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THE VERIFICATION OF HYBRID IMAGE DEFORMATION ALGORITHM FOR PIV

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ABSTRACT
The aim of this paper was to test a newly designed algorithm for more accurate calculation of the image displacement of seeding particles when taking measurement using the Particle Image Velocimetry method. The proposed algorithm is based on modification of a classical iterative approach using a three-point subpixel interpolation and method using relative deformation of individual areas for accurate detection of signal peak position. The first part briefly describes the tested algorithm together with the results of the performed synthetic tests. The other part describes the measurement setup and the overall layout of the experiment. Subsequently, a comparison of results of the classical iterative scheme and our designed algorithm is carried out. The conclusion discusses the benefits of the tested algorithm, its advantages and disadvantages.
KEYWORDS: PIV, DEFORMATION, ACURACCY, TESTING, HYBRID, ALGORITHM, MEASUREMENT

SHRNUTÍ
Cílem této práce bylo otestovat nově navržený algoritmus pro přesnější výpočet posunutí obrazů značkovacích částic při měření metodou Particle Image Velocimetry. Navržený algoritmus je založen na modifikaci klasického iteračního přístupu s využitím tříbodové sub pixelové interpolace a metodě využívající vzájemné deformace jednotlivých oblastí pro přesné stanovení polohy signálového peaku. V první části je stručně popsán testovaný algoritmus spolu s výsledky již provedených syntetických testů. V další části práce je popsána měřicí trať a celkové uspořádání experimentu. Následně je provedeno srovnání výsledků klasického iteračního schématu a námi navrženého algoritmu. V závěru jsou pak diskutovány přínosy testovaného algoritmu jeho výhody a nevýhody.
KLÍČOVÁ SLOVA: PIV, DEFORMACE, PŘESNOST, TESTOVÁNÍ, ALGORITMUS, MĚŘENÍ

1. MODIFIED IMAGE DEFORMATION METHOD – IDM

Currently, several algorithms are used for measurement by the PIV method. Most often these are iterative methods based on relative displacement of interrogation areas, both on integer and subpixel displacement [1], [2], [3], [4], [5]. Another group of methods are algorithms based on relative deformation of particular areas with the aim of obtaining suitable deformation function that describes a spatial displacement of particles [5], [7], [8], [9]. Last but not least, various modifications of these methods and algorithms known as PTV are used during the PIV measurement. When taking measurement using the micro PIV method the calculation of time-averaging correlation equation is preferably used. When calculating the correlation function, either the direct calculation of the discrete function or quick Fourier transformation is used [1], [5], [10], [11]. Each of these algorithms has its advantages and disadvantages and their function has to be always verified using both synthetic tests and real experiments. The work includes testing of our designed and already tested algorithm on real measurement. The tested algorithm is based on a combination of classical iterative scheme and relative deformation of interrogation areas in last iteration. Such proposed algorithm has been thoroughly tested [1], [12], using synthetic data and measurement errors were determined depending on individual parameters (density of particles Ni, gradient....) On the grounds of the previous analysis a new algorithm based on IDM method and using 2D regression when calculating the center of the signal peak was designed, programmed and verified. The proposed algorithm can be summarized in several following points:

- Calculation of the relative displacement using the iterative scheme with the possibility of data validation in particular intermediate steps
- Determination of spatial gradient
- Relative deformation of double images

- Detection of noise level inside Interrogation Area – IA and its subsequent removal using threshold value.
- Correlation plane calculation with the help of FFT
- Using of linear filter for "smoothing" the correlation plane

Detection of signal peak center in the correlation plane with the use of 2D regression.

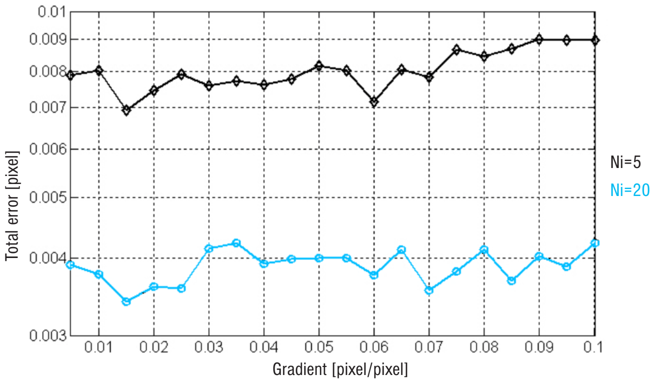

FIGURE 1: Result of UFT for hybrid IDM method, test of sensitivity to velocity gradient, IA = 32 × 32 pixels, data without noise.
OBRÁZEK 1: Výsledky UFT testu pro hybridní IDM metodu. Test citlivosti na rychlostní gradient, IA = 32 × 32 pixels, syntetická data bez přidaného šumu

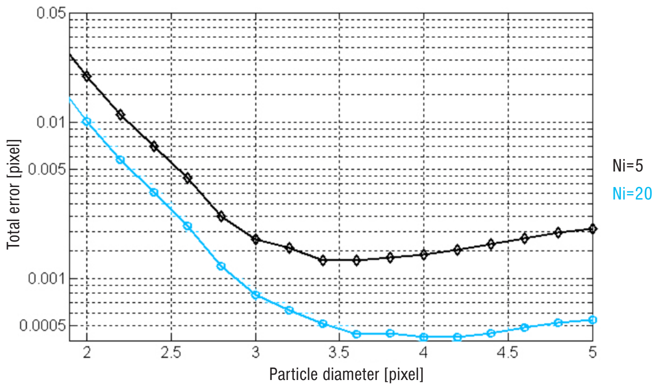

FIGURE 2: Result of UFT for hybrid IDM method, test of sensitivity to size of particle diameter, constant displacement of 0.5 pixels, IA = 32 × 32 pixels, data without noise.
OBRÁZEK 2: Výsledky UFT testu pro hybridní IDM metodu. Test citlivosti na velikost obrazu značkovacích částic, IA = 32 × 32 pixels, syntetická data bez přidaného šumu

It can be concluded that, based on the results of the synthetic tests [1], [2], [8], the foregoing algorithm has a potential to provide greater measurement accuracy of the PIV method compared to the classical approach and it does not substantially increase the time required for the displacement calculation. The main advantage of the algorithm is the especially significant insensitivity to the velocity gradient magnitude inside IO. Another significant advantage is that detection and the subsequent noise removal enables to greatly suppress the negative impact of noise on measurement accuracy. This method is effective enough to completely suppress the negative impact of noise for the noise level up to 5%. At higher values the measurement error is lower by about 70% when using the filter. The presented results indicate that the proposed evaluation method significantly increases the measurement accuracy even under conditions where due to the present noise the accuracy of ordinary algorithm is insufficient Figure 1 and Figure 2.

2. TEST OF NEW ALGORITHM ON REAL DATA

Since the foregoing algorithm has been thoroughly tested only on synthetic data [13] it was necessary to use real data from the measurement for its final verification. For testing of the new algorithm the measurement of laminar flow in rectangular channel behind a step was chosen. The reason why such measurement was chosen as testing was the large spatial gradient in the measured area and also, given the achieved Reynolds number, the expected low level of turbulence in the flow. Due to the quality layout of the experiment it was possible to reach the Reynolds number in the place of sudden enlargement, Re=360. A brief description of the experiment is provided in the following chapter.

2.1 MEASUREMENT SETUP AND EXPERIMENT LAYOUT

The measurement was carried out in the laboratory of the Institute of Hydrodynamics in the channel of rectangular cross-section of 20 × 200 mm whereby the channel is abruptly enlarged to 40 × 200 mm [14]. The enlargement was performed by retreating of the channel bottom. The measured part of the channel was made from Plexiglas. The flow rate in the channel

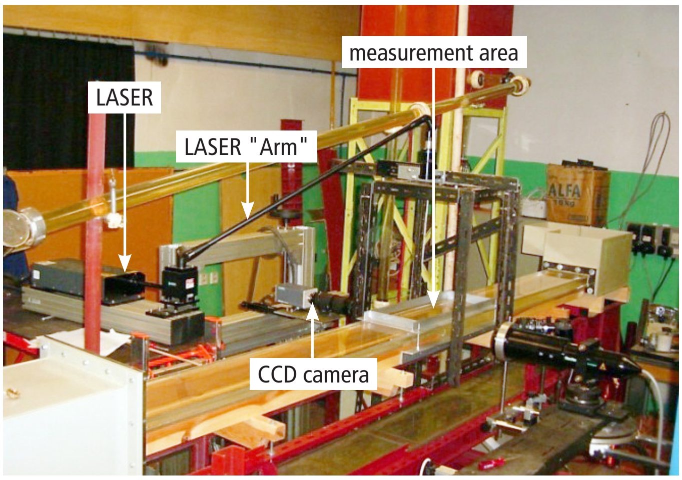

FIGURE 3: Measurement system layout in laboratory of the Institute of Hydrodynamics
OBRÁZEK 3: Uspořádání experimentu v laboratořích Ústavu pro hydrodynamiku.

was set to a value corresponding to the maximum velocity of 0.018 ms^{-1}. Standard polyamide particles with a diameter of 10 μm were used as seeding particles. The indicated density of these particles is 1030 kgm^{-3}. For ease of traversing of the light sheet across the channel and also CCD camera, it was necessary to use precise linear actuators. The optics forming the laser sheet was installed on the so-called LASER "Arm", which allows easier handling with the light sheet without having to move with the whole laser, which significantly increases the demands on the rigidity of the structure. A more accurate picture of the experiment layout can be obtained from Figure 3.

Prior to the verification of the functionality of the new designed algorithm it was necessary to verify the acceptability for use of the chosen particles. In order to verify the suitability of the used particles it is necessary to know the kinematic viscosity of the flowing fluid, in our case the water. Kinematic viscosity of water was considered $\nu = 1.004 \times 10^{-6}$. Furthermore, it is necessary to estimate the maximum frequency of the disturbance to be expected in the flow. In the laminar regime, which is presented here, we assume the frequencies to be proportionally lower than in the turbulent regime, however, if we are about to apply the conclusions of the work also on the turbulent regime we have to consider a maximum frequency of disturbance at least 1 kHz. The calculated value of the Stokes number according to [15] for given experiment is N_s=1.268. If we know the value of the Stokes number we can according to [15] determine the phase delay $\beta = 0.1°$ and amplitude ratio $\eta = 0.999$. It follows from the above that these seeding particles are capable of monitoring the flow in the liquid at frequencies up to 1 kHz. In order to better illustrate the properties of the used particles it is necessary to indicate the time response of a given particle for movement in water, which is 5.71 μs. The size of the time response is also adequate for monitoring of flow of frequency of about 1 kHz.

3. MEASUREMENT RESULTS

The measured data were subjected to two analyses. The first was an analysis using the classical algorithm known as adaptive correlation. The size of the target IA was set to 32 × 32 pixels. The algorithm was carried out in two iterations. The size of IA in first iteration was 64 × 64 pixels. Overlapping of IA was set to 75%. Due to the second algorithm the modification of the IDM algorithm was designed. The modified IDM algorithm is also an iterative algorithm and the main difference was that after the second iteration which was performed according to classical procedure the third iteration was carried out. In this iteration the individual IAs were mutually "deformed" based on the knowledge of the displacement field calculated in previous iterations. 200 double images in eight bit resolution were processed. The results are shown in the form of velocity profiles downstream of the fluid. Furthermore, the values of fluctuations in the same direction are provided. Another observed parameter was the shape of histogram of the measured displacements which due to the flow character should have uniform distribution. The presented results Figure 4 up to Figure 7 obtained using the classical adaptive correlation several things must be noticed:

1. Medium velocity profile shows significant ripples for which there is no physical reason.
2. Values of fluctuations indicate low values in places where the measured displacement in last iteration was near zero.
3. Values of fluctuations are higher in places corresponding to the measured displacement of 0.5 pixels in the last iteration.
4. Maximum values of fluctuations reach 0.26 pixels.

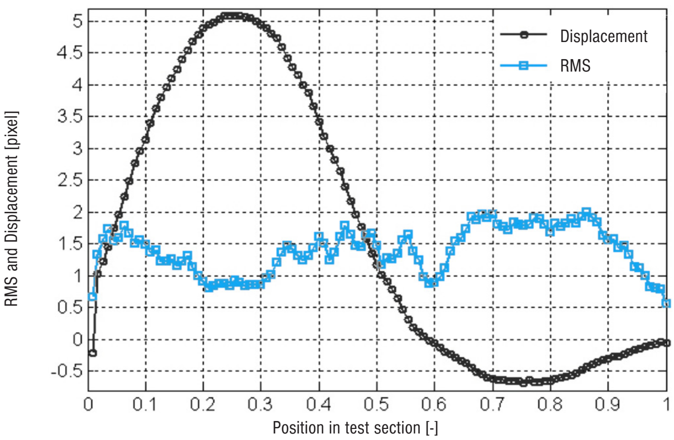

FIGURE4: Measured displacements and RMS using adaptive correlation. RMS fluctuations are multiplied by 10.
OBRÁZEK 4: Naměřený rychlostní profil a fluktuace pomocí adaptivní korelace. Hodnoty fluktuace jsou desetkrát zvětšeny.

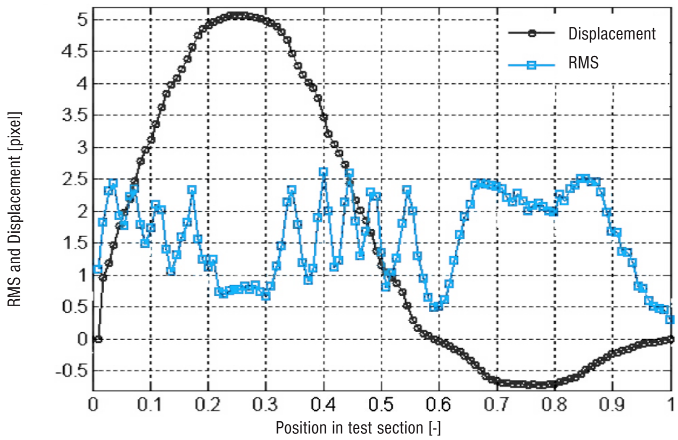

FIGURE 5: Measured displacements and RMS using hybrid IDM algorithm. RMS fluctuations are multiplied by 10.
OBRÁZEK 5: Naměřený rychlostní profil a fluktuace pomocí hybridního IDM algoritmu. Hodnoty fluktuace jsou desetkrát zvětšeny.

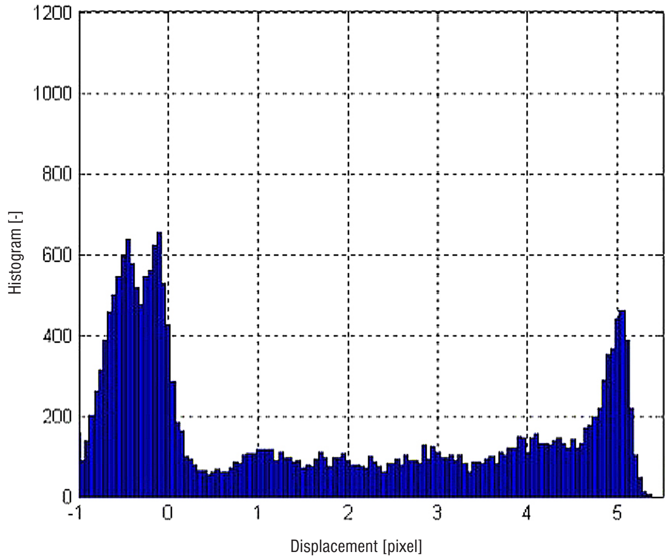

FIGURE 6: Histogram of measured displacements using adaptive correlation.
OBRÁZEK 6: Histogram naměřených posunutí – adaptivní korelace.

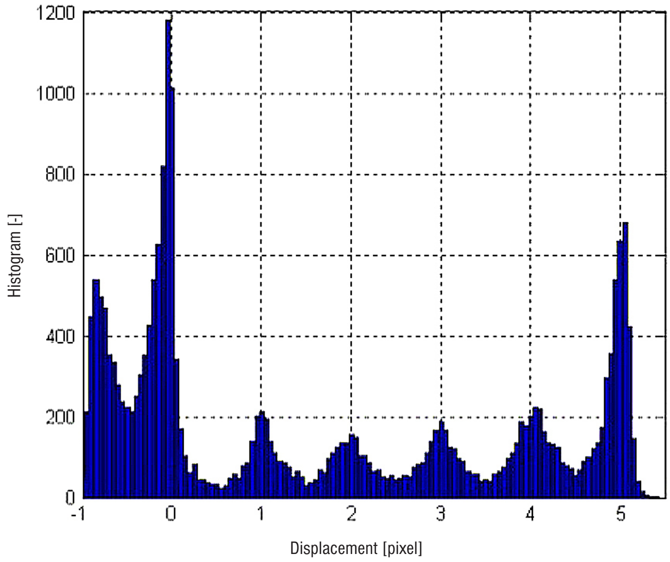

FIGURE 7: Histogram of measured displacements using hybrid IDM algorithm
OBRÁZEK 7: Histogram naměřených posunutí – hybridní IDM algoritmus.

The histogram of the measured displacements indicates an increased amount of integer displacements.The reason for these deficiencies is the worsened quality of the used data, especially the noise level and the number of overexposed pixels considering the number of particles. In this case, the classical adaptive correlation indicates "susceptibility" to measure the integer displacements. This imperfection of the algorithm becomes evident particularly at low number of particles inside the IA and at deterioration in the quality of the analyzed data. Described imperfection is clearly identifiable from the histogram of the measured displacements (Figure 6). It is clearly evident that the amount of integer displacements measured with the help of this method is significantly higher than the amount of non-integer displacements. Minimum rate values are in places where the measured displacement in the last iteration was ±0.5 pixels. The other pair of diagrams in Figure 5 and Figure 7 shows similar results obtained by analyzing the same data, however, using the modified IDM algorithm. If we compare the results obtained with the adaptive correlation with the results obtained using the modified IDM algorithm, Figure 4 and Figure 5, we come to the following findings:

1. The mean velocity profile does not show any ripple in points of measurement of the integer displacement.
2. Values of fluctuation do not show significant minima in points of measurement of the integer displacement.
3. Values of fluctuation do not show significant maxima in points of measurement of the 0.5 pixel displacement.
4. Maximum values of fluctuations reach 0.2 pixels.

The histogram of the measured displacements does not indicate an increased amount of integer displacements. Increase in accuracy using the modified IDM algorithm is particularly evident when comparing the values of fluctuations measured with the help of a pair of tested algorithms (Figure 8). This comparison clearly shows that using the IDM algorithm, given the quality of the measured data, the values of fluctuation were reduced by about 30%. Furthermore, the significant tendency of the adaptive correlation to evaluate the integer displacement has been removed. This phenomenon caused that the values of fluctuations show a periodic character and the inexperienced experimenter could come to false conclusions based on such

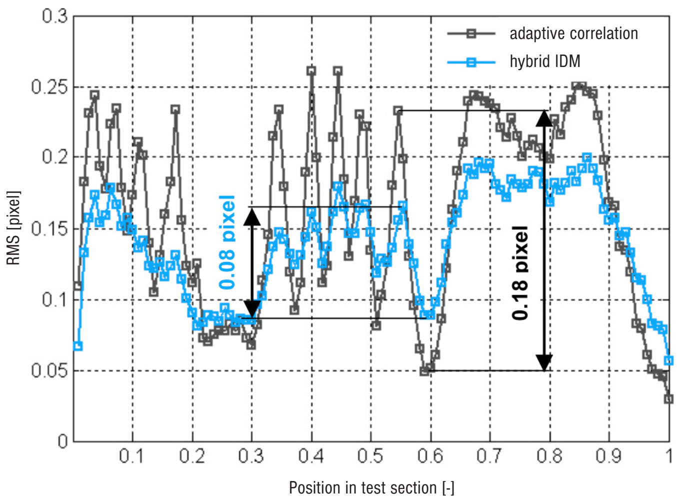

FIGURE 8: Comparison of fluctuations measured by adaptive correlation and modified IDM algorithm.
OBRÁZEK 8: Porovnání fluktuací naměřených pomocí adaptivní korelace a hybridního IDM algoritmu.

evaluated results. Wavy character of the velocity profile as well as periodic increase and decrease of fluctuations measured by the adaptive correlation is caused only by poor quality of recorded data and by used algorithm. Our proposed method does not indicate such deficiency and can be used even if the quality of the measured data is not the best. Maximum differences in measured fluctuations for both methods are plotted in diagram in Figure 8. The maximum differences in values of fluctuations correspond to values of accuracy which can be determined based on results of the sensitivity tests.

4. CONCLUSION

The aim of the presented work was to verify the newly designed algorithm based on modification of the IDM algorithm and adaptive correlation. The results of the comparison confirm the assumptions arising from the sensitivity tests. Decreased level of fluctuations by 30% and uniform distribution of the histogram of the measured displacements clearly prioritize the modified IDM method compared to the classical adaptive correlation. The classical adaptive correlation indicates significant non-uniform distribution in measured displacements and fluctuations based on which the experimenter can come to false conclusions. Such deficiencies are not indicated when using the modified IDM method. Part of the newly designed algorithm is also a procedure to eliminate the noise and its impact.

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