Mechanical Systems and Signal Processing 85 (2017) 567–590

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Blind identification of full-field vibration modes from video measurements with phase-based video motion magnification

Yongchao Yang [a,*], Charles Dorn [b], Tyler Mancini [c], Zachary Talken [d], Garrett Kenyon [e], Charles Farrar [a], David Mascareñas [a]

[a] Los Alamos National Lab, Engineering Institute, PO Box 1663, MS T001, Los Alamos, NM 87545, USA
[b] Department of Engineering Physics, University of Wisconsin, Madison, WI 53706, USA
[c] Department of Aerospace Engineering and Engineering Mechanics, University of Texas, Austin, TX 78712, USA
[d] Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, MO 65409, USA
[e] Los Alamos National Lab, Applied Modern Physics, PO Box 1663, MS D454, Los Alamos, NM 87545, USA

A R T I C L E I N F O

Article history:
Received 22 January 2016
Received in revised form
5 August 2016
Accepted 28 August 2016

Keywords:
Operational modal analysis
Non-contact measurements
Video processing
Blind source separation
Motion magnification

A B S T R A C T

Experimental or operational modal analysis traditionally requires physically-attached wired or wireless sensors for vibration measurement of structures. This instrumentation can result in mass-loading on lightweight structures, and is costly and time-consuming to install and maintain on large civil structures, especially for long-term applications (e.g., structural health monitoring) that require significant maintenance for cabling (wired sensors) or periodic replacement of the energy supply (wireless sensors). Moreover, these sensors are typically placed at a limited number of discrete locations, providing low spatial sensing resolution that is hardly sufficient for modal-based damage localization, or model correlation and updating for larger-scale structures. Non-contact measurement methods such as scanning laser vibrometers provide high-resolution sensing capacity without the mass-loading effect; however, they make sequential measurements that require considerable acquisition time. As an alternative non-contact method, digital video cameras are relatively low-cost, agile, and provide high spatial resolution, simultaneous, measurements. Combined with vision based algorithms (e.g., image correlation, optical flow), video camera based measurements have been successfully used for vibration measurements and subsequent modal analysis, based on techniques such as the digital image correlation (DIC) and the point-tracking. However, they typically require speckle pattern or high-contrast markers to be placed on the surface of structures, which poses challenges when the measurement area is large or inaccessible. This work explores advanced computer vision and video processing algorithms to develop a novel video measurement and vision-based operational (output-only) modal analysis method that alleviate the need of structural surface preparation associated with existing vision-based methods and can be implemented in a relatively efficient and autonomous manner with little user supervision and calibration. First a multi-scale image processing method is applied on the frames of the video of a vibrating structure to extract the local pixel phases that encode local structural vibration, establishing a full-field spatiotemporal motion matrix. Then a high-spatial dimensional, yet low-modal-dimensional, over-complete model is used to represent the extracted full-field motion matrix using modal superposition, which is physically connected and manipulated by a family of unsupervised learning models and techniques, respectively. Thus, the proposed method is able to

* Corresponding author.
E-mail addresses: yyang@lanl.gov, yangyongchaohit@gmail.com (Y. Yang), charlesjdorn@gmail.com (C. Dorn), tylermancini@gmail.com (T. Mancini), zrtalken@gmail.com (Z. Talken), gkenyon@lanl.gov (G. Kenyon), farrar@lanl.gov (C. Farrar), dmascarenas@lanl.gov (D. Mascareñas).

http://dx.doi.org/10.1016/j.ymssp.2016.08.041
0888-3270/Published by Elsevier Ltd.

blindly extract modal frequencies, damping ratios, and full-field (as many points as the pixel number of the video frame) mode shapes from line of sight video measurements of the structure. The method is validated by laboratory experiments on a bench-scale building structure and a cantilever beam. Its ability for output (video measurements)-only identification and visualization of the weakly-excited mode is demonstrated and several issues with its implementation are discussed.

Published by Elsevier Ltd.

1. Introduction

Structural dynamics based vibration methods, centering on modal analysis, are among the most widely used techniques for health monitoring and model characterization and updating of civil, mechanical, and aerospace structures [1]. Experimental and operational modal analysis are two general classes of methods used to identify the dynamic properties of structures from measured data. Experimental modal analysis refers to methods that identify such properties when a measured input to the structure is available while operational modal analysis relies only on measured response data. Traditional experimental and operational modal analysis require physically-attached wired or wireless sensors, such as accelerometers that are affixed to the structure, for vibration measurements. While these sensors are reliable, they could result in mass-loading on lightweight structures, and their installation on larger structures is a costly, time and labor-consuming process. For long-term applications such as structural health monitoring (SHM), significant maintenance is required for cabling (wired sensors) or to assure adequate battery power (wireless sensors). Furthermore, these sensors only provide sparse, discrete point-wise measurements, yielding low spatial sensing resolution that is usually inadequate for modal-based damage detection, model correlation and updating of larger-scale structures. For example, a comparative study [2] showed that the spatial resolution of the sensor measurement critically limits the effectiveness of a family of popular mode shape or mode shape curvature based damage detection and localization methods. Additionally, abundant high-resolution experimental or operational measurement data and modal information (e.g., resonant frequencies and mode shapes) are extremely valuable for more accurately correlating and updating highly refined and detailed finite element models [3,4].

Non-contact vibration measurement techniques, such as displacement measurements made with scanning laser vibrometers [5–7], provide high spatial resolution sensing capacity without the need of sensor installed on the structures or inducing the mass-loading effect. However, these measurement devices are relatively expensive and perform measurements sequentially, which could be time and labor tedious when the desired sensing areas are large. As an alternative non-contact method, digital video cameras are relatively low-cost, agile, and provide simultaneous measurements with very high spatial resolution. Combined with image processing algorithms (e.g., image correlation [8] , optical flow [9]), video camera based measurements have been successfully used for vibration measurement of various types of structures [10–18]. Recently, digital image correlation (DIC) and the 3-dimensional point-tracking techniques have been introduced in experimental modal analysis [19–24]. A noticeable advantage of these methods is that high-resolution mode shapes can be obtained in a relatively efficient manner. However, these methods typically require speckle pattern or high-contrast markers to be placed on the surface of structures for deformation computation based on image intensity correlation or feature point tracking, which raises the surface preparation and target installation issue especially when the measurement area is large or inaccessible.

In order for modal analysis methods based on video camera measurements to gain wide acceptance, it is most desirable to develop methods that utilize the video measurements only without additional structural surface preparation. Lately, a video processing based method using phase-based optical flow computation [25,26] and video motion magnification technique [27] has been proposed for operational modal analysis [28] , with the advantage of providing high resolution mode shapes without the use of paints or markers on the structure's surface. In addition, it enables convenient visualization of the vibration mode. However, this procedure of the proposal depends on several user input parameters and supervision that are not suited for efficient and automated implementation in operational modal analysis. Furthermore, this video motion magnification based technique is unable to handle closely-spaced modes and the interpretation of the motion magnification technique in modal parameters identification is unclear.

By modifying the phase-based video motion magnification framework, this study aims to develop a novel output-only (video measurements) modal analysis algorithm that requires no structural surface preparation and that can be implemented in a relatively efficient and autonomous manner. Using a multi-scale pyramid decomposition and representation method [29] and the unsupervised learning approach, blind source separation (BBS) [30], to extract, model, and manipulate the full-field spatiotemporal pixel phases that encode the local structural vibration in the video measurement only, the proposed method is able to blindly extract resonant frequencies, damping ratios, and high-resolution mode shapes from line of sight video measurements of the structure. The proposed method requires little user inputs or supervision to blindly identify modes using BSS, which is able to handle closely-spaced modes. In addition, the motivation and interpretation of motion magnification is presented for identification and visualization of the weakly-excited mode with subtle vibration