AUTOMATED, OUTPUT-ONLY EXTRACTION OF FULL-FIELD, VERY HIGH SPATIAL RESOLUTION DYNAMIC PARAMETERS FROM VIDEOS OF OPERATING STRUCTURES

Y. Yang(1), C. Dorn(2), T. Mancini(3), Z. Talken(4), G. Kenyon(5), C. Farrar(6), D. Mascareñas(7)

(1) *Director's Postdoctoral Fellow, Los Alamos National Lab – Engineering Institute, PO Box 1663, MS T001, Los Alamos, NM 87545, USA.* ***Corresponding author***: *yyang@lanl.gov; yangyongchaohit@gmail.com*
(2) *Dept. of Engineering Physics, Univ. of Wisconsin – Madison, Madison, WI 53706, USA. charlesjdorn@gmail.com*
(3) *Dept. of Aerospace Engineering, University of Texas at Austin, Austin, TX, 78712, USA. tylermancini@gmail.com*
(4) *Dept. of Mechanical Engineering, Missouri Univ. of Science and Technology, Rolla, MO 65409, USA. zrtalken@gmail.com*
(5) *Technical Staff Member, Los Alamos National Lab – Applied Modern Physics, PO Box 1663, MS D454, Los Alamos, NM 87545, USA. gkenyon@lanl.gov*
(6) *Laboratory Fellow & Engineering Institute Leader, Los Alamos National Lab – Engineering Institute, PO Box 1663, MS T001, Los Alamos, NM 87545, USA. farrar@lanl.gov*
(7) *Technical Staff Member, Los Alamos National Lab – Engineering Institute, PO Box 1663, MS T001, Los Alamos, NM, 87545, USA. dmascarenas@lanl.gov*

Abstract

Modal analysis is essential for dynamic modeling and analysis of seismic excited structures. Experimental or operational modal analysis traditionally requires physically-attached wired or wireless sensors for vibration measurement of structures. The sensor instrumentation could result in mass-loading on lightweight structures, and is costly and time-consuming for large civil structures, especially for long-term applications (e.g., structural health monitoring and seismic dynamic analysis) that require significant maintenance and labors for cabling (wired) or energy supply (wireless). In addition, these sensors are discrete point-wise, providing low spatial sensing resolution that is hardly sufficient for larger structures. Non-contact optical methods such as scanning laser vibrometers provide high-resolution sensing capacity without the mass loading effect; however, they operate sequential measurement that requires 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 or template matching, optical flow, etc.), video camera based measurements have been successfully used for experimental and operational vibration measurement and modal analysis, such as the digital image correlation (DIC) and the point-tracking techniques. However, they typically require speckle pattern or high-contrast markers instrumented on the surface of structures, which raises the instrumentation issue 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 output-only modal analysis method that removes the need of structural surface preparation in existing vision based methods. By manipulating the motion encoded in the video measurements only using multi-scale image decomposition and unsupervised machine learning techniques, the proposed method efficiently and accurately extract modal frequencies, very high spatial (pixel) resolution mode shapes, and damping ratios of the structure. The method is validated by laboratory experiments on bench-scale structures including a building structure and a cantilever beam. Video demos of these experimental results are on http://www.lanl.gov/projects/national-security-education-center/engineering/research-projects/blind-modal-id.php.

Keywords: Output-only Modal Analysis; Full-field Structural Dynamics; Video Processing; Motion Magnification; Blind Source Separation;

1. Introduction

Traditional experimental and operational modal analysis typically requires physically-attached wired or wireless sensors, such as accelerometers affixed to the structure. Physical instrumentation of these sensors is an expensive and time-consuming process and may have the effect of mass-loading the structure. Non-contact measurement methods such as scanning laser vibrometers can address some of these challenges; however, it is relatively expensive and can only provide sequential measurements that are time and labor consuming.

As an alternative non-contact methods, video camera based measurement is relatively low-cost and agile with high spatial sensing resolution. Video camera based measurement techniques such as digital image correlation (DIC) and point-tracking methods have recently been successfully applied in experimental modal analysis [1-5]. Nevertheless, they normally require structural surface preparation such as speckle paint or high-contrast makers, which can be cumbersome when the measurement area is relatively large or inaccessible. Lately, a video processing based method using phase-based optical flow and video motion magnification technique has been proposed for operational modal analysis [6], which has the advantage of being used without paints or markers on structures. To date, this method has focused on simple structures consisting of one edge (e.g., a cantilever beam or a pipe cross-section) and relies heavily on the user for the necessary inputs in the model identification process. In order for video-based modal analysis methods to gain acceptance, it must be verified for more complicated structures and the user dependency must be minimized.

The objective of this study is to broaden the capabilities of video-based operational modal analysis by developing an advanced computer vision and machine learning based method that is efficient requiring little user supervision and eliminating the need for surface preparation on structures. This method improves upon the previous work by automating the mode identification process and allowing for complicated geometries and motion to be analyzed. Videos of vibrating structures are first filtered using multiscale decomposition and representation techniques to extract local phase and amplitude, which is then blindly separated into individual modes by a blind source separation technique called complexity pursuit (CP) [7]. The proposed method efficiently and accurately extract frequency, very high spatial resolution (full-field) mode shapes, and damping ratio of the structure [8].

2. Background

2.1 Phase-based optical flow

A method known as phase-based motion magnification of video [9] has shown promise in its ability to achieve large magnification factors without magnifying noise, leaving relatively clean video with few unwanted artifacts. This capability is extremely important for extending computer vision to modal analysis since noise can easily unravel the process. The phase-based magnification process begins with the spatial decomposition of each video frame. A complex steerable pyramid [10] is used to decompose the image and separate the local phase and amplitude. There are multiple levels of the pyramid, corresponding to different spatial scales. The local phase is filtered temporally to isolate the frequency band specified by the user. Before the reconstruction of the video, the phases in the specified frequency band are scaled by a magnification factor.

2.2 Phase-derived vibration motions of structures

Video based modal analysis techniques have recently been developed utilizing phase-derived optical flow algorithms [6]. In this method, displacement signals at various regions of the structure are extracted from video. Unlike [1-5], targets on the structure are not necessary. Motion signals are extracted from the edges of the structure instead. The process begins by convolving a quadrature pair of filters with each frame of the image to determine local phase and amplitude at each pixel. Local amplitude is related to edge strength while local phase is related to velocity at each pixel.

In Ref. [6], regions of interest are cropped from the video corresponding to where accelerometers would traditionally be placed on a structure, called ‘virtual accelerometers,’ where velocity signals are computed from the temporal phase contours. Afterwards the peak-picking methods are used to identify the modal frequency, which is then used as inputs to the motion magnification method to magnify the specified frequency band contents and reconstruct the magnified video. This process – the selection of interested region and picking the modes – needs to be supervised by modal analysis experts and has high risk of losing the weakly-excited and closely-spaced modes.

The proposed method in this study eradicates these constraints by automating the video based modal analysis process using computer vision and machine learning technique that requires little user supervision. Instead of selecting a region of interest, our method extracts the local phases and local amplitudes of each pixel of the whole video, keeping the genuine high-resolution spatial information of the structural vibration and blindly and autonomously separates the extracted local phases into individual structural modes, which are then magnified, respectively, and reconstructed to a video containing only one mode [8].

2.3 Blind Separation of modes

Blind source separation is a class of unsupervised learning problems that seeks to break up a set of mixed signals into the individual source signals without any knowledge of the input. The key idea of using BSS for output-only modal identification is that modal expansion of the structural responses (local phases) has the exact same form with the linear BSS model, such that BSS can blindly and efficiently separate the structural responses into individual modes. Filtering each frame by the complex steerable pyramid results in a set of local phase time series signals $\delta(x,t)$ for each pixel. A BSS technique called complexity pursuit (CP) can blindly separate $\delta(x,t)$ into individual modes $q(t)$ [7] where

$$q(t) = W\delta(x,t). \tag{1}$$

Frequency and damping ratio can be identified from the time domain modal coordinates $q(t)$.

2.4 Motion magnification of individual modes

Magnification of the blindly separated individual modes can be conducted by multiplying $q_i(t)$ (i is the mode number to be magnified) and reconstructing back to obtain the video with only the single magnified mode. Visualization of the single mode vibration is possible in the video. Edge detection can be conducted on the magnified video to obtain the mode shape with very high spatial density. The whole video processing based modal analysis process is conducted blindly and efficiently to extract the frequency and the high-resolution mode shapes with very little user supervision [8].

3. Experimental Study

Bench-scale models of a three story structure and a cantilever beam were used to validate the developed video based automated full-field output-only modal analysis method. An impact hammer was used to excite both structures. The structural motion was mostly in one direction, parallel to each floor of the structure and perpendicular to the plane of the camera lens; however, no calibration is needed in the process. Three uniaxial accelerometers were used to extract mode shapes for comparison and validation. A single stationary camera was positioned perpendicular to the motion of the structures. Video was captured at 240 frames per second at a resolution of 1920 x 1080 pixels. For processing the frames were downsampled to 384 x 216. The experimental setup is shown in Fig. 1.

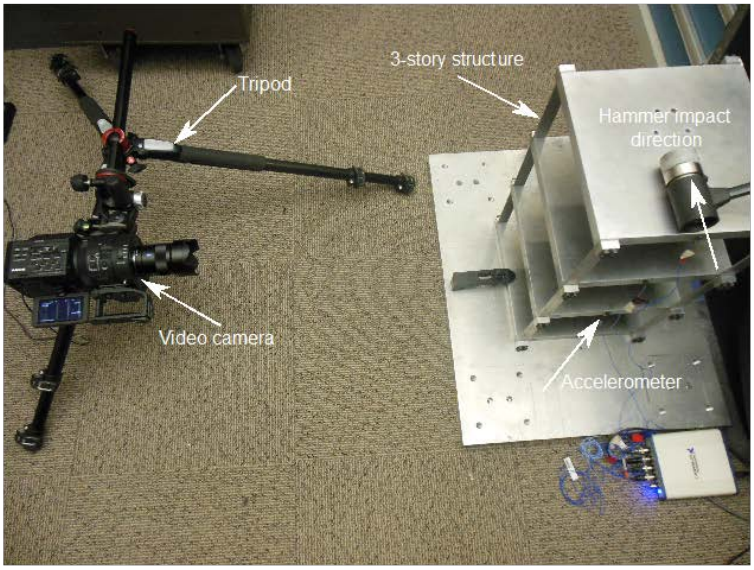


Fig. 1 – Experimental Setup of the 3-story building structure and the cantilever beam, both excited by the impact force.

3.1 Full-field Output-only Modal Identification Procedure and Results

The proposed method uses the video measurements only to extract the natural frequency of each mode and a video containing only one single operating mode, which corresponds to the full-field, very high spatial (pixel) resolution mode shapes. The process begins with the spatial decomposition of each frame of the video using a complex steerable pyramid. The framework of original phase-based magnification was used to decompose and the video into spatial sub-band using a complex steerable pyramid. Each level of the pyramid is processed separately. The processing procedure for each pyramid level is as follows. A complex filter is convolved with the intensity matrix of each frame. The magnitude and argument of the complex valued filtered image correspond to the local amplitude and local phase of each pixel, respectively [8].

The time series local phase signal for each pixel are analyzed using CP. Fig. 2 shows the three CP signals of the laboratory scale three story structure used in our experiment. Each signal oscillates at only one frequency, as shown by their frequency spectra which match those from the accelerometers quite well (accelerometers results are not shown here due to limited space but referred to [8]).

The output of CP is a time series signal corresponding to each active structural mode in the video. One CP signal is multiplied by a magnification factor. The CP process is then reversed, reconstructing the magnified local phase matrix. Magnified local phase is then recombined with the unchanged local amplitude. This process is conducted on each level of the steerable pyramid. The collapse of the steerable pyramid constructs a magnified video with one operating mode shape strongly dominant. Fig. 3 shows frames (full-field mode shapes) from the magnified videos; for limited space, only the second mode is shown. Fig. 4 shows the experiment results for the cantilever beam structure. For the complete video demos of the experimental results, see at http://www.lanl.gov/projects/national-security-education-center/engineering/research-projects/blind-modal-id.php. More discussions are referred to [8].

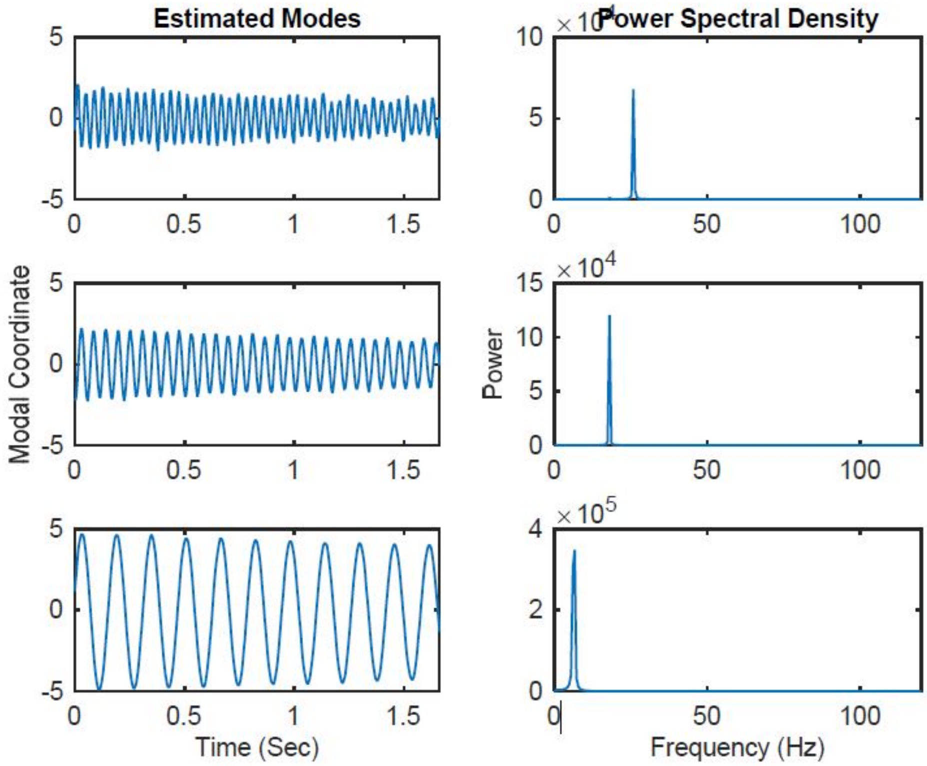
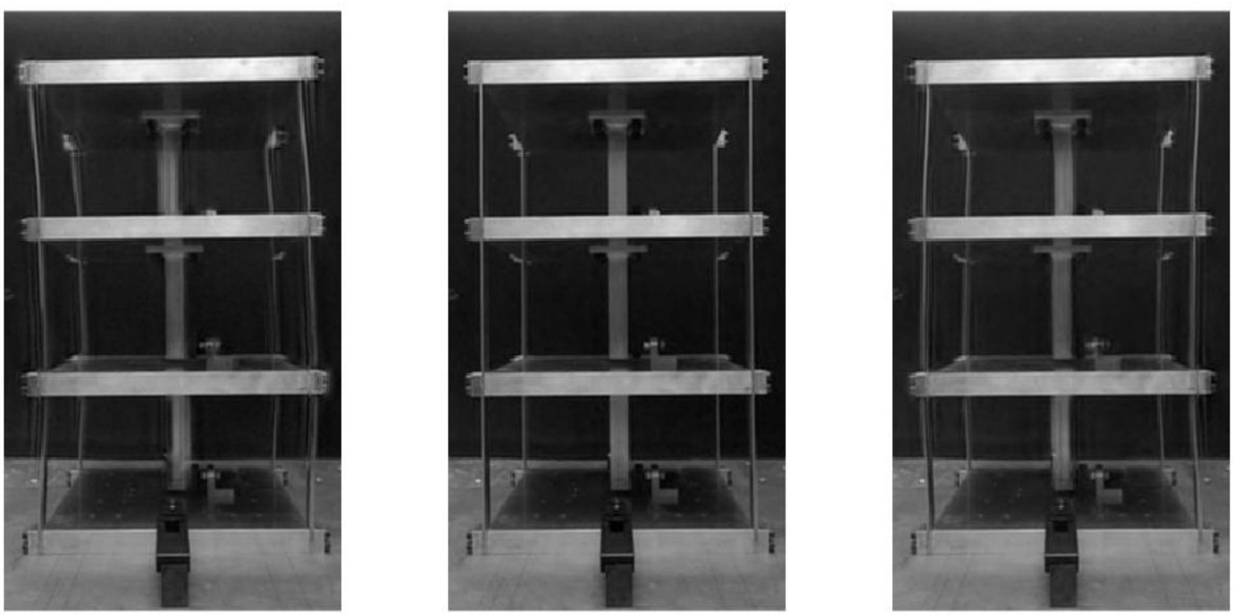


Fig. 1 – Complexity Pursuit (CP) estimated modal coordinates and their power spectral density from the video measurement of the vibrating building structure.



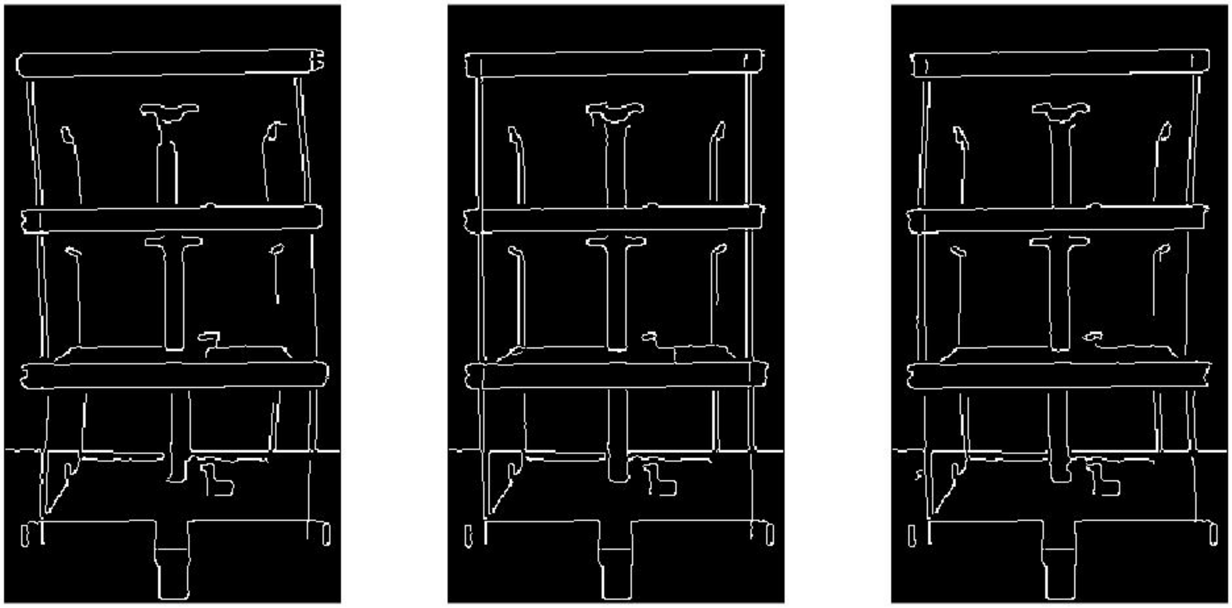


Fig. 3 – A few frames from the blindly-separated, motion magnified Video (**Mode 2**) (**first row**) of the building structure (excited by an impact) and their corresponding full-field, very high spatial (pixel) resolution mode shapes (**second row**) by conducting the edge detection. For the complete video demos of the experimental results (including other modes), see at http://www.lanl.gov/projects/national-security-education-center/engineering/research-projects/blind-modal-id.php.

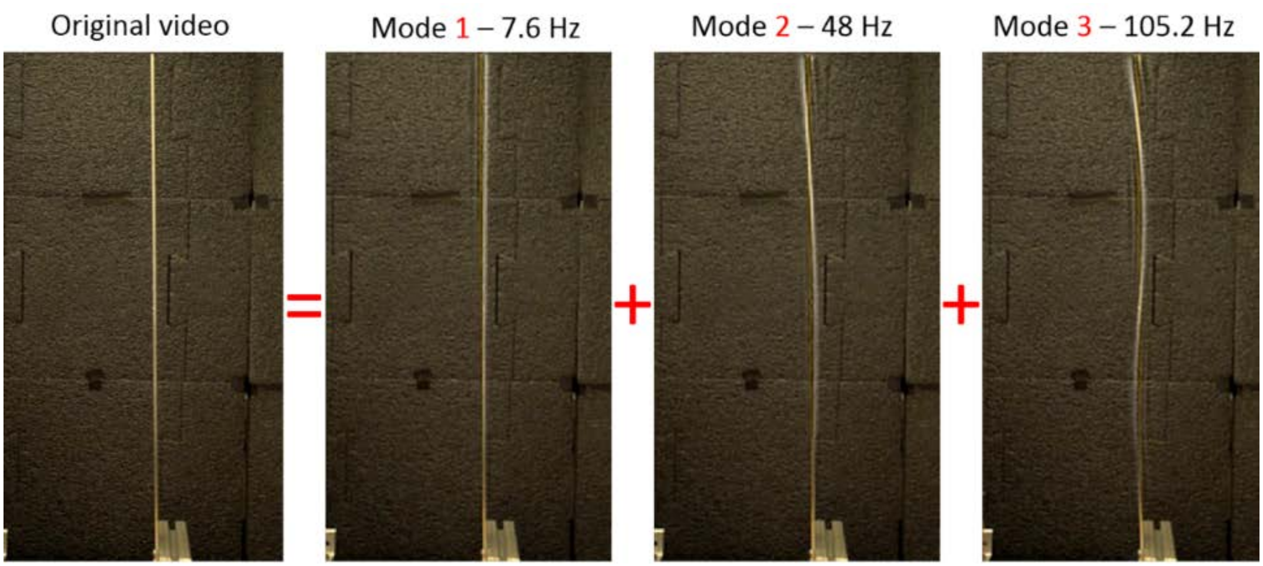


Fig. 4 – The proposed video-based, full-field dynamic extraction technique applied to a vibrating cantilever beam excited by an impact. The original video (left) is blindly and autonomously separated into three videos, each contains one individual vibration mode with very high spatial (pixel) resolution. For the complete video demos of the experimental results, see the **Video demo:** http://www.lanl.gov/projects/national-security-education-center/engineering/research-projects/blind-modal-id.php.

4. Conclusion

This work proposes a novel fully automated video-based, full-field output-only modal analysis technique using advanced computer vision and machine learning techniques. Using an unsupervised blind source separation technique, this new method removes user supervision by blindly and efficiently identify and magnify mode contents from the multi-scale representation of local phases, while extending possible applications to complicated motion patterns and geometries. While inheriting the virtues of the video-based measurement that is cost-efficient, non-contact, agile, and high spatial sensing resolution, the developed method also avoids the need of structural surface preparation that is traditionally required in image-based modal analysis methods. The developed method is validated by laboratory experiments on bench-scale structures including a building structure and a cantilever beam. Future study can apply the proposed method on real-world structures**.**

5. Acknowledgements

We would like to acknowledge the support of the Los Alamos National Laboratory Lab Directed Research and Development (LDRD) program. This program has supported this work in the form of an Early Career Award for David Mascarenas and a Director's funded postdoctoral fellowship for Yongchao Yang.

6. References

[1] Helfrick MN, Niezrecki C, Avitabile P, Schmidt T, (2011): 3D Digital Image Correlation Methods for Full-Field Vibration Measurement. *Mechanical Systems and Signal Processing*, **25**(3), 917-927.

[2] Wang W, Mottershead, JE, Ihle A, Siebert T, Schubach, HR (2011): Finite element model updating from fullfield vibration measurement using digital image correlation. *Journal of Sound and Vibration*, **330**(8), 1599-1620.

[3] Warren C, Niezrecki C, Avitabile P, Pingle P (2011): Comparison of FRF Measurements and Mode Shapes Determined using Optically Image Based, Laser, and Accelerometer Measurements. *Mechanical Systems and Signal Processing*, **25**(6), 2191-2202.

[4] Wang W, Mottershead JE, Siebert T, Pipino A (2012): Frequency response functions of shape features from fullfield vibration measurements using digital image correlation. *Mechanical Systems and Signal Processing*, 28, 333-347.

[5] Baqersad J, Niezrecki C, Avitabile P (2015): Extracting Full-Field Dynamic Strain on a Wind Turbine Rotor Subjected to Arbitrary Excitations using 3D Point Tracking and a Modal Expansion Technique. *Journal of Sound and Vibration*, 352, 16-29.

[6] Chen JG, Wadhwa N, Cha YJ, Durand F, Freeman WT, Buyukozturk O (2015): Modal Identification of Simple Structures with High-Speed Video using Motion Magnification. *Journal of Sound and Vibration*, 345, 58-71.

[7] Yang Y, Nagarajaiah S (2013): Blind Modal Identification of Output-Only Structures in Time Domain Based on Complexity Pursuit, *Earthquake Engineering & Structural Dynamics*, **42**(13), 1885-1905.

[8] Yang Y, Dorn C, Mancini T, Talken Z, Kenyon G, Farrar C, Mascarenas D (2016): Blind Identification of Full-field Vibration Modes From Video Measurements with Video Motion Magnification, *Mechanical Systems and Signal Processing*, tentatively accepted.

[9] Wadhwa N, Rubinstein M, Durand F, Freeman WT (2013): Phase-Based Video Motion Processing. *ACM Transactions on Graphics.* **32**(4), 80.

[10] Simoncelli E, Freeman WT (1995): The Steerable Pyramid: A Flexible Architecture for Multi-Scale Derivative Computation. *International Conference on Image Processing*.