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Modal parameter identification based on combining transmissibility functions and blind source separation techniques

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ABSTRACT

Transmissibility-based operational modal analysis is a recent and alternative approach used to identify the modal parameters of structures under operational conditions. This approach is advantageous compared with traditional operational modal analysis because it does not make any assumptions about the excitation spectrum (i.e., white noise with a flat spectrum). However, common methodologies do not include a procedure to extract closely spaced modes with low signal-to-noise ratios. This issue is relevant when considering that engineering structures generally have closely spaced modes and that their measured responses present high levels of noise. Therefore, to overcome these problems, a new combined method for modal parameter identification is proposed in this work. The proposed method combines blind source separation (BSS) techniques and transmissibility-based methods. Here, BSS techniques were used to recover source signals, and transmissibility-based methods were applied to estimate modal information from the recovered source signals. To achieve this combination, a new method to define a transmissibility function was proposed. The suggested transmissibility function is based on the relationship between the power spectral density (PSD) of mixed signals and the PSD of signals from a single source. The numerical responses of a truss structure with high levels of added noise and very closely spaced modes were processed using the proposed combined method to evaluate its ability to identify modal parameters in these conditions. Colored and white noise excitations were used for the numerical example. The proposed combined method was also used to evaluate the modal parameters of an experimental test on a structure containing closely spaced modes. The results showed that the proposed combined method is capable of identifying very closely spaced modes in the presence of noise and, thus, may be potentially applied to improve the identification of damping ratios.

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1. Introduction

Transmissibility functions have been used in recent years as an alternative to methods aiming to identify the modal parameters of vibrating systems in operational conditions. Compared with other methodologies in the frequency domain, methods that use transmissibility functions present significant advantages in that they do not make assumptions related to the characteristics of excitation, i.e., the assumption of white noise excitation with a flat spectrum.

Two approaches are currently used to evaluate modal parameters with transmissibility functions. In the first approach, the natural frequencies of the system can be identified with transmissibility functions under different loading conditions [1,2]. The second approach uses transmissibility functions considering power spectral density (PSD) to identify the modal parameters. The first approach takes into account the finding that transmissibility functions from different loading conditions converge to the same relationship of the amplitude of vibration modes when approaching natural frequencies. Based on the concept of the combination of transmissibility functions under different loading conditions have been proposed different methodologies for modal parameters identification [3–6]. By contrast, the second approach combines different PSDs with different transferring outputs to identify modal parameters [7–11]. The transmissibility function with PDS also converges to the same amplitude of vibration modes when approaching natural frequencies for different transferring outputs. When compared with the first approach, the second presents the advantage of using only one loading condition, instead of several, to extract modal parameters.

Unfortunately, a major shortcoming of methodologies based on transmissibility is difficulty in identifying modal parameters when the vibration modes are closely spaced modes or when signals with low signal-to-noise ratios (SNRs) are present. This situation is usually encountered in civil engineering structures under operational loads. The use of blind source separation (BSS) techniques, which can perform signal separation in modal components, may be an alternative approach with which to improve identification results in these conditions.

The applicability of BSS techniques in combination with traditional identification methodologies for operational modal analysis has been investigated in detail in a number of fairly recent publications [12–17]. These works show that identification methods using signal decomposition yield better results than direct application of the method on the signals. Therefore, modal parameter identification with separate signals can improve identification in methods that use transmissibility functions. This combination of BSS techniques with modal identification methods based on transmissibility functions has not been studied previously.

BSS techniques aim to extract a set of signals, called sources, from observations of their mixtures and by making general assumptions about them [18]. In this aspect, the dynamic response of a structure can be assumed to be modeled as a linear and static mixture of sources that can be expressed in matrix form as follows [12]:

$$x(t) = \mathbf{A}s(t) \tag{1}$$

where s(t) is the vector of unknown source signals, A is the mixing matrix, and x(t) is the vector of the dynamical response of the system. The applicability of BSS techniques to vibration data is due to their similarity with the modal expansion of the dynamic responses of a system.

$$x(t) = \mathbf{\Phi}p(t) \tag{2}$$

where $\mathbf{\Phi}$ is the modal matrix and $p(t)$ is the vector of the modal coordinates. Comparison of Eqs. (1) and (2) reveals a direct relationship between the mixing matrix and modal matrix, as well as between the vectors of the sources and modal coordinates. In the case of a linear and static mixing matrix, two approaches can be employed to separate the blind sources. The first approach, also known as independent component analysis (ICA), is based on high-order statistics and uses sources that are considered as statistically independent [19]; the second approach uses second-order statistics with uncorrelated sources.

The main assumption of ICA when solving blind identification problems is that the source signals are considered to be mutually independent and non-Gaussian. Under this assumption, the source signals can be identified by the solution of an optimization problem based on a cost function. However, the main problems of ICA techniques are related to the use of higher-order statistics, the estimation of which is demanding and difficult when insufficient data are available. Furthermore, ICA methods work well only in the case of under-damped systems with damping ratios lower than 1% [12]. Considering these features, ICA techniques are unattractive for modal parameter identification.

Techniques based on second-order statistics assume that the sources are not correlated for all delays. These techniques include the algorithm for multiple unknown signal extraction (AMUSE) [20] and second-order blind identification (SOBI) [21]. Both algorithms are based on the use of the covariance matrix. In SOBI, joint diagonalization of several covariance matrices with delays is performed. By contrast, in AMUSE, eigenvalue decomposition of the covariance matrix is performed in a single delay. Thus, SOBI overcomes the problems of AMUSE, which are related an inappropriate choice of delay. Indeed, considering the noise in signals, SOBI has been proven to outperform AMUSE [14,22].

McNeill and Zimmerman [15] illustrated that SOBI presents limitations in the presence of closely spaced modes. However, Rainieri and Fabbrocino [23] showed that “SOBI can be reliably applied even in the case of structures characterized by very closely spaced modes, provided that there are no repeated frequencies.” Taking this finding into account and considering that the vibration modes used for the analyses are orthogonal to each other, SOBI can be expected to be applicable to identification of closely spaced modes.