer function (NTF) measurements. In these measurements, a roving hammer with an appropriate tip for low frequency applications is used as an exciter. Measured complex FRFs have real and imaginary parts, where the latter is associated with damping and has smaller signal to noise ratio due to its respectively small magnitude. The real part that represents the mass and stiffness effect is relatively more reliable, since it is known that the exponential window used during impact tests specifically increases apparent damping.

The matter in question with the matrix inversion method is the decoupling of source during frequency response function measurements. Removal of the source changes the dynamic behaviour of the passive part, which is expected to be different, while the system is operating [9]. Additionally, the system may not be linearised at chosen locations for artificial excitation, or linearity assumption may be held more reasonably at another location, other than the chosen one. Brandl et al. [10] performed a sensitivity analysis to quantify measurement errors caused by deviations at excitation locations and directions. Frequency response functions, which are used to populate the accelerance matrix, differ substantially according to the chosen location and the direction of applied force. Inversion of accelerance matrix further increases deviations, which results in poor outcomes. Even if these problems are resolved, measurement of frequency response functions is prone to some other deficiencies in representing actual system characteristics. Ozgen et al. [11] investigated variance and bias type errors in measured data of an aluminium beam. They reveal that leakage in frequency response function measurements is responsible for unexpected results. Leakage in measurements is mainly the result of short time record, and can be reduced using window functions [12]. All common data acquisition systems offer various window functions to compensate for leakage. Unfortunately, once entered as raw data, total elimination of leakage is not possible; moreover, windowing functions introduce artificial damping effects to processed data [13]. Schoukens et al. [14] offered a Taylor series based method to reduce leakage in SISO systems; in follow-up studies, leakage phenomenon is discussed further, and extension of the method to MIMO systems is given [15,16].

Above stated experimental difficulties and potential measurement errors of indirect force estimation techniques induce researchers to come up with more accurate and feasible methods. Operational transfer path analysis (OTPA), a one-step method, is presented as one of the promising alternatives. The method, based on transmissibility concept [17–19], does not require the removal of active part, e.g. engine. Since the method requires only operational data, measurements are more easily obtained. Due to the direct and indirect application of transmissibility, two classes of OTPA are proposed. The former uses a transmissibility matrix instead of an accelerance matrix [20,21], whereas the latter indirectly estimates an accelerance matrix by using measured transmissibilities [9]. Gajdatsy et al. assessed the applicability of OTPA methods in the sense of their limitations and associated errors. Effects of neglected paths, cross-coupling in between passive side accelerations and orthogonality problems in estimated transmissibilities are pointed out [22]. OTPA methods are further studied to increase the accuracy of results [23]. A Tikhonov regularisation-based OTPA is proposed to solve ill-posed problems [24]. Such problems are widely examined in a recent review paper [25]. Based on a parametric load modelling technique, a new TPA procedure [26] is also proposed, which needs extra measurements for the identification of operational forces. This method offers to combine the widely accepted accuracy of traditional TPA approaches with time efficiency of operational TPA methods. A new approach is proposed for load identification based on mixed and penalised cost function optimisation [27]. The proposed technique has better accuracy in force reconstruction compared to classical methods, however, computation time is increased.

Trade-offs between accuracy and time cost motivate researchers to develop several approaches. In pseudo force method [28,29], estimation of operational forces is based on transfer function measurements in combination with operational response measurements. However, the characterisation of source is not completely independent of the passive part of an assembled structure, and to compare sets of pseudo forces, which are determined at different locations of the same source or on another source, may lead to errors, although they might be equivalent. Power based methods are also proposed to characterise the structure borne noise [30,31]. Dynamic coupling between active and passive parts of the structure prevents source characterisation based upon the transmitted power. Although it is possible to assume the passive part to be dynamically stable in certain cases, to generalise this assumption is not reasonable [32]. A blocking force approach, which isolates forces from the environment, is presented [33,34]. The need of specified test rigs for measurements is the main disadvantage of this approach. Global transfer direct transfer (GTDT) is one of the two-step path analysis methods, which does not require the knowledge of operational forces [35]. In the first step, direct transfer functions (DTFs) are calculated from measured GTDT functions, whereas in the second step, operational signal reconstruction is made by means of calculated DTFs. In an analytical study, the path blocking GTDT method and traditional TPA procedure are discussed, and their prediction capabilities are assessed [36]. Recently, an experimental work on a simple mechanical set up is first time presented [37], where GTDT method is adopted. Although, in conclusion it is said that the method can be applied to a more complex structure like an automobile, a generic application will not be so straightforward. First, to model engine mounts as linear springs is not realistic; second, without removing the active part, it is often impossible to access excitation locations.

Advances in testing and measurement technologies provide new solution approaches for TPA. Using PU probes, both sound pressure and particle velocity can be simultaneously acquired [38]. Particle velocity based methods are efficiently used for airborne TPA studies [39,40]. Since the lower limit for measurements is around 200 Hz, it is not possible to use the method for structure borne TPA, at least for the present. Unlike for airborne sources, there is no widely applicable method yet available for independent characterisation of structure borne sound sources. As mentioned, blocked force method that characterises the source independently is not practical, since it requires a tailored test rig. An in situ measurement method that identifies the blocked force, without