MEASUREMENT OF STRUCTURAL VIBRATION THROUGH VIDEO IMAGES

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Abstract. *Structural mechanical vibration is commonly measured through punctual sensors, i.e. sensors that measure the structural behavior at only one point. Examples of such sensors are accelerometers, LVDTs, non-scanning laser vibrometers, and proximity probes. This project aims at developing an acquisition system able to measure the dynamic behavior of a structure as a whole (many points) using only one sensor: a video camera. After video image acquisition, the vibration at specific points of interest in the structure is obtained by computer post processing, adopting image processing techniques. Experimental results show the feasibility of measuring unidirectional vibration with a 30 fps camera, resulting in good amplitude resolution when compared to proximity probe measurements. Due to the camera sample rate, direct measurement of vibration is limited in frequency. For this reason, a faster video camera was used to measure orbits in a rotating system, thus achieving good experimental results in two directions of movement. In general, acquisition rate and exposure time of the camera have shown to be critical parameters to achieve good quality measurements of vibration.*

Keywords: *vibration measurement, image processing, structural vibration*

1. INTRODUCTION

Structural vibration measurement is usually performed by punctual sensors, i.e. sensors that measure displacements at a single point of the structure. Examples of such sensors are: accelerometers; LVDTs; non-scanning laser vibrometers; and proximity probes. If one needs to know the overall dynamic behavior of a structure, it is necessary to mount a series of these sensors on the system. Such procedure can be costly not only because of the number of sensor, but also because of the acquisition system, which must have enough number of A/D channels, and of the time to prepare the experiment.

Scanning laser vibrometers are a solution to the problem of simultaneously measuring vibration of many different points of the structure, also called full field measurement (Maia and Silva, 1997). In this case, a single light beam is oriented to various points of the structure, scanning it and measuring vibration in each point of interest. However practical, scanning laser vibrometers are extremely expensive devices. An alternative is the use of video cameras for measuring the structural vibration.

Initially, video cameras were used together with laser measurement systems, what has been called as ESPI (Electronic Speckle Pattern Interferometry - Buckberry *et al.* (2000)) and DSPI (Digital Speckle Pattern Interferometry - Shakher *et al.* (2004)). In these cases, the laser beam is divided in two: the first beam is directed to the camera as a reference signal; the second beam is directed to the vibrating object. The video recording of the reference laser beam together with the reflected beam from the object generates interferometric fringes in the video images. The recorded fringes can be processed and analyzed in order to determine the object behavior. Studies on reduction of time of the video processing and on the precision of such measurements are presented by Tang and Lu (1992) and Shakher *et al.* (2004).

From the beginning of the XXI century, video cameras began to be used as measurement devices without the help of laser techniques (interferometry). In this case, with modern image processing techniques and the decreasingly cheap CCD digital video camera, it became possible to extract the dynamic movements of a structure directly from its digitalized images. Initially, the technique was implemented in civil structures (bridges and buildings - Wahbeh *et al.* (2003)) and bidimensional structures (Patsias and Staszewski, 2002), where vibration was measured in a single direction through the use of a single video camera. Later, other methods arouse for tridimensional measurements of structure vibration (Yoshida *et al.*, 2003), requiring a pair of cameras. An interesting revision work is presented by Chang and Ji (2007), where it is described the calibration technique of the acquisition system and the extraction of vibration measurements from image processing. Other application of such technique is the structure health monitoring by measuring normal modes of the structure (Patsias and Staszewski, 2002; Helfrick *et al.*, 2009b).

The use of video cameras for measuring vibration involves the definition of important parameters such as acquisition rate, image resolution, focal distance, and light intensity over object. For example, Quan *et al.* (2004) showed that proper illumination allowed the adoption of a six time higher acquisition rate with a measurement error below 2%. On the other hand, this problem can be overcome by applying compensation techniques to blurred images, as proposed by Wang *et al.* (2007). These techniques, however, are limited to unidimensional harmonic movements, where the image plane is considered parallel to the vibration plane, and background must be dark or lightly and homogenously lighted. More recent developments focus on the extraction of normal mode information from video images through the adoption of model updating based on Tchebichef polynomials (Wang *et al.*, 2011).

A recent application of structural vibration measurement via video images has motivated this work. In the work of Helfrick *et al.* (2009a), the technique is applied to the measurement of vibration in the blades of a ventilator, whose rotating frequency is 18 Hz. Although the adopted camera had a 12 fps (frames per second) acquisition rate (below the rotating frequency of the blades), a sub-sampling technique was applied. Through image post-processing via software, the rotation of the system was eliminated and the movements of the blades were measured and presented for one revolution of the rotor. Hence, one can see that it is not mandatory to have a high sampling video camera for measuring the vibration behavior of structures.

In this work, a video image processing is implemented in order to measure structural vibration. Firstly, the one dimensional vibration of a shaker is measured using 30 fps camera. Secondly, the two dimensional orbit of a whirling shaft is measured by a fast camera (500 fps). All video images are post-processed and displacements are calculated via the proposed method.

2. VIDEO IMAGE PROCESSING

The method proposed in this project consists in the capture of a sequence of images of the vibrating system; the search and calculation of the position of the point of interest in each image; and finally transform this position from pixels to millimeters, thus determining the vibration amplitude.

The first step is to define the correlation equation. According to Zhang (2000), the position vector $\mathbf{m} = \{u, v, t\}^T$, in pixels, and the position vector $\mathbf{M} = \{X, Y, Z, t\}^T$, in millimeters, at time t are related by the following equation:

$$\lambda \mathbf{m} = \mathbf{K}\,\mathbf{R_t}\,\mathbf{M} \tag{1}$$

where λ is a scale factor; $\mathbf{R_t}$ is the matrix of extrinsic parameters and represents the transformation from the physical coordinate system to the image coordinate system; and $\mathbf{K}$ is the matrix of intrinsic parameters, given by:

$$\mathbf{K} = \begin{bmatrix} \alpha_x & s & u_0 \\ 0 & \alpha_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

with (u_0, v_0) the coordinates of the point of interest in the image, in pixels; α_x and α_y the scale factors in axes U and V of the image; and s is the parameter describing the skewness of axes U and V.

In addition to Eq.(1), there is another factor to be considered in the analysis. Commercial cameras usually present a radial lens distortion, which has to be compensated. Let $\tilde{\mathbf{m}} = \{\tilde{u}, \tilde{v}, t\}^T$ be a distorted image point and $\mathbf{m} = \{u, v, t\}^T$ the ideal image position, calculated from Eq.(1). The distortion relationship between $\tilde{\mathbf{m}}$ and $\mathbf{m}$ is given by (Zhang, 2000):

$$\tilde{u} = u + (u - u_0)[k_1(x^2 + y^2) + k_2(x^2 + y^2)^2] \tag{3}$$

$$\tilde{v} = v + (v - v_0)[k_1(x^2 + y^2) + k_2(x^2 + y^2)^2] \tag{4}$$

where k_1 and k_2 are normalized coordinates of vector $\{u, v\}^T$.

Hence, by knowing the formula, the problem consists in finding the intrinsic, the extrinsic, and the distortion parameters values for each assemble of the camera. For that, the following minimization problem is solved:

$$\min \sum_{i=1}^{n} ||m_i - \tilde{m}_i||^2 \tag{5}$$

where m_i is the position of the i-th known image point (reference), and $\tilde{m}_i$ is the position of the i-th image point, calculated by image processing.

To solve this parameter identification problem, firstly one has to identify the points of interest in the image, and secondly one has to solve the minimization problem of Eq.(5). In this work, both steps were performed with the help of OpenCV library, based on C++ language.

The Open Source software GML Camera Calibration Toolbox, developed by Vladimir Vezhnevets and Alexander Velizhev at Graphics and Media Lab of Moscow State University (Vezhnevets and Velizhev, 2005), finds the common square vertices from a given chessboard pattern image like the one shown in Fig.1. Hence, once the calibration image is composed of a chessboard image, whose geometric dimensions are known in millimeters, one can apply the GML Camera Calibration Toolbox to find the position in pixels of desired points (vertices) according to the image reference frame (U, V).

The minimization problem is solved by the Microsoft Easy Camera Calibration Tool Software, developed by Z. Zhang himself. For that, one can use the output file of GML Camera Calibration Toolbox as the information on the point position

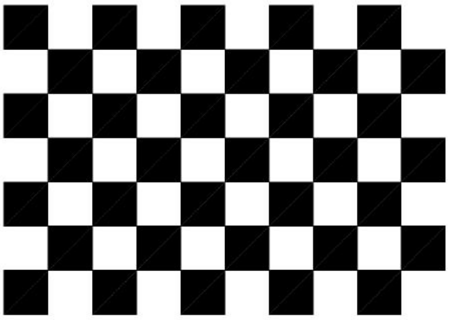


Figure 1. Chessboard 10×7 image used to calibrate the measurement system (vertices are adopted as points of interest).

in the image reference frame. By additionally supplying the position of reference points, in millimeters, the algorithm returns all intrinsic, extrinsic and distortion parameter values for the adopted assemblage of the camera. The output file is composed by the parameters, the rotation matrix $\mathbf{R_t}$, and the translation vector, for each image. It is important to note that for calculating these parameters, there has to be taken three non-coplanar images of the reference chessboard.

Hence, after calibration and parameter identification, it is possible to obtain the vector $\mathbf{m}$ (point position in pixels) from vector $\mathbf{M}$ (point position in millimeters). However, the objective of this work is the inverse: obtain the position in millimeters (in space) from the position in pixels (in the image), which would inevitably involve the inversion of a non-squared matrix. To tackle this problem, Chang and Ji (2007) suggests to minimize the following function:

$$\min ||\mathbf{m}_i \hat{\mathbf{m}}_i||^2 = \left(u_i - \frac{\mathbf{p}_1 \mathbf{M}_i}{\mathbf{p}_3 \mathbf{M}_i} \right)^2 + \left(v_i - \frac{\mathbf{p}_2 \mathbf{M}_i}{\mathbf{p}_3 \mathbf{M}_i} \right)^2 \tag{6}$$

where $\mathbf{p}_j$ is the j-th line of matrix $\mathbf{P} = \mathbf{K}\,\mathbf{R_t}$; and $\hat{\mathbf{m}}_i$ is the calculated image position of i-th point, in pixels, adopting the identified parameter values in the calibration.

The minimization of the above function was implemented in MATLAB. For solving the problem, an initial guess is required, which is obtained by correlating the axes X and U, and Y and V by linear approximation. With all this information, it is possible to find the position of any point of interest in an image.

Now, to measure the structure vibration, one has to find points of interest in the structure, and find their position in each video frame. Thus, the vibration movement of the points of interest in the structure are obtained by gathering and composing the identified positions in time domain.

3. TEST APPARATUS

Two different set-ups are tested to validate the proposed measuring method. The first set-up aims at measuring one-dimensional vibration of a structure mounted on a shaker. The second set-up aims at measuring two-dimensional vibration of a disk mounted on a whirling shaft.

Figure 2 shows the first set-up. A Sony T2 Cyber-Shot commercial camera, with 30 fps acquisition rate and 640×480 pixel resolution, is placed at approximately 1 meter from the vibrating object of interest. The vibrating object is mounted on a shaker, whose oscillating movements are commanded by a PC and an acquisition board. In this case, sinusoidal waves are imposed to the object by the shaker with controlled amplitude and frequency. An accelerometer and a proximity sensor are also used to measure the vibration of the object, and results are compared to those obtained with video image processing.

The second set-up is shown in Fig. 3. In this case, the objective is measuring the orbit of a rotating system, i.e. measuring the plane motions of the shaft as it vibrates due to unbalance. The chessboard pattern is attached to the disk and rotates. Due to the adopted rotating speeds, the commercial camera used in the first set-up did not present good results. Camera exposition time was too big and the images of the chessboard became blurred. Linear velocity of the disk circumference was very high for the exposition time, even in low rotation speeds like 300 rpm (5 Hz). Hence, a fast camera is used (Optronis CamRecord 600 with 50 mm Nikon lens), whose maximum acquisition rate is 50 kfps. In order to increase illumination, a 35W Xenon spotlight is adopted. Proximity sensors mounted in orthogonal directions are also used to measure the vibration of the shaft, and results are compared to those obtained with video image processing.

Although the adoption of a fast camera solved the problem of image blurring, another problem affected the results quality. When the disk rotates, the chessboard is eventually shadowed by the shaft, thus hiding the chessboard for some frames. This situation could not be solved, but minimized, and the resulting curves will inevitably show some discontinuities.

Figure 2. Set-up for testing one-dimensional vibration measurement (shaker movements).

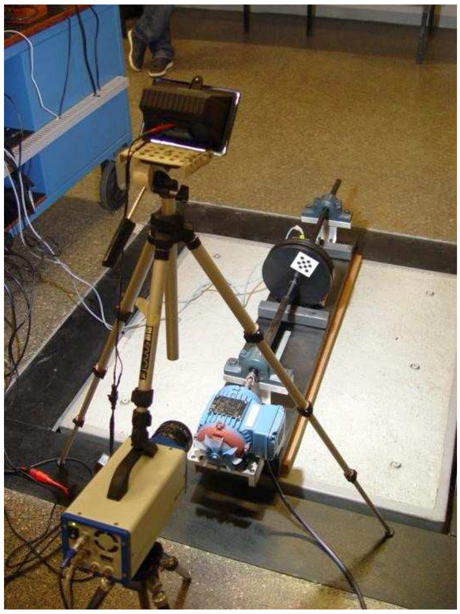
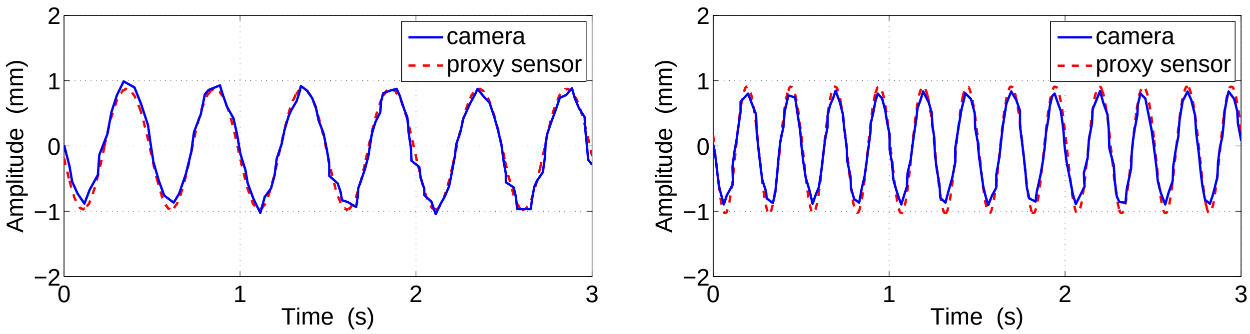


Figure 3. Set-up for testing two-dimensional vibration measurement (shaft orbit).

4. RESULTS

4.1 Unidimensional Results: Shaker Excitation

Figure 4 presents the results of vibration measurements for amplitude of 1 mm and frequencies of 2 and 4 Hz of vibration. As one can see, good agreement is found between the video measurements and proximity probe measurements for the frequency of 2 Hz. As frequency increases (e.g. 4 Hz), one can detect a deviation in amplitude prediction. This is caused by two factors: (a) fixed image exposure time; (b) fixed video acquisition rate.



(a) 2 Hz

(b) 4 Hz

Figure 4. Comparison between video image processing and proximity probe measurements of object subjected to 1 mm amplitude one-dimensional vibration (shaker).

The fact that image exposure time is fixed (commercial camera) can cause image blurring. As vibration frequency increases, the object velocity increases and the camera starts detecting the movement of the object. The camera is not fast enough to get a snapshot of the object's position. Hence, images become to blur and image processing is jeopardized. As a result, one has deviations of the predicted vibration amplitude.

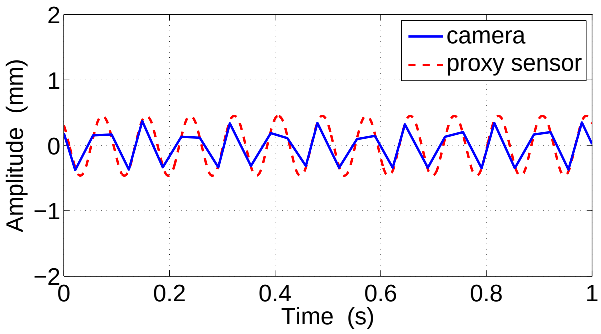
The second cause of measurement deviation is video acquisition rate. Signal resolution decreases as vibration frequency increases because acquisition rate is fixed in 30 fps (commercial camera). Hence, one has fewer points per period to describe the vibration signal. Considering that a sinusoidal signal can be built with acceptable resolution by a minimum of 7 points per period, one can see that measurements of 4 Hz vibration is near this limit (30 fps / 4 hz = 7.5 frames per period). Any measurement of higher frequency vibration will result in less resolution and higher deviation in the prediction of vibration amplitude.

In order to solve the problem of fixed acquisition rate, one can rely on the sub-sampling technique. The sub-sampling technique depends on the assumption that vibration is periodic and its frequency is known. In this case, one can reconstruct one period of the signal from measurement points of different periods of oscillation. Hence, the measurement of at least 7 points per period is no longer necessary (the 7 or more points come from different periods of oscillation). The number of points per reconstructed period will be a result of the following equation:

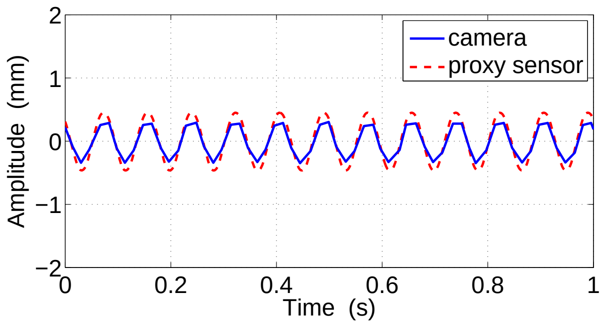
$$\frac{n}{k} = \frac{\tau_v}{\tau_s} = \frac{\omega_s}{\omega_v} \tag{7}$$

where n is the number of points of the reconstructed period, k is the number of vibrating periods necessary to reconstruct one period of signal, τ_s is the sampling period, τ_v is the vibration period, ω_s is the sampling frequency, and ω_v is the vibration frequency.

As an example, Fig. 5(a) presents the vibration of the object under amplitude of 0.5 mm and frequency of 12 Hz. As one can see, the 30 fps sampling frequency is not sufficient to completely describe de oscillation. By applying the sub-sampling technique, one obtains the results presented in Fig. 5(b). In this case, a sampling frequency of 30 fps and a vibration frequency of 12 Hz results in a ratio n/k = 2.5, i.e. it is possible to measure 5 points to reconstruct one period (n) and these points are measured during 2 periods of oscillation (k).



(a) original signal



(b) reconstructed signal

Figure 5. Comparison between video image processing and proximity probe measurements of object subjected to 0.5 mm amplitude one-dimensional vibration (12 Hz) – Reconstruction of signal with sub-sampling technique.

The difference in amplitude observed between the proximity probe measurements and the reconstructed signal from video measurements is due to the low number of points per period of the reconstructed signal (five points). The relationship between sampling and vibration frequencies was not favorable, thus resulting in only five points per period (below the desirable minimum of seven points per period).

4.2 Bidimensional Results: Shaft Orbit Measurements

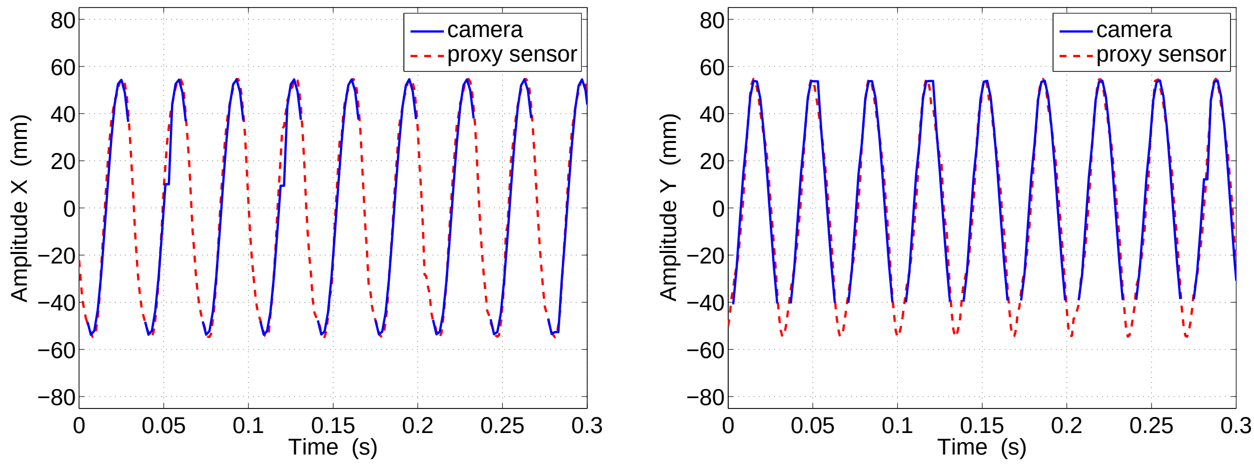
Shaft orbit measurements were performed with the fast camera adopting an acquisition rate of 500 fps and exposition time of 1/12500 s. The target is the center axis of the chessboard grid attached to the disk (Fig 3). Figure 6 presents a comparison between the results obtained with video image processing and those obtained with the proximity sensor. As one can see, good agreement is found when an appropriated acquisition rate is used and enough points per period are measured. The discontinuities in the video measurements are caused by the shadowing effect of the shaft, i.e. the chessboard is eventually shadowed by the shaft for some frames when the disk rotates. Hence, it is impossible to measure the position of the target and no measurements are available for these positions. This is also clear in Fig. 7, where the orbit of the target is presented. The lower part of the orbit was not measured due to the shadowing effect of the shaft.

5. CONCLUSION

The measurement of structural vibration via video images is a real possibility. However, acquisition rate and exposure time are critical parameters in performing a successful video measurement. As shown in the example tests, one must carefully choose acquisition rates and exposure times to get good agreement with proximity probes and, consequently, higher precision in the vibration measurements (Figs. 4(a) and 6).

One possibility to overcome acquisition rate restrictions of the video camera is the adoption of the sub-sampling technique. Depending on the relationship between sample acquisition frequency and vibration frequency, one can reconstruct periods of the vibrating signal from data measured in different periods of oscillation. This is useful, but requires knowledge of the vibrating frequency in advance. In addition, depending on the frequency relationship one will inevitably result in a poor discretization of the reconstructed signal, as shown in Fig. 5(b). In this case, a change in the acquisition rate of the camera is mandatory.

Image processing is also a critical part of the technique. The numerical algorithm must be able to correctly and precisely find the vertices of the chessboard cells, because position identification is based on the position of theses vertices



(a) X direction (b) Y direction

Figure 6. Comparison between video image processing and proximity probe measurements of shaft rotating at 1770 rpm (29.4 Hz) – vibration of measuring point at chessboard grid.

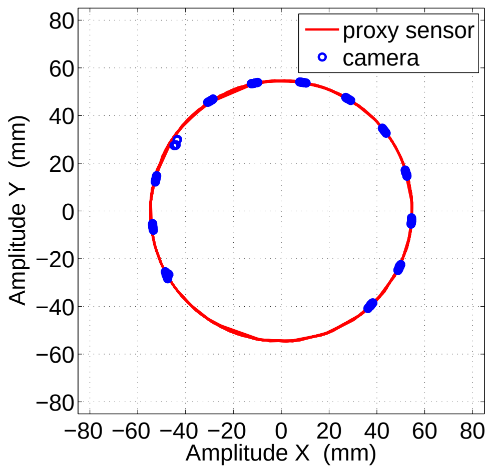


Figure 7. Comparison between video image processing and proximity probe measurements of shaft rotating at 1770 rpm (29.4 Hz) – orbit of measuring point in chessboard grid.

in the video image. When the algorithm is mislead by a ill illuminated or a low brightness image frame, one can perceive some deviation of the position measurements, as detected in the second and fourth periods of Fig. 6(a). As a result, one will measure a false position of the target, as seen in Fig. 7 (see outliner points in left of the shaft orbit).

Taking into account all these parameters, and appropriately tuning them, one can use video image processing to find the position of different parts of the structure. Considering that in a video image one has a picture of the whole structure, one can expand the adopted measurement methodology to a full field identification technique, and measure the vibration of the whole structure in a single run of experiments.

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