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High frequency modal identification on noisy high-speed camera data

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ABSTRACT

Vibration measurements using optical full-field systems based on high-speed footage are typically heavily burdened by noise, as the displacement amplitudes of the vibrating structures are often very small (in the range of micrometers, depending on the structure). The modal information is troublesome to measure as the structure's response is close to, or below, the noise level of the camera-based measurement system. This paper demonstrates modal parameter identification for such noisy measurements. It is shown that by using the Least-Squares Complex-Frequency method combined with the Least-Squares Frequency-Domain method, identification at high-frequencies is still possible. By additionally incorporating a more precise sensor to identify the eigenvalues, a hybrid accelerometer/high-speed camera mode shape identification is possible even below the noise floor. An accelerometer measurement is used to identify the eigenvalues, while the camera measurement is used to produce the full-field mode shapes close to 10 kHz. The identified modal parameters improve the quality of the measured modal data and serve as a reduced model of the structure's dynamics.

1. Introduction

True full-field mode shapes are hard to measure. Measurements using accelerometers produce sparse spatial information [1], laser vibrometers need to scan the surface and do not produce an instantaneous measurement [2,3] and interferometric techniques such as Electronic Speckle Pattern Interferometry [4] measure the out-of-plane displacements, only. Displacement measurements using high-speed cameras are increasingly being used in modal analysis, because they can produce a dense, simultaneous, full-field 3D measurement [5,6]. The displacements can be identified from image sequences with methods such as Digital Image Correlation [7], Gradient-based Optical Flow [8–10], Point Tracking [11] and Phase-based methods [12].

Optical measurements using cameras have been used in civil engineering, where the displacement response at lower frequencies (below 100 Hz) is relatively large [13–18]. Measurements with dynamic responses up to approximately 1 kHz have also been demonstrated in [3,19–23] with some spanning up to about 2 kHz [24–26] and at most up to 2.4 kHz [10,27]; however, frequencies above 1 kHz are problematic because the displacement response is generally less than micrometers, depending on the structure [10,24]. Such small displacements are significantly below the camera's pixel size and therefore produce signals which are at, or below, the camera noise floor, making them appear unidentifiable.

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Modal identification returns the modal parameters from the measurements. These modal parameters are usually in the form of a modal model [28], which comprises the natural frequencies and damping (eigenvalues) and the mode shapes (modal constants). Among the large number of modal-parameter identification methods the LSCF (Least-Squares Complex Frequency) [29] in combination with the LSFD (Least-Squares Frequency Domain) [30] is the most commonly used, because it is fast and robust [31].

Perhaps the first modal identification performed on camera measurements was performed by NASA on the MIR space station, where they used the Eigenvalue Realization Algorithm [18]. Modal identification has also been performed on optical measurements by implementing motion magnification and edge detection to produce mode shapes [22]. In [32] the authors used modal parameter identification to determine mode shapes for damage detection. The authors of [33] compared the mode shapes measured by Digital Image Correlation, 3D Point-Tracking, 3D Laser Vibrometry, and accelerometer measurements. Among others, papers [34,35] demonstrate the operational modal analysis using camera systems. Modal identification has also been used as a concept for building-structure health monitoring [14].

The above mentioned papers are examples of lower-frequency vibrations (range of tens to hundreds of Hz) with relatively larger displacements. The goal of this research is to identify the modal information up to 10 kHz, where the camera noise prevails. The identification is expected to improve the quality of the measured data and increase the range of use for high-speed camera systems in modal analysis. The widely accepted LSCF/LSFD method is used on a hybrid measurement combining a precise accelerometer and a full-field displacement response identified from a high-speed camera measurement using a simplified Gradient-based Optical Flow [10]. The accelerometer measurement is used to produce reliable eigenvalue identification using LSCF and these eigenvalues are then used in the LSFD mode shape identification on the full-field camera measurement.

The text is organized as follows: Section 2 covers an overview of the Gradient-based Optical Flow used to identify the motion from videos, followed by an overview of the LSCF/LSFD modal-parameter-identification techniques. Section 3 combines the motion identification and modal parameter identification in an analysis of a lab-scale experiment, demonstrating modal parameter identification at high frequencies and with high levels of noise.

2. Theoretical background

2.1. Gradient-based Optical Flow

To identify the motion from an image sequence, a simplified Gradient-based Optical Flow (SGBOF) [10] was used in this research. The method is based on a linear relation between the change in intensity of pixels (or subsets of pixels) $I(x, y, t)$ and the displacements Δs. Displacements Δs are obtained as the change in intensity over time divided by the intensity gradient ∇I:

$$\Delta s = \frac{I(x, y, t) - I(x, y, t + \Delta t)}{|\nabla I|} \tag{1}$$

Variables x and y are the discrete pixel locations and t is time. The SGBOF method produces the most direct route from the optical information to the displacement. The intensity gradient $|\nabla I|$ is determined by the numerical derivation of a reference image. From Eq. (1) it is clear that the sensitivity to displacement is best where the intensity gradient is highest and that the displacement Δs of a pixel can only be determined in the direction of the image gradient. The displacements in 2D can be measured by filming a speckle pattern and using a subset of pixels to produce an estimate of the motion and 3D measurements can be performed using a stereoscopic set-up.

2.2. Modal parameter identification

A common viscously damped model for a structure's dynamic response is formulated with partial fractions as:

$$\alpha_{jk}(\omega) = \sum_{r=1}^{N} \left(\frac{{}_rA_{jk}}{\mathrm{i}\,\omega - \lambda_r} + \frac{{}_rA^*_{jk}}{\mathrm{i}\,\omega - \lambda^*_r} \right), \tag{2}$$

where $\alpha_{jk}(\omega)$ is the displacement frequency-response function (receptance) of a response point j to an excitation at point k, λ_r are the system eigenvalues containing the angular eigenfrequencies ω_r and the damping ratios ζ_r according to:

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

and ${}_rA_{jk}$ are the modal constants, which result in the mode shapes. The formulation (2) indicates the modal decomposition, where the response equals the sum of the modes $(\lambda_r, {}_rA_{jk})$ and their complex conjugates $(\lambda^*_r, {}_rA^*_{jk})$. The purpose of modal-parameter-identification techniques is to identify the modal parameters $(\lambda_r, {}_rA_{jk})$ from measurements of a structure's response.

One such identification technique is the Least-Squares Complex Frequency (LSCF) method. LSCF is a frequency-domain method derived from a common-denominator receptance model [29]: