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VELOCITY FIELD DETERMINATION USING SIMPLE PIV METHOD

WYZNACZANIE POLA PRĘDKOŚCI Z WYKORZYSTANIEM METODY OBSERWACJI RUCHU CZĄSTEK WSKAŹNIKOWYCH (PIV)

The paper describes the cross-correlation method for velocity field determination on the basis of measurements performed with the use of a simple PIV method. The test stand for the image recording by two CCD synchronized cameras has been developed. Cameras make digital frames in two successive time intervals. The same observation field is provided by an optical beam splitter. Image acquisition system is controlled by the assembly which allows changing of exposure time and time delay between images in a pair. The digital frames showing fluid convection movements in cubicoid cuvette were numerically treated to adjust them to the needs of determining the velocity profile. The description of transformations leading to evaluation of the brightness correlation which results in a two-dimensional vector map of velocity field was also presented.

Keywords: velocity field, flow visualization, cross-correlation method, PIV

W artykule opisano zastosowanie metody korelacji krzyżowych (cross-correlation) do wyznaczania pola prędkości na podstawie pomiarów wykonanych z wykorzystaniem metody obserwacji ruchu cząstek wskaźnikowych PIV. W obserwacjach wykorzystano stanowisko pomiarowe do rejestracji obrazów oparte o dwie zsynchronizowane ze sobą kamery CCD. Kamery wykonują cyfrowe zdjęcia w dwóch następujących po sobie chwilach czasu. Jednakowe pole obserwacji zapewnia optyczny rozdzielacz obrazu. System rejestracji jest sterowany układem pozwalającym na zmianę czasów ekspozycji oraz odstępu czasowego pomiędzy obrazami stanowiącymi parę. Na przykładzie wykonanych przez autorów cyfrowych zdjęć par obrazów przedstawiających ruchy konwekcyjne wody ogrzewanej w prostopadłościennej kuwecie zaprezentowano zastosowanie metody cyfrowej korekty obrazu mające na celu dostosowanie obrazów do potrzeb wyznaczenia wektorów prędkości. Zaprezentowano opis przekształceń prowadzących do wyznaczenia korelacji jasności, których rezultatem jest dwuwymiarowa wektorowa mapa pola prędkości.

1. Introduction

Liquid flow studies belong to the basic scientific and engineering tasks. Determining the flow parameters such as the velocity field, temperature or pressure allows to gain the cognitive knowledge about the process. Moreover it often serves for verification or identification of mathematical models especially when the complexity of a model is considerable. The knowledge of velocity is basic for a description of various phenomena in metallurgy and related areas. For instance heat and mass transport in gases and liquids strongly depends on velocity field. The movements of liquid steel in a steel making converter or in a casting mould can be mentioned as examples. The velocity measurements are very difficult in industrial practice, particularly for hot liquid metals, therefore so-called cold models are frequently investigated. The steel is replaced by the water (or other liquid) which allows to carry out experiments under much lower temperature. Sometimes an experiment is the only instrument to estimate phenomenon for which creating the theoretical description or obtaining its solution is very difficult.

There are many measurement methods to estimate liquid velocity, from the simple ones mostly used in industrial investigations, to the complex adjusted to the individual requirements of examined phenomena. In many cases the aim of the velocity measurement is to estimate its average value. This mainly concerns the methods of the flow flux estimation.

The well-know and accurate methods are, among the others: hot-wire anemometry, Laser Doppler Anemom-

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etry (LDA) and Particle Image Velocimetry (PIV). The first one is an invasion system which is its major defect. It requires a probe immersed in moving liquid, therefore application of this method is limited, particularly in such cases where the presence of a probe disturbs the flow. But the method is not expensive and often offers good alternative in comparison to others. Laser anemometer does not need any probe therefore does not disturb the flow. It is used to determine the velocity in one point only and does not allow the observation of velocity profile. PIV method requires the illumination of the added particles in a flowing liquid and recording two successive images (pair of images) of the same area. The particles displacements observed in two different frames allow to determine a velocity field in the observed area, knowing the time interval between taking these images. In the case when image recording is taken by digital cameras CCD, such research method is called Digital Particle Image Velocimetry (DPIV).

Velocity measurements face two basic problems:

– carrying lots of successive good quality picture pairs, having a possibility of precise determination of a time gap between pictures in a pair, while the time range selection should be wide enough to enable the measurement of very high ($\Delta\tau \longrightarrow 0$) and very low velocities,

– determination velocity profiles by means of statistical analysis on the base of taken pictures.

Therefore the PIV technology consists of two stages: first, the two successive images of the liquid containing seeded particles are recorded during the experiment, then the specific processing of the images leads to the estimation of velocity profile. A pulsed laser of very short time period (e.g. 5ns for YAG laser) providing a high radiation power density is usually used [1], what enables “freezing” the particle in the image even at the very high velocities (above 100m/s). The impulse reception frequency of a laser used in PIV is precisely defined (10-30Hz for YAG lasers). The measurement range is limited therefore to the velocities fixed by the watching area dimension and the repetition time. For this reason double-pulsed lasers are used which enable applying of the delay between two successive images in considerable greater range. When very high velocities are to be measured, recording a pair of frames by CCD camera is very difficult therefore. A special cross-correlation camera should be used that shifts the investigation costs to a very high level.

2. Image recording

2.1. Optical system

For slow movement observations a simple, relatively inexpensive and effective PIV based experimental method can be applied for image recording. Pairs of pictures are registered by means of two separate synchronized cameras CCD. Similar solutions have been successfully adopted in practice [2, 3, 4].

The optical system must provide recording the same area by both cameras. This effect can be accomplished using a perpendicular system of two cameras CCD supplied with an image splitter, behind which two identical lenses of properly chosen focal length were applied to transmit images on camera photosensitive matrix. (Fig. 1.).

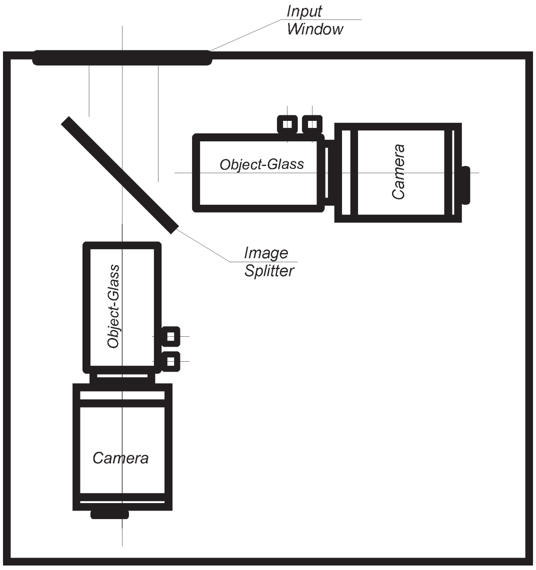

Fig. 1. Optical system of image recording

The assembly of cameras lenses and a beam splitter are enclosed in a dust proof housing. The image enters the housing through an input window made of a glass plate bilaterally coated by an antireflecting coat. There are inevitable differences in the field of view of each camera caused by an image splitter and separate glasses. It is therefore necessary to calibrate the optical system before measurements by means of a special matrix prepared for this purpose. The matrix is equipped with several light emitting diodes and situated in the field of view of cameras. For the illumination of a field of view the set of continuously working luminous laser knife made up of a laser line generator and a cylindrical lens was applied. A line generator supplied a divergent flat beam, 1mm wide, with diminishing light density at growing distance from a generator. To maintain a constant light density, a light beam was collimated by a cylindrical lens into a 1mm x 100mm flat band. Laser light knife system is shown in Fig. 2.

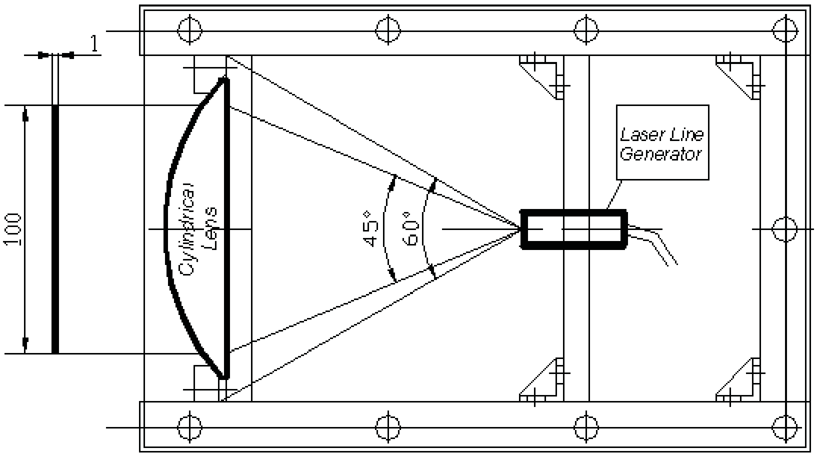

Fig. 2. Laser illuminator system

2.2. Remote control system

Microcomputer PC class is used for an image acquisition control. It is equipped with two fire wire cards with interfaces IEEE-1394, to witch CCD cameras are connected, and a timer card allowing the precise impulse generation released by the cameras.

TABLE

The selected parameters of image recording system

Matrix resolution	1280*960 pixels
Number of recording pairs of images	1 – 50
Range of a time gap between pairs	1 – 600s
Range of a time gap between images in a pair	0,001 – 10s but more then 0.9 gap between pairs
Range of exposure time	0,00005s – 1,0s
Maximal dimensions of a field of view	100*100mm

A specific program was written for control of image recording. The most important system parameters are given in Table 1.

When parameters of the test have been established (e.g. 10 image pairs with an exposure time equal to 1ms and time delay between images in pair equal to 3ms), an impulse generation program is sent to a counter card which starts generation of an adequate impulse sequence for releasing cameras after 2-3s. A time precision of such impulses is very high because they are disturbed neither by not-open microprocessor nor operational system routines. The program can be applied on computers equipped with Windows 2000 or Windows XP operating systems.

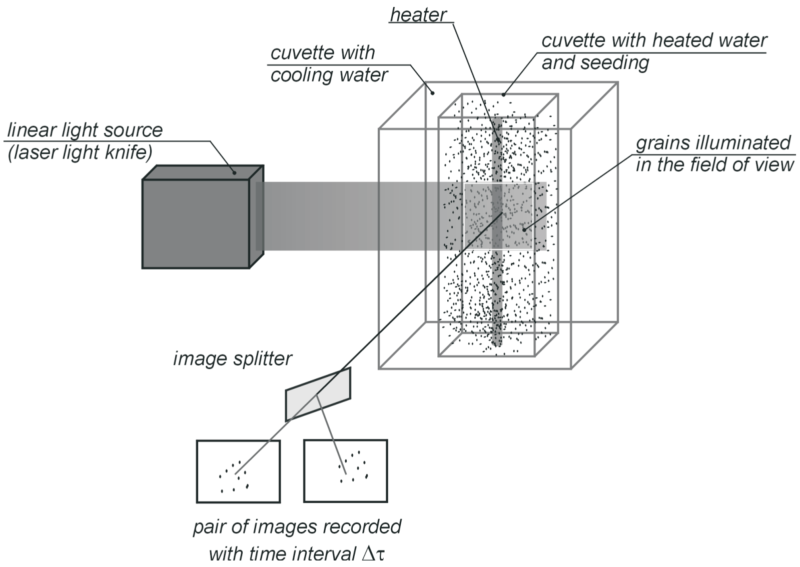

Fig. 3. Schematic diagram of the measurement stand used in experiments

3. Measurement laboratory stand

The presented method was used for a determination of a velocity profile in moving water. The natural convection caused by the electric heater located in a symmetry center of a cubicoid cell put liquid into motion. The experimental stand (Fig. 3) consists of the following items:

- cubicoid cell filled with liquid,
- source of a coherence light,
- optical system shaping laser beam into “flat” light knife of a perpendicular cross section,
- image acquisition system,
- numerical processor.

In most cases the addition of seeding particles to the liquid is necessary, when a PIV method is applied. The polyamid, size of grains 50 μm, was used in experiments. Light dissipated by seeded particles is recorded in a plane normal to the light wave propagation, by means of two CCD cameras linked to a computer card (Frame Grabber). The recorded images are stored on a computer hard disc. Then they are submitted to a numerical processing. Computer recording is continuously performed. The suitable selection of quantity of image pairs, time delay between images in a pair and time delay between pairs permits to trace the particles movement in the liquid and subsequently to determine velocity profile (e.g. by image correlation method).

4. Image correction

In the presented PIV method a flat light beam (a laser beam transformed by the appropriate optical configurations into a luminous knife) illuminates seeded particles situated in a moving liquid. Then several (following one by one) image pairs of the same field are recorded.

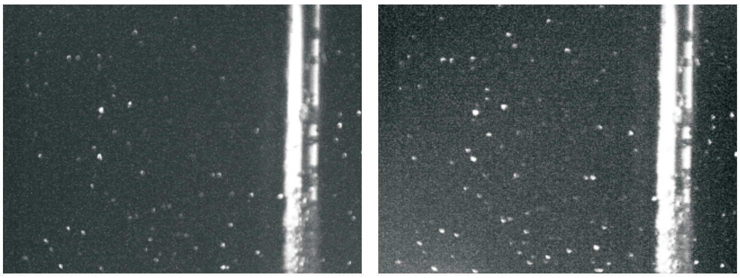
4 2006-01-04_13-13-50 camera1 (obraz 5z10_ 0,300s_ 1,0s).bmp 4 2006-01-04_13-13-50 camera2 (obraz 5z10_ 0,300s_ 1,0s).bmp

Fig. 4. The example images of the flow recorded using the laser beam illumination. The bright dots of a polyamide seeding are visible in the pictures

The acquired images yield some limitation when used for the further correlation analysis:

- The adequate concentration of added particles should be applied (too large concentration is not recommended),
- Steady saturation and brightness of recorded images are required.

The initial frames were black and white in 256 grade gray color scale. The images showed the successive phases of water movement. The size of recorded images was 1280 x 960 pixels with 11 pixels/mm resolution. The size of the observed plane illuminated by the laser light was 100 × 100mm (Fig. 4).

The numerous number of images received as a result of experiment must be usually analyzed, so it is very helpful to apply the automatic image correction system. Using well known in scientific literature tools [5÷7], the author computer program was developed. It allows to decrease a preparation time of images acquired during the experiment for the further analysis. The images are processed using the basic transformations [8÷12]:

- median filter,
- balance,
- contrast lifting,
- the palette change from eight to one bit,
- submitting image to the detection of a grain edge,
- a morphological operation of closing selected objects.

The results of the digital image treatment are shown in the Figures No Fig. 5a, Fig. 5b, Fig. 5c, Fig. 5d.

The analysis of the seeded particles displacement required elaborating separate algorithms of an additional image treatment. They were based on an interpolation of spline functions [13, 14]. Two digital images recorded at a time delay $\Delta\tau$ are represented by rectangular discrete distribution of pixel brightness. The brightness correlation was estimated with the aid of two subfields (windows): a subfield ***s1*** situated in the first image in a pair and a subfield ***s2*** situated in the second one. The different window magnitude was examined: 16×16, 32×32, 64×64 pixels. The similarity of two windows (cross-correlation method) was estimated by a correlation factor. After taking into consideration a scale coefficient and the time between recorded images one can calculate the velocity field from the displacement field (Fig. 6)

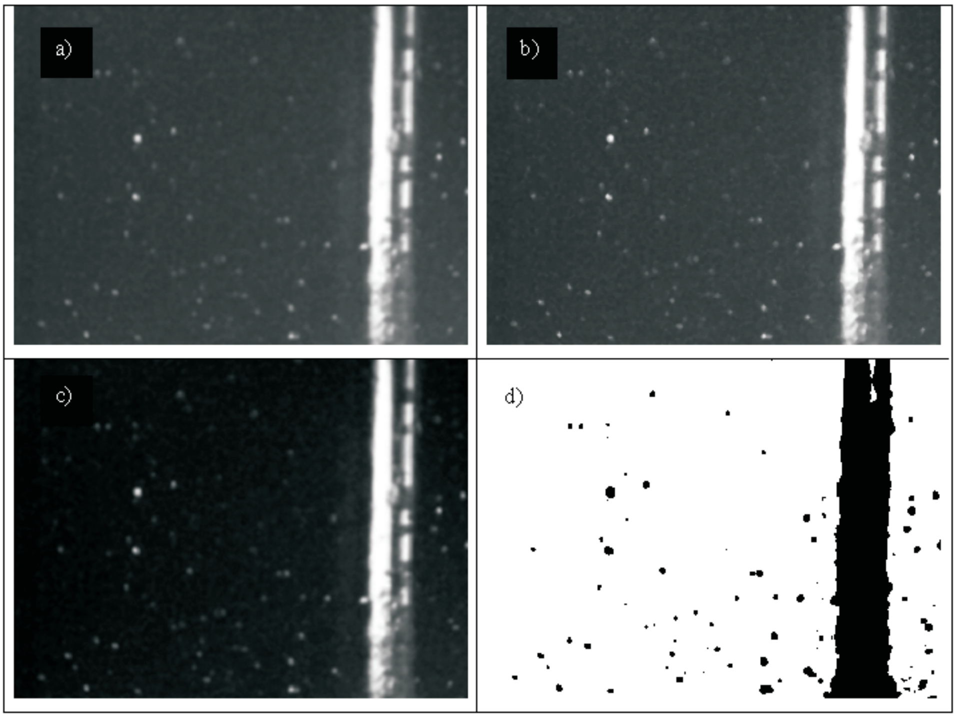

Fig. 5. Digital image transformation with the use of a) median filter; b) contrast lifting; c) averaging filter; d) after tresholding operation

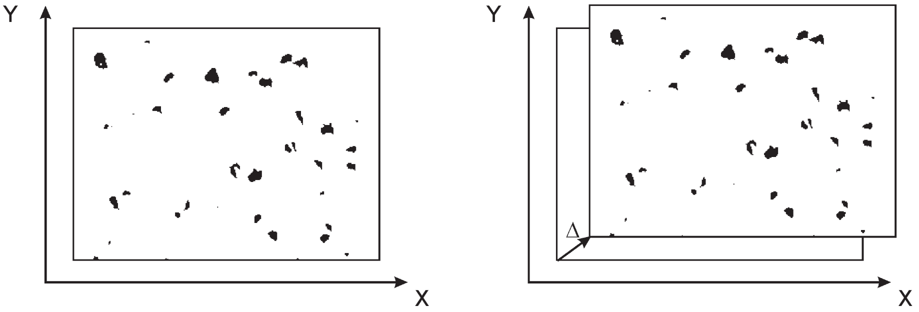

Fig. 6. Principle of the window displacement [14]

The direct correlation function in a standard shape can be written as [15]:

$$\Phi_{\Delta i,\Delta j} = \frac{\sum\limits_{i=0}^{N}\sum\limits_{j=0}^{M}\left[I_{i,j}^{s1}\cdot I_{i+\Delta x,j+\Delta y}^{s2}\right]}{\sqrt{\sum\limits_{i=0}^{N}\sum\limits_{j=0}^{M}\left[I_{i,j}^{s1}\right]^2}\sqrt{\sum\limits_{i=0}^{N}\sum\limits_{j=0}^{M}\left[I_{i+\Delta x,j+\Delta y}^{s2}\right]^2}}$$

where:

NxM – the field size,

$s1$, $s2$ – subfields in the successive images in a pair,

Δx, Δy – a subfield displacement in x and y direction respectively,

I – brightness of particular pixels in the recorded image.

The errors resulting from data (image quality) and the correlation method inaccuracy were eliminated by multiplication a correlation table of tested subfield by a correlation table coming up from an adjacent subfield or subfields:

$$\Phi'_{\Delta i,\Delta j} = \frac{\sum\limits_{i=0}^{N}\sum\limits_{j=0}^{M}\left[I_{i,j}^{s1}\cdot I_{i+\Delta x,j+\Delta y}^{s2}\right]}{\sqrt{\sum\limits_{i=0}^{N}\sum\limits_{j=0}^{M}\left[I_{i,j}^{s1}\right]^2}\sqrt{\sum\limits_{i=0}^{N}\sum\limits_{j=0}^{M}\left[I_{i+\Delta x,j+\Delta y}^{s2}\right]^2}} \cdot \frac{\sum\limits_{k=0}^{N}\sum\limits_{l=0}^{M}\left[I_{k,l}^{s1}\cdot I_{k+\Delta x,l+\Delta y}^{s2}\right]}{\sqrt{\sum\limits_{k=0}^{N}\sum\limits_{l=0}^{M}\left[I_{k,l}^{s1}\right]^2}\sqrt{\sum\limits_{k=0}^{N}\sum\limits_{l=0}^{M}\left[I_{k+\Delta x,l+\Delta y}^{s2}\right]^2}}$$

As a result of the performed analysis a two -dimensional vector map of velocity profile was determined (Figs. Fig. 7,Fig. 8)

Fig. 7. The determined velocity vectors marked in image

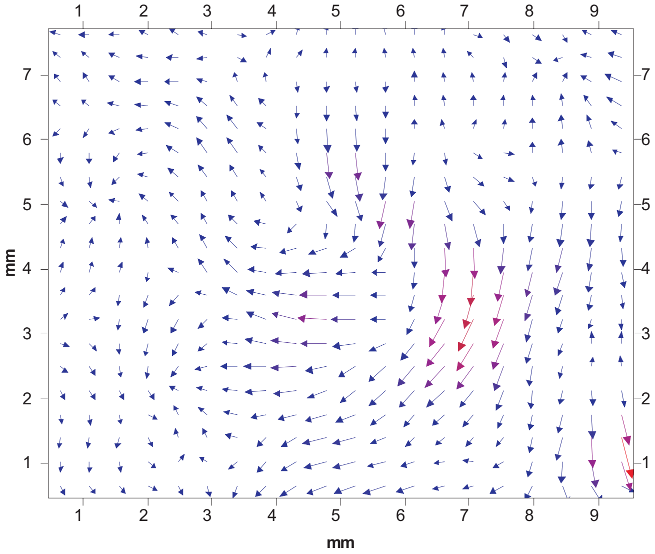

Fig. 8. Interpolated velocity field

5. Final Remarks

The estimation of the velocity profiles in a slow moving liquid using the presented technique requires taking pairs of good quality images with properly chosen time delay $\Delta\tau$ fitted to the measured velocity. For the Polyamid seeding – size of grains 50 μm – applied in presented experiment, the best image to determine particle trajectories suspended in the flow and the determination of velocity field was obtained when the range of a time gap between pairs was 1s, the range of a time gap between images in a pair was 0.7s and the exposure time 5ms.The quality of images depends on their unique saturation, brightness and the setting of camera depth sharpness. The movement of seeded particles in a direction perpendicular to observation plane (luminous knife's) disturbs the searched velocity profile resulting in spurious vectors. The influence of the dimension of an interrogation windows was observed. The best results occurred for a subfield 64×64 pixels in size. Experimental investigations confirmed the usability of developed numerical procedures applying cross-correlation method for velocity profile evaluation.

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