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Review

A review of output-only structural mode identification literature employing blind source separation methods

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ABSTRACT

Output-only modal identification has seen significant activity in recent years, especially in large-scale structures where controlled input force generation is often difficult to achieve. This has led to the development of new system identification methods which do not require controlled input. They often work satisfactorily if they satisfy some general assumptions – not overly restrictive – regarding the stochasticity of the input. Hundreds of papers covering a wide range of applications appear every year related to the extraction of modal properties from output measurement data in more than two dozen mechanical, aerospace and civil engineering journals. In little more than a decade, concepts of blind source separation (BSS) from the field of acoustic signal processing have been adopted by several researchers and shown that they can be attractive tools to undertake output-only modal identification. Originally intended to separate distinct audio sources from a mixture of recordings, mathematical equivalence to problems in linear structural dynamics have since been firmly established. This has enabled many of the developments in the field of BSS to be modified and applied to output-only modal identification problems. This paper reviews over hundred articles related to the application of BSS and their variants to output-only modal identification. The main contribution of the paper is to present a literature review of the papers which have appeared on the subject. While a brief treatment of the basic ideas are presented where relevant, a comprehensive and critical explanation of their contents is not attempted. Specific issues related to output-only modal identification and the relative advantages and limitations of BSS methods both from theoretical and application standpoints are discussed. Gap areas requiring additional work are also summarized and the paper concludes with possible future trends in this area.

Contents

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1. Introduction

Estimating modal properties, i.e. natural frequencies, mode shapes (normal modes) and damping ratios using vibration measurements have been extensively studied for over half a century as summarized here [1–3]. The volume of work in this area is vast. Generally speaking, many of the original ideas and tools employed for this purpose in the frequency domain are now being carried out in the time-domain. Initially, a majority of these methods required input (excitation) to be explicitly measured and be used in the analysis [4]. Subsequently, new methods which relaxed the requirement of input measurement started to be developed, and were found to be useful especially for large-scale applications (e.g., civil structures) where input generation is impractical (due to their inertia). Such methods have been called differently depending on the discipline, e.g. output-only modal identification, ambient modal identification or operational modal analysis (OMA). For simplicity, OMA will be used to describe these methods in this paper. The modes so extracted are unscaled; nevertheless they have successfully been used for a wide range of end uses such as serviceability assessment in bridges [5,6], model updating [7,8] and damage identification [9,10].

Blind Source Separation (BSS) emerged in the 90s as a powerful signal processing tool for de-mixing audio sources from recordings, e.g., see [11]. BSS is often described using the cocktail party problem, where the basic objective is to identify individual speakers (sources) from a simultaneous recording (together called mixing) of multiple speakers. In this signal separation problem, unknown individual signals and contributions in the resulting mixtures are defined as the sources and mixing matrix, respectively. The problem is called separation if all the sources are identified simultaneously, or called extraction if only a subset of sources are sequentially separated [12–14]. In their work, [15,16] demonstrated the use of BSS in structural dynamics, however without explicitly considering the connection between the modal expansion theorem and the BSS models used in OMA. In the following papers [17,18], the mathematical equivalence with the problem of structural dynamics, namely modal superposition using normal modes for lightly damped systems, was established. In this relationship, the sources are nothing but the modal responses and the mixing matrix contains the amplitudes, or the arbitrarily scaled mode shapes (it is well-known fact that only un-scaled mode shapes can be obtained in OMA) of the system. Even though scaling and permutation ambiguities exist in the resulting sources, it can be circumvented using, say an ordering scheme based on the frequencies of hidden sources [19]. In OMA, a simple ordering according to natural frequencies is deemed sufficient. The mathematical analogy (i.e., measured response equals the mixing matrix times the source components; physical response equals the modal matrix times the modal responses) only provides a necessary condition for application of BSS to OMA; the sufficient condition requires a relationship to exist between the identified sources and modal responses, for example the correlation structure of amplitude modulated sinusoids [20,21]. Recently [22] showed how least action principles can be used to provide physical insights into the mechanism of BSS within the context of modal expansion theorem.

The main advantage of BSS over parametric methods is its simplicity. In its most basic (and widely used) form, the problem of OMA is framed in terms of a non-parametric linear system of algebraic equations, alleviating the difficulties associated with model formulation or model order selection (e.g., Kalman filter or Stochastic Subspace Identification [23]). The solution is largely carried out using standard numerical optimization tools, which can be further simplified using frequency and time-frequency transformations. Furthermore, the need for expert intervention, say for the interpretation of peak-picking, stabilization diagrams, etc. in frequency domain methods [24,25], also does not present itself in this framework. BSS therefore has increasingly been viewed as a practical tool for simplifying a large system into a series of simple components where simple single-degree-of-freedom identification schemes can be used to extract the modal parameters.