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On using the Hilbert transform for blind identification of complex modes: A practical approach

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ABSTRACT

The modal identification of dynamical systems under operational conditions, when subjected to wide-band unmeasured excitations, is today a viable alternative to more traditional modal identification approaches based on processing sets of measured FRFs or impulse responses. Among current techniques for performing operational modal identification, the so-called blind identification methods are the subject of considerable investigation. In particular, the SOBI (Second-Order Blind Identification) method was found to be quite efficient. SOBI was originally developed for systems with normal modes. To address systems with complex modes, various extension approaches have been proposed, in particular: (a) Using a first-order state-space formulation for the system dynamics; (b) Building complex analytic signals from the measured responses using the Hilbert transform. In this paper we further explore the latter option, which is conceptually interesting while preserving the model order and size. Focus is on applicability of the SOBI technique for extracting the modal responses from analytic signals built from a set of vibratory responses. The novelty of this work is to propose a straightforward computational procedure for obtaining the complex cross-correlation response matrix to be used for the modal identification procedure. After clarifying subtle aspects of the general theoretical framework, we demonstrate that the correlation matrix of the analytic responses can be computed through a Hilbert transform of the real correlation matrix, so that the actual time-domain responses are no longer required for modal identification purposes. The numerical validation of the proposed technique is presented based on time-domain simulations of a conceptual physical multi-modal system, designed to display modes ranging from normal to highly complex, while keeping modal damping low and nearly independent of the modal complexity, and which can prove very interesting in test bench applications. Numerical results for complex modal identifications are presented, and the quality of the identified modal matrix and modal responses, extracted using the complex SOBI technique and implementing the proposed formulation, is assessed.

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1. Introduction

The modal identification of dynamical systems under operational conditions, when subjected to wide-band unmeasured excitations (turbulence, wind, waves, traffic), became an active topic of research and is today a viable alternative to more traditional modal identification approaches based on processing sets of measured FRFs or impulse responses. The advantages of operational modal identification are particularly obvious for systems that are difficult to excite, in particular civil structures such as bridges, towers or offshore platforms, but also for systems subjected to strong unmeasured force fields, such as turbulence-excited pipe systems. For most structures subjected to wide-band excitations, cross-correlation functions can be computed from the vibratory responses, which display the typical exponentially decreasing oscillatory behavior of impulse responses, sharing with them the essential dynamical properties stemming from multi-modal systems.

This is the basis of NExT (Natural Excitation Technique) procedures, developed in the early 1990s, see Ref. [1]. These correlation functions, or their corresponding spectra, may then be used for modal identification purposes, through various currently-available time-domain or frequency-domain identification techniques. The work by Rainieri & Fabbrocino [2] and Brincker & Ventura [3], as well as the overviews by Zhang & Brinker [4] and Brinker [5], offer recent reviews on the Operational Modal Analysis (OMA) and the techniques used for the modal identification of structures subjected to unmeasured excitations.

Ideally, identification should be based on correlation or spectral matrices computed with all the available cross-measurement data. Nevertheless, with some slight restrictions, incomplete experimental spectral and correlation response matrices can still be used with the techniques developed by Antunes et al. [6]. A classic limitation of OMA is that the number of sensors must be equal or greater than the number of active modes. A possible way of bypassing this issue is to perform the modal extraction by filtering the measured responses on successive frequency bands, so that the inverse problem is always well posed. More sophisticated approaches described in recent papers resort to specific features of the modal responses to overcome ill-posedness, when measurements are sparse in relation to the number of active modes, see Antoni & Chauhan [7], Ghahari et al. [8] and Qin et al. [9].

Among the approaches to operational modal identification, the so-called Blind Source Separation (BSS) methods are non-parametric modal extraction techniques which are currently the subject of considerable investigation. In an interesting paper, Antoni et al. [10] discuss how source separation criteria in BSS methods, originally developed in the signal-processing community, relate to physical principles when dealing with modal response extraction, stated in the form of least-action criteria. Techniques based on Independent Component Analysis (ICA), introduced by Jutten & Hérault [11], have been developed and enforce the statistical independence of modal responses. They rely on higher-order statistics and are applicable to systems displaying non-Gaussian responses, by seeking the mixing matrix that maximizes non-Gaussianity of the unknown sources or a given contrast function, see Cardoso [12] or Hyvarinen et al. [13].

Another technique well suited to operational modal identification is the Second-Order Blind Identification (SOBI) method, originally developed by Belouchrani et al. [14] and closely related to the Algorithm for Multiple Unknown Signals Extraction (AMUSE), see Tong et al. [15]. Contrary to ICA, the SOBI approach relies solely on second-order statistics, and can therefore be applied to Gaussian responses and is less sensitive to noise. SOBI operates by extracting sources with a different second-order temporal structure; therefore the identified system must not feature degenerate modes, which would lead to modal responses with identical frequency content. As pointed out in the work by Poncelet et al. [16], ICA-based modal identification is only suitable for weakly-damped structures, and even for such systems the SOBI technique was found to be more robust. SOBI is being increasingly used for the identification of real-life systems, see Zhou & Chelidze [17] or Rainieri [18]. Furthermore, an extension of the ICA identification approach to complex mode systems, based on a time-frequency analysis developed by Nagarajaiah & Yang [19], is worthy of mention.

SOBI was originally developed to identify systems with normal modes. To address systems with complex modes, extension approaches have been proposed, which are mainly as follows: (a) Formulating the system dynamics in state-space first-order form; (b) Building complex analytic signals from the measured responses. The first approach builds on correlation matrices computed from the general formulation of complex mode systems in state-space form, as extensively discussed by Antoni & Chauhan [7]. This approach enables the identification of heavily-damped modes, which constitutes a considerable advantage. A drawback of this approach is that it requires twice as many sensors as the standard (real) SOBI for the extraction of a given number of active modes. However, the authors discuss ways of alleviating this limitation. The second approach, based on the "complexification" of the measured data, is conceptually interesting and comparatively simple, while preserving the order and size of the model. It consists in adding the imaginary counterpart of the response to the observed signals, and then uses the built complex analytic signal for the identification procedure. This framework was first proposed by Spina & Valente [20], later extended in more recent work, see Spina et al. [21] and Gabriele et al. [22], via the use of the Hilbert transform to construct the imaginary counterparts of the system responses. In a similar spirit, McNeill & Zimmerman [23,24] proposed a generalization of the SOBI techniques to systems with complex modes, where the measured data set is augmented with its imaginary counterpart. Originally, informal procedures were used to provide the imaginary signal components orthogonal to the physical responses, and McNeill [25,26] then proposed a more rigorous and compact formulation in terms of the Hilbert transform. Interestingly, Feeny [27] used a similar approach for the complex orthogonal decomposition of travelling waves. And, more recently, Ghahari et al. [28] replaced the Hilbert transform for the time-derivative of the system response, in order to obtain imaginary signals orthogonal to their corresponding response measurements.