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Propulsion System Analysis Based on Particle Image Velocimetry Method in Biomimetic Unmanned Underwater Vehicle

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Abstract: The article presents a laboratory stand for direct measurement of the thrust generated by the undulating propulsion system of a biomimetic underwater vehicle. The laboratory water tunnel enables research and comparison of the generated thrust with the results of the fin and fluid interaction analysis using the Particle Image Velocimetry method. The water tunnel is equipped with an industrial camera for recording changes in the position of markers highlighted with a line laser in the area of analysis. The comparison of the results obtained by the PIV method with the industrial force sensor allows for the analysis of the efficiency of the biomimetic propulsion system as a function of both design and control parameters.

Keywords: Biomimetic Unmanned Underwater Vehicle (BUUV), Fluid-Structure Interaction (FSI), Particle Imagine Velocimetry (PIV), underwater robotics

1. Introduction

The undulating propulsion system is commonly used in newly designed biomimetic underwater vehicles, specially dedicated for autonomous missions [3, 9, 14, 15]. Biomimetic Underwater Vehicles (BUVs) are equipped with an innovative, energy-efficient driving system consisting of artificial fins [10, 11, 15]. Because these driving systems are not well developed yet, there are great possibilities to optimize them in materials and control parameters [12, 13]. However, the fluid-structure interaction is a nonlinear problem without a ready-to-use mathematical model.

One of the methods widely spread for fluid-structure interaction analysis is Particle Image Velocimetry (PIV) [6]. PIV is a non-invasive image processing method to measure fluid velocity in a specific region. The cross-correlation and optical flow methods have been developed to extract velocity fields from particle images. The first method searches maximum cross-correlation between two interrogation windows of an image pair, while optical flow optimizes an objective function. The PIV technique based on machine learning [7, 8] has shown advantages like higher accuracy and higher spatial resolution. As the PIV method has become essential in the last decades, many software packages are available. In this paper, the PIVlab under MATLAB software has been used [17]. PIVlab was initially published in 2010. Since then, 30 updates with new features or fixes have been released, based on users' feedback and personal demands. A paper on PIVlab was published in the Journal of Open Research Software in 2014 [16] and has been cited more than 1800 times to date.

The paper is organized as follows. In the next section, the BUUV is presented. Then the laboratory test stand and PIV method are described. The last section covers experimental results as well as discussion and direction of future research.

2. Biomimetic Unmanned Underwater Vehicle

The underwater vehicle used for tests is the next version of the small Biomimetic Unmanned Underwater Vehicle (BUUV) designed in 2021 during the Polish Minister of Defense competition [18] by a group of students and PhD students from the Polish Naval Academy.

The propulsion system construction is based on the two flexible tail fins and two flexible side fins. The main reason for that construction is to imitate marine animal movements like a harbour seal. The propulsion system made from a flexible fin can avoid leaking electronic components inside compared to the propulsion system designed from rigid movable elements and a flexible fin at the end [1, 2, 9]. Two caudals were used to ensure the vehicle's course stability.

The thrust produced by the fin depends not only on the fin dimensions but also the frequency oscillation, angle of attack and on the fin flexibility [4, 6]. This is a challenging task for analysis due to the lack of ready to use mathematical models. In addition, the water velocity is another factor that must be taken

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into consideration, especially at a close distance to the fin as well as the at the fin's trailing edge. Some analysis can be done using PIV method. The laboratory test stands for FSI analysis using PIV method is depicted in the next section.

3. Laboratory Test Equipment and Measurement Methods

The water tunnel presented in Fig. 1 and Fig. 2 (dimensions: 2 m length, 0.6 m width and 0.6 m depth) was designed especially for the biomimetic underwater vehicle investigation. The water tunnel has a partition for the forced flow of water upside down in one direction and downwards in the opposite direction. For illumination from different places, all the walls were made from glass. The vehicle is directly connected to the force sensor for the net thrust measurements (Fig. 2). The surface of the analysis is highlighted by a linear green laser with a power of 1 W. The camera with a slow-motion option is mounted at some distance to the highlighted surface for recording the highlighted plate. The camera is put perpendicular to the highlighted surface, and it records the motion of particles. For the calibration process of the laboratory test stand, the following factors were taken into consideration: the distance between the camera and the region of analysis; the marker parameters and their size should not affect the fluid properties; the seed density (the number of markers in the area unit); the power of linear green laser; resolution of the image recorded by the camera (HSC); the frequency of image acquisition (fps – frames per second), the fluid velocity and area of analysis.

Fig. 1. Biomimetic Unmanned Underwater Vehicle inside the water tunnel
Rys. 1. Biomimetyczny bezzałogowy pojazd podwodny w tunelu wodnym

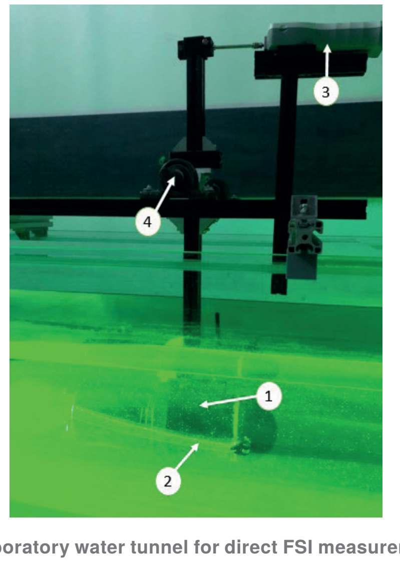

Fig. 2. The laboratory water tunnel for direct FSI measurement with highlighted the plane of analysis: 1 – BUUV, 2 – side fin, 3 – force sensor, 4 – bearing
Rys. 2. Stanowisko laboratoryjne do bezpośredniego pomiaru naporu z płaszczyzną analizy podświetloną laserem, 1 – pojazd podwodny, 2 – płetwa boczna, 3 – czujnik siły, 4 – łożysko

4. Particle Image Velocimetry Descritpion

The PIV analysis typically consists of three main steps (image pre-processing, image evaluation and post-processing) [17]. The workflow is presented in the paper [16], starting with image input and pre-processing options and then continuing to the image evaluation/PIV analysis, post-processing and data exploration. The PIV method was used for vehicle side fins analysis (Fig. 2). In Fig. 3, the image is presented during the side fin movement. The differences between Fig. 3 and Fig. 4 are due to the different cameras used. In Fig. 3 the blurred markers can be observed in the side fin movement region.

In Fig. 4, the image from a high-speed camera (HSC) is presented. The HSC captured series of images with resolution

Fig. 3. An example of an image with blurred markers made during the side fin movement
Rys. 3. Zdjęcie podświetlonych markerów w obszarze analizy wykonane podczas przemieszczania bocznej płetwy

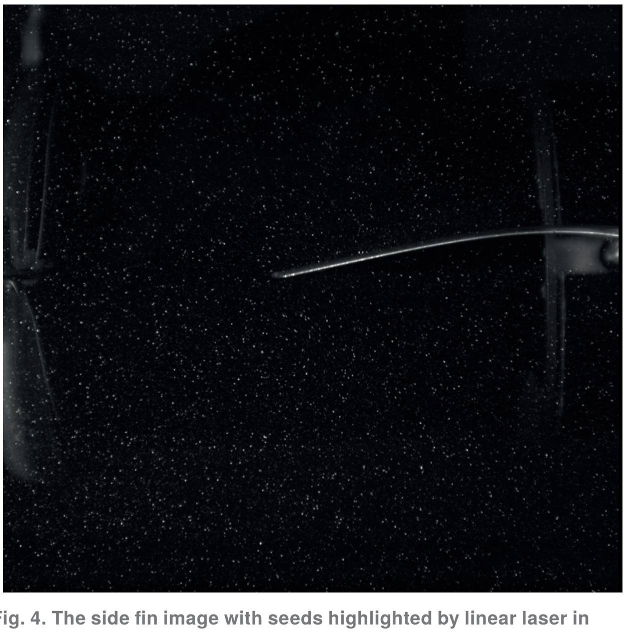

Fig. 4. The side fin image with seeds highlighted by linear laser in region of analysis
Rys. 4. Zdjęcie bocznej płetwy z podświetlonymi markerami w płaszczyźnie analizy

1000 frames per second (fps) with 2 MB resolution. The PIV method demands each marker's description based on the Gaussian distribution function spread over 3–5 pixels. Bright particles or bright spots within the area will contribute statistically more to the correlation signal, which may bias the result in non-uniform flows. Also, the number of markers in cross-correlation function depends on seeds density and dimensions of the interrogation window. The PIV method assumes that all particles within an interrogation window have the same motion. This will not be the case in reality, as the perfectly uniform flow hardly exists.

One common approach to ensure high measurement quality is enhancing images before the actual image correlation. Contrast limited adaptive histogram equalization was developed to increase the readability of image data. Contrast limited adaptive histogram equalization operates on small regions (tiles) of the image: in every tile, the most frequent intensities of the image histogram are spread out to the full range of the data (from 0 to 255 in 8-bit images). Regions with low exposure and regions with high exposure are therefore optimized independently. Inhomogeneous lighting can cause low-frequency background information, which can be removed by applying a high-pass filter that mostly conserves the high-frequency information from the particle illumination. The filter emphasizes the particle information in the image and suppresses any low-frequency information in the images.

Considering the pre-processing parameters, it seems reasonable to use a Wienner filter with a low-pass filter. Where the variance is large, the filter performs little smoothing. Where the variance is slight, the filter performs more smoothing. This approach often produces better results than linear filtering. The adaptive filter is more selective than a comparable linear filter, preserving edges and other high-frequency parts of an image. In addition, there are no design tasks; the filter function handles all preliminary computations and implements the filter for an input image; however, it does require more computation time than linear filtering.

5. Experimental Results

In Figs. 5 and 6, a direct measurement of FSI is presented for different fin dimensions. Figure 5 shows the thrust as a function of time for fin length equal to half of the fin length with thrust presented in Fig. 6. The main goal of the research is to find out the construction and control data to achieve maximal value of thrust. Here the same control algorithm was used for all tested fins. As it can be observed in the results of direct measurements of the thrust even if the control signal is symmetrical in both direction of the fin movements, the output signals differs. This is caused by different fin dimension (here only the fin length was changed). Although the mean thrust is similar for both fin measurements, the shape of the characteristic is different.

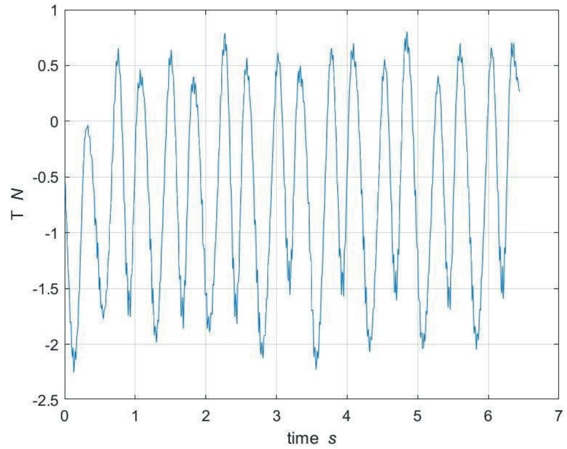

Fig. 5. The thrust measured by force sensor as a function of time for fin length 150 mm
Rys. 5. Napór zmierzony za pomocą czujnika siły w funkcji czasu dla płetwy o długości 150 mm

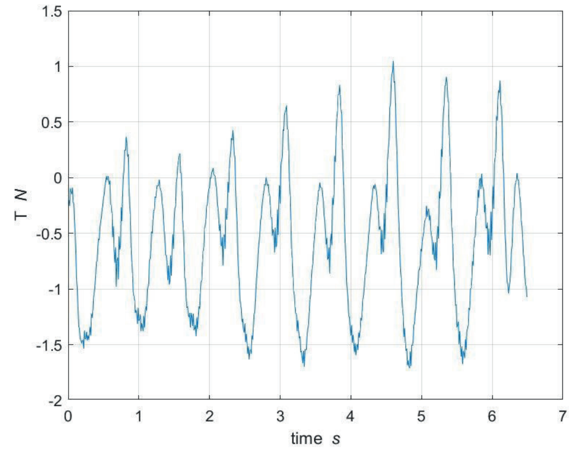

Fig. 6. The FSI measured by force sensor as a function of time for fin length 300 mm
Rys. 6. Napór zmierzony za pomocą czujnika siły w funkcji czasu dla płetwy o długości 300 mm

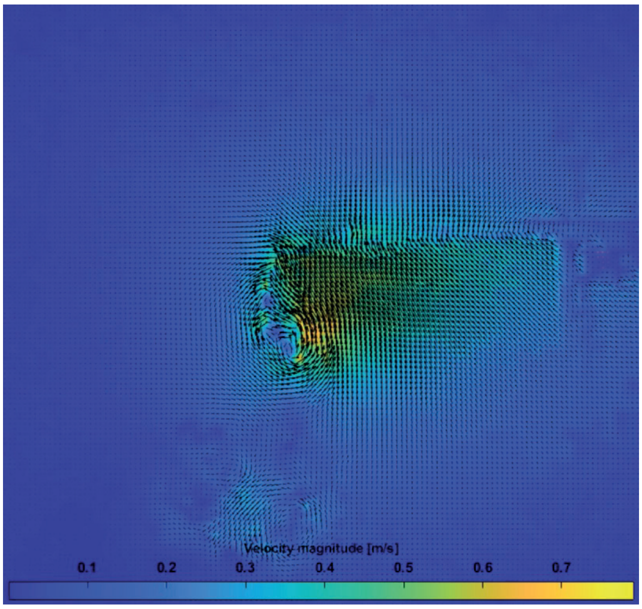

Fig. 7. The results of the PIV method for the fin in the middle during the movement to the top position
Rys. 7. Wynik analizy metodą PIV dla płetwy w środkowym położeniu podczas przemieszczania do górnego położenia

A more complex propulsion systems comparison can be provided with the PIV method. The velocity vectors are highlighted in colour with a scale at the bottom of each figure. In Fig. 7–9 the PIV results are presented for fin length equal to 150 mm in different stages of the movement. In Fig. 7 the analysis is presented for the fin in the middle position during the movement to the upper position. The vortex can be seen below the fin trailing edge. The vortex is generally undesirable due to energy dissipation.

In Fig. 8 and 9, the top and bottom positions of the fin are captured, respectively. The velocity vectors depicted in both figures show the fluid direction propelled by the fin. This analysis is crucial for comparison the fluid velocity with thrust

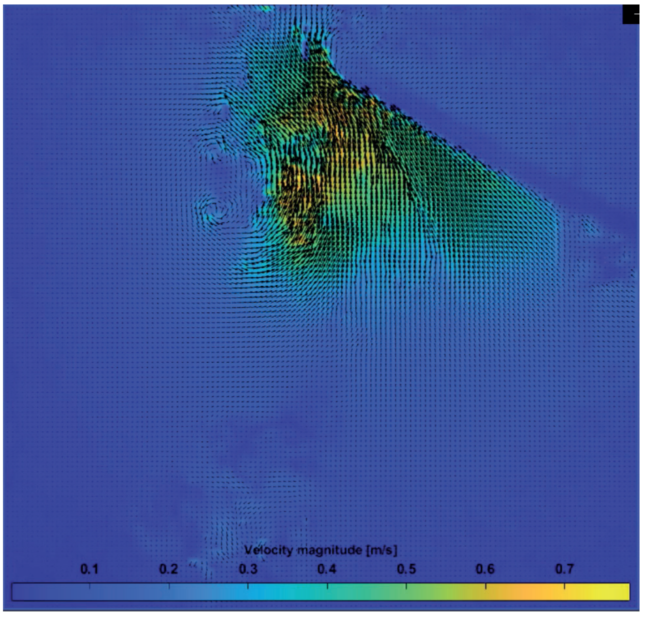

Fig. 8. The results of the PIV method during the movement of the fin to the top position
Rys. 8. Wynik analizy metodą PIV dla płetwy podczas przemieszczania do górnego położenia

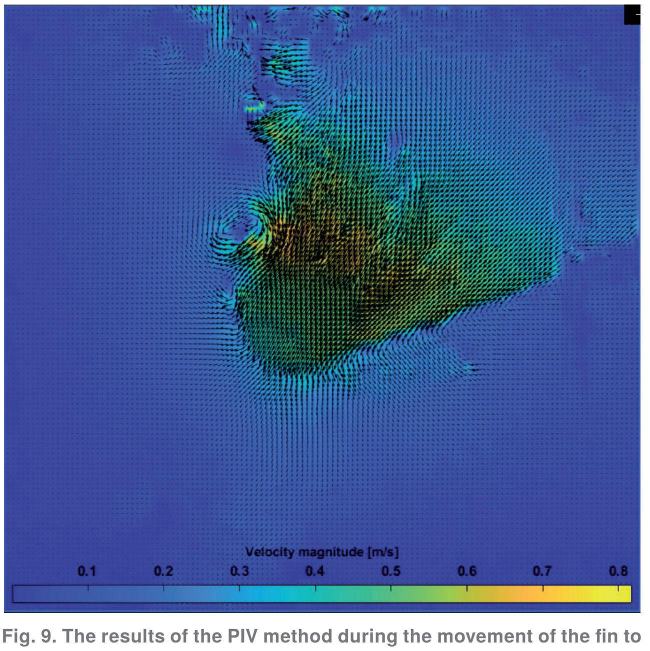

Fig. 9. The results of the PIV method during the movement of the fin to the bottom position
Rys. 9. Wynik analizy metodą PIV dla płetwy podczas przemieszczania do dolnego położenia

generated. It gives information about the velocity for every time step and also the fluid acceleration can be calculated. The desired direction of fluid velocity is opposite to that of the vehicle.

6. Conclusion

In this paper, both experimental results are presented: the direct measurement of thrust generated by the biomimetic propulsion system and the fluid velocity field achieved from the PIV method. The fluid dynamics using the PIV method is used to examine fluid velocity in the region of interest in the transient state analysis. Using the PIV method velocity fields are obtained with high spatial and temporal resolution in a non-intrusive manner.

Although experimental tests are time-consuming, the results achieved can be used for propulsion system improvements. In the next step of research, different control algorithms will be tested using a designed laboratory water tunnel and the PIV method.

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Analiza układu napędowego z wykorzystaniem metody PIV w biomimetycznym bezzałogowym pojeździe podwodnym

Streszczenie: W artykule przedstawiono stanowisko laboratoryjne do bezpośredniego pomiaru naporu generowanego przez napęd falowy biomimetycznego pojazdu podwodnego. Stanowisko umożliwia przeprowadzenie badań i porównanie generowanego naporu z wynikami analizy interakcji płetwy i płynu z wykorzystaniem metody PIV. Stanowisko wyposażone jest w kamerę przemysłową do rejestrowania zmiany położenia markerów podświetlonych liniowym laserem w obszarze analizy. Porównanie wyników uzyskanych metodą PIV z przemysłowym czujnikiem siły pozwala na analizę sprawności biomimetycznego układu napędowego w funkcji zarówno parametrów konstrukcyjnych jak i sterujących.

Słowa kluczowe: biomimetyczny bezzałogowy pojazd podwodny, interakcja płynu i napędu falowego, anemometria obrazowa, robotyka podwodna

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