Analysis of high-speed photography of cavitating flow in convergent-divergent nozzle

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Abstract. Cavitation is a phenomenon that is difficult to observe, as well as to analyse. Many methods are being applied in order to study cavitation – high-speed photography is one of them. Analysis of images that were obtained in this way gives the possibility of superficial assessment of the phenomenon, but the use of digital image analysis allows obtaining more information on the studied series of images. In the paper, we propose two methods intended for such analysis - they are destined specifically for obtaining variability maps of cavitating flow based on series of high-speed photography. The work is based on the analysis of three different cavitating flows induced in convergent-divergent nozzles. Obtained results show that described methods can be helpful in analysis of cavitation - variability maps can be used for example as reference images for validation of results of numerical simulations of cavitating flow, which is not possible in case of a direct use of high-speed photographs.

1. Introduction
Cavitation is a phenomenon of liquid evaporation in the areas, where the local fluid pressure drops below the saturated vapour pressure [1]. Cavitation is usually an undesirable phenomenon, as it causes noise, erosion and vibration, hence, among other things, scientific interest in this phenomenon [2]. This first description of cavitation, without using the established term, appeared in 1985 [3]. Such expression as “cavitation” was used not until the work of Thornycroft and Barnaba [4]. One of the most absorbing problems with cavitation is observation of the phenomenon itself, not only its effects. In the first experimental works, mainly photography was applied to investigate this phenomenon. Then the normal photography was replaced with the high-speed photography. Both these tools give a general information about dimensions and intensity of the cavitation area. Many other methods are being applied for the study of cavitating flow [5], but the photography is still used most often.

As the progress in tools for imaging analysis allows obtaining more information on the studied images, the article proposes to implement the methods of digital image processing in order to obtain so-called variability maps that reveal more information on the analysed series of high-speed photographs.

The main aim of this work it to show a new method of high-speed photographs processing, which is intended for analysis of cavitating flows.
The main motivation for the research was to obtain information on the shape and intensity of cavitation cloud for the needs of validation of results of numerical simulations of cavitating flow when using chosen cavitation models applying homogeneous approach [6] but the described method can be successfully utilized for the purpose of analysis of different cavitating flows as well – the only condition is possibility of acquiring high-speed photographs of the flow.

2. Material and methods

2.1. Laboratory stand

The laboratory stand, shown in Figure 1, which was used in the experiment, is intended specifically for investigation of cavitating flows. Its detailed description can be found in [7].

The maximum linear velocity of water in the cavitation chamber is 1 m/s. The length of the cavitation chamber is 900 mm and the internal diameter of the chamber is equal to 50 mm. The test rig is equipped with seven sensors: sensors of inlet and outlet static pressure, sensors of inlet and outlet temperature, sensor of linear fluid velocity, sensors of water level and proximity sensor of the chamber.

Figure 1. Laboratory stand used in the experiment.
2.2. Cavitation inducers
Cavitation flow observed in the cavitation chamber was an effect of the use of two cavitation inducers, each in a form of small-sized nozzle with a small throat ratio. The dimensions of these cavitation inducers are presented in Figure 2. For both nozzles, the following dimensions are common: external diameter – 50 mm, the diameter of the throat – 3 mm and the length of the throat – 6 mm. The nozzles differ in the angles of converging and diverging sections. For the first cavitation inducer (see Figure 2 – left image), the angle of converging section is equal to 30° and the angle of diverging section is equal to 60°. For the second cavitation inducer (see Figure 2 – right image) the both angles are equal to 45°. The throat ratio for each cavitation inducers (i.e. ratio of the throat diameter to the external diameter) is equal to 0.06.

![Figure 2. Dimensions of the cavitation inducers used in the experiment [7]](image)

2.3. Experiment
In the whole experiment, three inlet velocities were considered for the first cavitation inducer ($v = 0.1, 0.2$ and $0.3$ m/s) and five inlet velocities for the second cavitation inducer ($v = 0.1, 0.2, 0.3, 0.4$ and $0.5$ m/s). The medium temperature, i.e. water, was set to $21^\circ$C. The outlet total pressure was always equal to the value of the atmospheric pressure. The inlet pressure values, as well as more details on the experiment, are presented in [7].

In the work, three flows were analysed: one for the first inducer ($v = 0.3$ m/s) and two for the second inducer ($v = 0.3$ m/s and $0.5$ m/s).

2.4. High-speed photography
To obtain the series of high-speed photographs, the Olympus i-SPEED TR camera with 1000 frames per second was used. Two halogen lamps (with 500 W power) were used to illuminate the scene. Figure 3 shows three exemplary high-speed photographs of cavitating flow from the analysed series, for both used cavitation inducers. In the Figure 3A, a cavitating flow with the inlet velocity $v = 0.3$ m/s for the first cavitation inducer is shown. In the Figure 3B, a cavitating flow with the inlet velocity $v = 0.3$ m/s for the second cavitation inducer is shown. In the Figure 3C, a cavitating flow with the inlet velocity $v = 0.5$ m/s for the second cavitation inducer is shown.

2.5. Computing environment
Obtained images are analysed with the use of Matlab R2013a environment, which is one of the most often used computing environments when it comes to image processing. The connection of basic Matlab functions with Image Processing Toolbox gives an opportunity of simple implementation and testing of created algorithms of digital image processing.
2.6. Used algorithms

Each image from the series is converted to a page of a three-dimensional matrix with number of pages consistent with number of photographs in analysed series. Then, vectors corresponding to each combination of x and y coordinates of created matrix are subjected to variability analysis, performed using two methods.

The first method obtains each pixel of the resulting image based on the minimum, maximum and mean values of each vector corresponding to each combination of x and y coordinates - it is defined as follows:

\[ v_2 = \frac{A_{\text{max}} - A_{\text{min}}}{A_{\text{mean}}} \]  

The second method obtains the value of each pixel of the resulting image as variance of each vector corresponding to each combination of x and y coordinates and so it is defined as follows:

\[ v_1 = \frac{1}{N-1} \sum_{i=1}^{N} |A_i - A_{\text{mean}}|^2 \]

As a result, for each single series of high-speed photographs two variability maps are obtained, with dimensions corresponding to dimensions of analysed series of images.

3. Results and discussion

Figure 4 shows obtained variability maps for three different cavitating flows. As it can be seen, performed analysis allows obtaining much more information on the cavitation than the simple observation of series of high-speed photographs (see Figure 3 for comparison). The places where the number of cavitation bubbles increases, have clearly another colour. For the first method of image conversion, places where the number of cavitation bubbles is close to zero, are in shades of blue, while
places with a high number of vapour bubbles are in shades of yellow to red. In the second method of image conversion, the obtained images are not as contrast as the images obtained using the first method. The first method of image conversion gives a more detailed view of the intensity of cavitation phenomenon in the analysed region of the cavitation chamber, while the second method gives a general information about the shape of the cavitation cloud. Thanks to achieved variability maps, it is possible to point places, which are putted at risk of cavitation erosion.

**Figure 4.** Variability maps of the cavitating flows in a convergent-divergent nozzle: A – first inducer (v = 0.3 m/s), B and C – second inducer (v = 0.3 m/s and 0.5 m/s, respectively).
For example, variability maps clearly show that the character of cavitation changes with the distance from the inducer. For the first inducer (Figure 4A), bigger bubbles appear further from the nozzle, while for the second and third one (Figure 4B and Figure 4C), they appear closer and higher. Furthermore, areas with greater and lesser intensity of cavitation can be clearly observed, what is clearly visible in Figure 4B and Figure 4C, where for different inducers and the same velocity, we see different character of cavitation (i.e. cloud shape), and of course different intensities. It leads to a conclusion that not only the throat diameter and inlet velocity have influence on the cavitation shape and intensity, but also the angles of converging and diverging sections.

In the experiment it was observed that the changes in the angles of converging and diverging sections could help to limit the maximum inlet velocity, what is not without an influence on the mass flow rate. The performed image analysis shows that the changes in these angles have a big impact on the shape and intensity of the obtained cavitation clouds.

Above discussion leads to the conclusion that while the high-speed photography can be really handy tool, especially for the purpose of the coarse evaluation of the cavitating flow, more accurate differentiation of the cavitating flows is much easier when based on the images shown in Figure 4.

4. Summary and conclusions

The paper shows the methods destined for the purpose of analysis of high-speed photography of cavitating flow, which can be very helpful in analysis of this phenomenon. Obtained variability maps can be used as reference images for validation of results of numerical simulations of cavitating flows, what is not possible in a case of a direct use of high-speed photographs.

For the analysed shape of cavitation inducers, i.e. small-sized converging-diverging nozzles with a small throat ratio (equal to 0.06), the use of described methods allow evaluating the influence of the changes in the angles of converging-diverging sections on the shape and intensity of the cavitation cloud. These results are very important for designers of such devices, as they give valuable information concerning places that are putted in risk of cavitation erosion.

In this paper, presented is a series of images that were obtained for a flow induced in convergent-divergent nozzles, but it should be noted, that the described method could be successfully utilized for different cavitating flows, which can be recorded as a series of high-speed photographs. It should ba also noted, that increased speed of taking photos by the camera would allow observing phenomena with a higher rate of change, but when considering cavitation, there is no need of using faster camera, as the visual assessment of obtained series of images leads to the conclusion that used camera is fast enough.

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