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PRECISION OF SUB-PIXEL IMAGE DISPLACEMENT MEASUREMENTS

Key words: digital image correlation, optical flow, displacement detection, sub-pixel.

Abstract: Digital image correlation (DIC) and Optical flow method (Flow) are among the widely used methods in displacement detection applications. Both methods allow the use of sub-pixel information, leading to increase accuracy. The authors decided to verify the accuracy of the displacement detection of these methods by comparing the results with real displacement. The tests were performed on a special system for fatigue properties testing of microobjects (MFS). It allows setting very small movement, smaller than the value corresponding to the pixel size in the image. This allowed estimating measuring errors for both methods.

Precyzja pomiaru subpikselowych przesunięć obrazu

Słowa kluczowe: cyfrowa korelacja obrazu, wykrywanie przesunięcia obrazu, subpiksel, przepływ optyczny.

Streszczenie: Cyfrowa korelacja obrazów (DIC) i metoda przepływów (Optical flow) należą do szeroko wykorzystywanych metod w aplikacjach pozwalających na wykrywanie przemieszczeń. Obie metody pozwalają na wykorzystanie informacji subpikselowych, co prowadzi do zwiększenia dokładności. Autorzy artykułu postanowili sprawdzić i zweryfikować dokładności wykrywania przesunięcia przez te metody poprzez porównanie wyników z rzeczywistymi przesunięciami. Badania wykonano na specjalnym stanowisku badawczym MFS. Pozwala ono na zadawanie przesunięć w bardzo małym zakresie, tzn. o rząd mniejszych niż wartości odpowiadające rozmiarowi piksela w obrazie. Przeprowadzone badania pozwoliły na wyznaczenie błędu pomiaru obu metod.

Introduction

The measurements of displacements and strain are important topics in experimental mechanics. They can be implemented as contact and non-contact techniques. Conventional methods using strain gauges and direct measurements offer solutions to relatively simple problems, because they are based on point-wise measurements. Various optical methods, referring to non-contact techniques, have advantages over direct techniques, because they allow for full-field assessment. Holographic interferometry [1, 2], electronic speckle pattern interferometry (ESPI) [3, 4], Moiré interferometry [5], and Digital Image Correlation (DIC) [6, 7, 8, 12] are the most widely used ones. However, all the interferometric techniques have stringent requirements for system's stability and coherent light source. Moreover, they need processing of fringe patterns which is toilsome and time-consuming. Relatively smaller requirements are needed in DIC. This is one of the main digital signal processing methods. The basic set-up for DIC is simple, and it's composed of only a CCD detector with lens. The idea of work is based on the comparison of two images, before and after deformation. The resolution of this method can be increased when sub-pixel information is calculated. There are many algorithms performing this calculation. The basic theory of digital image correlation (DIC), as one of the methods to determine image motion, distortions, or cracks, has been used for many years. The second, commonly used method is the optical flow method. While the theoretical accuracy of sub-pixel methods is well known, little is known about real accuracy.

The main goal of this paper is to determine the real accuracy of two commonly used, sub-pixel methods used for displacement determination. The methods to be investigated will be DIC and optical flow.

1. Methods

1.1. Digital Image Correlation

Digital image correlation is a technique for measuring displacement and strain in real time. It is based on the analysis of high-resolution images captured during strain testing of the examined element. The surface of the testing object must be randomly textured (covered with a random pattern). If there is no texture, it must be applied onto the object before measuring. One of the images in the series is selected as a reference picture for all subsequent analyses. The reference image is divided into small rectangular regions (called subsets) containing N x N pixels (Fig. 1). The size of the subset depends on the quality and size of the random pattern. The DIC algorithm tracks the position of each subset from the reference image in all other images of the measurement series. Subsets search is accomplished by the cross-correlation coefficient calculation. For each subset, the displacement vectors U and V are calculated (Fig. 1). Thanks to the use of advanced interpolation methods, subpixel accuracy is achieved. As a result, a set of displacement maps is obtained that can be used for the computation of deformation maps.

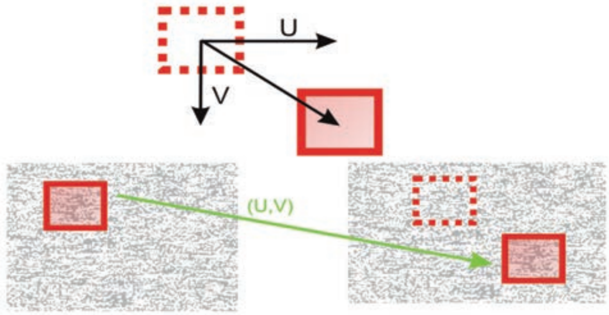

Fig. 1. The principle of DIC method
Source: Authors.

Finding the deformation in a subset is realized with the DIC algorithm by finding the maximum of the correlation function. Two different correlation criteria are used for the initial guess finding and its subsequent refinement. The initial guess is found by computing at integer locations the normalized cross correlation (NCC) (1).

Here f and g are, respectively, the reference and current image grayscale intensity functions at a specified location (x, y). Functions f_m (2) and g_m (3) correspond to the mean grayscale values of the reference and current subset.

$$C_{cc} = \frac{\sum_{(i,j)\in S}\left(f\left(\tilde{x}_{ref_i},\tilde{y}_{ref_j}\right)-f_m\right)\left(g\left(\tilde{x}_{cur_i},\tilde{y}_{cur_j}\right)-g_m\right)}{\sqrt{\sum_{(i,j)\in S}\left[f\left(\tilde{x}_{ref_i},\tilde{y}_{ref_j}\right)-f_m\right]^2\sum_{(i,j)\in S}\left[g\left(\tilde{x}_{cur_i},\tilde{y}_{cur_j}\right)-g_m\right]^2}} \tag{1}$$

$$f_m = \frac{\sum_{(i,j)\in S} f(\tilde{x}_{ref_i},\tilde{y}_{ref_j})}{n(S)} \tag{2}$$

$$g_m = \frac{\sum_{(i,j)\in S} g(\tilde{x}_{ref_i},\tilde{y}_{ref_j})}{n(S)} \tag{3}$$

where $n(S)$ is the number of data points in subset S. The initial guess thus yields u and v with integer (pixel) accuracy. The next step uses a nonlinear optimizer to refine these results with sub-pixel resolution by finding the minimum of Equation 4.

$$C_{LS} = \sum_{(i,j)\in S}\left[\frac{f\left(\tilde{x}_{ref_i},\tilde{y}_{ref_j}\right)-f_m}{\sqrt{\sum_{(i,j)\in S}\left[f\left(\tilde{x}_{ref_i},\tilde{y}_{ref_j}\right)-f_m\right]^2}}-\frac{g\left(\tilde{x}_{ref_i},\tilde{y}_{ref_j}\right)-g_m}{\sqrt{\sum_{(i,j)\in S}\left[g\left(\tilde{x}_{ref_i},\tilde{y}_{ref_j}\right)-g_m\right]^2}}\right]^2 \tag{4}$$

2. Optical flow

The usage of optical flow can examine the motion of objects between two consecutive image frames. The motion can be caused by the movement of object or camera. It is 2D vector field, where each vector is a displacement vector showing the movement of points from the first frame to the second frame.

Optical flow works on several assumptions:

1. The pixel intensities of an object do not change between consecutive frames.
2. Neighbouring pixels have similar motion.

Consider a pixel $I(x, y, t)$ (5) in first frame. It moves by distance (dx, dy) in next frame taken after dt time. Since those pixels are the same and intensity does not change, the following relationship is used:

$$I(x,y,t) = I(x+dx, y+dy, t+dt) \tag{5}$$

Then, take the Taylor series approximation of right-hand side, remove common terms and divide by dt to get Equation 6 as follows:

$$f_x u + f_y v + f_t = 0 \tag{6}$$

where

$$f_x = \frac{\partial f}{\partial x}; f_y = \frac{\partial f}{\partial y}$$

$$u = \frac{dx}{dt}; v = \frac{dy}{dt}$$

Equation (6) above is called the Optical Flow equation. In it, we can find f_x and f_y, and they are image gradients. Similarly, f_t is the gradient along time, but (u, v) is unknown. We cannot solve this one equation with two unknown variables. So several methods are provided to solve this problem and one of them is Lucas-Kanade.

3. Research system

In order to perform tests, an original research system for fatigue properties testing of microobjects (MFS) has been adopted. The system includes a primary loading unit ‘nanodrive’, a secondary loading unit ‘microdrive’, a unit for strain measurement by the digital image correlation method (CID), a unit for the measurement of strain by laser grating interferometry technique (moiré interferometry) (LFI), units for precise alignment and fastening of objects, and a computerized control an supply system [10, 11]. A scheme of the system is shown in Figure 2a. An overall view of the system is shown in Figure 2b.

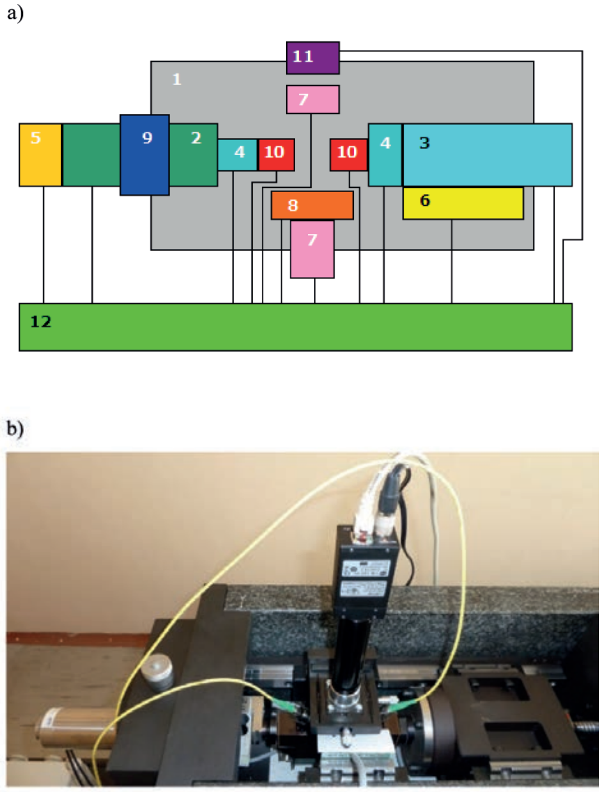

Fig. 2. Scheme of MFS system: (a) [10]: carrying base (1), primary loading unit ‘nanodrive’ (2), (3), force measurement unit (4), nanoscale displacement measurement unit (5), microscale displacement measurement unit (6), strain measurement unit by the digital image correlation technique (7), strain measurement unit by the laser grating interferometry technique (8), alignment unit (9), fastening unit (10), thermographic analysis (11), control and supply unit (12). The overall view of MFS system (b)

Source: a) material [10]; b) Authors.

In the discussed research, stand camera CM-140GE was used. Camera parameters are as follows: 1380 (h) x 1040 (v) active pixels, 4.65 µm square pixels, and 31 frames/second with full resolution. Microscope lens MOTIC PLAN APOCHROMAT ELWD 10 X were also used in the optical path.

Table 1. Basic technical parameters of the system

No.	Parameter	Value
1	The range of 'nanodrive' unit load	+ 3 500 N ÷ – 30 000 N
2	The range of 'nanodrive' unit movement	180 μm
3	The 'nanodrive' unit movement precision	1.8 nm
4	The range of 'microdrive' unit load	± 10 000 N
5	The range of 'microdrive' unit movement	0 – 100 mm
6	The 'microdrive' unit movement precision	1 μm
11	Workspace size	100x100x100 mm
12	Linearity error of 'nanodrive' movement	0.05 % of movement range

4. Methodology of the research

The MFS system described above has been used as a tool for precise specimen shifting. Figure 3 schematically shows the research system used in this article. Since the purpose of the study was not to check the behaviour of the sample under load conditions, the sample was mounted in only a moving grip, omitting jaws locking in the fixed grip – Fig 3. The result is an ability to precisely move the sample (with a resolution of 1.8 nm) without being subject to any action of forces. Because the physical area covered by the CCD camera was 25 mm wide and 18.84 mm high, and the pictures resolution was 1380 x 1040 pixels, the test system provided the ability to move the specimen horizontally with 0.0001 pixel precision.

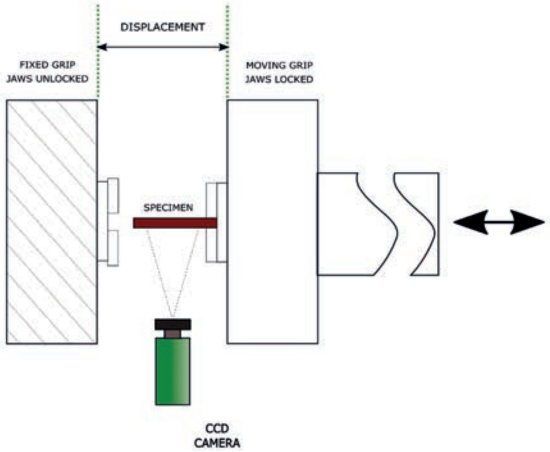

Fig. 3. Scheme of the test system used in this article
Source: Authors.

The configured test stand allowed the comparison of optical shift measurements with actual shift values set and executed by MFS. As a result of the tests, a sequence of 269 specimen images was obtained. The specimen shift between the first and last image of the above image sequence was 54.342 μm (3 pixels) – see Fig. 4.

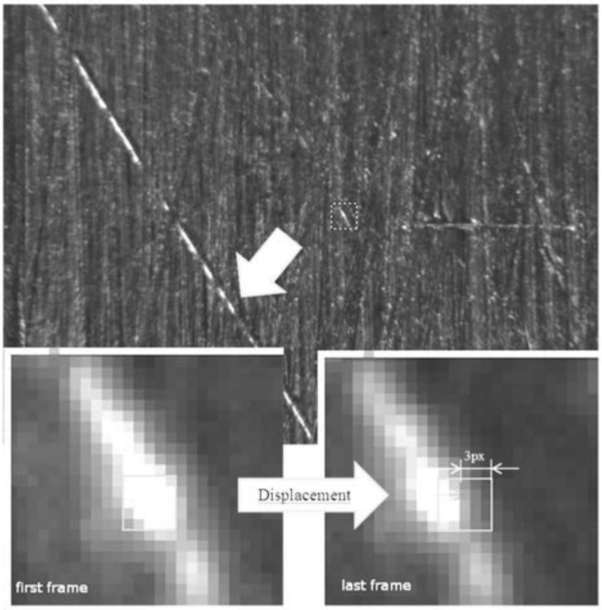

Fig. 4. Scheme of the test system used in this article
Source: Authors.

Two popular methods of image shifting calculation were used in the study: the classical digital image correlation method with normalized cross correlation (NCC) use – DIC, and the Lucas-Kanade method for optical flow estimation – Optical flow.

The configuration of the operating parameters of these methods was selected so that it was possible to compare their accuracy. Both methods calculated the shifts of the points determined by a grid of 120 by 80 points – see Fig. 5, which allow calculating shifts for 9600 points for each pair of images. For both methods, the position of the grid itself in the image was the same.

The common configuration parameter of these methods was the size and shape of the analysed neighbourhood of the surveyed point, which is a square-shaped area of 80 pixels per side. The final sample displacement was determined as the arithmetic mean of the shifts for all grid points (9600 points).

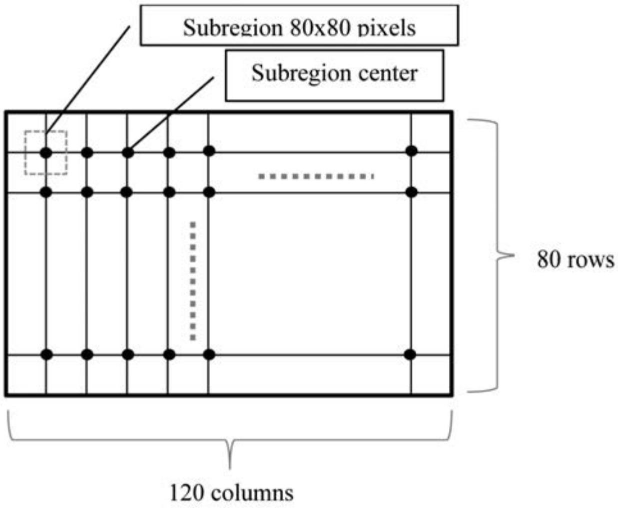

Fig. 5. Grid of analysed points
Source: Authors.

5. Results of the research

Figure 6 shows a comparison of the obtained results with the physical displacement (REAL). As we can see in Figure 6, the results obtained from both measurement methods (CORR, FLOW) are similar to the real measurement system settings. The incremental calculated displacement changes correspond to changes in the physical displacement set on the MFS system. Figure 6 also shows errors of optical measurements relative to real displacement (FLOW-REAL DELTA, CORR_REAL DELTA). From this part of the figure, we can see that changes in MFS generated displacement value do not affect the measurement error.

Figure 7 shows the difference of displacements calculated for each measurement method in comparison with the real displacement value. As we can see, the obtained results are similar for both methods.

Standard deviations were calculated for both errors and are given in Table 2.

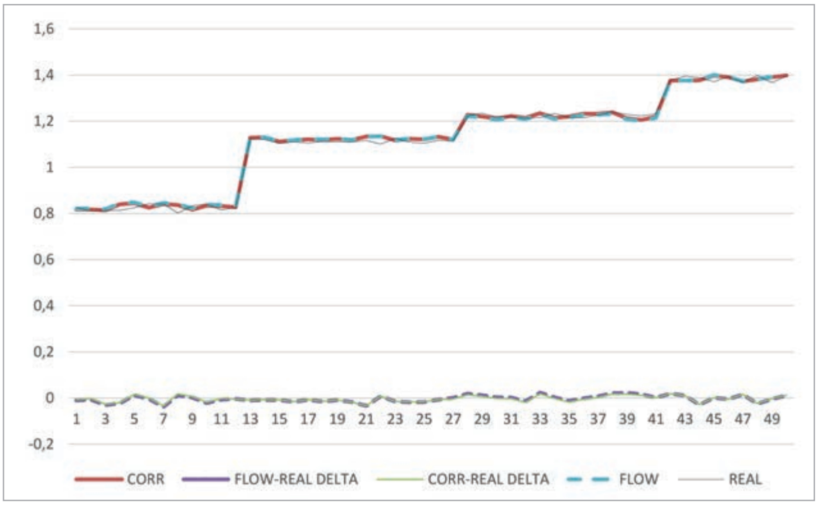

Fig. 6. Values of displacement for DIC and Optical Flow methods and reference displacement
Source: Authors.

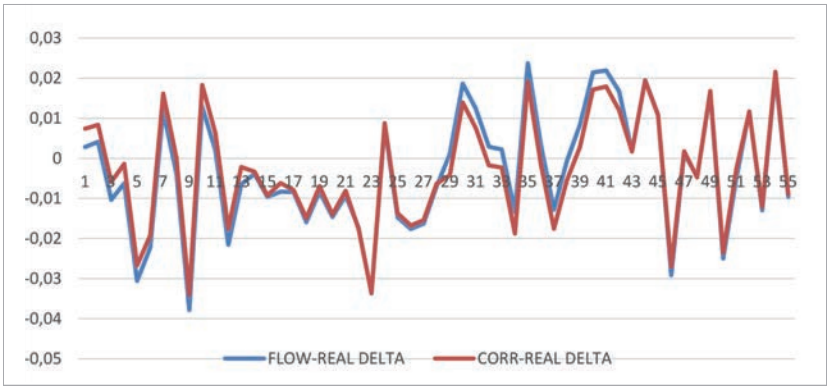

Fig. 7. Values of displacement for DIC and Optical Flow methods and reference displacement
Source: Authors.

Table 2. Standard deviation and average for a series of measurements

Method	Standard deviation	Average
Optical flow	0.015101	-0.00329
DIC	0.014143	-0.00341

Table 2 shows that the accuracies of both methods are similar and are approximately 0.01 pixels. Calculation time is an important parameter determining the use of optical measurement methods. Table 3 shows obtained calculation times for both methods, corresponding to determining of the displacement value between the two images at the 120x80 grid. Calculations were performed on a PC computer with an i5 2GHz processor and 8GB RAM memory. According to the measurements presented in Table 2, the faster method is the Optical Flow method (approximately 42 times).

Table 3. Calculation times

Method	Calculation time [s]
Optical flow	0.89
DIC	37.4

Conclusions

Based on the experiments, the accuracies of the two optical methods for measuring displacement (DIC and Optical flow) were determined. A displacement accuracy of 0.015 pixel has been reached (0.27 µm). In addition, it was found that the difference in accuracy between the two methods do not exceed 0.001 pixel. A simple speed test showed that the Optical Flow method was much faster. With comparable accuracy to DIC, it can be competitive with it in real time systems.

In summary, the Optical flow method achieves comparable results with the DIC method; however, due to the computing speed, it can be recommended for real time systems.

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