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Experimental modal analysis on full-field DSLR camera footage using spectral optical flow imaging

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ABSTRACT

High-speed camera measurements are increasingly being used in modal analysis to instantaneously measure full-field structural responses by extracting the displacement information from images using digital-image-correlation and other optical-flow methods. High-speed cameras capable of filming full frame at high frame rates can be very expensive and produce image resolutions of only approximately 1 mega pixel, which is why this research aims at measuring and identifying the full-field response using cheaper, still-frame cameras with a higher image and intensity resolution, such as digital single-lens reflex (DSLR) and mirrorless cameras. Using spectral optical flow imaging (SOFI) full-field operational shapes can be acquired using still-frame cameras. This study demonstrates the hybrid modal-parameter identification of full-field mode shapes using an accelerometer and a DSLR camera for responses far above the DSLR camera's frame rate (demonstrated up to 1 kHz).

1. Introduction

Displacements can be tracked in videos by monitoring the pixel-intensity variations [1] using optical flow algorithms such as the Lucas-Kanade method [2] (commonly referred to as digital image correlation) with displacement resolutions typically quoted at around 1/100 of a pixel frame-to-frame and 1/10000 of a pixel in the amplitude spectrum for longer time series [1]. High-speed cameras are increasingly being used in modal analyses because of their many advantages [3]: the measurements are non-contact and do not affect the measured structure with any dummy mass. In addition, by using cameras the entire full-field is measured instantaneously and not by scanning the surface over time, like in the case with scanning-laser vibrometers [4], enabling measurement of rotating structures as well [5]. Lastly, because cameras measure displacements, lower-frequency oscillations with larger motions (in the range of centimetres to metres), as is often the case with large structures [6], can be measured, opening possibilities for structural health monitoring [7].

A limitation when using measurements based on high-speed cameras is the price, which can range up to a couple of hundred thousand euro for high-end stereoscopic (3D) measurement set-ups. Lower-frame-rate cameras are much less expensive, which is why many research papers describe attempts to measure dynamic responses with such cameras. One such example is the use of a mobile-phone camera to measure a stay cable's natural frequency and in turn its tension [8]. Under-sampling and re-mapping the time instances can be implemented to measure above the Nyquist frequency [9], as well as by setting a short exposure time and using frequency zooming, thereby allowing for aliasing [10]. Another possibility is filming at different frame rates and combining the information to produce the aliased spectrum [11]. Furthermore, the rolling-shutter effect has been

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used to sample high frequencies from a normal DSLR camera video [12]. As explained in Ref. [10] aliasing approaches from Refs. [9–11] and the use of the rolling-shutter [12] require very short exposure times, since longer exposures act as temporal filters producing a sort of low-pass filtering. Aliasing approaches are somewhat limited by this short exposure requirement in that little light can be captured without the use of strobe lights, which produce an intense but short pulse of light, resulting in an image with little-to-no blur [13]. The paper [14] is an example of using strobe lights to measure the dynamics of an oscillating wing in 3D using multiple viewpoints and [15] uses strobe lights to measure at higher frequencies. Due to the time invariance of linear system responses, stereoscopic information can be acquired with repeated measurements at different angles [16,17] or by using a dividing mirror, producing two viewing angles [18], thereby requiring only one camera instead of two. Lower-frame-rate cameras typically achieve lower image-noise values, a higher image resolution and higher dynamic range. For instance, DSLR and mirrorless cameras in the 500–2000 euro price range typically boast a 14-bit colour-intensity resolution and a 24 mega-pixel count.

It was recently shown that images indicating individual displacement spectral components can be produced by harmonically varying the illumination, thereby producing an analogue Fourier transform [19]. This method, known as spectral optical flow imaging (SOFI), can obtain operational displacement shapes using still-frame cameras such as DSLR or mirrorless cameras, by acquiring a reference image, an image with a sine phase and an image with a cosine phase, and then combining the information into a full-field complex displacement field for a chosen frequency, determined by the harmonic of the blinking lights.

In another publication [20] a hybrid modal-parameter identification was used to combine eigenvalues measured by an accelerometer and full-field mode shapes measured by a high-speed camera, making it possible to identify mode shapes below the camera's noise floor up to 10 kHz.

This research implements SOFI measurements to acquire high-frequency full-field displacement fields for selected frequencies up to 1 kHz and combines this data in the hybrid modal-parameter identification from Ref. [20], where by using the least-squares complex-frequency method (LSCF) [21] to identify the eigenvalues from a single point sensor (accelerometer and/or laser vibrometer) and using the least-squares frequency-domain method (LSFD) [22] on the SOFI measurements, the full-field mode shapes are produced.

2. Spectral optical flow imaging

Spectral optical flow imaging (SOFI) was introduced in Ref. [19]. In this section the method is briefly explained. For more on the method, please refer to the original publication.

An object reflects light L from a surface pattern with a reflectance $P(x, y)$ (where (x, y) are the coordinates of the camera's image plane) producing a radiance field $r((x, y), L)$:

$$r\left((x,y),L\right) = P(x,y)\,L \tag{1}$$

A camera produces an image with intensity values $I(x, y)$ by integrating the radiance falling on individual pixels over the camera's exposure time T_e:

$$I\left((x,y),L\right) = \int_0^{T_e} r\left((x,y),L\right)\,\mathrm{d}t, \tag{2}$$

By assuming small displacements, a displacement s will produce a change in the radiance approximately equal to:

$$r\left((x,y)+s,L_0\right) = r\left((x,y),L_0\right) + s\,\nabla r\left((x,y),L_0\right), \tag{3}$$

where ∇r is the radiance gradient. The produced relation is based on brightness conservation and is used to estimate the displacements in gradient-based optical flow such as Lucas-Kanade [1,2]. The equation is typically written in the form of pixel intensities instead of radiance.

By additionally incorporating a harmonically varying illumination $L(t) = L_0 + L_A \sin(\omega_l t)$ the radiance can be expressed as:

$$\begin{aligned} r\left((x,y)+s\left((x,y),t\right),L(t)\right) &= \frac{L(t)}{L_0}\, r\left((x,y)+s\left((x,y),t\right),L_0\right) = \\ &= \frac{L(t)}{L_0}\left(r\left((x,y),L_0\right) + s\left((x,y),t\right)\,\nabla r\left((x,y),L_0\right)\right) \end{aligned} \tag{4}$$

By integrating both sides of the Eq. (4) over the exposure time T_e and neglecting non-significant terms, the following relation can be produced:

$$\underbrace{I\left((x,y)+s\left((x,y),t\right),L(t)\right)}_{\text{blinking \& vibrations image}} = \underbrace{I\left((x,y),L_0\right)}_{\text{reference image}} + \; + \underbrace{\frac{L_A}{L_0}}_{\text{illumination scaling}} \underbrace{\nabla I\left((x,y),L_0\right)}_{\text{reference image gradient}} \underbrace{\frac{S_s\left((x,y),\omega_l\right)}{2}}_{\text{displacement spectral component}} \tag{5}$$

the above equation indicates that an image of a vibrating structure illuminated with a harmonically varying light (blinking & vibrations image) is composed of a motionless image under constant illumination (reference image) and the distortion caused