ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

MEASUREMENT OF ROTOR VIBRATION THROUGH PHOTOGRAPHIC IMAGES

Marcos Tan Endo
University of São Paulo, São Carlos School of Engineering, Trabalhador São-Carlense 400, 13566-590, São Carlos, Brazil
marcos.tan.endo@gmail.com

Arlindo Neto Montagnoli
Federal University of São Carlos, Via Washington Luis km 235, 13565-905, São Carlos, Brazil
arlindo@ufscar.br

Rodrigo Nicolleti
University of São Paulo, São Carlos School of Engineering, Trabalhador São-Carlense 400, 13566-590, São Carlos, Brazil
rnicolet@sc.usp.br

Abstract. *The analysis of vibration in rotating machines is important to increase the life of the equipment, reducing wear and possible failure of the rotating system. Non-contacting measurement methods are usually employed due to the difficulty of fixing a sensor on a rotating part. Some examples of these methods include the ESPI, LDV and proximity sensors. This project aims at developing a capturing system of images able to measure the dynamic behavior of a rotor shaft using the photogrammetry technique, together with a microcontroller for data acquisition in real time. The proposed method aims at obtaining the measurements of vibrations through sub-sampling techniques, which are used in structure or machines with known vibration frequencies (e.g rotating machines). After image acquisition, the vibration at specific points of interest in the structure is obtained by computational post processing, by adopting a suitable image processing technique. Results showed the feasibility of using a camera with fast shutter, good light and a device which measures the real vibration frequencies. The proposed methodology was applied to a rotor properly insulated from the external environment through a seismic base. The shaft of the system was driven by an electric motor, controlled by a frequency inverter. The measurements were carried out in frequencies of 300 rpm (5 Hz), 840 rpm (14 Hz) and compared to proximity probe measurements.*

Keywords: *vibration measurement, digital photogrammetry, sub-sampling, image processing, instrumentation*

1. INTRODUCTION

In literature, there are many methods dedicated to the measurement of vibration. They can be divided into contact and non-contact sensing devices. The contact sensors, like the accelerometers, strain gauges and LVDTs (Linear Variable Differential Transformers), must be coupled to the system to be measured, thus generating inconveniences as the addition of mass in the system and the difficulty of installation in hard to reach places. On the other hance, the non-contact sensors do not require any physical contact with the system to be measured. Examples of such devices are the ESPI (Electronic Speckle Pattern Interferometry), DSPI (Digital Speckle Pattern Interferometry), non-scanning LDV (Laser Doppler Vibrometry) and proximity sensors that have a relatively high cost compared to the traditional contact sensors. In the measuring methods listed above (contact and non-contact), the measurements are generally performed in a specific point (single point measurements). Hence, if there is interest in more points of measurement, it is necessary to use several sensors or increase the number of samples, significantly increasing the time and cost of the measurement process.

An alternative for doing multipoint measurements of vibration, with no contact and low cost, is by using a digital camera. The analysis and processing of images captured by digital cameras were initially used together with laser measuring systems, and has as examples the ESPI and DSPI, which are well established techniques for measuring small deformations, vibration analysis and nondestructive testing (Rastogi, 2001). López *et al.* (2002), using the technique ESPI with a camera CCD in the system NTSC and frame rate of 30 fps (frames per second), associated with a laser of sampling rate of 60hz, carried out qualitative studies of transverse vibrations in a fan blade. The high precision of these techniques is obtained, using high-speed cameras perfectly synchronized with laser system.

Technological evolution contributed to the development of the method known as digital photogrammetry, which uses only digital cameras for vibration measurements. Photogrammetry has more than a century of history and development, and can be defined as a science-based technology (Linder, 2009) that, through images, can perform measurements and interpretations of the shape and location of an object from one or more photographs (Luhmann *et al.*, 2006). Initially, the measurements were implemented with compact digital cameras. Olaszek (1999) was one of the first authors to use the photogrammetric technique to measure the dynamic behavior of bridges, using a single video camera. Other approaches studied vibration measurements in three dimensional space (3D), as in the case of Ryall and Fraser (2002) that used a single CCD camera, perfectly synchronized with the stroboscopic illumination, for measuring the vibrating modes of an airplane wing. In other example, Yoshida *et al.* (2003) measured the three-dimensional dynamic behavior of membranes with three synchronized CCD cameras and a sampling rate of 30 fps. However, due to limitations of compact digital cameras, such as low resolution and sampling rate set at 30 fps (maximum), the vibration measurements do not exceed the frequencies of 5Hz (Chang and Ji, 2007).

Aimed at increasing the range of measures frequencies, high speed cameras, which are equipment able to capture images with high sampling rates(Maas, 1992), began to be used in the vibration measurement. With such devices, JEON *et al.* (2010); Ferrer *et al.* (2011) performed measurements of structural vibrations. However, the lower resolution of the cameras restricted the distance of measurements. Due to the increasing utilization of high-speed cameras for vibration measurements, commercial softwares were developed for camera control and image processing. Helfrick *et al.* (2009); Warren *et al.* (2010); Helfrick *et al.* (2011) used the commercial ARAMIS system together with high-speed cameras for measurements of mechanical and structural systems. Despite the cost of such systems, the high-speed cameras are the most widely used equipment in photogrammetric techniques today.

In this work, in order to measure the vibrations of rotating systems through sub-sampling techniques, the principles of photogrammetry are applied using a digital camera, with sampling rate of 3 frames per second. The measurements were performed in shaft coupled to a three phase asynchronous electric motor, controlled by a frequency inverter, and the measurement were performed at frequencies of 300rpm (5Hz) and 840rpm (14Hz). The specific points of each image are obtained by computational post processing, being later compared with proximity sensors. Good agreement was observed between the results obtained with the camera and those obtained with the proximity probes.

2. DIGITAL IMAGE ACQUISITION AND PROCESSING

In this work, one adopts the coherent sub-sampling techniques for capturing the sequence of images of the vibrating system. Therefore, the signal is reconstructed from long acquisition periods. The position of interest in each image is obtained by computational post processing, which relates the 2D image coordinates (in pixels) with the 3D world coordinates (in millimeters).

The reconstruction of a signal through the sub-sampling method depends on the assumption that vibration is periodic and its frequency is known. By knowing this, the next step is to perform image acquisition using a microcontroller, which adds a small increment of time in each period sampled, or mathematically:

$$T_s = n(kT + \triangle_s) \tag{1}$$

where, n is an integer, k is the integer number of periods between consecutive samples, T is the period of the signal, and $\triangle_s$ is the time increment.

The relationship between the image coordinates that can be described by vector **m** $= [u, v]^T$ and the world coordinates **M** $= [X, Y, Z]^T$ was presented by Zhang (2000), following the equation:

$$s\,\tilde{m} = P\tilde{M} \tag{2}$$

where s is an arbitrary scale factor, $\tilde{m} = [u, v, 1]^T$ and $\tilde{M} = [X, Y, Z, 1]^T$ are the homogeneous coordinates, and P is the perspective projection matrix, given by:

$$P = K\begin{bmatrix} R & t \end{bmatrix} \tag{3}$$

where [R t] are the extrinsic parameters (rotation and translation), and K is the matrix of intrinsic parameters of the camera, described as follows:

$$\mathbf{K} = \begin{bmatrix} \alpha_x & \gamma & u_0 \\ 0 & \alpha_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

where (u_0; v_0) are the coordinates of the main point in the image, α_x and α_y are the focal lengths (in pixels), and γ represents the pixel skew.

With the extrinsic parameters and the matrix of intrinsic parameters found, it is necessary to carry out the correction of radial lens distortion due to the fact of using a non-metric digital camera. According to Zhang (2000), the coefficients k_1 and k_2 that represent the radial distortion of the camera can be calculated by the equation:

$$\begin{bmatrix} (u-u_0)(x^2-y^2) & (u-u_0)(x^2-y^2)^2 \\ (v-v_0)(x^2-y^2) & (v-v_0)(x^2-y^2)^2 \end{bmatrix} \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} = \begin{bmatrix} \tilde{u}-u \\ \tilde{v}-v \end{bmatrix} \tag{5}$$

and, the coefficients k_1 and k_2 are estimated by the linear method of least squares (Moré, 1977), where $\tilde{u}$ and $\tilde{v}$ are points of the distorted image.

In this work, all parameters were calculated with the aid of a camera calibration toolbox for MATLAB developed by Jean-Yves Bouguet at Computer Vision Research Group of the Department of Electrical Engineering California Institute of Technology. The toolbox finds the camera parameters by processing a sequence of images in different positions of a planar pattern, as shown in Fig.1, using the method of camera calibration proposed by Zhang (2000).

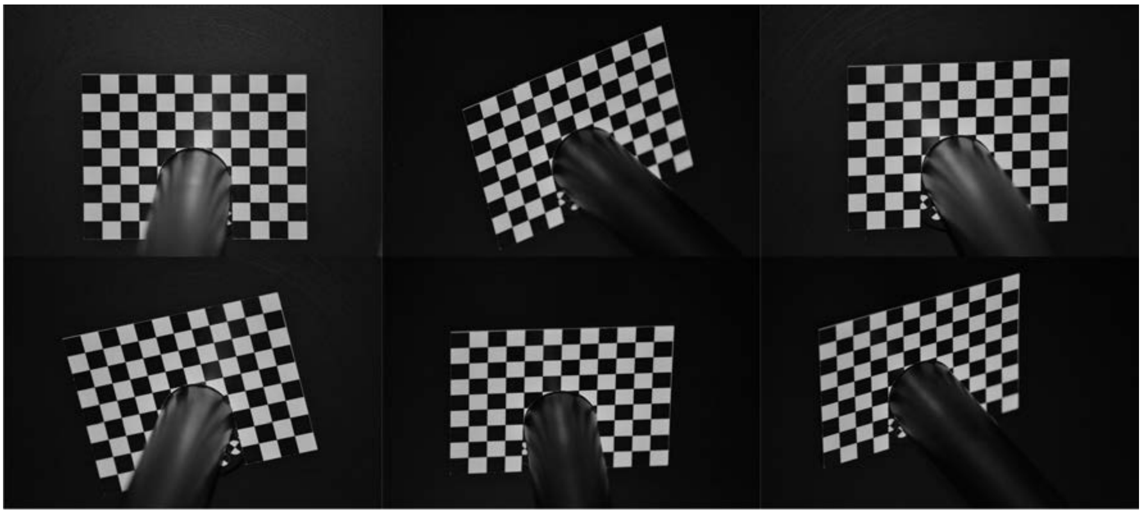


Figure 1. Sequence of images used to calibrate the measurement system.

After the definitions of intrinsic and extrinsic parameters of the camera, and of the radial distortion correction of the lenses, it is necessary to convert the points of interest (in pixels) of each sampled image for world coordinates (in millimeters). In the case of finite cameras, the expression that relates the coordinates in pixels to those in millimeters can be represented by:

$$\mathbf{M} = \mu \begin{bmatrix} (KR)^{-1}m \\ 0 \end{bmatrix} + \begin{bmatrix} (KR)^{-1}p_4 \\ 1 \end{bmatrix} = \mu \begin{bmatrix} \tilde{X} \\ 0 \end{bmatrix} + \begin{bmatrix} \tilde{C} \\ 1 \end{bmatrix} \tag{6}$$

where p_4 is the last column of matrix P, $\tilde{X}$ is an inhomogeneous 3-vector representing the coordinates of a point in the world coordinate frame, and $\tilde{C}$ is the inhomogeneous representation of the camera center. The coefficient μ is given by:

$$\mu = -\frac{\tilde{C}_3}{\tilde{X}_3} \tag{7}$$

with $\tilde{C}_3$ and $\tilde{X}_3$ being the last elements of each vector $\tilde{C}$ and $\tilde{X}$ respectively.

By knowing that the points of interest in each image were corrected and converted to millimeters, the next step is finding the displacement of the center of the shaft (rotating system), which is performed by an optimization algorithm developed in MATLAB. The task of this algorithm is to generate a circumference from the minimization of the chosen points, which are located at a constant distance from the shaft center. Hence, the centers of circumferences generated of each image are the points of vibration of the rotating system.

3. TEST APPARATUS

The validation of the measurement method was performed in the rotating system shown in Fig.2. The aim is measuring the orbit (two-dimensional vibration) of a disk mounted on a whirling shaft. The target developed to find the points of interest in each image was positioned as close as possible to the center of the shaft to reduce the effect called motion blur. This effect occurs due to the high linear velocity of the disk combined with a big time exposition camera for the acquisition of images. The tests were carried out using a Nikon D3100 professional camera, with AF 150 mm lenses, maximum

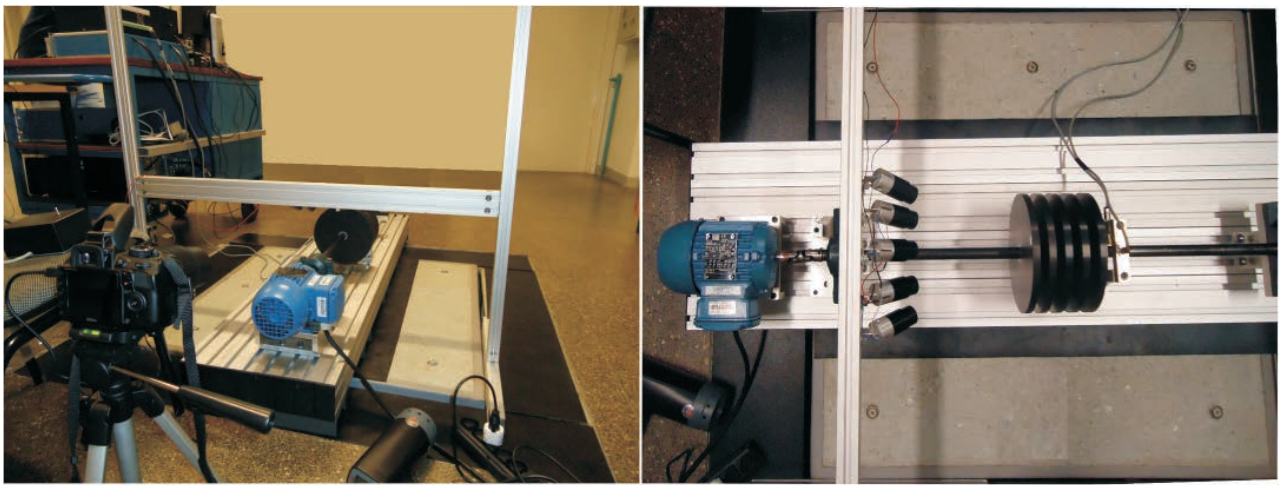
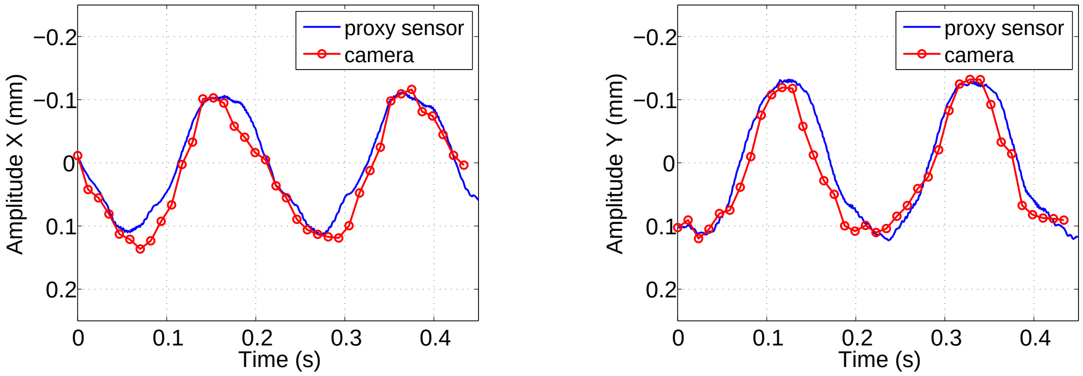


Figure 2. Measurement system of shaft orbit by the digital photogrammetry technique.

acquisition rate of 3 fps, exposition time of 1/4000 s and 4608 x 3072 image pixel resolution, placed at approximately 1 meter away from the rotating system. In order to improve the lighting, five optical assemblies with LEDs were used, with luminous power of 170 lumens each. Proximity sensors mounted in orthogonal directions are also used to measure the vibration of the shaft and results are compared to those obtained from the image processing.

4. EXPERIMENTAL RESULTS

Shaft orbit measurements were performed at rotating frequencies of 300 rpm (5 Hz) and 840 rpm (14 Hz). Figures 3 and 4 present the results of vibration measurements with photographic images in the rotating frequency of 5 Hz and a comparison to the results obtained with the proximity sensors. As one can see, two periods were reconstructed with 18 points sampled in each period and the vibration amplitude for this frequency has an amplitude of approximately 0.2 mm (peak to peak). The reconstructed signal presents a small deviation compared to the signal measured by the proximity sensors. This is mainly caused by the low resolution of the measuring system, that was of 0.0217 mm/pixel. The error caused by the low image resolution occurs mainly in small amplitudes of vibration. In such cases, the simple alteration of the position of one pixel regarding your real location significantly increases the deviation of the reconstructed point when compared to measurements performed by proximity sensors.



(a) X direction

(b) Y direction

Figure 3. Comparison between image processing and proximity sensor measurements of the shaft at the rotating speed of 300 rpm (5 Hz).

Another source of measurement error is the fact that the sub-sampling technique acquires points during different periods. Hence, it is required that the waveforms be identical in all periods. However, due to small variations in the frequency of the rotation system, and noise caused by the electrical network, waveforms in each period are not exactly the same, making it difficult to reconstruct perfectly the measured signal.

The results of vibration measurements in the rotating frequency of 14 Hz are shown in figures 5 and 6. As one can see,

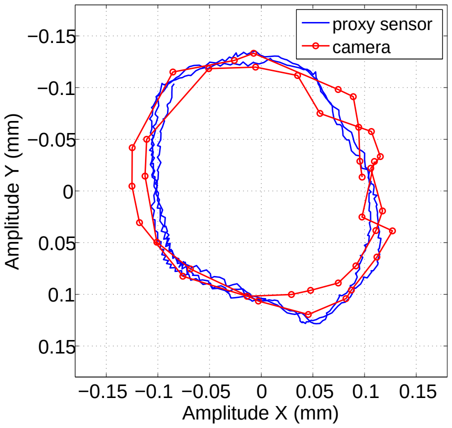
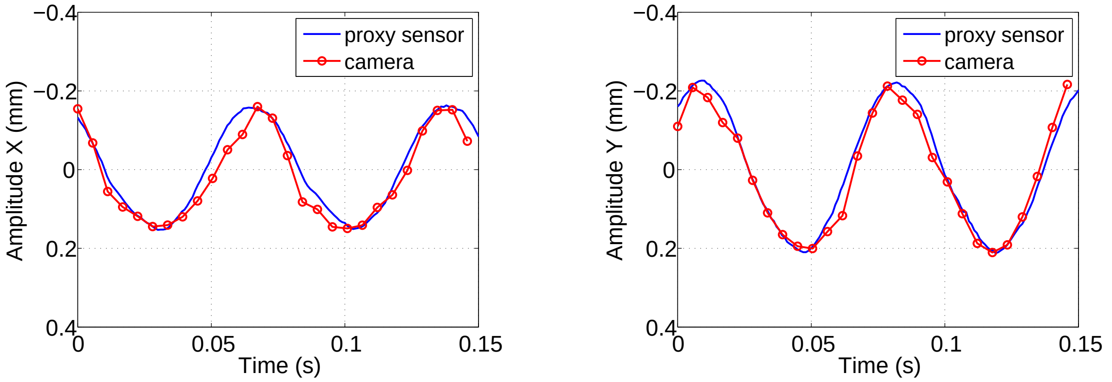


Figure 4. Comparison between image processing and proximity sensor measurements of the shaft at the rotating speed of 300 rpm (5 Hz) – shaft orbit.



(a) X direction

(b) Y direction

Figure 5. Comparison between image processing and proximity probe measurements of shaft rotating at 840 rpm (14 Hz).

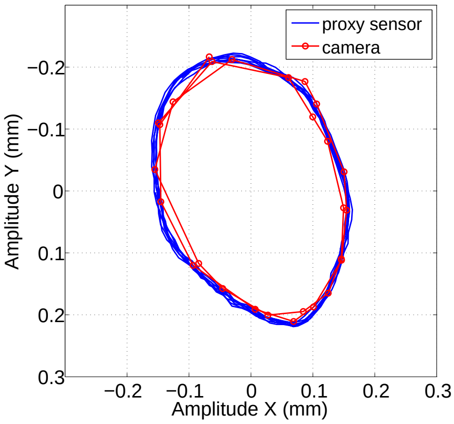


Figure 6. Comparison between image processing and proximity probe measurements of shaft rotating at 840 rpm (14 Hz).

there is much better agreement between the results of the image processing and those obtained with the proximity sensors. In this case, the vibration amplitude (peak to peak) in figure 5(b) is approximately twice as that of the measurements shown in figure 3(b). Thus, this higher vibration amplitude significantly reduce the positioning error of the reconstructed points.

Considering the experimental results shown in figures 3 to 6, one can see that the photogrammetric technique is a good technique for measuring the orbits of rotating systems, even for the small vibrating amplitudes observed at the rotating frequencies of 5 Hz (0.2 mm peak to peak in X direction and 0.25 mm peak to peak in Y direction) and of 14 Hz (0.3 mm peak to peak in X direction and 0.45 mm peak to peak in Y direction).

5. CONCLUSION

A photogrammetric measurement system together with the sub-sampling technique allows the realization of non-contact multi point measurements, and at frequencies above the conventional sampling technique. Another important characteristic, specific of the developed measurement system, was the use of a low cost digital photographic camera, as a single measurement sensor.

In this case, the measurement of vibration via a digital photographic camera required the application of the sub-sampling technique for capturing of the points to reconstruct the signal. This was necessary because of the limiting acquisition rates of the camera, which generally did not exceed 3 fps. Positioning errors were observed in the reconstructed signal because the sub-sampling technique reconstructed a signal from long acquisition periods, and the waveforms were not identical along the periods. However, despite this drawback, good agreement was observed in the comparison between the image processing and the proximity sensor measurements.

Due to limitations in the resolution of the image acquisition system (0.0217 mm/pixel), the numerical algorithm that calculated the location of the shaft center in each image was very sensitive to variations in the points of interest in the each image, especially in measurements done under small vibration amplitudes. As a result, it was observed some deviations in the position measurements.

6. ACKNOWLEDGEMENTS

The authors would like to acknowledge CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) and the technical staff of the Laboratory of Dynamics (EESC/USP) for supporting this research.

7. REFERENCES

Chang, C. and Ji, Y., 2007. "Flexible videogrammetric technique for three-dimensional structural vibration measurement." *Journal of Engineering Mechanics*, Vol. 133, No. 6, pp. 656–664.

Ferrer, B., Espinosa, J., Pérez, J., Ivorra, S. and Mas, D., 2011. "Optical scanning for structural vibration measurement". *Research in Nondestructive Evaluation*, Vol. 22, No. 2, pp. 61–75.

Helfrick, M.N., Niezrecki, C., Avitabile, P. and Schmidt, T., 2011. "3D digital image correlation methods for full-field vibration measurement". *Mechanical Systems and Signal Processing*, Vol. 25, No. 3, pp. 917–927.

Helfrick, M.N., Pingle, P., Niezrecki, C. and Avitabile, P., 2009. "Using full-field vibration measurement techniques for damage detection". In *Proceedings of the IMAC XXVII*. Orlando, Florida, pp. 1–11.

JEON, H.S., CHOI, Y.C., PARK, J.H. and PARK, J.W., 2010. "Multi-point measurement of structural vibration using pattern recognition from camera image". *Nuclear Engineering and Technology*, Vol. 42, No. 6, pp. 704–711.

Linder, W., 2009. *Digital Photogrammetry A Practical Course*. Springer.

López, C.P., Santoyo, F.M., Vera, R.R. and Funes-Gallanzi, M., 2002. "Separation of vibration fringe data from rotating object fringes using pulsed ESPI". *Optics and Lasers in Engineering*, Vol. 38, No. 3-4, pp. 145–152.

Luhmann, T., Robson, S., Kyle, S. and Harley, I., 2006. *Close Range Photogrammetry Principles, Methods and Applications*. Whittles Publishing.

Maas, H.G., 1992. "High-speed solid state camera systems for digital photogrammetry". In *Proceedings of XVIIth ISPRS Congress, Technical Commission V: Close-Range Photogrammetry and Machine Vision*. Washington, D.C., USA, pp. 482–485.

Moré, J.J., 1977. "The levenberg-marquardt algorithm: Implementation and theory". In G.A. Watson, ed., *Numerical Analysis*, Springer, Berlin, Vol. 630, pp. 105–116.

Olaszek, P., 1999. "Investigation of the dynamic characteristic of bridge structures using a computer vision method". *Measurement*, Vol. 25, No. 3, pp. 227–236.

Rastogi, P.K., 2001. *Digital Speckle Pattern Interferometry & Related Techniques*. John Wiley & Sons.

Ryall, T.G. and Fraser, C.S., 2002. "Determination of structural modes of vibration using digital photogrammetry". *Journal of Aircraft*, Vol. 39, No. 1, pp. 114–119.

Warren, C., Pingle, P., Niezrecki, C. and Avitabile, P., 2010. "Comparison of image based, laser, and accelerometer measurements". In *Proceedings of the IMAC XXVIII*. Jacksonville, Florida, pp. 1–7.

Yoshida, J., Abe, M., Kumano, S. and Fujino, Y., 2003. "Construction of a measurement system for the dynamic behaviors of membrane by using image processing". In *Proceedings of the 1st International Conference on Textile Composites and Inflatable Structures*. Barcelona, Spain, pp. 1–10.

Zhang, Z., 2000. "A flexible new technique for camera calibration". *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 22, pp. 1330–1334.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.