American Journal of Mechanical Engineering, 2015, Vol. 3, No. 6, 195-200
Available online at http://pubs.sciepub.com/ajme/3/6/8

DOI:10.12691/ajme-3-6-8

High-speed Digital Image Correlation as a Tool for 3D Motion Analysis of Mechanical Systems

František Trebuňa[1,*], Róbert Huňady[1], Martin Hagara[1], Ivan Virgala[2]

[1]Department of Applied Mechanics and Mechanical Engineering, Technical University of Košice, Faculty of Mechanical Engineering, Košice, Slovakia
[2]Department of Mechatronics, Technical University of Košice, Faculty of Mechanical Engineering, Košice, Slovakia
*Corresponding author: frantisek.trebuna@tuke.sk

Abstract The contribution deals with the use of high-speed digital image correlation in a measurement and motion analysis of relatively big objects such as robots or manipulators. Digital image correlation method is an optic non-contact technique, which can be used in a wide range of applications in experimental mechanics. This method uses two precise CCD cameras for measuring. Cameras are usually placed stereoscopically, what allows to determine displacements and deformations in 3D space. In this contribution the theoretical basis of this method as well as the practical aspects concerning high-speed measurements are contained. As an example the experimental measurement of the motion of manipulator arm is mentioned. The output of the measurement is in the form of trajectories of its investigated points and the displacements of oscillation as well.

Keywords: *digital image correlation, high-speed measurement, motion analysis, vibration analysis*

Cite This Article: František Trebuňa, Róbert Huňady, Martin Hagara, and Ivan Virgala, "High-speed Digital Image Correlation as a Tool for 3D Motion Analysis of Mechanical Systems." *American Journal of Mechanical Engineering*, vol. 3, no. 6 (2015): 195-200. doi: 10.12691/ajme-3-6-8.

1. Introduction

Displacements measurement of moving objects is a task which demands of application of special measuring methods and principles, especially in cases if the displacements are relatively high or the processes are very quick and short. In technical practice the sensors which allow measuring of displacements only in a certain very small range are most often used. These usually are laser, eddy current, inductive or capacitive sensors. Such sensors are capable to determine displacements in only one place and one direction as well. In a case, if it is needful to register the motion of the mechanism or mechanical system with multi degrees of freedom, it is necessary to use optical methods which are able to track the great deal of points of the object or system of bodies in 3D space, simultaneously. Digital image correlation (DIC) belongs amongst such methods. DIC is well-known since the beginning of the eighties, when it was conceived at the University of South Carolina [1]. Due to an advance reached in optics and computer technique, digital image correlation finds increasing use in experimental analyses as well as solving of various engineering problems [2,3,4,5,6].

2. Modan3D

Digital image correlation is a non-contact optical method, based on a comparison (denoted as correlation) of the digital images acquired during the investigated object loading by using one or more CCD cameras. Digital images are compared along small image elements called facets. Shape of facets use to be squared with usual size from 15x15 to 30x30 pixels, whereby using smaller facets the results are influenced by increasing systematical error [7].

Stochastic black and white speckle pattern is created on the object surface in order to correlate identical parts of the images, whereby the size of pattern has to be adequate to the size of the investigated object and its distance from the cameras. There are various forms of finer or coarser patterns creation, e.g. spraying black dots on white background using spray color or spray gun, easy coating of Xerox toner on wet white surface, manual painting by indelible ink pen or chemical etching of metal materials. For the reason, that the minimal size of facet is determined by size of created pattern and every one facet has to contain white and black color in order to ensure regular facets correlation, it is very convenient to create the pattern printing black dots on matt white vinyl foil, which is consequently attached to the investigated specimen surface and moves or deforms with it together. The most advantages of this pattern creation form are:

- simplicity of its achievement,
- simple adjustment of the pattern size in regard to the size of investigated specimen,
- its homogeneity.

Using digital image correlation method it is possible to determine displacement and strain fields. Values of displacements are determined in virtual grid corners created automatically by the software delivered with correlation system. Similarly, like by FEM programs where computation accuracy depends on the size of finite elements also quality of the results achieved by digital image correlation depends on the size of virtual grid element.

One or two CCD cameras are generally used in performing of experimental tests using correlation systems. If the investigation is performed by one camera, then the measurement is constrained only for planar objects situated parallel with camera image plane (Figure 1). For this instance it is not possible to perform spatial analysis but only planar one.

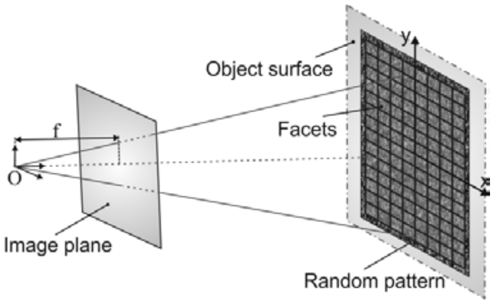

Figure 1. Setup of 2D correlation system

The use of two-camera setup (Figure 2) is conditioned by the visibility of each investigated object point by both cameras simultaneously, what considerably complicate the investigation of objects with other than flat shape or objects with bigger surface rounding.

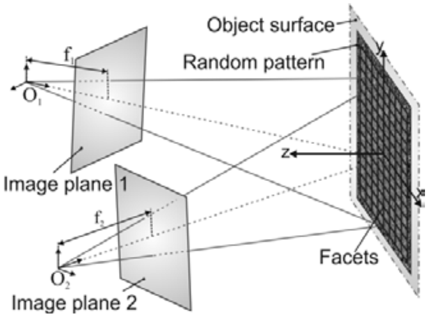

Figure 2. Setup of 3D correlation system

Digital image correlation system determines the transformation coordinates and of the investigated object using algorithm working on the pseudo-affine transformation of the points coordinates from one captured image to the second one. If a_0, a_1, a_2, ..., a_7 are labeled as the transformation parameters of potential displacement, tension, shear or torsion of the object (Figure 3), then:

$$\begin{aligned} x_t\left(a_0, a_1, a_2, a_3, x, y\right) &= a_0 + a_1 x + a_2 y + a_3 xy, \\ y_t\left(a_4, a_5, a_6, a_7, x, y\right) &= a_4 + a_5 x + a_6 y + a_7 xy. \end{aligned} \quad (1)$$

Transformation parameters are determined using minimization of the difference between the value of intensity in actual image $G_2(x, y)$ and the previous one $G_1(x, y)$ as follows:

$$\min_{a_0,\ldots,a_7,g_0,g_1} \sum_{x,y} \left\| \begin{matrix} G_1(x,y) + g_0 \\ -g_1 G_2\left(x_t(x,y), y_t(x,y)\right) \end{matrix} \right\|, \quad (2)$$

where g_0 and g_1 represent the illumination parameters [7].

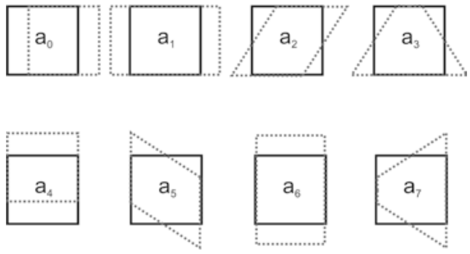

Figure 3. Transformation parameters of potential translation, stretch, shear and distortion

Among main factors, which influence accuracy of the results obtained by digital image correlation method, can be included:

- calibration of the cameras,
- sufficient sharpness and image contrast,
- sufficient lighting of investigated object with appropriate frequency of light source,
- if use a large number of cameras the same conditions of lighting for all cameras,
- quality and correct size of stochastic pattern created on the surface of the object,
- size and possible non-linear distortion of facets in consequence to strong curvature of the specimen.

The aim of calibration is a definition of internal parameters (geometrical and optical characteristics) and also external parameters of the cameras (relative position and camera rotation) in a form of three-dimensional location and rotation of camera imaging system in respect to the same global coordinate system. These parameters are necessary for consequential correlation of images and evaluation of measurement. The calibration has to be performed under the same conditions as acquisition, i.e. at the same setting of cameras and lens.

Very simple and in practice often used calibration technique is this, which is based on Zhang's algorithm [8]. This algorithm is also used in optical correlation system Q-450 Dantec Dynamics, by which measurements described below were performed. In general the whole procedure of cameras calibration consists of following steps:

1. Creation of calibration pattern on the plane plate to size corresponding to the area of investigated object → calibration target (Figure 4).
2. The acquisition of several images of calibration target in different positions obtained by movement of the target.
3. Finding characteristics points with precisely defined locations in the acquired images (Figure 4).
4. Estimation of internal and external parameters of cameras by using mathematical algorithm.
5. Estimation of the coefficients of radial distortion by using method of least squares.
6. Improvement of mentioned coefficients estimation.

During the calibration process the user rotates calibration target in fields of view of both cameras. The cameras capture different spatial positions of target and obtain sufficient amount of data for the calculation of necessary calibration parameters. Software in any position registers nodes of its checkerboard pattern and by the known geometry sets for every camera:

- focal length,
- coordinates of principal point,
- radial and tangential distortion of the image,

- components of displacement vector and rotation matrix.

The algorithm calculates the values of these parameters for each registered location change of target. Maximum number of calibration steps, which system is able to capture, is twenty-five. As mentioned in [9] the values of internal image parameters as focal length and coordinates of principal point after 12th step calibration change considerably in smaller extent and with increasing calibration steps the interval of changes is markedly narrowed. With the exception of external parameters plots from individual calibration targets are approached, and the most approaching is possible to observe after 20th step. Estimated inaccuracies of image parameters with increasing steps are declined, whereby the lowest value is achieved in the last steps.

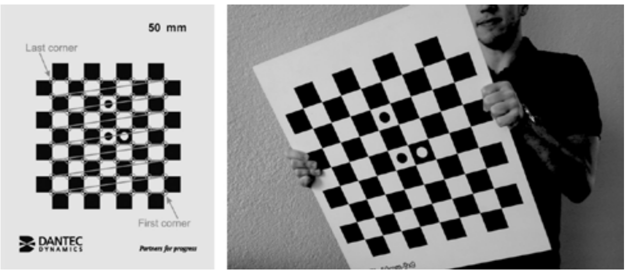

Figure 4. Calibration target Dantec Dynamics PL-50mm-9x9. Grey circles on the left image show detection of characteristics points with known location

Using correlation systems it is possible to investigate the objects of size from several mm^2 to some m^2.

3. Measuring System for High-speed Measurements

Correlation system Q-450 Dantec Dynamics contains two high-speed CCD cameras Phantom SpeedSense 9070 with image resolution of 1080x800 px. Each of the cameras is equipped with 50 mm objectives Carl Zeiss Makro-Planar 2/50 ZF. Capacity of the cameras memory is 16 GB. It is possible to use full image resolution of the sensors up to the sampling frequency equal to 3140 fps. By the performing of motion analysis or observing other quick processes it is often needful to accomplish measurements at much higher sampling frequencies. For that reason it was necessary to assess, how the sampling frequency influences the efficiency of CCD sensor.

From Table 1 it is obvious, how the maximal image resolution of the cameras is changing with the increasing sampling frequency. Moreover, in this table a maximal number of snapshots and a corresponding acquisition time, which can be by particular sampling frequencies recorded, are presented. The data mentioned in Table 1 signify that the maximal sampling frequency of the correlation system Q-450 with CCD cameras Phantom SpeedSense 9070 is 13300 fps. Using this sampling frequency it is utilized only 23.2% of maximal camera image resolution.

Table 1. Size of sensor's image resolution, number of snapshots and acquisition time relative to the cameras sampling frequency

Sampling frequency [fps]	Maximal resolution [px]	Maximal number of sampled snapshots by maximal resolution*	Maximal acquisition time [s]
500	1080x800 (full)	17260	34.52
1000	1080x800 (full)	17260	17.26
3000	1080x800 (full)	17260	5.75
3500	688x688	31510	9.00
5000	576x576	44947	8.99
7500	544x544	50400	6.72
10000	512x512	56900	5.69
13300	448x448	74307	5.58
**values are valid for cameras with 16GB of internal memory*			

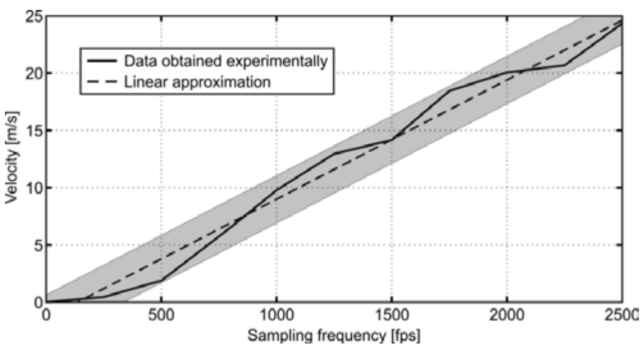

Figure 5. Dependence between sampling frequency of the cameras and maximal velocity of a point, which can be recorded at given frequency

During realization of object motion analysis it is essential to ensure sufficient contrast and sharpness of random pattern created on the object surface and thus the images can be correlated with the highest accuracy. In the case, if the sampling frequency was too low, the images will be blurred and the results will be affected by the correlation or 3D reconstruction errors [7]. Using higher frequency, not only the correlation process but also the time resolution is improved. On the other hand the acquisition time is shortened. The choice of sampling frequency depends on maximal velocity of the analyzed object or its point. An experiment was done in laboratory conditions, which aim was to determine a relation between sampling frequency of cameras and the highest object velocity, when the random pattern remained still sharp enough to be correlated. The result of the experiment is a dependence depicted in Figure 5.

Following the obtained dependence it is obvious that the maximal velocity is growing with sampling frequency approximately linear and thus using maximal sampling frequency of the cameras (13300 fps) it should be possible to evaluate the point moving with velocity of ca. 115-125 $m.s^{-1}$. In a case, if the approximate maximal velocity of the object $v_{\max}$ is known, the sampling frequency F_s can be determined from the relation:

$$F_s = k \cdot v_{\max}, \tag{3}$$

where $k = 105 \div 115$ [fps/m.s^{-1}].

4. Measurement of Spatial Displacements of Moving Manipulator Arm

The aim of the experiment was to record and subsequently analyze 3D displacements of chosen points of a moving object. The object of the measurement was one of the arms of manipulator, which has six degrees of freedom and was installed on a moving chassis. Displacements of ending points A and B of mentioned arm were analyzed by using correlation system Q-450 (Figure 6). The measurement was evaluated in software Istra4D, which is a part of correlation system. This program allows to correlate images from the cameras and to determine the displacements of object surface points. The measurement data were consequently processed in Matlab.

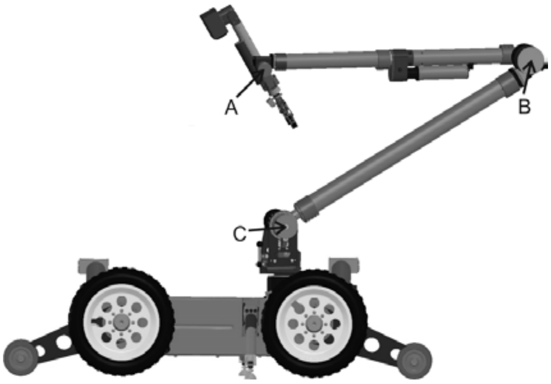

Figure 6. Illustrative picture of the manipulator

By the realization of motion analysis it is needful to adjust the arrangement and spacing of the cameras to the size and working space of analyzed object. During its motion the correlated areas (i.e. investigated parts of the object) has to be well visible in fields of view of both cameras. In a case, if it is not possible, the correlation system with three or more cameras can be used for realization of the measurement. The arrangement and spacing of the cameras relative to the analyzed points A and B can be seen in Figure 7.

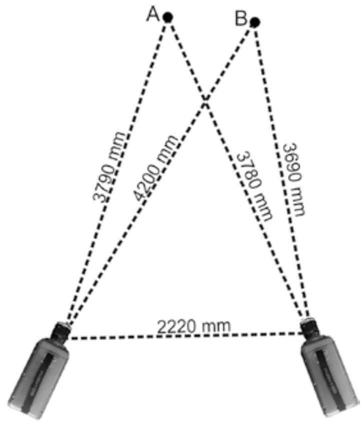

Figure 7. Illustrative picture of the arrangement and spacing of the cameras relative to analyzed points in their initial position

Applied random pattern should have always high contrast. For that reason it is necessary to ensure the best possible light conditions. The illumination has to be intensive enough and even unchanging. During measurement, when the object is moving, the formation of reflections and darkening of random patterns must not to occur. It is required to modify the size of random pattern speckles with respect to the distance of cameras to an object and the size of correlated area. In our case, the vinyl foils with pre-printed random pattern, which speckles had a width of several millimeters, were applied at the places A and B (Figure 8).

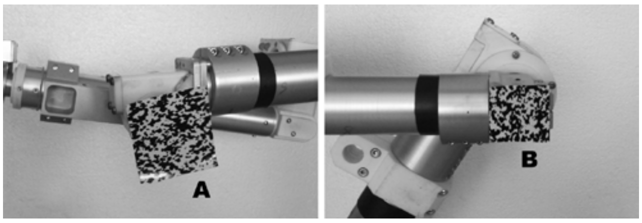

Figure 8. Speckle patterns applied at the places A and B

Selection of the calibration target depends on the size of cameras field of view. The target PL-50mm_9x9 (Figure 4) was used for the calibration.

Motion analysis of manipulator arm was realized by the full image resolution of both cameras and sampling frequency set to 1000 fps. Total acquisition time was 16.447 s. For the high-speed measurements very short shutter times (several μs) are typical. The achievement of optimal lighting conditions was realized using two powerful sources of specified achromatic light with the power of 1000 W and supply voltage frequency of 70 kHz. In Figure 9 and Figure 10 the snapshots, which capture the manipulator from the view of the left camera in initial and final position, can be seen.

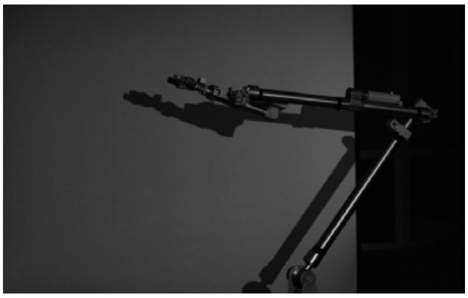

Figure 9. The view from the left camera capturing the manipulator in initial position

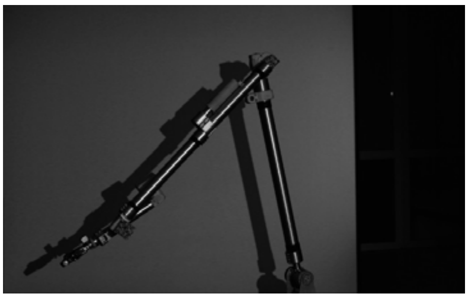

Figure 10. The view from the left camera capturing the manipulator in final position

In Figure 11 – Figure 13 the time dependences of coordinates of points A and B in coordinate system with the origin defined in point C are depicted. Note that program Istra4D allows arbitrarily define the orientation and the origin of coordinate system, in which the coordinates and displacements of moving object points are evaluated subsequently. The trajectories of points A and B, obtained by the locomotion of the manipulator from the initial to final position, are depicted in Figure 14.

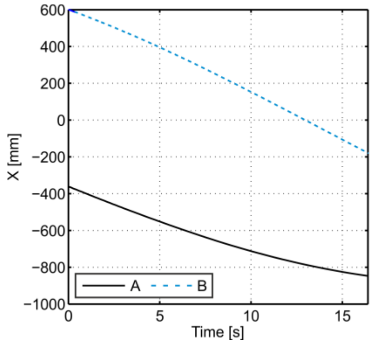

Figure 11. Time dependences of X coordinates of points A and B

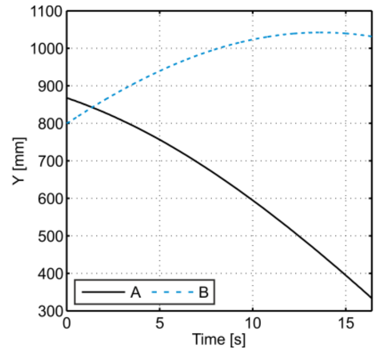

Figure 12. Time dependences of Y coordinates of points A and B

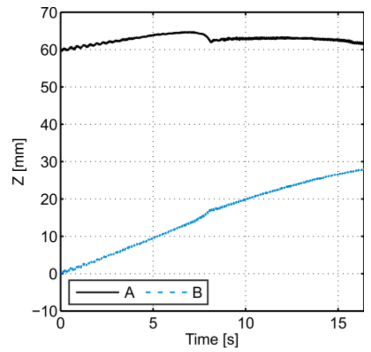

Figure 13. Time dependences of Z coordinates of points A and B

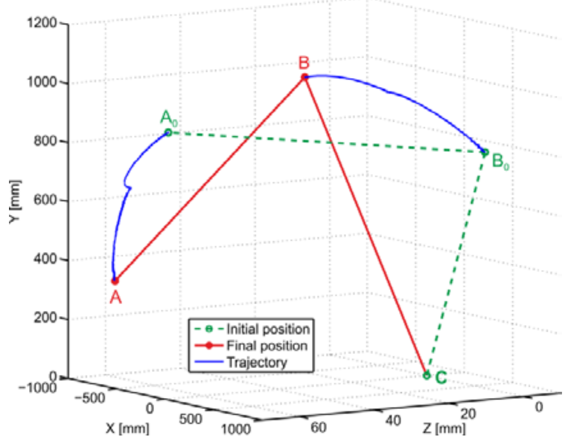

Figure 14. Spatial representation of the trajectories of points A and B

Correlation system Q-450 is able to record also the vibrations happened during the motion, e.g. in consequence of clearances or resonances. Function "Remove Rigid Body Movements" implemented in the software Istra4D calculates a rigid body movement between the reference and actual time step and subtract this from the measured displacement of an object, i.e. the rigid body movement consists of a translation between the balance point of the two contours and a rotation which minimize the distance between the contours [10]. It allows us to investigate vibrations in the frequency domain. Figure 15 and Figure 16 illustrate the time dependence of oscillations of point A and their frequency spectra obtained for time interval 7-8 s.

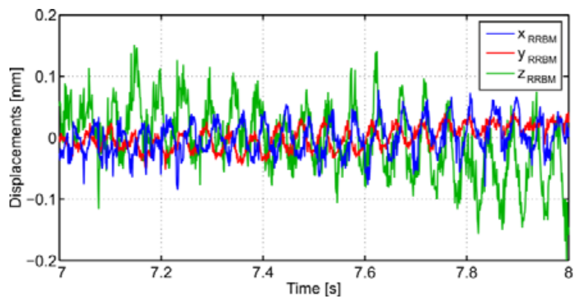

Figure 15. Time dependence of oscillations of point A obtained by the function "Remove Rigid Body Movements" for time interval 7-8 s

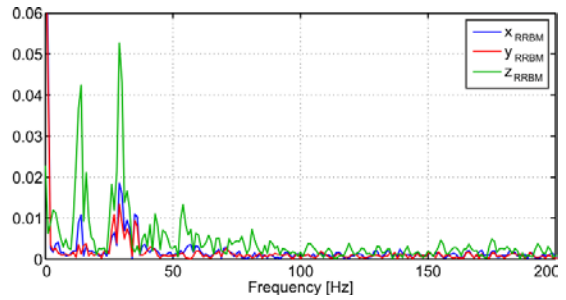

Figure 16. Frequency spectra of oscillations of point A obtained by the function "Remove Rigid Body Movements" for time interval 7-8 s

5. Conclusions

The paper presents the approach of measurement 3D displacements of moving object using high-speed digital image correlation method. In the contribution, the practical aspects of measurement that should be reflected in the preparation phase of experiment are described. The prime aspect is the range of investigated object or system of bodies' movement, from which the arrangement of cameras is depending. The analyzed areas, on which the random pattern is applied, have to be visible in fields of view of both cameras and cannot exceed the interval of their depth of focus. The size of the random pattern speckles has to correspond to the size of analyzed area as well as the distance of this area to the cameras to be correlated well. The choice of sampling frequency is an important factor, which limits the maximal measurable velocity of moving object. The increasing sampling frequency shortens a shutter time and this requires an assurance of sufficient additional illumination. The acquisition time depends on the used image resolution of the camera sensor and its inner memory. The sensitivity of measuring device is approximately 1/100 000 of field of view, so in the case of smaller objects the system is able to register displacements in micrometers. For this it is possible to use digital image correlation also in vibration analysis. Mentioned methodology is similarly convenient for experimental examination of the positioning accuracy of different manipulators and positioning devices.

Acknowledgement

This contribution is the result of the projects implementation VEGA 1/0937/12 “Development of nontraditional experimental methods for mechanical and mechatronical systems”, APVV-0091-11 “The use of experimental and numerical methods for the increase of competitiveness and innovation of mechanical and mechatronical systems” and ITMS: 26220220141 “Research of modules for intelligent robotic systems”.

References

[1] Sutton, M., Orteu, J.J., Schreier, H., Image Correlation for Shape, Motion and Deformation Measurements - Basic Concepts, Theory and Applications, Springer Science+Business Media, LLC 2009, pp. 321

[2] Trebuňa, F., Hagara, M., “Experimental modal analysis performed by high-speed digital image correlation system”, *Measurement*, Vol. 50, 78-85, 2014.

[3] Hagara, M., Šimčák, F., Kalina, M., “The knowledge acquired by using of optical methods by strain fields investigation”, *Applied Mechanics and Materials*, Vol. 486, 141-146, 2014.

[4] Huňady, R., Hagara, M., Schrötter, M., The Application of High-speed Digital Image Correlation in Vibration Analysis of a Rotating Object, in: *Proceedings of 50th Annual Conference on Experimental Stress Analysis*, Tábor, Czech Republic, 175-182, 2012.

[5] Huňady, R., Hagara, M., Schrötter, M., The determination of the kinematic quantities by using the high-speed DIC method, in: *Proceedings of 18th International Conference Engineering Mechanics*, Svratka, Czech Republic, 469-475, 2012.

[6] Trebuňa, F., Šimčák, F., Huňady, R., Vibration and modal analysis of mechanical systems (In Slovak), 1st edd., Košice : TU, 2012, pp. 236.

[7] Becker, T., Splitthof, K., Siebert, T., Kletting, P., Error Estimations of 3D Digital Image Correlation Measurements (Technical Note), Dantec Dynamics, 2008.

[8] Zhang Z., “A Flexible New Technique for Camera Calibration”, *IEEE Transactions on Pattern Analysis and Machine Intelligence*. November 2000, Vol. 22, No. 11, p. 1330-1334.

[9] Huňady, R., Hagara, M., Schrötter, M., “Impact assessment of calibration parameters on accuracy method of digital image correlation”, *Acta Mechanica Slovaca*, Vol. 16, no. 2, 6-12, 2012.

[10] Istra4D – Software manual, Q-450 System, Dantec Dynamics GmbH, pp. 87, 2009.