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THE DETERMINATION OF THE KINEMATIC QUANTITIES BY USING THE HIGH-SPEED DIC METHOD

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Abstract: *A measuring of deformations and displacements of a moving object can be considered for one of the most complicated tasks in the experimental mechanics. Thanks to modern optical methods like method of digital image correlation, we are able to record displacements during the time variable actions such as dynamic loading or motion. The article deals with possibilities of using high-speed digital image correlation for determination of some kinematic quantities of rotating objects.*

Keywords: ***motion, kinematic quantities, digital image correlation***

1. Introduction

The kinematics can be integrated from theoretical aspect as part of classic physics. Its main objective is description of point/body movement or system of points/bodies but it does not deal with forces which cause this movement. For description of this movement it is necessary to find out the trajectory of this motion and also the velocity and acceleration. In practice kinematics can serve for determining a range of movement of some mechanism or for finding out velocities or accelerations of its components movement.

There is a plenty of sensors for measuring of kinematics quantities which utilize various physical methods and can be divided as follows:

- according to a signal output and an operating principle
  a) with analog signal (resistive, capacitive, inductive, inductactive, ultrasound, optoelectronic, piezoelectric,...)
  b) with discrete signal (electrocontact, image, oscillatory, magnetic with Hall probe, optoelectronic, optronic, incremental, absolute,...)
- according to a kind of measured quantity
  a) position sensor
  b) velocity sensor
  c) acceleration sensor
- according to a contact with an investigated object
  a) contact
  b) non-contact

To the position sensors we can include also rpm sensors so called tachometers. Tachometers can be divided according to transfer of rotation frequency to an output signal as follows:

a) hydraulic tachometers

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b) pneumatic tachometers

c) tachometers with non-electric output (mechanical, resonant, chronometric, stroboscopic)

d) tachometers with electrical output

Likewise, they can be divided into contact and non-contact.

In some cases it is convenient to use for measurement non-contact methods which do not disturb measured structure. Among modern non-contact methods which are more and more popular nowadays belongs also digital image correlation (DIC).

2. Digital image correlation

Digital image correlation is a non-contact optical method served for identification of spatial displacements and strains of investigated object. Three-dimensional displacements are determined by correlation of digital images obtained by CCD cameras during movement of an investigated object.

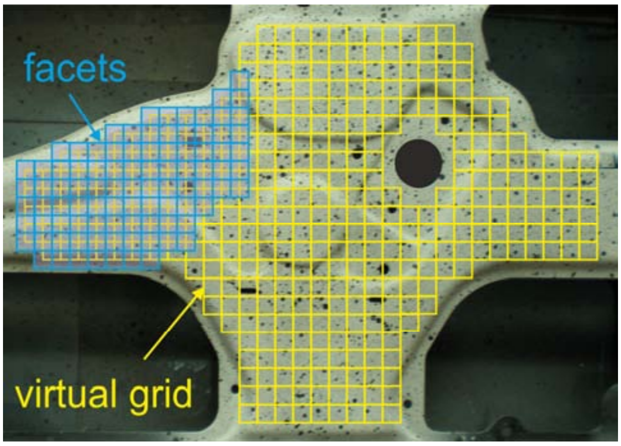

Fig. 1: Random black and white pattern created on the surface of investigated object

The object surface is in software application automatically divided into small image elements called facets. Each of these facets contains a characteristic contrast random pattern usually created by spraying of black stochastic dots on a white background (Fig.1). This pattern imitates the object contour, moves and/or deforms together with it. Displacement fields are determined by correlation of corresponding facets determined on digital images before and after object movement.

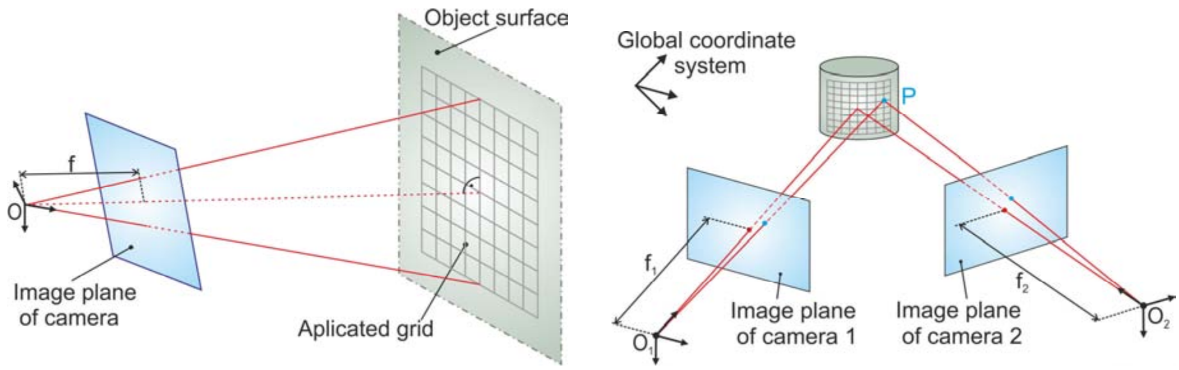

Fig. 2: The principal of 2D (left) and 3D (right) digital image correlation

If one camera with perpendicular position to investigated object is used for sampling images displacements can be determined just in plane parallel to image plane of camera (Fig. 2 left). This configuration is called two-dimensional digital image correlation (2D-DIC).

A three-dimensional digital image correlation (3D-DIC) is used in spatial analysis. In this case the determination of 3D-displacement could not be realized by one camera. For this reason two cameras are used to capture images from two different locations and directions (Fig. 2 right). This configuration allows studying mainly flat objects or planar objects with small curvature. Nowadays systems with three, four, six or eight cameras are developed to observe spatial objects from all directions. Discrete values of displacements in three mutually perpendicular directions of each investigated point are obtained as output from correlation system. Subsequently it is necessary to process these data numerically to obtain required kinematic quantities (Sutton et al., 2009; Siebert et al., 2005; Pan et al., 2009; Yoshizawa, 2009; Siebert et al., 2009).

3. Motion analysis of an object with constant rotary movement

The investigated object was a cooling fan of an automobile Škoda Felicia powered by stabilized generator with constant voltage 5V.

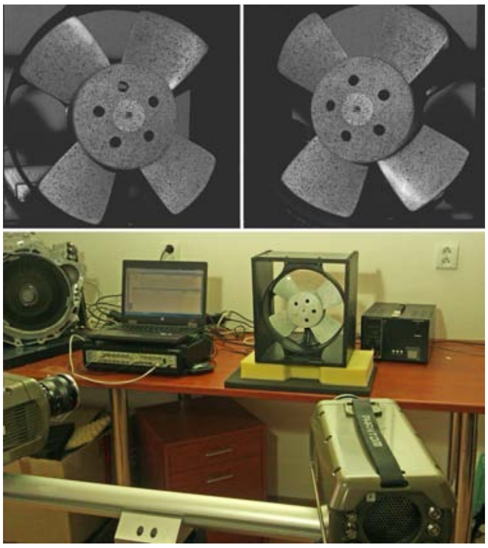

Fig. 3: Cameras configuration and views of investigated cooling fan from both cameras

Since a frequency of rotation of the cooling fan was relatively high, it was necessary to perform a high-speed measurement with a sampling frequency FS=5000fps to obtain continuous displacements of rotating fan. By this high frequency cameras shutter time was too short to get enough light onto the sensor. Therefore it was required to use a high-performance point source of white light to illuminate the fan during measurement. Likewise it was necessary to ensure that the whole investigated object could be seen by both cameras. Since fuzzy images could introduce some inaccuracies in a form of correlation errors captured images had to be really sharp with optimal contrast. Total acquisition time was prescribed to 0,5s and 2500 images were captured by both cameras. Cameras configuration and views of investigated cooling fan obtained by both cameras can be seen in the Fig. 3.

A reconstructed contour of the investigated area is depicted in the Fig. 4. Displacements were investigated in three points lying in the same straight line. These points are in the Fig. 4 depicted by green dots and marked by numbers from 1 to 3.

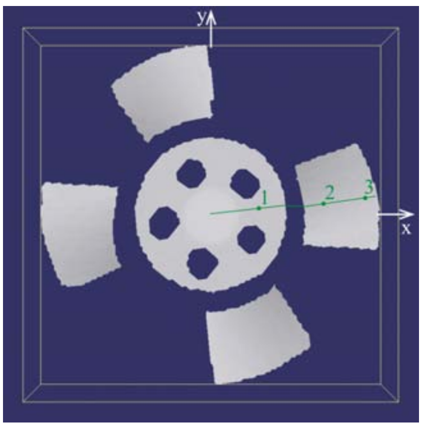

Fig. 4: Reconstructed contour of cooling fan after correlation with selected investigated points

The time dependences of displacements of each point in x and y directions (see Fig. 5) were consequently imported into Matlab and numerically processed. Trajectories of these three points can be seen in the Fig. 6.

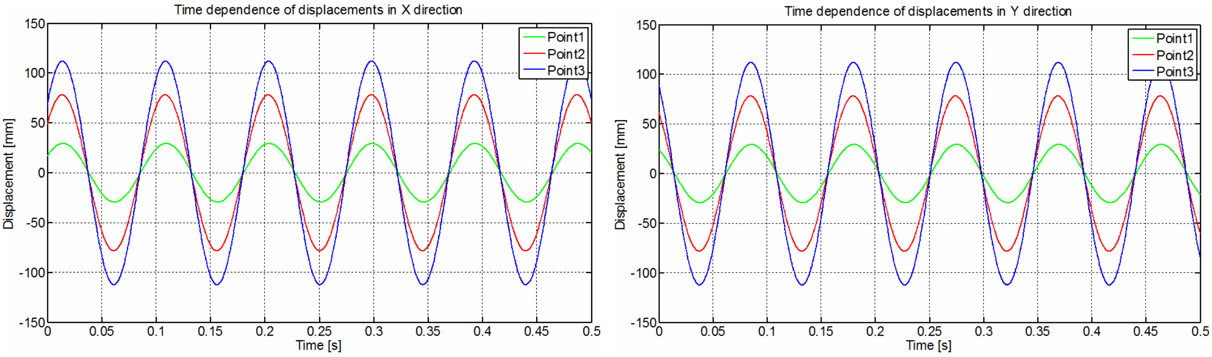

Fig. 5: Time dependence of chosen points displacements in directions x, y

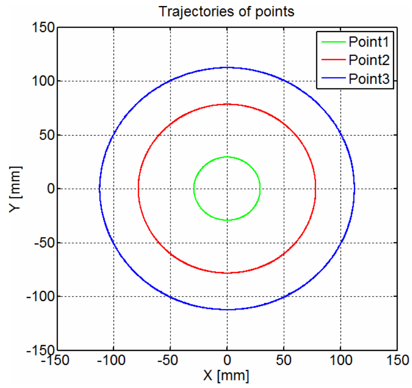

Fig. 6: Trajectories of cooling fan chosen points

Rotation frequency f_o of the cooling fan with constant rotary movement was determined from the frequency dependences of displacements in x and y direction. The time dependences of displacements were transformed into a frequency domain by Fast Fourier Transform (FFT). Frequency spectrums of displacements of each investigated point are depicted in the Fig. 7.

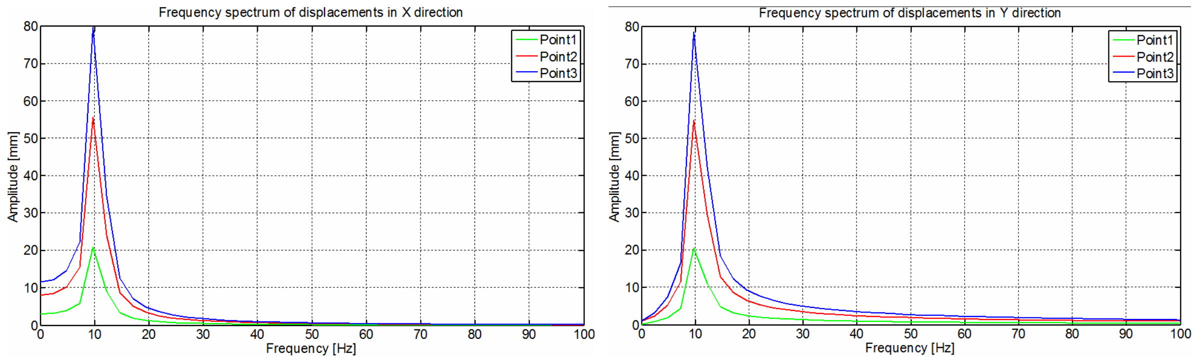

Fig. 7: Frequency spectrum of displacements in directions x,y

Because time dependences of displacements obtained by measurement represented set of discrete values it was necessary to utilize method of numerical differentiation for obtain another kinematic parameters (for instance velocity, angular velocity etc.) (Rizwan, 2008). Derivation of arbitrary function $f(t)$ with respect to time t can be expressed by term:

$$f'(t) = \lim_{\Delta t \to 0} \frac{f(t+\Delta t) - f(t)}{\Delta t} . \tag{1}$$

When the table values are equidistant in terms of time and Δt is assumed small enough (fig. 7) we can obtain formula for numeric differentiation by derivation of interpolation formulas expressed by the help of differences. For three successive values it is possible to obtain assumption of first and second differentiation of given function by terms:

$$f'(t) = \frac{f(t+\Delta t) - f(t-\Delta t)}{2\Delta t}, \tag{2}$$

$$f''(t) = \frac{f(t+\Delta t) - 2f(t) + f(t-\Delta t)}{\Delta t^2}. \tag{3}$$

By using of presented terms the angular velocity ω of cooling fan rotations was determined by numerical differentiation of rotation angle φ:

$$\omega(t) = \frac{\varphi(t_{i+1}) - \varphi(t_i)}{\Delta t}, \tag{4}$$

where:

$$\varphi(t) = \arctan\frac{y(t)}{x(t)}, \tag{5}$$

$$\Delta t = \frac{1}{F_S}. \tag{6}$$

Time dependence of rotation angle and angular velocity are graphically depicted in the fig. 8 and fig. 9.

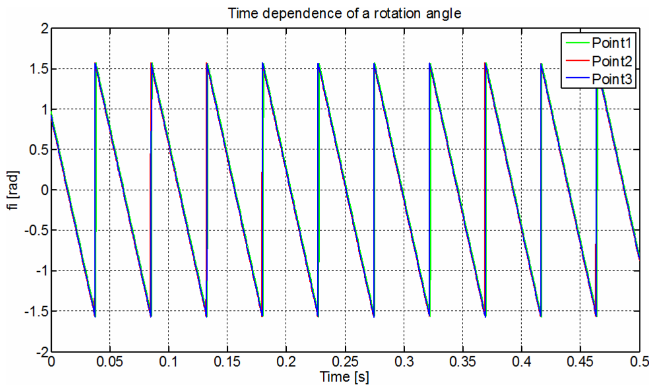

Fig. 8: Time dependence of rotation angle of cooling fan

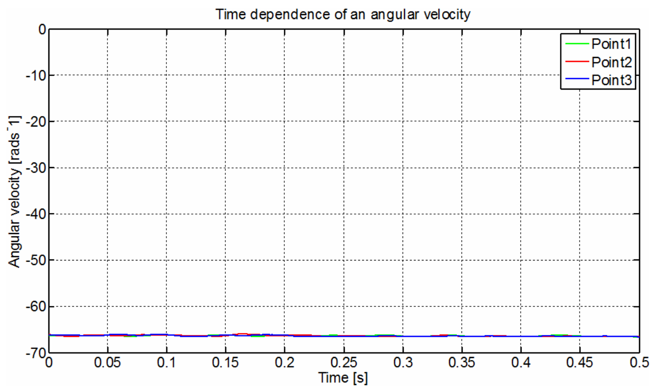

Fig. 9: Time dependence of angular velocity of cooling fan (after smoothing)

The velocity of particular points was determined by two methods. In the first case known frequency f_o of cooling fan rotation determined from frequency dependence of displacements was used. For calculation of velocities in this case was used:

$$v(t) = 2\pi f_o r(t), \tag{7}$$

where:

$$r(t) = \sqrt{x(t)^2 + y(t)^2}. \tag{8}$$

Dependence of velocities of particular points is for this approach showed in the fig. 10.

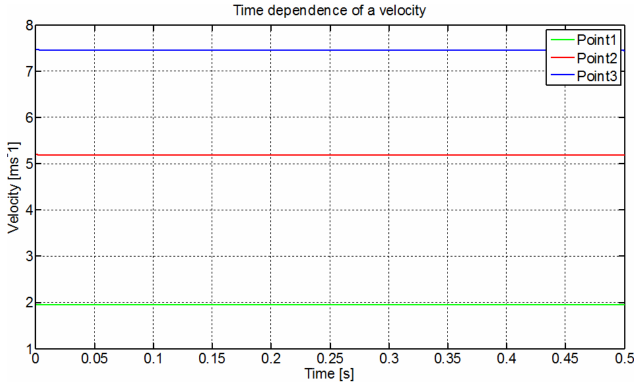

Fig. 10: Time dependence of velocity of chosen points

In the second one the velocity of cooling fan points was defined upon time dependence of angular velocity ω obtained by numerical differentiation. In contrast to former case it is possible to apply this computation also by accelerated or decelerated rotation movement. Velocities were determined according to:

$$v(t) = \omega(t)\, r(t) \tag{9}$$

For this instance the time dependence of velocities of particular points is showed in the fig.11.

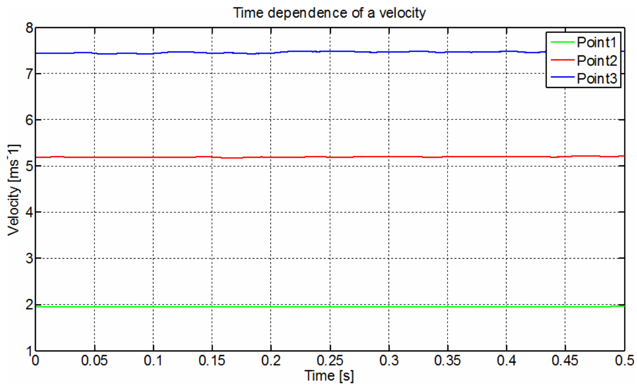

Fig. 11: Time dependence of velocities of selected points

4. Conclusions

Using of digital image correlation method is a convenient choice to solve a lot of strength or dynamic problems of mechanics. It does not face to almost any restrictions of investigated materials and can be used for various conditions. Operating software of correlation system offers background with intuitive interface which considerably facilitates researcher's work.

One of the restrictions by DIC movement analysis can be a fact that investigated object has to be situated in visual field of all cameras for all the time. With respect to that correlation systems use to be mostly formed by two cameras it is possible to use them particularly for solving of flat objects. With increasing number of cameras it is not so easy to ensure illuminating conditions equal for all respective cameras. Because of that it is necessary to exclude all shadows and reflections from snapshots. Another obstruction can be technical parameters of CCD cameras. Confined inner memory of cameras allows take 16000 snapshots with full resolution what gives rise to shorter acquisition time by higher sampling frequencies. Because of increasing sampling frequency the illumination of image is decreasing due to faster shutter time there is need to use more powerful source of light.

By investigation of rotary object movement the correlation error is increasing due to increasing distance of investigated points from centre of rotation. This phenomenon is due to that by higher speeds is displacement of points between two particular correlated snapshots higher. Because the numerical differentiation does not work with continuous values but with discrete ones it installs certain inaccuracy to calculation. This inaccuracy obtained by higher sampling frequencies is not such strong to influence accuracy of results.

The same way i.e. by sampling of displacements and their consecutive numerical processing in Matlab it is possible to perform analysis of decelerated motion. The results obtained by investigation of physical pendulum decelerated movement were verified by means of simulation in program MSC Adams/View and are described in other technical publications.

As correlation system is created by high speed digital cameras there is possibility to use it also for investigation of objects vibrations. Operating software of correlation system enables direct performing of spectral analysis from measured values which serves for acquirement of natural frequencies of investigated motion. By using of complementary program Modan 1.0 which was created on Technical University of Košice, the Faculty of mechanical engineering and the Department of applied mechanics and mechatronics, we can obtain not only natural frequencies of vibrations but also corresponding modal shapes. In this way we can perform experimental modal analysis directly on rotating components of construction (Trebuňa et al., 2010; Huňady et al., 2011).

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