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Visualisation and measurement of high-speed pulsating and continuous water jets

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ABSTRACT

The results of an experiment focused on the visualisation of pulsating and continuous water jets are presented in this paper. Water jet technology is widely used for surface cleaning, removal of damaged material layers, preparation of surfaces, and in many other applications. The aim of the experiment was to test the applicability of the shadowgraph technique combined with PIV processing algorithms to visualise water jet structure and analyse flow velocity field. Knowledge of the geometry and velocity fields of pulsating water jets generated by a high-pressure system is necessary for the optimal tuning of the system in respect of the maximum disintegration effect on treated material. Visualisation methods also significantly contribute to the development of new pulsating systems at the design stage. The presented procedures and experimental results demonstrate the above mentioned method as an effective analytical tool for the study of water jet geometry and velocity fields. Problems related to the application of this method are also described in the paper, together with a concept of how the problems could be solved.

1. Introduction

High-speed water jet represents a progressive, recently developed technology enabling disintegration of most existing materials. The principle of disintegration is based on high energy transmission to an extremely small area [1,2]. The material destruction is caused by complicated physical processes during the jet impact [2–5]. Several types of water jets have been developed over the years, where abrasive water jet (jet with addition of abrasive particles), continuous water jet and pulsating water jet are the most commonly used. Each water jet type is suitable for different technological operations.

The abrasive water jet (AWJ) is used for a variety of material processing applications such as 2D and 3D cutting, drilling, milling, turning and roughening [6–13]. AWJ enables machining of wide range of materials, such as metals, composites, structural ceramics, high-strength alloys, glass and rocks [8,9,14–18].

Pulsating water jet (PWJ) and continuous water jet (CWJ) are widely used for surface cleaning, removal of damaged material layers, preparation of surfaces, disintegration of biological materials, and in many other applications [6–9,19]. The generation of pulses into a continuous water jet significantly increases jet performance and the disintegration effect on material surface layers during the cleaning or surface preparation process at relatively low energy costs. The input water pressure necessary for the generation of a pulsating jet is significantly lower than for a continuous jet. The impact pressure on a target

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material generated by a bunch of water is considerably higher than the stagnation pressure of a corresponding plain continuous water jet [20]. The fatigue failure of a target material due to cyclic loading contribute to the higher performance of pulsating jets and intensify the removal of surface layers [3,20]. Pressures up to 150 MPa are commonly used to generate PWJs.

The creation of a PWJ is based on the generation of acoustic waves. An acoustic transducer acts on the pressure liquid, which is transmitted via a pressure system to the nozzle [21]. Acoustic waves, generated by an acoustic actuator in an acoustic chamber filled with pressure liquid, are amplified by a mechanical amplifier of pulsations. The acoustic waves are consequently transferred to the nozzle by the liquid waveguide. The liquid compressibility and tuning of the acoustic system contribute to a more effective transfer of pulsating energy from the generator to the nozzle, where pressure pulsations are transformed into velocity pulsations [22,23].

Knowledge of geometry and velocity fields of a PWJ generated by a high-pressure system is an essential prerequisite for the optimal tuning of the system with respect to the maximum disintegration effect on treated material. Visualisation methods represent an important analytical tool in this area. In addition to the optimum system configuration, the PWJ visualisation also significantly contributes to the development of new pulsating systems, especially with regard to the CFD (computational fluid dynamics) modelling of fluid flow at the design stage.

The results of an experiment focused on PWJ and CWJ visualisation are presented in this paper. The aim of the work was to test the applicability of the shadowgraph method, combined with PIV processing algorithms to visualise the water jet structure and analyse the velocity vector fields.

2. Visualisations of pulsating water jet

The first tests of CWJ and PWJ visualisation were performed by Vijay et al. in 1995 [24]. The authors used Nd:YAG laser (10 Hz, 532 nm, 200 mJ, pulse width 4–6 ns, in single pulse mode of operation) with a light sheet for water jet illumination. The images were captured by Canon T 70 camera with FD 50 mm lens in a totally darkened room. When the appropriate conditions were set, the camera shutter was kept open and the laser was triggered to produce a pulse of light with the required intensity of energy. The images were stored on colour films. This technique allowed the determination of the optimal structure of water jets from the point of view of their maximal ability to erode the tested material [24]. The visualisation of water jets using a special stroboscope, performed in the period 2005–2009 and published by Scucka et al. [25], brought an improvement in the observation method especially for high-frequency pulsed jets. Two LED light sources were used to illuminate the PWJ. Each of the light sources was equipped with 6 white Luxeon Star/O LEDs. The frequency of stroboscope flashing was controlled by the frequency of pressure pulsations of PWJ. The synchronisation of the stroboscope with water pulsations allowed the observation of formed pulses with the naked eye. The first high-speed time resolved recording of PWJ was tested by Foldyna et al. [26] in 2007. The authors used the LaVision VC-HighSpeedStar 5 high-speed camera equipped with LaVision HighSpeed IRO image amplifier and New Wave Research laser Solo 120 (pulse duration of 5 ns). The recording rate of the camera used in the experiment was 35,000 fps (frames per second).

In our experiment the shadowgraph technique for PWJ and CWJ visualisation was applied. This method is commonly used for the study of the motion of liquid droplets in many technical applications of fluid dynamics [27–29]. This technique allows the analysis of the distribution of velocity fields, velocity of individual droplets, and determining the size, shapes, position and mass flux of droplets in water flow. The most widespread shadowgraph systems comprise one or more digital cameras (CCD or CMOS) and a light source. Continuous and pulsed light sources (like flash lamps, lasers, diodes) are commonly used for the illumination of object planes. The image information is acquired on the principle of high-resolution imaging with backlight illumination. The light source, mostly equipped with an optical diffusor, creates a homogenous light background during the acquisition of experimental images [30,31]. A schematic assembly of the shadowgraph system used in the performed experiment is illustrated in Fig. 1.

The camera lens images the target on the sensor array of a digital camera. Depending on the type of lens used, different magnifications of an object plane are determined. Water droplets of the PWJ seeded in the flow are illuminated by the optical diffusor. Droplets and bunches of water are displayed as shadow points and areas in the contrast background of a recorded image. The first experimental image is taken at the time t and the next image after a short time delay dt. Each image is taken under laser illumination. The camera and laser are synchronised. The change in position of identical droplets in different images allows the determination of their movement, which is essential for subsequent velocity analysis. The image is dimensionally calibrated. After the acquisition of at least two images, the images are subdivided into small areas called interrogation windows (hereinafter referred to as IW) [32–34]. The IWs are cross-correlated to each other, pixel by pixel, using a cross correlation function. For two digital images $f(m,n)$ and $g(m,n)$ with a dimension of $M \times N$, the discrete cross-correlation function is given by:

$$R_{fg}(l,k) = \sum_{m=1}^{M}\sum_{n=1}^{N} f(m,n)\ g(m+l,n+k) \tag{1}$$

where l and k are pixel offset parameters between two images.

Locating the peak of the cross-correlation function gives the displacement between two images inside one IW. Standard evaluation procedures PTV (Particle Tracking Velocimetry) and PIV (Particle Image Velocimetry) allow the study of the motion of individual particles which are spread in flow. The PTV approach is required for low density of particles inside an IW. This method determines velocity vectors based on the positional changes of identical particles. The PIV method is applicable to mid- and