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A simple iterative independent component analysis algorithm for vibration source signal identification of complex structures

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ABSTRACT: *Independent Component Analysis (ICA), one of the blind source separation methods, can be applied for extracting unknown source signals only from received signals. This is accomplished by finding statistical independence of signal mixtures and has been successfully applied to myriad fields such as medical science, image processing, and numerous others. Nevertheless, there are inherent problems that have been reported when using this technique: instability and invalid ordering of separated signals, particularly when using a conventional ICA technique in vibratory source signal identification of complex structures. In this study, a simple iterative algorithm of the conventional ICA has been proposed to mitigate these problems. The proposed method to extract more stable source signals having valid order includes an iterative and reordering process of extracted mixing matrix to reconstruct finally converged source signals, referring to the magnitudes of correlation coefficients between the intermediately separated signals and the signals measured on or nearby sources. In order to review the problems of the conventional ICA technique and to validate the proposed method, numerical analyses have been carried out for a virtual response model and a 30 m class submarine model. Moreover, in order to investigate applicability of the proposed method to real problem of complex structure, an experiment has been carried out for a scaled submarine mockup. The results show that the proposed method could resolve the inherent problems of a conventional ICA technique.*

KEY WORDS: Iterative independent component analysis algorithm; Blind source separation problem; Vibration source separation; Complex structure; Correlation analysis.

INTRODUCTION

Noise and vibration control is undoubtedly a crucial issue in design, construction, and operation of ships and offshore structures. If one could properly identify noise and vibration source signals, as well as estimate their contributions to concerning responses, appropriate control means could be efficiently applied to corresponding noise and vibration sources and paths. Recently, source identification methods based on Blind Source Separation (BSS) have been studied. BSS reconstructs unknown source signals without information of sources and corresponding paths. Siano (2012) has originally introduced the BSS method of noise control. Popescu (2010a; 2010b) has separated vibration signals and detected source changes using machine moni-

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toring data; he also has used the BSS method to analyze traffic-induced vibrations in buildings. Zhou and Chelidze (2007) have identified vibration modes of a beam structure based on BSS that has been verified with experimental investigation. Yu et al. (2014) have estimated modal parameters of the structure using sparse component analysis based on underdetermined blind source separation.

Independent Component Analysis (ICA), a BSS method, extracts source signals having statistically independency exclusively from concerning response signals. ICA has been successfully applied to myriad fields such as medical science (Wollny et al., 2012), image processing (Murillo-Fuentes, 2007), and numerous others. Moreover, there are substantive expectations that ICA, as it develops, could be applied to extensive fields in the future (Hyvärinen et al., 2001). Liu and Randall (2005) have used ICA to separate pure-tone signals of an internal combustion engine piston slap from measured vibration signals. Gelle and Colas (2001) have monitored faults of a rotating machine, while Ajami and Daneshvar (2012) have applied the technique for fault detection and diagnosis of a real turbine system. Guo et al. (2014) have proposed a method of combining the envelope extraction and ICA to diagnose fault of the rolling element bearing. Cheng et al. (2010; 2011) have separated vibration source signals from time domain response (acceleration data) measured on the transverse bulkhead consisting of a ship based on an ICA method; they have analyzed their correlations of the separated signals with respect to the source signals acquired underneath a diesel engine for ship propulsion and diesel generators. Cheng et al. (2012) have proposed a source number estimation based on ICA and clustering evaluation analysis from signal mixtures. In addition, Kim et al. (2012) have adopted ICA to separate the vibration source signals from the numerically calculated responses of simple structures such as a flat plate and cylindrical shell and analyze their correlation to the input source signals. These studies have successfully shown that ICA could be efficiently applied to vibration source separation of real complex structures.

Most of studies above, however, have been based on conventional ICA like FastICA (Hyvärinen et al., 2001). FastICA adopts a fast fixed-point algorithm to find solution and has some drawbacks: losing scale and order information, as well as occasionally providing unstable solutions. Among these drawbacks, the scale information lost in whitening process of response signals could be simply restored using dewhitening process with respect to the separated signals (Hyvärinen et al., 2001). Meanwhile, to resolve the occasional instability of the solution, various improved methods such as group ICA, statistical validation of the reliability of ICA results, correlation analysis among separated source signals, improved estimation of linear decomposition have been proposed recently and they are well introduced by Hyvärinen (2013). Representatively, Himberg and Hyvärinen (2003) have developed ICASSO software for investigating the reliability of ICA estimates by clustering and visualization. ICASSO is one of the most powerful tools to obtain stable solution. But, it might not be appropriate to applications needing real-time processing because it requires a complicated procedure including massive calculations (Himberg et al., 2004). Moreover, to the author's knowledge, studies to improve invalid ordering of separated signals in Multiple-Input-Multiple-Output (MIMO) system are few.

In this study, a simple iterative ICA algorithm has been proposed to mitigate inherent problems associated with the conventional ICA algorithm. The proposed method based on the conventional ICA includes a series of processes: centering and whitening, estimating demixing (or separating) matrix, reconstructing sources, correlation analysis, rearrangement of mixing matrix, and reconstructing finally converged source signals. In particular, an iterative and reordering algorithm, referring to the magnitudes of correlation coefficients between the intermediately separated signals and the signals measured on or nearby sources, is applied for the extraction of more accurate source signals having valid order with a few additional calculation burdens. Numerical analyses of a virtual response model and a 30 *m* class submarine model are carried out to verify the proposed algorithm, and an experiment for a scaled submarine mockup is performed to investigate applicability of the proposed method to a real complex structure.

FORMULATION AND ALGORITHM

Blind source separation method

Vibration energy caused by onboard equipment is propagated to structure members of ships and offshore structures through various transmission paths, where the onboard equipment and concerning structure members can be regarded as multiple vibration sources and multiple vibration receivers, respectively. In this case, the relationship between the vibration sources and