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THRUST MEASUREMENT OF BIOMIMETIC UNDERWATER VEHICLE WITH UNDULATING PROPULSION

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ABSTRACT

In the recent years, a dynamical development of an underwater robotics has been noticed. One of the newest group of underwater robots are biomimetic underwater vehicles. These vehicles are driven by undulating propulsion imitating fins of underwater creatures, e.g. a fish, a seal, etc.

This paper undertakes problem of thrust measurement of new biomimetic underwater vehicle equipped with undulating propulsion. At the beginning, the stand for thrust measurement is described. Then, two constructions of BUVs imitating a fish and a seal are presented. Further, the results of thrust measurement for two different undulating propulsions are inserted. At the end of the paper containing conclusions from performed measurements and foreseen research is included.

Key words:
biomimetic underwater vehicle, undulating propulsion, thrust measurement.

Research article

INTRODUCTION

Increasingly, biomimetic underwater vehicles BUVs are designed and built. These vehicles imitate underwater creatures not only in the term of their appearance, but also in the term of their way of propulsion and motion. In the last decade, a number of interesting designs of underwater vehicles was created which mimic the appearance and way of motion of underwater creatures, e.g. fishes, seals, etc. [2, 5, 6, 12]. Sometimes smart actuators such as artificial muscles are used for their propulsion [1].

These vehicles have different shapes, sizes and configuration of fins for their propulsion system. They have also different hydrodynamic properties depended especially on the animals which these vehicles imitate. The measurement of hydrodynamic properties and then attempt of optimization of these properties is one of most important questions for the engineers who design and build the BUVs [2–4]. Usually, particle video velocimetry [4, 7] and complex fluid dynamics methods [3, 7] are used to determine hydrodynamics properties of BUVs.

This paper undertakes problem of thrust measurement generated by the new undulating propulsion system consisting of one or two fins. The main goal of the research is to build mathematical model of undulating propulsion for further simulation of the BUV motion. There is a lack of a simple and robust model of undulating propulsion, therefore development of such a model will be useful for future research, e.g. on controllers of main parameters of the BUV motion. Some research focused on measurement of one tail fin has been conducted earlier [11], but this paper includes more results of research taking into consideration different configuration of undulating propulsion and BUVs with different sizes. Therefore, this approach seems to be more comprehensive.

The robust mathematical model of BUV motion allows us to optimize motion of the artificial fin, e.g. for achieving higher thrust or better energetic efficiency of the propulsion system. Optimization methods in most cases demand iterative calculations, therefore the final model of the undulating propulsion should be simple and robust.

In the next section, the measurement stand for BUV thrust is described. Then, the two construction of BUVs and undulating propulsion are described. Further, the results of measurement of these two constructions are included. At the end, the conclusions from the research and schedule of the next research are inserted.

The presented results of the research on BUVs were achieved within two projects. The first project (with codename: SLEDZIK) is carried out in Poland by the consortium consisted of the following scientific and industrial partners: Polish Naval Academy PNA — the leader, Cracow University of Technology CUT, Industrial Institute of Automatics and Measurement PIAP and Forkos Company. The main objective of the SLEDZIK project was to build heterogeneous torpedo-shaped BUVs with undulating propulsion for selected scenarios of underwater ISR. In this case the degree of similarity to the living organism is rather small. The second project (with codename: SABUVIS) was started in connection with Unmanned Maritime Systems Programme in European Defense Agency. The SABUVIS project is carried out by the consortium consisted of the mentioned above Polish partners and also Bundeswehr Technical Center for Ships and Naval Weapons WTD 71 in Eckernförde, Germany. The main objective of this international project is to build BUVs characterized by a greater similarity to real inhabitants of underwater environment taking into account the possibility of their operation as a swarm.

STAND FOR THRUST MEASUREMENT

The stand for thrust measurement has been designed and built taking into account the following assumptions:

1. The stand has to be mobile, i.e. it enable to make the research in different reservoirs.
2. The measurement of thrust is carried out for the tethered vehicle.
3. It is possible to measure force *X* generated in longitudinal axis of symmetry and moment of force *N* relative to vertical axis of symmetry.
4. The stand should be relatively cheap.

Taking into considerations mentioned above assumptions, the stand consists of the following components (fig. 1):

- the frame for mounting the measurement system;
- the set of two strain gauges with the transmission of power via a lever with unequal arms (the arms are attached to both sides of the vehicle) — they enable to measure force *X* and moment of force *N*;
- the microprocessor system for the thrust measurement, processing the data from the strain gauges to the proper format of data transmitted by a serial link [9];
- the PC with software for control, registration, visualization and archivisation of motion parameters of the tail fin module.

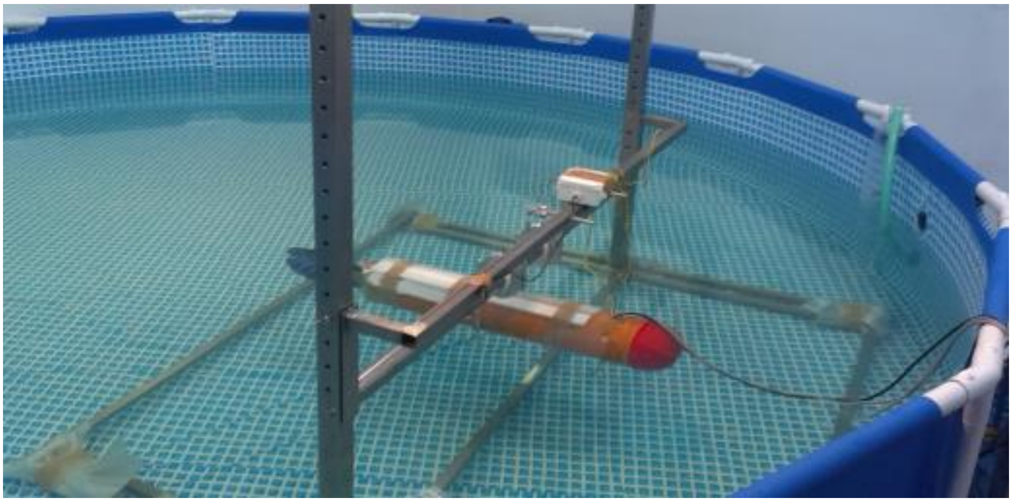


Fig. 1. The laboratory stand for the thrust measurement (Polish Naval Academy)

The frame has height-adjustable mounting point of the measurement system, which make it possible to measure thrust generated by different vehicle acing on different depths. Each of the strain gauges used in the stand can measure maximal value of force equal to 50N. Measurement of the forces generated by the model of undulating propulsion is performed by strain gauge beams 1B-S/10. The microprocessor system allows us to exchange the gauges, in case there is the need to measure force larger than 50 N.

The strain gauge beam 1B-S/10 has quite high accuracy of 0.03% and sensitivity equal to 1,8±0,1 mV/V, which at a voltage equal to 5 V gives 9±0,5 mV for the maximum load equal to approx. 45.3 N. The signal from strain gauge beam is amplified over 100 times without introducing additional noise and then A/C processed by ADS1234 chip from Texas Instruments [9].

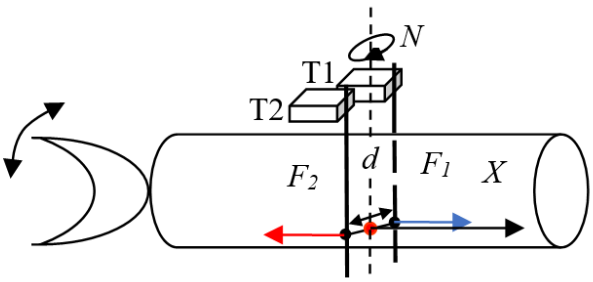


Fig. 2. Measurement of force *X* and moment of force *N* based on forces F_1 and F_2 received from strain gauges T1 and T2

The measurement stand enables to measure force *X* (fig. 2) acting in longitudinal axis of symmetry generated by different fins (different shape, dimensions and stiffness) and different parameters of oscillation (amplitude, frequency). The force *X* is a sum of forces obtained from two strain gauge beams F_1 and F_2. Moreover, the moment of force *N* (fig. 2) can be calculated. Assuming that the angle between the force F_1 or F_2 and a lever arm is equal to 90 deg, the moment of force *N* is a result of a product of difference between forces F_1 and F_2 and the lever arm equal to a half of distance *d* (fig. 2).

Fig. 2 illustrates the schematic view of the measurement of BUV's thrust, while the fig. 4 shows the real measurement of thrust of mini CyberSeal, which is one of the tested vehicles. The strain gauges can be seen in the upper left part of the fig. 4, while the BUV can be observed in the lower part of the figure under a crossbeam that serves as an assembly for two levers with uneven arms for the F_1 and F_2 measurement.

BUVS USED IN TESTS

One of the BUVs used in tests is ABPP2 (fig. 3) designed and built within the Polish development project called Śledzik. The project was started at the end of 2013 and it was finished in April 2017. The final effect of the project are two technology demonstrators of the BUVs: one built in Cracow and the second built in Gdynia. The first BUV is equipped with two movable segments tail fin, while the second is equipped with one movable segment tail fin. The both BUVs have 2 side fins for generating additional thrust and/or for depth change. During the tests the second BUV (ABPP2) was used. This BUV is presented in fig. 3.

The BUV is based on torpedo shaped hull with the following modules (beginning from the bow): video and front echosounder module, module of communication and navigation sensors, module of side fins, module of electronics and batteries, module of tail fin. The diameter of the cylindrical hull is about 0.2 m and the length (without tail fin) about 1.7 m.

The BUV tail fin with the trapezoidal shape and the surface equal to approx. 0.07 m^3 oscillates with different frequency and constant amplitude (fig. 3). The changes of frequency influence on changes of thrust. The negative side effect of such a motion is oscillations of course generated by additional moment of force relative to the vertical axis of symmetry.

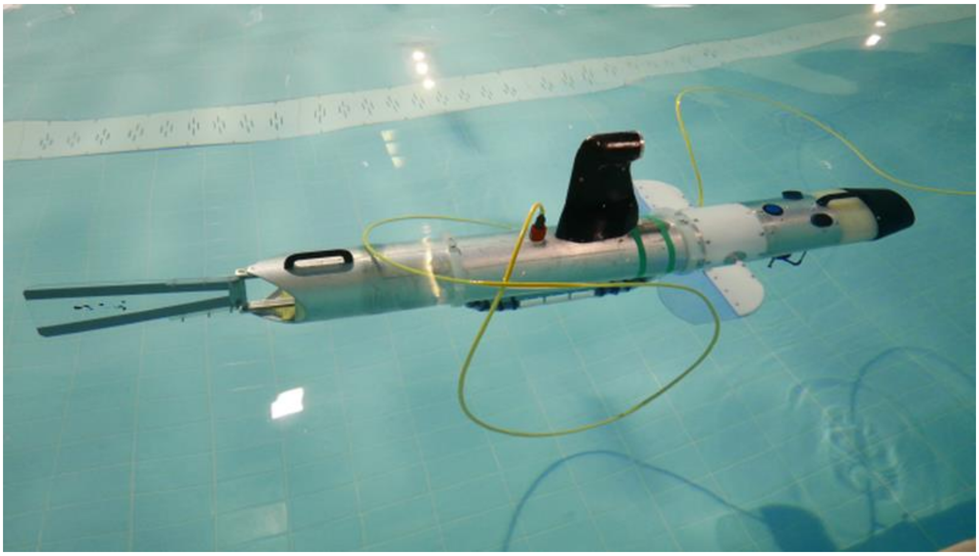


Fig. 3. The BUV No. 2 in the swimming pool

The second BUV used in tests is mini CyberSeal (fig. 4) designed by Polish Naval Academy which is a prototype of the full-scale CyberSeal being constructed within SABUVIS project.

Vehicle structure is based on a pipe made of thermoplastic material with high mechanical strength which includes the entire electronic devices, sensors and servomechanisms. The complete robotic system is supplied through on-board 7.2 V, 10 Ah Li-ion based rechargeable battery.

The driving system consists of two tail fins and two side fins. The drive of four fins is controlled by mini Maestro servo controller (POLOLU-1353) via RS-232 interface. Four servomotors (HD-1207TG) with the 1:1 angular gears are used to drive both pair of fins.

The mini CyberSeal fins were made of 3 mm thick rubber. In order to obtain the proper stiffness, the tail fins were reinforced with a 2 mm layer of polycarbonate in the fore part of the fins. The approximate value of the surface area is about 0.01 m^2 and the shape resembles a trapezoid.

The both pair of fins may move with speed up to 3 Hz. The side fins range of motion are 45 degrees, whereas tail fins may move in range of 68 degrees outside (ε) and 9 degrees inwards (γ) of the axis of symmetry (fig. 5).

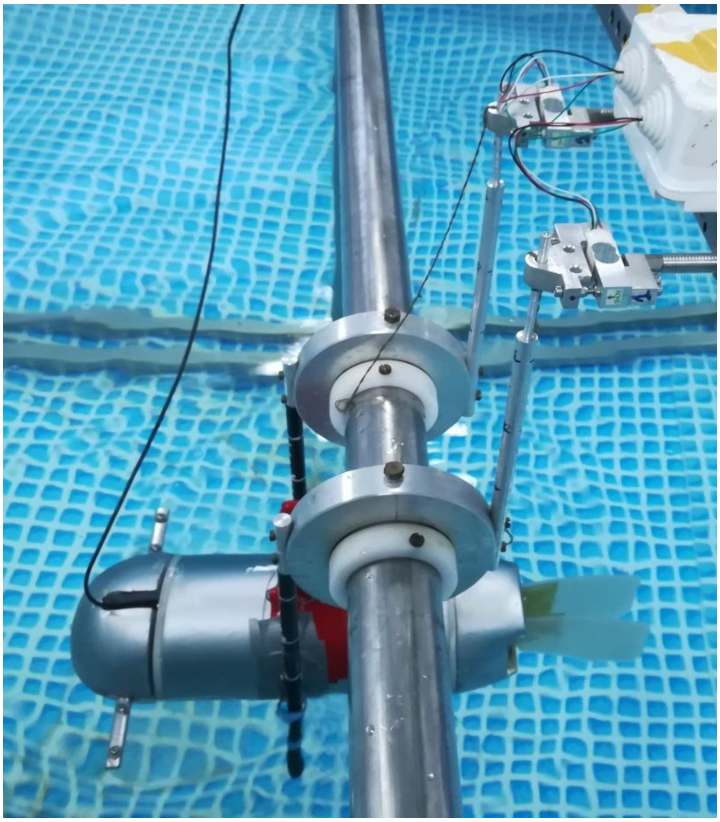


Fig. 4. The measurement of the thrust generated by the mini CyberSeal
using laboratory stand built in Polish Naval Academy

The movement of the rear fins takes place in counterphase, which results in the lack of oscillation and moment of force relative to the vertical axis of symmetry N running through the vehicle's center of gravity. The construction of this type of drive increases the positioning accuracy of the underwater vehicle using the dead reckoning.

The ABPP2 built in Sledzik project and the mini CyberSeal built in SABUVIS project have the similar undulating propulsion in the front part of their hulls, i.e. the side fins for generation of additional thrust and/or dynamical change of depth. However, the side fins have different dimensions and consequently they can generate different thrust. Both vehicles have different undulating propulsion on the stern, consisting of different number, shape and dimensions of fins. The thrust generated by the fins mounted on the stern is compared in the following section.

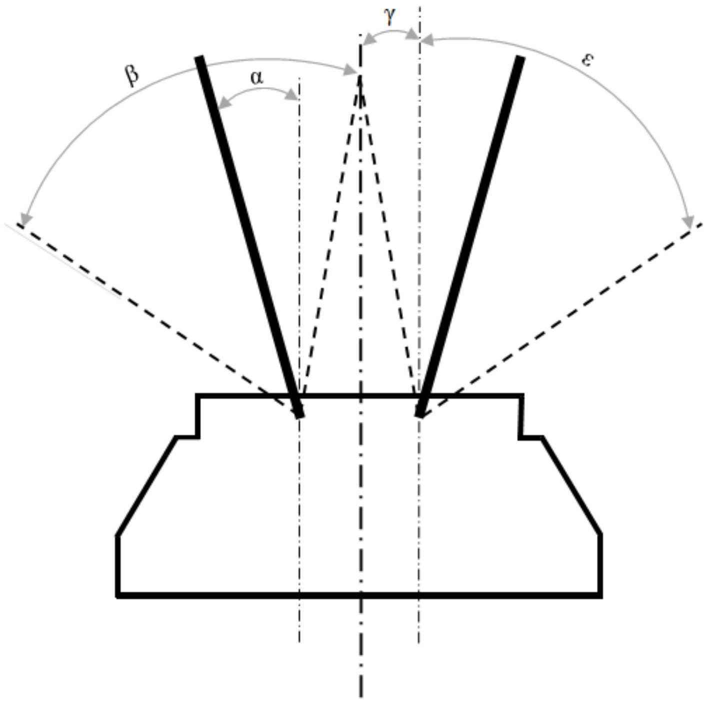


Fig. 5. Range of motion of the tail fins: ε — external angle, γ — internal angle, α — normal position, β — motion angle

RESULTS OF MEASUREMENTS

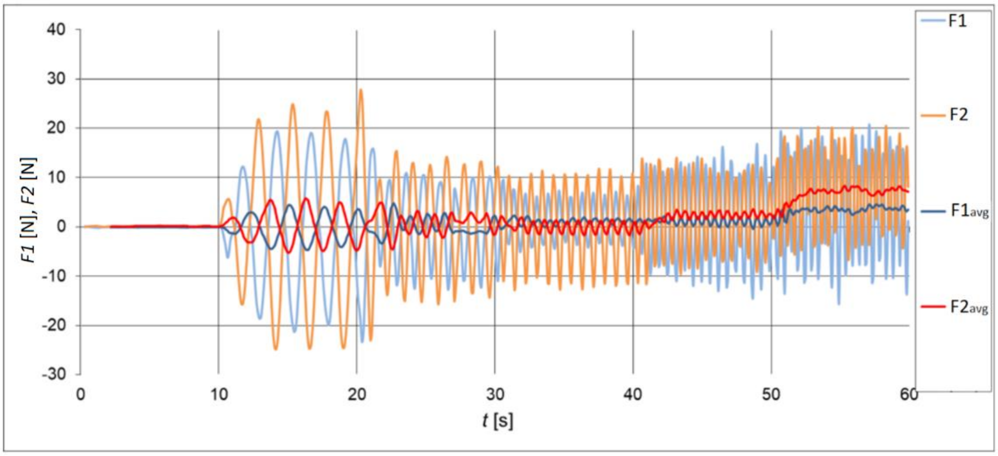
The tests were carried in two stages. At the beginning the thrust measurement of the ABPP2 was conducted, and then the research on mini CyberSeal was performed.

During the first stage, the tail fin of the ABPP2 consisting of only one movable segment was oscillating with increasing frequency per 10 seconds and constant amplitude approx. ±25 deg. It allows us to estimate how the frequency of the fin oscillation influences on the generated thrust.

The second stage of the test includes force measurement generated by the mini CyberSeal tail fins at a frequency change of 0.33 Hz in range from 0 to 2 Hz every 10 seconds. The measurements were carried out for a constant amplitude β of about 31 degrees at different normal position α.

In the fig. 6, the example measurement of thrust generated by the ABPP2 with the trapezoidal tail fin is illustrated.

a)



b)

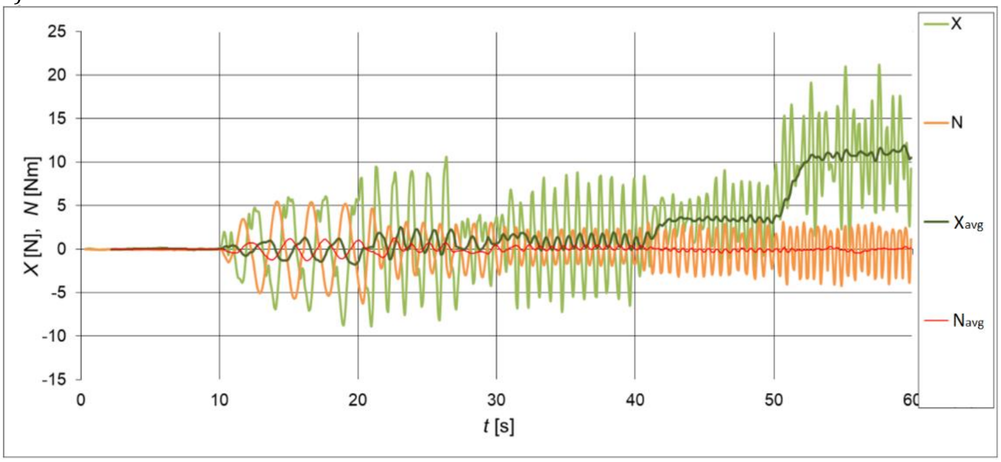


Fig. 6. Forces: a) F_1 and F_2 received from strain gauges T1 and T2; b) acting in longitudinal axis of symmetry X and moment of force relative to vertical axis of symmetry N for the trapezoidal fin oscillating with increasing frequency per 10 seconds (0, 0.47, 0.85, 1.3, 1.6 and 2 Hz)

The received responses on different frequency of oscillation in the form of generated force X and moment of force N allows us to formulate the following conclusions:

1. There is an asymmetry in the tail fin oscillation, what is observed by different average values of forces F_1 and F_2 (adequately red and dark blue lines in the fig. 6 a).
2. Increase of frequency oscillation influences on the increase of average value of thrust (dark green line in the fig. 6 b).
3. The largest moment of force N resulting in the largest oscillation of course was received for the smallest frequency of oscillation (orange line in the fig. 6 b).

4. The smallest moment of force N was obtained for the specific frequency of the fin oscillation which is in the middle of the tested range of frequencies (between 30th and 40th seconds of experiment).

Considering one movable segment fin, the force X can be calculated as a sum of an average value X_{AV} and an additional sinusoidal oscillation X_{OSC} depended on the frequency of the fin oscillation, while the moment of force N can be calculated as a sinusoid function of the frequency of the fin oscillation:

$$X = X_{AV}(f) + X_{OSC}(f) * sin(\omega * t); \quad (1)$$

$$N = N_{OSC}(f) * sin(\omega * t), \quad (2)$$

where ω is $2\pi f$.

The parameters of the mentioned above functions can be determined using the interpolated functions received from the measurements (fig. 7).

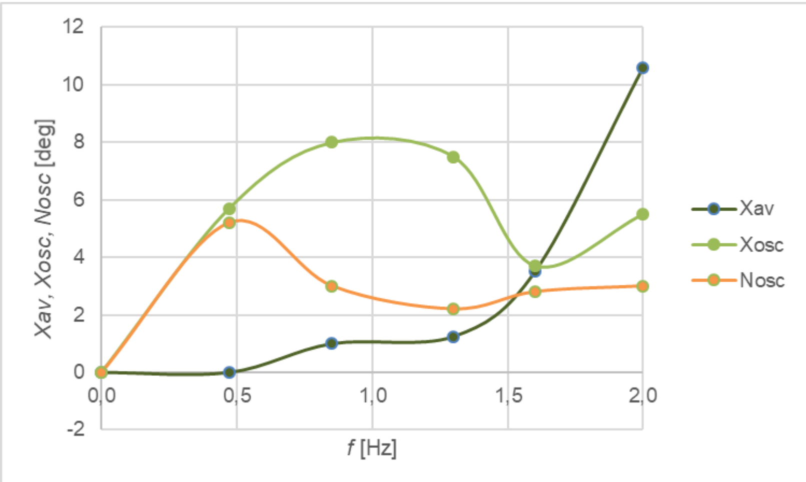


Fig. 7. Interpolated functions of X_{AV}, X_{OSC} and N_{OSC} depended on the frequency f of the tail fin oscillation

The object of the research on the mini CyberSeal was to measure the change in force generated by the rear fins depending on the frequency change and normal position of the tail fins. The initial assumption was that the movement of the fins would take place on the skeleton's outline, so that the deflection of the fins would not generate additional resistance caused by water movement.

Fig. 8 shows an example of the measurement results. Tail fins of the mini CyberSeal during the test were moved at a speed from 0 to 2 Hz with step of 0.33 Hz and amplitude equal to 31.5 degrees. The best results were obtained for the velocity in the range of 1 to 2 Hz, where the average value of the force increases in proportion to the frequency.

What's more, to the frequency of fins oscillation above 1.33 Hz, the amplitude of the oscillations began to decrease and the vehicle's motion was more flowing.

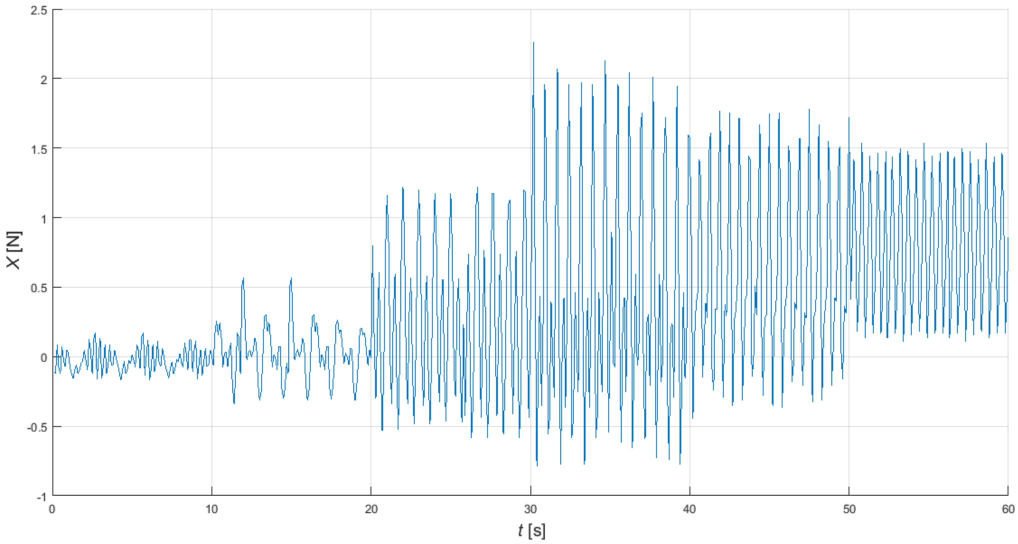


Fig. 8. Force acting in longitudinal axis of symmetry *X* oscillating with increasing frequency (0.33, 0.67, 1, 1.33, 1.67 and 2 Hz) every 10 seconds

In the fig. 9 the example measurement of thrust generated by different tail fins normal position. Two cases were considered, namely the first for the deflection of the fin from the longitudinal axis of the vehicle by 6.25 degrees and the second by 11.25 degrees.

In the first case (α = 6.75) during the symmetrical work of the fins, they remain in some distance to the each other in final phase of movement. The average force generated by the fins is comparable to the force generated in the second case (α = 11.25) where the tail fins meet in the end phase of each cycle. However, it can be seen that the amplitude of the oscillations is reduced in the full frequency range.

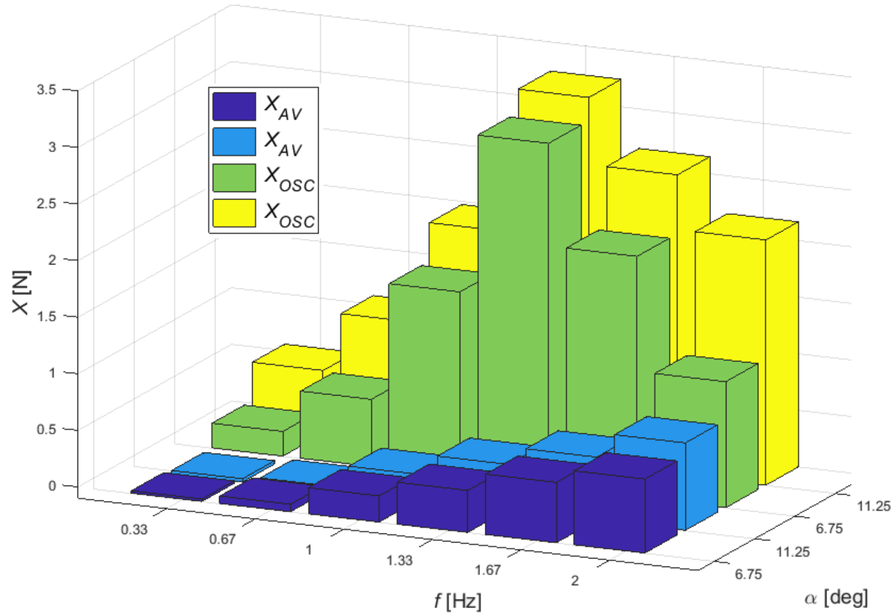


Fig. 9. Force average value X_{AV} and an additional sinusoidal oscillation X_{OSC} acting in longitudinal axis of symmetry X oscillating with increasing frequency (0.33, 0.67, 1, 1.33, 1.67 and 2 Hz) every 10 seconds at different normal positions of the caudal fins

Taking into account the fact that amplitude of angle motion (β) and normal position (α) of tail fins are constant that the X force generated by two fins is calculated in the same way as for ABPP2 in accordance with the formula No. 1. Using the interpolated function for the average values received from measurements, we can obtain any value of the X force for frequency from zero to two Hz. Approximate force value for a single fin is divided by two.

CONCLUSIONS

The conducted research on two BUVs with different size and propulsion system mounted on the stern proves that:

1. Increasing the frequency of fins oscillation affects the increase of generated thrust.
2. There is defined frequency of the fin oscillation which gives the smallest side-effect oscillation of the course during the advance motion.

3. The use of two tail fins in counter-phase eliminates the moment of force and improves the vehicle positioning.
4. The distance between two fins in a final phase of motion influences on amplitude of oscillation X_{OSC}.

The received results will be used to in the following future research:
1. Taking into consideration the specified category, e.g. minimization of energy consumption, minimization of the course oscillation, etc. the best function for the fin oscillation will be searched.
2. The mathematical model of the tail fins will be implemented in the simulation environment and further it will be used in numerical research on the BUV's control system.

Acknowledgements

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POMIAR NAPORU BIOMIMETYCZNEGO POJAZDU PODWODNEGO Z NAPĘDEM FALOWYM

STRESZCZENIE

W ostatnich latach nastąpił dynamiczny rozwój robotyki podwodnej. Jedną z najnowszych grup robotów podwodnych są biomimetyczne pojazdy podwodne (BPP) napędzane ruchem falowym imitującym ruch płetw podwodnych zwierząt, np. ryb, fok itp.

W artykule dokonano pomiaru naporu nowego BPP wyposażonego w napęd falowy. Na początku opisano stanowisko do pomiaru naporu. Następnie przedstawiono dwie konstrukcje BPP imitujących ruch ryby i foki. W dalszej kolejności zaprezentowano wyniki pomiarów naporu dla dwóch różnych typów napędu falowego. Na końcu artykułu zawarto wnioski z przeprowadzonych pomiarów, a także przewidywane kierunki dalszych prac badawczych.

Słowa kluczowe:

biomimetyczny pojazd podwodny, napęd falowy, pomiar naporu.

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