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Mode-shape magnification in high-speed camera measurements

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ABSTRACT

Image-based displacement measurements provide a contactless, full-field, high-spatial resolution alternative to conventional measurement approaches in the field of structural dynamics. Particularly at higher frequencies, vibrations are exhibited with relatively small displacement amplitudes, that are often hidden below the noise floor. Motion magnification methods can be used to magnify and visualize displacements, invisible to the naked eye. In the present work, a mode-shape magnification method, based on experimental modal analysis is presented as an alternative to established motion magnification methods. The response of the structure to dynamic excitation is simultaneously measured using a high-speed camera and a reference piezoelectric accelerometer. A simplified gradient-based optical flow method is extended to two dimensions in this work and used to extract full-field displacements. A hybrid modal analysis is then performed, combining the high dynamic range of the accelerometer and full-field image-based measurements to extract the studied structures mode-shape with high spatial resolution. Mode-shape magnification is then performed by first forming a planar triangle mesh on top of the image data. The mesh is then warped according to the identified mode shape, scaled by a scalar factor. The known locations of the mesh nodes in their original and translated state are used to perform element-wise affine transformation of the image. The final result of the procedure is an image of the magnified mode shape. In the present research, the hybrid modal identification method is extended to two dimensions and employed to extract and visualize very subtle motion completely covered by image noise. The presented mode-shape magnification method is also computationally efficient, as the displacements are identified using a linear relation to image intensity values. Compared to established motion-magnification methods, the present approach is therefore faster and capable of magnifying smaller motion. The performance of the mode-shape magnification method is demonstrated on two test cases; flexural modes of a simply supported notched beam and a sheet-metal impeller cover exhibiting complex geometry and a 3D dynamic response.

Keywords: Optical methods, Frequency domain, Motion magnification, Experimental modal analysis

1. INTRODUCTION

Due to recent developments in high-speed camera technology, image-based displacement measurement techniques have become a viable alternative to conventional measurement approaches in the field of structural dynamics. Their non-contact nature prevents the mass-loading effect when measuring the vibrations of lighter objects. In addition, full-field measurement capabilities can lead to significant reductions in measurement times. Several methods of image-based displacement identification have been applied to the field of structural dynamics, including point-tracking (PT) [1, 2], 3D digital image correlation (DIC) [3, 4], gradient-based optical flow [5] and phase-based motion estimation [6, 7]. Javh et al. combined a simplified gradient-based optical flow method with traditional vibration measurement approaches to perform a hybrid modal-identification [8], while Gorjup et al. introduced a frequency-domain triangulation method, that enabled the extraction of 3D operating deflection shapes using a single high-speed camera [9]. More recently, Wang et al. [10] performed experimental modal analysis above the Nyquist limit of a high-speed camera measurement by using the PolyMAX method [11] with random sampling.

Displacements, used as the basis for accurate identification of modal parameters, are commonly invisible to the naked eye, measuring in the range of a few micrometers. Consequently, the development of motion-magnification methods is a closely related field of research to the use of image-based displacement identification methods for structural dynamics. Motion magnification methods can roughly be split into Lagrangian methods [12], where displacements of particles are explicitly determined and Eulerian methods. Phase-based motion magnification methods [13, 14] fall into the later category and are currently the most commonly used motion magnification approach. They rely on spatio-temporal band-pass filtering of video data to magnify the motion in a recording. In the field of structural dynamics, they have been used as a pre-processing step before displacement identification using PT or 3D DIC [15, 16]. It has been recorded, that phase-based motion magnification methods can lead to inaccurate results and artifacts [6, 17].

2. THEORETICAL BACKGROUND

2.1. Simplified Gradient-Based Optical Flow method

The image-based displacement identification method, employed in the present work is based on the Simplified Gradient-Based Optical Flow (SGBOF) method, introduced by Javh et al [5]. It is assumed that the reflectivity pattern of the observed objects surface along with the lighting conditions are constant and that the camera is stationary throughout the measurement. Consequently, the change of the image-intensity value in a given pixel over time can be attributed to the displacement of the object. Additionally considering that, when using a high-speed camera in the field of structural dynamics, both the time step between sequential frames and the expected displacements are small, the optical flow equation can be written as:

$$\frac{\partial I}{\partial x}\Delta x + \frac{\partial I}{\partial y}\Delta y + \frac{\partial I}{\partial t}\Delta t = 0 \tag{1}$$

In Eq. (1), the time step Δt is known from the recording frame rate. The image intensity function $I(x, y, t)$ represents the series of images that are the result of a high-speed camera recording, and its partial derivatives can readily be computed. For each pixel, a single equation can be written, but there are two unknowns; the displacements in the x and y directions Δx and Δy respectively. The SGBOF consequently limits the identification of displacements to the direction of the image-intensity gradient:

$$s(x_j, y_k, t) = \frac{I_0(x_j, y_k) - I(x_j, y_k, t)}{|\nabla I_0|}, \tag{2}$$

where $s(x_j, y_k, t)$ is the identified displacement at pixel coordinates (x_j, y_k) and time step t, and $|\nabla I_0|$ is the image-intensity gradient magnitude. Considering that the expected displacement amplitudes are in the sub-pixel range, the gradient magnitudes can be precomputed based on a reference image I_0 (*e. g.* the average of the first 100 images of the recording).

2.2. Hybrid modal parameter identification method

Image-based displacement measurements typically include relatively high levels of noise, making modal parameter identification difficult. Javh et al. [8] proposed a hybrid modal identification approach, leveraging both the high dynamic range of an accelerometer measurement and the full-field nature of image-based displacements.

The Least-Squares Complex Frequency (LSCF) method [18] is first applied to the accelerometer measurement based frequency response functions (FRFs). The denominator polynomial roots of the employed common denominator FRF model, that correspond to the poles of the system are first determined for increasing polynomial orders. A stabilization chart is constructed and the stable poles are selected as physically meaningful. Their values correspond to the systems complex eigenvalues λ_r:

$$\lambda_r = -\zeta_r \, \omega_r \pm \mathrm{i} \, \omega_r \sqrt{1 - \zeta_r^2}, \tag{3}$$

from which the structures natural frequencies ω_r and damping ratios ζ_r can be determined.

High-spatial resolution mode shapes are then identified by applying the Least-Squares Frequency Domain (LSFD) method [19] to the image-based displacement information. Here, the complex eigenvalues, obtained in the previous step, are considered.

3. MODE-SHAPE MAGNIFICATION IN HIGH-SPEED CAMERA MEASUREMENTS

The novel mode-shape magnification method is performed in four steps. First, square subsets of the image are selected and the displacements are identified using an expanded simplified gradient-based optical flow technique (Sec. 2.1.). Secondly, experimental modal analysis is performed using the hybrid modal identification approach (Sec. 2.2.). Then, a triangle planar mesh is created on the basis of the displacement measurement locations. Lastly, the obtained mode shapes are used to transform the image of the structure and visualize its magnified mode shape.

During the data acquisition part of the proposed method, the response of the considered structure to a dynamic excitation signal is measured simultaneously using a high-speed camera and a reference classic structural dynamics approach (*e. g.* a piezo-electric accelerometer). The time signal of the excitation force is also measured as it is needed to perform the experimental modal analysis step.

The SGBOF can be used to obtain displacements based on a single pixel in the direction of the image intensity gradient in that pixel. In the present work, the method is extended to enable the identification of planar displacements and reduce the effect of noise. This is achieved by splitting the image of the structure into square (potentially overlapping) subsets of pixels. In each subset n_x and n_y pixels with the highest gradient in the *x* and *y* directions are selected. If the smallest gradient among the selection does not pass a predetermined threshold, the subset is discarded from further consideration. This step can serve to segment the area of interest (*i. e.* the structure) from the background.

The displacements in the *x*-direction and *y*-directions are then calculated in the selected n_x and n_y pixels respectively. The average displacement in both directions is calculated for each time step and attributed to the subset center point. Here, it is assumed that the subset size is relatively small and that consequently the relative motion of the subsets pixels is negligible. When larger subset sizes are used, the selected pixels can be gathered in a single corner of the subset, leading to bias problems. This can be addressed by attributing the average displacement to the center of the selected pixels, rather than the center of the subset.

Next, the hybrid modal parameter identification is performed. The image-based displacement measurements and the excitation force measurements are used to produce a frequency response function matrix in the form of receptance. Conversely, the reference accelerometer measurement leads to an accelerance FRF, that must be transformed into receptance before further computations are performed.

The accelerometer based FRF is then used to perform a LSCF analysis of the structure to extract its complex eigenvalues and consequently its natural frequencies and damping ratios. The obtained eigenvalues are then used in conjunction with the image-based displacement measurements to identify the structures eigenvectors (*i. e.* mode shapes) with high spatial resolution using the LSFD approach. The mode shapes are identified in the locations of the center points of the image subsets, discussed during the displacement identification step.

In the next step, a planar triangle mesh is constructed over the image of the structure. The center points of the subsets now present the nodes of the mesh, where the mode-shapes have also been identified. The nodes of the triangle mesh are translated in the next step, according to a given mode shape, multiplied by an appropriate scaling factor:

$$\begin{Bmatrix} x'_j \\ y'_j \end{Bmatrix} = \begin{Bmatrix} x_j + \phi_{x,j,r} \cdot c \\ y_j + \phi_{y,j,r} \cdot c \end{Bmatrix} \tag{4}$$

In Eq. (4), $\phi_{x,j,r}$ and $\phi_{y,j,r}$ represent the x and y components of the r-th mode shape at the j-th measurement point (subset). (x_j, y_j) and (x'_j, y'_j) represent the coordinates of the corresponding mesh node in its original and translated state and c is the scaling factor.

In the final phase of the proposed method, image warping is performed. A region of the image, corresponding to each element of the original mesh is cropped out. Based on the known locations of the three nodes in the original and deformed state, the affine transformation matrix for that region is obtained. The transformed region is inserted into the output image at the location of the corresponding deformed mesh element. This step is repeated until the image of the structures magnified mode shape is obtained.

4. EXPERIMENTAL DEMONSTRATION AND RESULTS

4.1. Laboratory Experiment

The described mode-shape magnification method was first applied to a notched steel beam in a laboratory experiment. The beam of dimensions $l \times w \times h = 500 \times 30 \times 15$ mm was placed on foam pads to simulate a freely supported state. The 7 mm deep and 2 mm wide notch was located 250 mm from the beams edge. The flexural modes of the beam were excited using a modal hammer strike in the vertical direction, 100 mm from its edge. The strike was performed in the middle of the beams width, so as to not excite any torsional modes.

The response of the beam was simultaneously measured using a Photron FastCam SA-Z high-speed camera and two reference single-axis accelerometers, attached to the underside of the beam 100 and 300 mm from its edge. The camera was aligned perpendicularly to one of the $l \times h$ sides at a distance of roughly 115 cm. A speckle-pattern was applied to the side of the beam, facing the camera. The sampling frequencies for the force and acceleration measurements was set to 51.2 kHz, while the frame rate of the camera was set to 100000 FPS to provide adequate measurement of the beams transient response to impulse excitation. The frame size was set to 1024×72 and the intensity quantization was 12-bit. All measurements were 1 second long.

The size of the subsets was set to 7×7 pixels and $n_x = n_y = 9$ pixels with the largest intensity gradients were selected for each subset. The smallest gradient values from each subset were displayed on histograms for either direction and a threshold value was determined accordingly.

The results of applying the introduced mode-shape magnification method to the first 5 bending modes of the notched steel beam are shown in figure 1. The physical scaling factors were calculated as the ratio between the displayed magnified mode shape and the displacement amplitude spectrum at the corresponding frequency for each measurement location. The values given in the caption of Fig. 1 are the average physical scaling factors for a given mode shape.

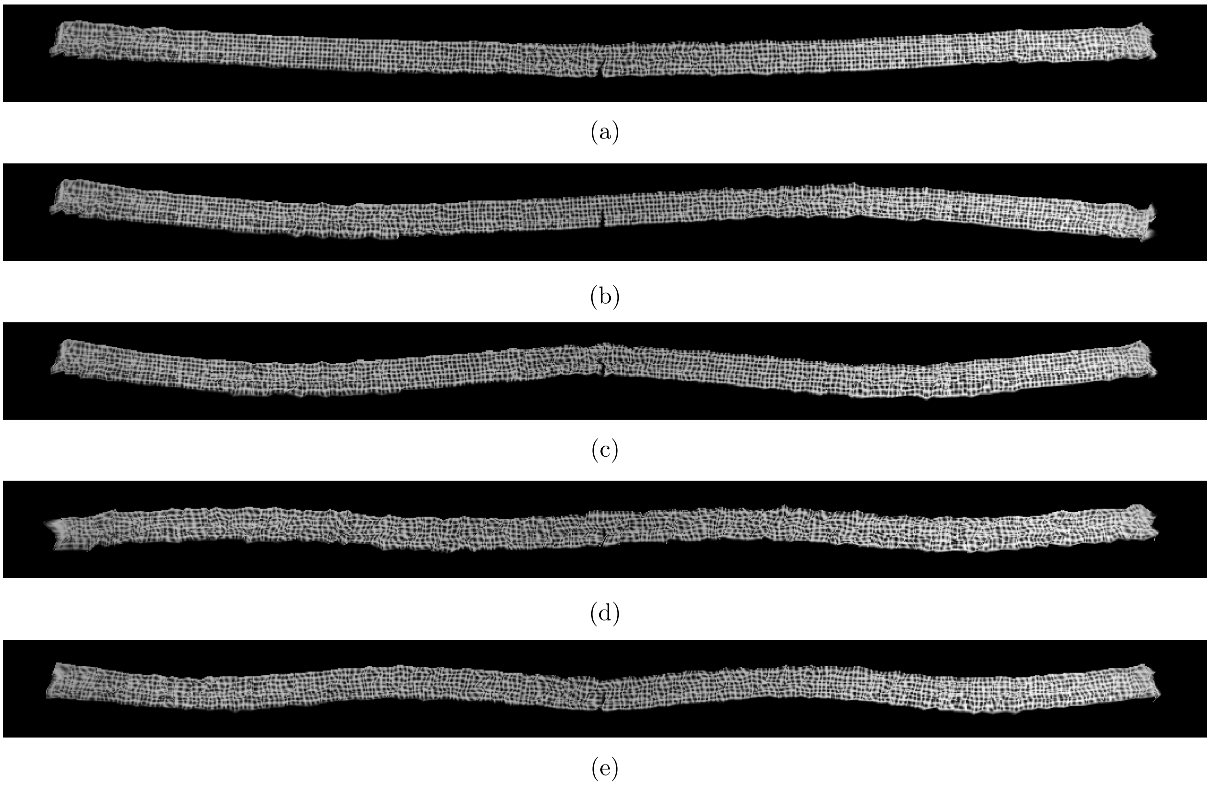


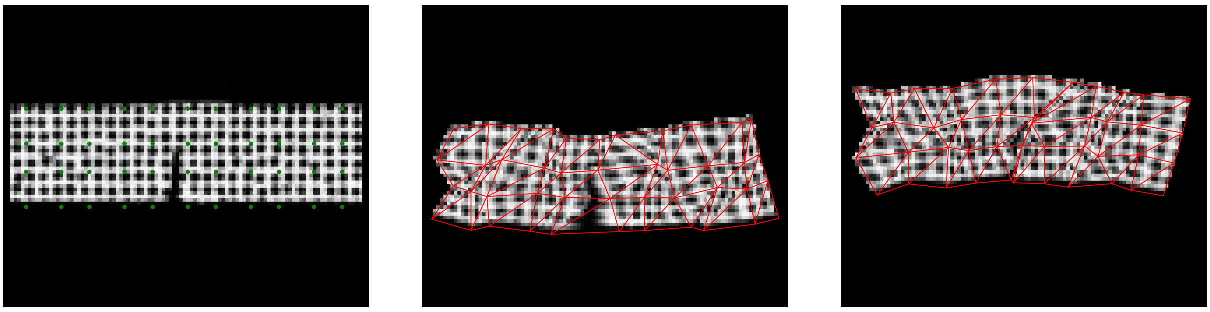
Figure 1: The first five magnified bending mode shapes of the beam, (a) Natural frequency - 270 Hz, at 1.4 thousand magnification (physical scaling factor), (b) 844 Hz at 1.4 thousand magnification, (c) 1507 Hz at 7 thousand magnification, (d) 2685 Hz at 39.6 thousand magnified, (e) 3649 at 27.5 thousand magnified.

The performance of the proposed mode-shape magnification method on local deformations was studied next. A region of the original video data, centered around the beams notch was cropped out. The displacement identification subsets were positioned so that a column of resulting mesh point was aligned to either side of the notch as shown in Fig. 2(a). The opening and closing of the mesh is evident from Fig. 2(b) and 2(c), that display the two boundary deflection states of mode shape 5.

4.2. Industrial test case: Impeller cover

An additional experiment was carried out on the case of a sheet-metal impeller cover of a vacuum-cleaner motor to demonstrate the applicability of the proposed method to industrial test cases. The cover had a diameter of 130 mm and exhibited a more complex geometry and modal shapes. A small electromagnetic shaker was used to excite the structure with a random signal in the frequency range between 50 and 5000 Hz. The dynamic excitation of the structure was recorded using a force sensor and similarly to the laboratory beam experiment, the response was simultaneously measured using the high-speed camera and a piezoelectric accelerometer.

A speckle pattern was applied to the outside surface of the impeller cover. The high-speed camera was

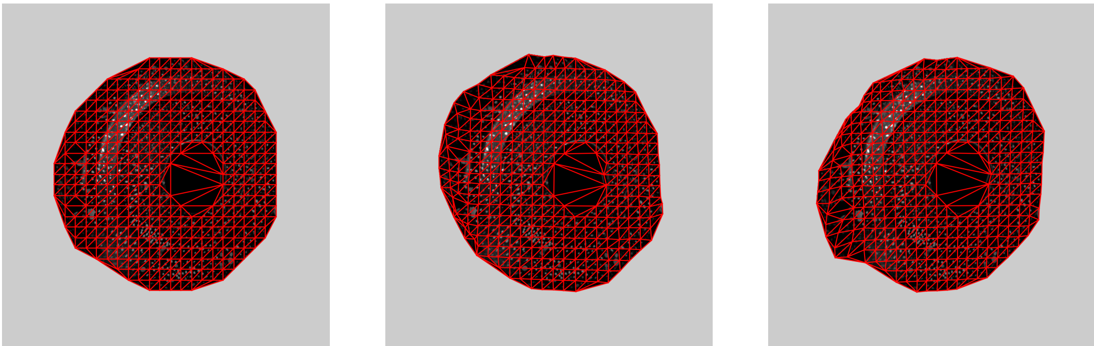


(a) (b) (c)

Figure 2: Magnified opening and closing of the notch at mode 5.

positioned roughly 150 cm from the object, at a 45° angle, relative to the axis of the cover. The frame rate of the camera was set to 10000 frames per second, and the duration of all measurements was 4 seconds.

The frequency range up to 2000 Hz was studied when performing the hybrid modal identification (Sec. 2.2.) and 11 modes of the impeller cover were found. The results corresponding to the third identified natural frequency at 353 Hz are presented in Fig. 3, for a physical scaling factor of 10^4.



(a) (b) (c)

Figure 3: Oscillation of the third identified mode shape of the impeller cover, overlaid with the deformed triangle mesh, (a) time = 0, (b) time = 1/3 oscillation period, (c) time = 2/3 oscillation period.

5. CONCLUSIONS

In this manuscript, the mode-shape magnification method was presented as an alternative to established motion magnification methods. The motion of an observed structure is first extracted using a simplified gradient-based optical flow method and the hybrid modal identification. A planar triangle mesh is constructed over the image data based on the displacement identification locations and deformed in accordance with an identified high-spatial-resolution mode shape. The area of the image, governed by each mesh element, is transformed using an affine transformation and assembled to produce the magnified image of the mode shape.

The simplified gradient-based optical flow method and consequently the hybrid modal identification are extended to two dimensions in this work. This enables the extraction and visualization of motion, completely covered by image noise. Since the displacement identification is linearly related to image intensity values, the introduced method is computationally significantly less expensive, compared to existing motion magnification methods.

The performance of the mode-shape magnification method was demonstrated on a laboratory experiment using a freely supported notched steel beam. Additionally, it has also been shown that the introduced method is applicable to industrial test cases exhibiting more complex geometry and dynamic response.

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