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Accuracy evaluation of sub-pixel structural vibration measurements through optical flow analysis of a video sequence

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ABSTRACT

As digital cameras become cheaper and faster, new opportunities for measuring structural vibration are unlocked. Measuring vibration through video sequences can provide full field measurements of a structure's motion. Digital image correlation is an established method for measuring structural vibration but requires visual surface preparation of the object being measured. Recently, a new method based on optical flow analysis of video sequences has surfaced that can measure structural vibration without any surface preparation whatsoever. This article presents an experiment to test the accuracy of the new method. The accuracy of the technique is evaluated for several sub-pixel vibration displacement amplitudes. The response is measured by an accelerometer, a laser vibrometer and marker tracking and compared to the optical flow method's results. The results obtained indicate that it is possible to measure vibration amplitudes 450 times smaller than a single image pixel accurately.

1. Introduction

Structural vibration measurements are commonly used in mechanical and civil engineering and can be divided into two groups, namely contact and non-contact techniques. A popular contact sensor is the accelerometer which is generally very accurate and exhibits high dynamic ranges. One can also measure dynamic strain by using strain gauges. One drawback of such contact methods is the addition of mass to the structure being studied altering its dynamic properties. On heavy structures this has a negligible effect but on light structures the effect can become significant. Another limitation of contact techniques is that it usually only measures the response at the location of the sensor, limiting its use for understanding the full field response. In addition to this, there are many situations where contact techniques are not desirable or difficult to apply. Examples are on rotating objects, high temperature applications, on mechanical structures that are difficult to access directly or where the installation of sensors may disturb the fluid flow unacceptably.

There are many non-contact measurement techniques used for vibration analysis. Laser Doppler Vibrometry (LDV) is commonly used to measure vibration at one specified location. Scanning laser vibrometers automatically direct the measurement laser onto different locations in order to measure at multiple points. Proximity sensors such as eddy current probes can be used when one can come relatively close to the vibrating object, with the requirement of the object to be electrically conductive.

The use of video sequences for vibration measurement is increasingly being studied. A now firmly established video technique capable of measuring deformation is Digital Image Correlation (DIC) [1]. The method uses correlation techniques to measure the movement of a characteristic pattern in the image as a structure deforms. Employing two cameras, three dimensional object deformations can be measured with good accuracy. It is however required to prepare the surface by applying a stochastic speckle pattern to the surface [2]. Marker Tracking (MT) is also used to track circular markers applied to the surface [3]. The number of degrees of freedom is then determined by the number of markers used.

Tracking algorithms are also used to measure the displacement of identifiable features throughout video sequences. These algorithms operate on a different principle than DIC. All markers on the structure are identified through fitting a model curve to the marker geometry. When all markers have been detected in all time frames, a correspondence algorithm is used to connect markers in different frames. Song et al. [4] proposed the use of 'virtual sensors' to measure vibration. They used the Circular Hough Transform (CHT) to track the movement of 48 markers placed along a cantilevered beam, excited at its free end. They managed to measure the mode shape and frequency of the structure's first three modes. It seems as though the maximum displacement of the beam was

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3 mm. Patsias and Staszewski [5] used a wavelet based edge detection algorithm to determine the edge of a cantilever beam as it was vibrating. They successfully extracted the displacements along the length of the beam from the position of the edge on the images. The vibration amplitude of the beam was 28 mm. In all video sequences, the vibration was relatively large, easily perceptible to the human eye.

All the tracking examples and DIC methods discussed above are examples of Lagrangian methods to measure vibration, where features are tracked in space. These methods require markers or surface preparation to operate, or large displacements of clearly defined edges [5]. This is a major drawback as it is not always possible or desirable to visually mark structures. Examples of such cases include long structures such as railway lines. Although it is possible to treat the surfaces of many structures, it remains a technique primarily suited for laboratory conditions. Having a technique able to measure vibration without surface treatment will open up a new range of real-world applications for optical measurement. This article investigates one such method, based on optical flow analysis.

Optical flow analysis has received most attention in computer vision research. Stated broadly, optical flow is the apparent velocity of movement in an image resulting from changing brightness values of an image pixel [6]. Optical flow is therefore an Eulerian method that calculates the velocity at a certain location (or pixel). Optical flow algorithms have recently been looked into for structural vibration applications. Caetano et al. [7] used two optical flow algorithms to measure the vibration of a footbridge and the cables of a large cable-stayed bridge. They used the Lucas-Kanade and Horn-Schunk methods. They managed to estimate the first five natural frequencies of the large bridge's cables successfully. The largest vibration amplitude of the cable was 170 mm. Schumacher and Shariati [8] determined the frequency content of both a bridge and a cantilever beam during motion. The method they used was inspired by a technique for motion magnification presented in Ref. [9]. The authors simply measured the intensity variations of a pixel near a vibrating structure. Converting the intensity time-history into the frequency domain yields meaningful frequency information. They could however not determine the amplitude of vibration.

Recently, a new technique was demonstrated that uses the localized phase information of an image convolved with a complex filter. The method was first demonstrated by Wadhwa et al. [10] for motion magnification in video sequences. The method is itself an optical flow method closely related to two methods proposed by Fleet and Jepson [11] and Gautama and Van Hulle [12]. It was claimed by Wadhwa et al. [10] that the method was more noise tolerant than methods that acted on pixel intensities. They measured the vibration of a structure with a camera at 60 frames per second and an accelerometer. They found that the two vibration signals matched closely to one another. They did not compare the two signals quantitatively. The smallest motion measured by the camera had an amplitude of 0.1 pixels.

Some of the same authors then went further to publish an article where the optical flow technique was used on three different structural vibration tests. Chen et al. [13] first validated the technique by measuring the response of an accelerometer attached to the tip of a cantilever beam when impacted with a hammer. The motion of the accelerometer was measured with a camera and processed by the optical flow technique. A laser vibrometer was also used to measure the response of the accelerometer. The correlation between the camera measured signal and the laser vibrometer was 99.6%. The 99.6% correlation was for the entire time-domain signal. It is therefore not known how accurate the method is for different frequency components with different amplitudes. The accelerometer signal was not used in this comparison because of low-frequency contamination due to double integration of the acceleration signal. The maximum amplitude of vibration of the beam tip was roughly 0.1 mm while the image resolution was 4.615 pixels/mm. The vibration amplitude was therefore $\frac{1}{2.16}$ the size of one pixel.

In a second test, a cantilever beam was instrumented with nine accelerometers and also impacted with a hammer. The beam response was measured with a high speed camera and processed by the optical flow technique. Validation measurements were taken with accelerometers attached to the beam. The authors managed to measure the first four natural frequencies and mode shapes of the beam. They calculated the Modal Assurance Criteria (MAC) values [14] for the first four modes as calculated through the accelerometer and optical flow signals. From the first to the last modes, the MAC values between similar modes were 95.58%, 97.78%, 97.56%, and 98.46%. The authors calculated the noise floor of the camera measurement as 1×10^{-5} pixels per root Hertz. This represents a capacity to measure extremely small vibration responses. The final test was an illustration of obtaining the mode shapes of the cross section of a PVC pipe with the optical flow technique.

The present article is concerned with investigating the accuracy of the Chen et al. [13] optical flow video processing method further. Although the method has been tested and validated on two occasions [13,10], the vibration amplitudes were relatively large, roughly $\frac{1}{10}$th of a pixel. The authors are not aware of any published research investigating the method's accuracy for smaller vibration amplitudes than this. It is the purpose of this article to experimentally validate the technique for several sub-pixel vibration amplitudes. This article does not investigate the accuracy of the method for vibration amplitudes larger than this. Nor does it investigate the occurrence of simultaneous large and small amplitudes at different frequencies.

The method will be used on video footage of an accelerometer mounted directly onto an electrodynamic shaker. The accelerometer is excited at a single frequency. The amplitude of excitation is decreased incrementally. The goal is to determine how the optical flow algorithm's accuracy changes when the amplitude of vibration becomes very small. The signal as obtained from the optical flow method is evaluated against conventional MT through instrumenting the accelerometer with markers. A laser vibrometer directly measures both velocity and displacement, and the signal from the accelerometer itself is also measured for validation. The original contributions of this article are (1) it is the first time the optical flow method is compared to MT in video sequences, (2) this article validates the optical flow algorithm for smaller vibration amplitudes than tested in previously published literature and (3) results from a sensitivity analysis are presented that show the optical flow algorithm's sensitivity to the choice of active pixel and the number of pyramid layers.

2. Optical flow analysis of video sequence

2.1. Complex convolution kernel

The derivation of the method is well documented and can be found in [10]. Only the necessary information will be presented for the reader to follow the article. The crux of the method rests on the fact that local phase information in an image, obtained after the image is convolved with a complex filter, can be used to calculate pixel intensity flow velocity [11]. Let $I(x, y, t)$ represent a grayscale video sequence, where x and y are integers denoting pixel position in the image and t indicates the time at which each image has been captured. In order to obtain local phase information at each pixel in I it is necessary to convolve the image with a complex