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System identification through nonstationary data using Time–Frequency Blind Source Separation

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A B S T R A C T

Classical output-only system identification (SI) methods are based on the assumption of stationarity of the system response. However, measured response of buildings and bridges is usually non-stationary due to strong winds (e.g. typhoon, and thunder storm etc.), earthquakes and time-varying vehicle motions. Accordingly, the response data may have time-varying frequency contents and/or overlapping of modal frequencies due to non-stationary colored excitation. This renders traditional methods problematic for modal separation and identification. To address these challenges, a new SI technique based on Time–Frequency Blind Source Separation (TFBSS) is proposed. By selectively utilizing "effective" information in local regions of the time–frequency plane, where only one mode contributes to energy, the proposed technique can successfully identify mode shapes and recover modal responses from the non-stationary response where the traditional SI methods often encounter difficulties. This technique can also handle response with closely spaced modes which is a well-known challenge for the identification of large-scale structures. Based on the separated modal responses, frequency and damping can be easily identified using SI methods based on a single degree of freedom (SDOF) system. In addition to the exclusive advantage of handling non-stationary data and closely spaced modes, the proposed technique also benefits from the absence of the end effects and low sensitivity to noise in modal separation. The efficacy of the proposed technique is demonstrated using several simulation based studies, and compared to the popular Second-Order Blind Identification (SOBI) scheme. It is also noted that even some non-stationary response data can be analyzed by the stationary method SOBI. This paper also delineates non-stationary cases where SOBI and the proposed scheme perform comparably and highlights cases where the proposed approach is more advantageous. Finally, the performance of the proposed method is evaluated using a full-scale non-stationary response of a tall building during an earthquake and found it to perform satisfactorily.

1. Introduction

Blind Source Separation (BSS) methods (e.g. Independent Component Analysis (ICA) [1], Algorithm for Multiple Unknown Signals Extraction (AMUSE) [2], Second-Order Blind Identification (SOBI) [3], Principle Component Analysis [4] etc.) have recently gained popularity in the output-only modal analysis/identification field [5–9], due to their appealing feature of only invoking the assumption of statistical independence or uncorrelatedness [10] of sources. Earlier studies in the system

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identification (SI) field have been dedicated to verify the efficacy of ICA, AMUSE and SOBI in separating vibration modes [11–13]. Later, research efforts mainly focused on improving the performance of BSS methods for highly damped systems [14,15], systems with complex modes [16], systems with closely spaced modes or low energy modes [17], and systems in underdetermined cases [18–21]. Most recently, a new BSS method adopted a sparse component analysis to identify systems with closely-spaced highly-damped modes in both determined and underdetermined cases [22].

Most of these methods have been developed based on the assumption of the stationarity of data. However, field monitored response data from buildings and bridges under strong winds (e.g. typhoon, downburst, and thunder storm etc.), earthquakes and time-varying traffic loadings, which are critical to structural safety, are usually non-stationary. Unfortunately, research efforts on BSS are limited in non-stationary SI. Only a couple of studies proposed measures to alleviate the effect of non-stationarity in a general sense by using non-overlapping windowed responses [18,23]. More specific problems caused by non-stationarity still remain unsolved. First, the modal responses excited by earthquakes and transient winds (e.g. downbust) may not be monochromatic due to the non-stationary background contribution. This may cause overlapping of frequency components of different modal responses in the time–frequency domain and diminish the modal separation accuracy of most of the existing BSS based SI methods, because they either explicitly or implicitly assume the broadband excitation, and thus treat the modal responses as monochromatic components. A decrease in the modal separation quality when excitation is colored has been reported by McNeill and Zimmerman [16]. Also, non-stationary excitations may lead to time-varying frequency contents characterized by modal components participating at different times. This may affect the modal separation accuracy of most of the existing SI methods based on the BSS, since these methods do not use local information in the time domain, rather, they utilize statistics calculated based on the entire time domain. These issues resulting from the non-stationary excitation may also render the traditional SI methods (such as Frequency Domain Decomposition (FDD) [24,25], Stochastic Subspace Identification (SSI) [26], Random Decrement Technique (RDT) [27], etc.) problematic [28,29] mainly due to the following three reasons: (i) nonstationary response is usually characterized by a short duration. The classical frequency-domain SI methods (e.g. half-power bandwidth (HPBW), spectral moments method (SMM), FDD, etc.) may not be able to provide accurate results, due to the lack of long stationary data segments needed for reliable spectral estimates; (ii) the non-white nonstationary excitations may render most of the existing methods (e.g. HPBW, FDD, etc.) based on the assumption of broadband excitation become problematic; (iii) The traditional SI methods (e.g. HPBW, FDD, SSI, etc.) are based on the averaged information in the entire time domain, therefore are not able to track time-varying system properties. In addition to the problems caused by non-stationary excitations, SI becomes even more challenging if a structure has closely spaced modes at the same time. For example, the non-stationary technique like HHT may become cumbersome in this case [30]. Additional concerns related to intermittency [31] or techniques such as band pass filtering [32], wavelet packet transform [33], etc. are usually required.

To address the aforementioned challenges caused by non-stationary data, this paper proposes a new SI technique based on Time–Frequency Blind Source Separation (TFBSS) using spatial time–frequency distribution (STFD). The TFBSS has been developed in the electrical engineering field for non-stationary source separation [34,35] and has not been used in SI related problems thus far to the best of authors' knowledge. Instead of utilizing information in the entire time domain as classical BSS based methods, the proposed technique can selectively utilize the "effective" information in local regions in time–frequency plane, where only one mode has energy. Therefore, compared to the classical BSS methods, the proposed method can improve accuracy of modal separation for non-stationary data and better handle closely spaced modes. In addition to the exclusive advantage of dealing with non-stationary data and closely spaced modes, the proposed technique also enjoys the benefit of no end effect in modal separation like the classical BSS based methods, which might be an advantage over conventional wavelet and empirical mode decomposition based SI methods [36,37] when extremely limited data is available. The efficacy of the proposed technique is verified utilizing several simulation studies, and compared to the popular BSS based modal identification method SOBI.

Another interesting finding of this study is that the modal separation for non-stationary cases depends markedly on the nature of non-stationary response. Not all types of non-stationary response is problematic for the classical SOBI, regardless of these being developed based on the assumption of stationarity. Thus, this paper also compares the SOBI and the proposed technique from a different perspective to illustrate non-stationary cases when both methods perform comparably and highlights situations where the proposed technique offers additional advantages.

2. Non-stationary SI based on Time–Frequency Blind Source Separation (TFBSS)

2.1. Problem formulation: casting modal identification in BSS framework

For a proportionally damped multi-degree-of-freedom (MDOF) system, the system dynamic characteristics can be uniquely defined by modal frequencies, damping ratios and mode shapes. The SI problem in this case is the modal identification problem. In this section, after a brief overview of the BSS background, a nonstationary modal identification problem is cast in the BSS framework. A BSS formulation can be expressed as

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

where $\mathbf{y}(t)$ is the observations, $\mathbf{y}(t) = [y_1(t), \ldots, y_m(t)]^T$;$\mathbf{s}(t)$ is a set of sources, $\mathbf{s}(t) = [s_1(t), \ldots, s_n(t)]^T$; $\mathbf{A}$ is a $m \times n$ mixing