Mechanical Systems and Signal Processing 100 (2018) 17–27

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Measuring full-field displacement spectral components using photographs taken with a DSLR camera via an analogue Fourier integral

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ARTICLE INFO

Article history:
Received 22 May 2017
Received in revised form 13 July 2017
Accepted 16 July 2017

Keywords:
DSLR camera
Optical flow
Modal analysis
Photogrammetry
Variable brightness
Lucas-Kanade

ABSTRACT

Instantaneous full-field displacement fields can be measured using cameras. In fact, using high-speed cameras full-field spectral information up to a couple of kHz can be measured. The trouble is that high-speed cameras capable of measuring high-resolution fields-of-view at high frame rates prove to be very expensive (from tens to hundreds of thousands of euro per camera). This paper introduces a measurement set-up capable of measuring high-frequency vibrations using slow cameras such as DSLR, mirrorless and others. The high-frequency displacements are measured by harmonically blinking the lights at specified frequencies. This harmonic blinking of the lights modulates the intensity changes of the filmed scene and the camera-image acquisition makes the integration over time, thereby producing full-field Fourier coefficients of the filmed structure's displacements.

1. Introduction

Displacement measurements using high-speed cameras are increasingly being used in modal analysis, because they can produce a dense, simultaneous, full-field 3D measurement [1,2].

Various image-processing techniques are being used to identify the displacements from image sequences. Some of the most commonly used techniques are: Gradient-Based Optical Flow [3–5], Digital Image Correlation [6], which is also gradient based, in fact the Lucas-Kanade method from [3] is the general form of DIC [7], Point Tracking [8] and Phase-Based methods [9].

Photogrammetry measurements using cameras enable many thousands or tens of thousands of points to be tracked simultaneously. The typical displacement resolution frame-to-frame is quoted at around 1/100 of a pixel and 1/10,000 of a pixel in the amplitude spectrum [5], and is limited by the camera noise. By measuring with a stereoscopic camera set-up, three-dimensional displacements can be measured [10].

Probably the first use of photogrammetry for vibration measurements was a study carried out on the MIR space station [11]. More recent applications include civil engineering [12,13], real-time measurements [14,15] and large structures where the measurements have to be stitched together [16]. Cases of higher-frequency response measurements up to a couple of kHz have been reported in some recent papers as well [5,17–23], where [17] covers the linear and non-linear responses compared to Continuous-Scan Laser Doppler Vibrometry, [18] is an example of model updating based on DIC data, [19] intro-

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http://dx.doi.org/10.1016/j.ymssp.2017.07.024

duces interactive video manipulating based on the filmed structural responses, [20] identifies vibrations using phase-based motion magnification, [21] measures out-of-plane displacements based on fringe elongation, [22] uses DIC for thermo-structural coupling measurements and [23] gives a feasibility review of the DIC measurement for a case of hypersonic aircraft panels. Responses above a couple of kHz are problematic to measure, because they produce smaller displacements [24] and because of the high-speed camera's frame-rate limitations.

Mid-range high-speed cameras are typically capable of filming at a couple thousand frames per second (500–4000 fps) in the camera's full resolution, typically in the range of one or two mega-pixels (1024×1024 to 1920×1080) and a 12-bit intensity resolution. Higher frame rates are possible when reducing the image resolution. High-end cameras are capable of full resolution frame rates up to 20,000 fps. High-speed camera set-ups incorporating high-intensity lighting, lenses, etc. typically cost many tens of thousands of euros, and up to a few hundred thousand euros for a stereoscopic pair of higher-end cameras (3D measurements). To reduce the equipment costs, single-camera measurement approaches have been explored; the stereo information can be acquired with repeated measurements at different angles [25] or by using a dividing mirror, producing two viewing angles for a single camera [26,27]. A simple approach to viewing fast phenomena is to use short pulses of light (strobe light) to produce still frames. Stroboscopes have been used since 1832 [28], where a slit in a disc would produce a flash of light and with it a discrete frame of an animated motion picture, in 1930 researchers used strobe lights to produce an analogue film high-speed camera capable of multiple thousand frames-per second [29]. Some more recent examples of using stroboscopes to measure dynamics are: [30] where strobe lights were used to capture time instances of an oscillating wing and the displacements identified in 3D using multiple viewpoints and [31] where pulsated air jets were used to excite tissue and strobe lights made the response and with that tumors visible to the operator. A number of researchers have used lower-speed cameras to measure structural dynamics, by under-sampling and remapping the time instances [32], by using frequency zooming and allowing for aliasing [33], or by using multiple measurements with different sampling speeds to pinpoint actual aliased frequencies and showing that the spatial information is unaffected by aliasing [34], also the researchers that extracted sound from vibrations in videos [35] were able to use the rolling-shutter effect to sample high frequencies from a normal DSLR camera video. DSLR cameras have the benefit of producing images with a higher colour-intensity resolution (14-bit) and a higher pixel resolution (24 mega-pixels) at a cost of around 500–2000 euros.

This study introduces the Spectral Optical Flow Imaging (SOFI) measurement technique that uses low-speed image-acquisition cameras such as DSLR cameras to measure the individual displacement spectral components. By harmonically blinking the light source during the image acquisition, the displacement gets modulated on top of the blinking light, combined with the camera acquisition, which works by integrating the intensity over time, a single full-field displacement spectral component image is formed. The described technique, in fact, produces an analogue Fourier transform and each image for a different harmonic blinking of light produces separate Fourier coefficients for the full camera field.

The text is organized as follows: Section 2 mathematically derives the proposed Spectral Optical Flow Imaging (SOFI) from the image-acquisition procedure and the Optical Flow theory, Section 3 demonstrates the use of the proposed method in structural dynamics, Section 4 discusses the limitations of the proposed method and the conclusions are drawn in Section 5.

2. Theoretical derivation

An image is formed as the illumination L is shown on a pattern with reflectance $P(x,y)$ (or transmissivity in the case of transparency). The pattern $P(x,y)$ is a function of the spatial coordinates x and y and reflects the light L to produce a radiance intensity $r((x,y),L)$:

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

A camera produces an image of intensity values $I(x,y)$ by integrating the radiance for individual pixels [36]. The pixels are discrete patches of phototransistors that produce a linear response to the radiance illuminating them; henceforth, the spatial coordinates x and y are interpreted as pixel location indices. The image $I((x,y),L)$ over pixels (x,y) at an illumination L equals the integral of the radiance $r((x,y),L)$ over the camera's exposure time T_e:

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

The camera's exposure time is the integration time that produces an image, and for DSLRs this typically ranges from 1/10,000 s to 30 s.

Fig. 1 shows a hypothetical radiance field plotted as a 3D function. A plane is plotted that dissects the radiance field in the direction of the radiance gradient, indicated with coordinate s for a point (x,y). The thicker black line is the dissection of the radiance field with the plane and represents the radiance profile in the direction of the radiance gradient.

Fig. 2 shows the intersection plane and the effect of a displacement and illumination change for a point (x,y). It is clear that, assuming small displacements that are within the area of constant gradient, a displacement s will result in a radiance approximately equal to:

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