Depth stabilization of biomimetic underwater vehicle without swim bladder

Piotr Szymak, Tomasz Praczyk

***Abstract*—**In recent times, we may notice some new designs of underwater vehicles, which imitate living underwater organisms, e.g. a fish. These vehicles are called biomimetic. They are driven by undulating propulsion, imitating wavy motion of fins and they can submerge using ballast tank called an artificial swim bladder. In the paper, problem of depth stabilization of biomimetic underwater vehicle (BUV) which was not equipped with a swim bladder is undertaken. At the beginning of the paper, introduction to the research area of biomimetic underwater vehicles is inserted. Then, the mathematical model of BUV with the new undulating propulsion is presented. Next, the controllers for depth stabilization used in the numerical research are described. The BUV model and depth controllers were implemented in Matlab environment for making numerical tests. At the end of the paper, the selected results of the numerical research are presented and then, the conclusions are formulated.

***Keywords*—**biomimetic underwater vehicle, undulating propulsion, depth control

I. Introduction

In the recent years, a dynamical development of underwater robotics has been noticed. One of the latest innovative constructions in this field are autonomous biomimetic underwater vehicles (BUVs) [1][2][3][10]. They imitate underwater living organisms, e.g. fishes, marine mammals, etc. They can imitate both the construction and kinematics of motion. BUVs are driven by undulating propulsion imitating real fins, e.g. of a fish – Fig. 1 [5][6].

They can be equipped with an artificial swim bladder similar to a fish bladder, which are used to control buoyancy and consequently to control depth. Usually, the artificial swim bladder is working as a ballast tank, which can increase or decrease a total mass of the vehicle by pumping into or outside the tank water. Depending on the depth of operation i.e. an outside pressure of a marine environment, the ballast tank very often needs an efficient and expensive pump. The other solution of a swim bladder is a cylindrical ballast tank with a piston driven by an electrical motor. Moving the piston in the cylinder influence on a volume of water inside the tank.

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Such swim bladders should be mounted in the center of gravity or very close to this center, what can prevent possible trim changes during water volume changes inside the cylindrical tank. This condition causes localization of the swim bladder into a middle compartment of the BUV destined for the electronics and batteries. It causes many design and implementation problems. Therefore, resignation from mounting a swim bladder in the BUV hull is quite often considered operation.

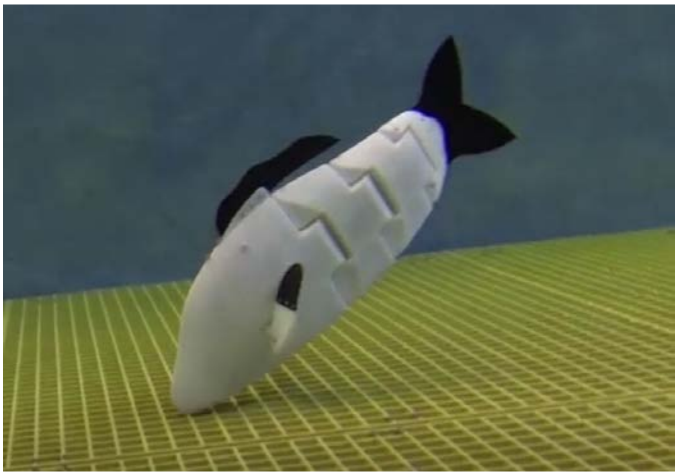

Fig. 1. BUV CyberFish ver. 5 in a swimming pool [6]

This paper undertakes problem of the depth control in the BUV without swim bladder – Fig. 2. This vehicle has a little positive buoyancy, therefore it needs additional dynamic force generated by its undulating propulsion for submerging. The disadvantage of this construction comparing to the BUV with swim bladder is that it needs continuous work of undulating propulsion even for stabilizing a depth.

Presented in the Fig. 2 ABPP2 was designed and built within Polish development project [7] carried out by the consortium consisted of the following scientific and industrial partners: Polish Naval Academy AMW – the leader, Cracow University of Technology PK, Industrial Institute of Automatics and Measurement PIAP and Forkos Company [9]. The main objective of this project was to build heterogeneous torpedo-shaped BUVs with undulating propulsion for selected scenarios of underwater ISR. Since today, two biomimetic vehicles were built which differentiate among others with a lack or a presence of the swim bladder. The first vehicle

ABPP1 was equipped with the bladder, while the second vehicle ABPP2 was not equipped.

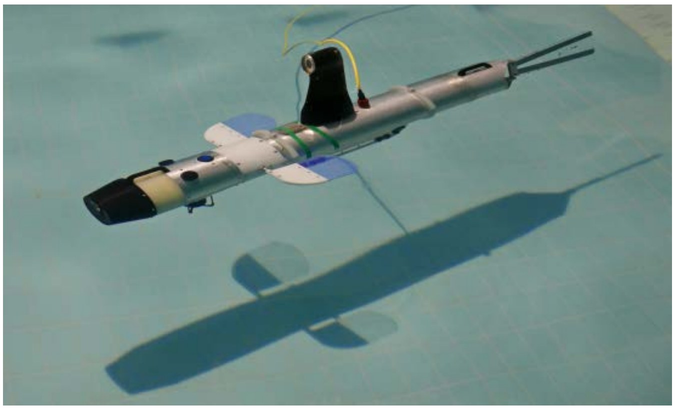

Fig. 2. BUV ABPP2 in a swimming pool

Currently, the work on BUVs is continued in the project which was started in European Defense Agency [8]. The 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 the project is to build BUVs similar to real inhabitants of underwater environment, prepared for their swarm operation.

As it was showed above, the research on BUVs are consistent and are developing in the direction of autonomous vehicles cooperating in a swarm. This development requires many different research focused on control algorithms, starting with low-level control and providing to semi– or fully–autonomous behaviors at the end of the research. One of the considered problems is the depth stabilization using only side fins in the case when the BUV is not equipped with a swim bladder.

In the next section, the mathematical model of biomimetic underwater vehicle used in simulation was presented in general. This model is based on classical Fossen model of motion of marine vehicle [4] with some improvements taking into account the new undulating propulsion system [9]. Then, in the next section, the proposed depth controllers are presented and next, results of their working are illustrated. In the last section, the conclusions are formulated. At the end, the acknowledgment and references are inserted.

II. Mathematical model of BUV motion

Usually, an underwater vehicle is considered as a rigid body with the following features:

- it has three planes of symmetry,
- it moves in six degrees of freedom,
- it moves at a low speed in a viscous fluid.

Motion of the vehicle is described by means of two reference systems: (1) the movable coordinate system associated with the vehicle $x_o y_o z_o$ and (2) the immovable coordinate system associated with the Earth xyz.

The origin of the movable coordinate system O responds to the center of gravity of the vehicle, while its axes are defined as: (1) x_o is a longitudinal axis directed from the stern to the bow, (2) y_o is a transverse axis directed to the starboard, and (3) z_o is a perpendicular axis directed from the top to the bottom. Changes of the position of the movable coordinate system $x_o y_o z_o$ are described with respect to coordinate system xyz associated with the Earth. Due to the fact that the vehicle moves at a relatively low speed, acceleration of points on the Earth's surface is ignored and the coordinate system xyz is considered as a stationary. Therefore, the centrifugal and centripetal forces and moments of force caused by the spin of the Earth may be neglected.

Taking into account mentioned above assumptions, to simulate motion of BUV, a nonlinear model of underwater vehicle in 6 degrees of freedom [4] was used. The motion of the vehicle is described by 6 differential equations, very often presented in the compact matrix form:

$$\mathrm{M}\dot{\nu} + \mathrm{D}(\nu)\nu + \mathrm{g}(\eta) = \tau \qquad (1)$$

here:

- ν – vector of linear and angular velocities in the movable system,
- η – vector of vehicle position coordinates and its Euler angles in the immovable system,
- M – matrix of inertia (the sum of the matrices of the rigid body and the accompanying masses),
- $\mathrm{D}(\nu)$ – hydrodynamic damping matrix,
- $\mathrm{g}(\eta)$ – vector of restoring forces and moments of forces of (gravity and buoyancy),
- τ – vector of control signals (the sum of vector of forces and moments of force generated by propulsion system τ_p and by environmental disturbances τ_d).

The left side of the equation (1) includes forces and moments of force caused by the following physical phenomenas: an inertia of the body of the vehicle and inertia of the accompanying masses of a viscous liquid, a hydrodynamic dumping of water environment, a balance of a gravity and a buoyancy. While the right side of the equation (1) represents the vector of forces and moments of force acting on the vehicle generated by a propulsion system and additional environmental disturbances (under surface of water especially a sea current). The parameters of the matrices included in the left side of equation (1) were calculated based on the dependencies included in [4]. The problem undertaken in this paper is to calculate the vector of forces and moments of force τ_p generated by the new type of propulsion system, which is an undulating propulsion imitating operation of real fish fins:

$$\tau_p = [X, Y, Z, K, M, N] \qquad (2)$$

here:

- X, Y, Z – the forces acting respectively in longitudinal, transverse and vertical axes of symmetry,

K, M, N – the moments of force acting relative to respectively longitudinal, transverse and vertical axes of symmetry

The calculation of the vector of force and moments of force generated by propulsion should take into consideration specific configuration of the considered undulating propulsion. In the Fig. 3, the 3D design of BUV with specific undulating propulsion is illustrated. In this case, the propulsion system consists of pivoted module of tail ended with movable tail fin and two independently driven side fins.

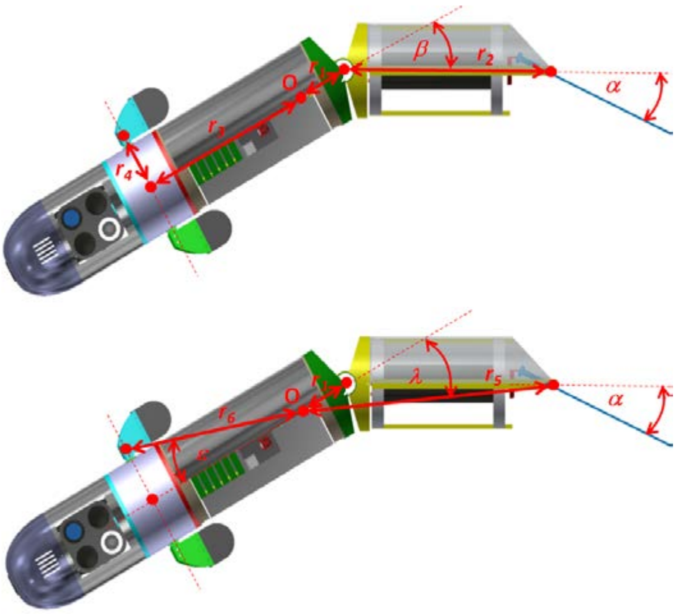

Fig. 3. BUV ABPP2 designed within Polish project (top view) [7]

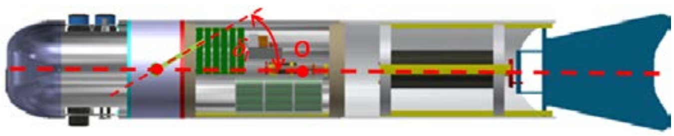

Fig. 4. BUV ABPP2 designed within Polish project (side view) [7]

The thrust generated by the each fin should be referenced to the origin of gravity O (Fig. 3) using simple dependencies on the vector transformation:

$$X = X_t + X_l + X_r - X_d \quad (3)$$

$$Y = Y_t \quad (4)$$

$$Z = Z_l + Z_r \quad (5)$$

$$K = 0 \quad (6)$$

$$M = M_l + M_r \quad (7)$$

$$N = N_t + N_l - N_r - N_d \quad (8)$$

here:
lower indexes t, l and r refer respectively to tail, left side and right side fins operation,
lower index d refers to damping caused by left or right side fin working as stern (the surface of fin set perpendicularly to the longitudinal axis of symmetry).

The vector components (e.g. X_t, Y_t, N_t) are calculated taking into consideration localization of fins relative to the gravity origin using the following formulas:

$$X_t = \cos\beta \cdot T_t \quad (9)$$

$$Y_t = \sin\beta \cdot T_t \quad (10)$$

$$N_t = -\cos\lambda \cdot r_5 \cdot Y_t \quad (11)$$

$$X_l = \cos\delta_l \cdot T_l \quad (12)$$

$$Z_l = \sin\delta_l \cdot T_l \quad (13)$$

$$N_l = r_4 \cdot X_l \quad (14)$$

$$M_l = r_3 \cdot Z_l \quad (15)$$

$$N_d = \cos(90-\varepsilon) \cdot r_6 \cdot X_d \quad (16)$$

here:
T_t, T_l, T_r – the thrusts generated respectively by tail, left and right side fins,
β, λ, δ_l, ε – the angles illustrated in the Fig. 3 and 4,
r_1 – the distance between the gravity origin and the center of rotation of the tail module,
r_2 – the distance between the center of rotation of the tail module and the center of rotation of the tail fin,
r_3 – the distance between the gravity origin and the center of rotation of the side fins,
r_4 – the distance between the center of rotation of the side fins and center of rotation of the left of right fin (it is a distance between the center of rotation of each side fin and the longitudinal axis of symmetry),
r_5 – the distance between the gravity origin and the center of rotation of the tail fin,
r_6 – the distance between the gravity origin and the center of rotation of the left or right side fin.

The vector components for right side fin X_r, Y_r, N_r, M_r can be calculated using formulas for left side fin (12-15) inserting instead of the angle δ_l proper angle for right side fin δ_r. The hydrodynamic dumping generated by left or right side fin X_d (set in position perpendicular to the longitudinal axis of symmetry) can be determinated using dependencies included in [4].

Each fin generates a thrust with the value changing in time depending on the control parameters of the fin, especially an amplitude and a frequency of the fin oscillation [9]. The thrust generated by the fin depends also on the type of used fin (stiffness of the fin membrane, shape and dimensions of the fin, etc.).

In the paper, the thrusts T_t, T_l, T_r were determinated in empirical way by measurement of the different fins using laboratory stand described in details in [9].

III. BUV DEPTH STABILIZATION CONTROLLERS

To control the motion of torpedo-shaped underwater vehicles, usually two main controllers are used. The first is a course controller and the second is a trim controller. The course controller is mainly used for steering motion in the horizontal plane, while the trim controller is usually used for steering motion in the vertical plane (to submerge or to emerge the vehicle). The results of operation of mentioned above controllers are included in [9].

To stabilize depth in the case that BUV is not equipped with a swim bladder, an additional depth controller is needed. This controller uses side fins as an actuator. It is worth mentioning that side fins are also used by trim controller. Therefore the action of these two controllers (of trim and of depth) are separated in time. They do not work together in the same time. Depth controller works only when the vertical motion is needed without any horizontal displacements. It is assumed that it should work similar to the swim bladder. In this case, the thrust generated by side fins should counteract positive buoyancy. It can be achieved by selecting proper frequency of side fins oscillation, which generate proper force counteracting a buoyancy force. The additional issue is that the side fins are not situated in the center of gravity. It causes two problems for depth stabilization, which should be taken into consideration. The first problem is that the vehicle changes trim when side fins work. Therefore, the trim should be taken into account for calculation of angles of setting the neutral position of right and left side fins δ_r, δ_l. The neutral position of a fin is considered as a position from which the fin starts to oscillate in a clockwise and then a counterclockwise direction. The second problem is that the side fins oscillation influence of a motion in the horizontal plane, i.e. a thrust generated by side fins transformed to the center of gravity can give the vertical and horizontal components. Therefore, the horizontal component of the thrust should be minimized by proper correction of setting angles δ_r, δ_l.

To examine how efficiently stabilize the depth of BUV without swim bladder, two control methods were used. At the beginning, proportional-integral-derivative action controller (PID) and then, slide mode controller (SMC) were tested. The depth controller produces on its output a frequency of oscillating right and left side fins. Both side fins oscillate with the same frequencies. The angles δ_r and δ_l are set taking into account a current value of the BUV trim. It should be noted that the neutral position of the side fins are determined with discretization step equal to 2 [deg]. It is caused by low-level control algorithm for the electric motors driving the fins.

In general, the PID controller is used to control objects, which are affected by big and rapid disturbances. It is described by the following formula in the discrete form:

$$u(k) = K_p \cdot e(k) + K_i \cdot \sum_{i=1}^{k} e(k) + K_d \cdot \Delta e(k) \qquad (17)$$

Where $u(k)$ is a control signal in k step of simulation. Variable $e(k)$ is an error signal in k step of simulation, while $\Delta e(k)$ is a change of error signals in k step of simulation ($e(k)$–$e(k-1)$). Constant quantities called gain factors are: K_p, K_i and K_d.

Sliding mode control (SMC) is a nonlinear control method that alters the dynamics of a nonlinear system by application of a discontinuous control signal that forces the system to slide along a cross-section of the system's normal behavior. It is calculated using the following formulas in the discrete form:

$$s(k) = \frac{\lambda \cdot e(k) + \Delta e(k)}{\varphi} \qquad (18)$$

$$\text{if} \quad |s(k)| > 1, \quad \text{then} \quad s(k) = sign(s(k)) \qquad (19)$$

$$u(k) = k_s \cdot s(k) \qquad (20)$$

Where $u(k)$ is a control signal in k step of simulation and $s(k)$ is a normalized control signal in k step of simulation. Variable $e(k)$ is an error signal in k step of simulation, while $\Delta e(k)$ is a change of error signals in k step of simulation ($e(k)$–$e(k-1)$). Constant quantities are: λ, φ, k_s.

To achieve efficient action of a controller, determination of constant quantity values is necessary. For this aim different methods could be used. In the paper, the constant quantity values were selected in an empirical way, based on observation of direct control quality indexes such as a rise time, a setting time and a first overshoot value. In all the simulations, a step equal to 1/18 [s] was accepted.

Stability of tuned controllers was tested by simulation for several values of desired depth: 1m, 2m, …, 5m in the presence of affecting sea current with maximal velocity 0.5 m/s.

IV. Results of Stabilizing Depth

At the beginning, settings of the PID controller were tuned. For the PID depth controller following values of constant quantities were received: $K_p = 286$, $K_i = 0.11$ and $K_d = 24$. In the Fig. 5, changes of depth Zreal in response of desired depth Zset were illustrated. It can be observed quite large first overshoot value and decreasing oscillations down to the desired value of the depth. In the next Fig. 6, changes of oscillation frequency of left side fin *F1* and generated by the side fins vertical force *Z* were presented.

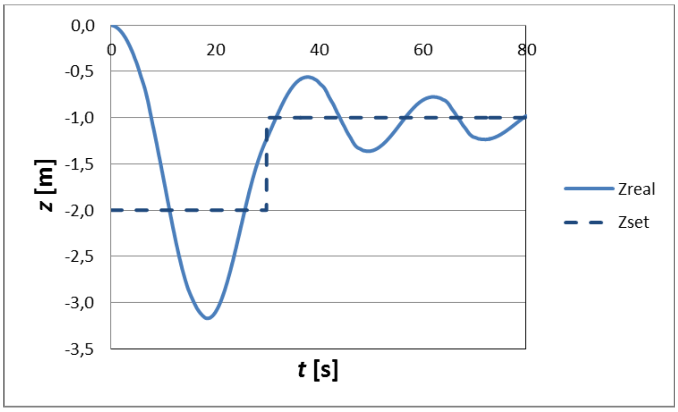

Fig. 5. Changes of desired and real values of BUV depth for PID controller

Frequency of right side fin F2 has the same course as a frequency F1. Oscillating changes of force Z corresponding to the oscillations of the side fins can be observed during PID controller work. The BUV reacts on the average value of this force. Its inertia is larger than momentary changes of the force Z.

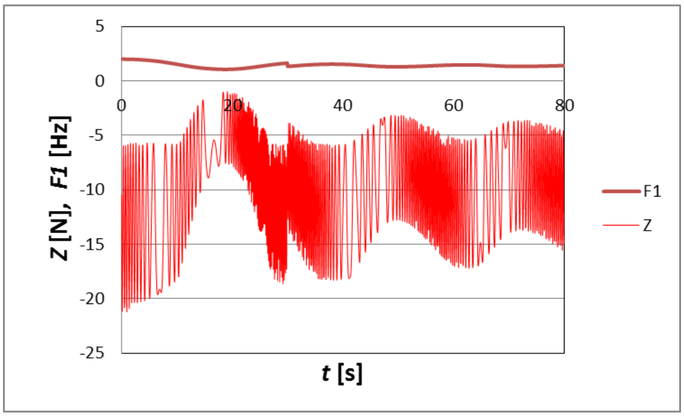

Fig. 6. Changes of oscillation frequency of left side fin *F1* and generated by the two side fins vertical force *Z* during PID controller operation

In the next step of the research, settings of the SMC depth controller were tuned. For the SMC controller following values of constant quantities were received: $\lambda = 0.021$, $\varphi = 0.001$ and $k_s = 3$.

In the Fig. 7, changes of depth Zreal in response of desired depth Zset were illustrated. No overshoot and oscillations may be seen for the SMC depth controller. For this controller a setting time is equal to 7,8 [s] and 6 [s] adequately for the changes from 0 to -2 [m] and from -2 to -1 [m]. In the next Fig. 8, changes of oscillation frequency of left side fin *F1* and generated by the side fins vertical force *Z* were inserted. Intensive work of side fins can be observed, which very often work with maximal frequency 3 [Hz]. Moreover, oscillations of force Z with larger amplitude than for PID controllers are noted, which are caused by the side fins oscillations.

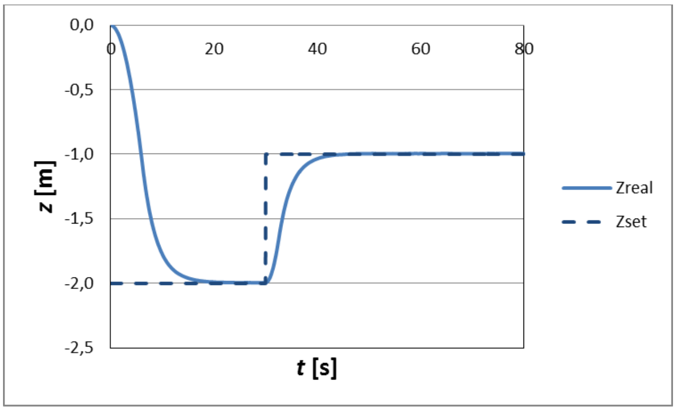

Fig. 7. Changes of desired and real values of BUV depth for SMC controller

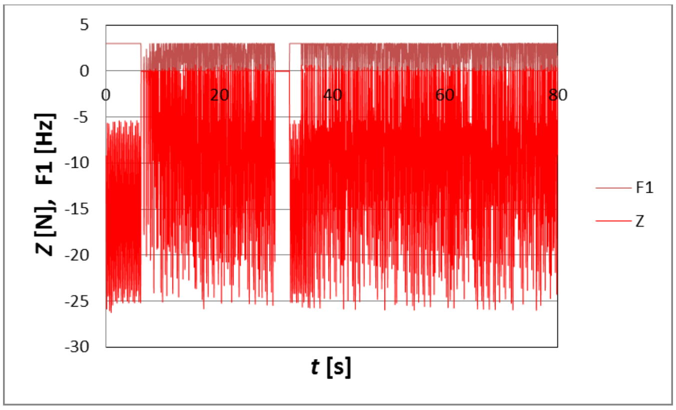

Fig. 8. Changes of oscillation frequency of left side fin *F1* and generated by the two side fins vertical force *Z* during SMC controller operation

In the Fig. 9, enlargement of oscillation frequency *F1* and generated vertical force *Z* was presented. Based on the zoom in, it may be noted quite often changes of side fins oscillation frequency from 3 to 0 [Hz]. These changes gives very good stabilization of depth (Fig. 7).

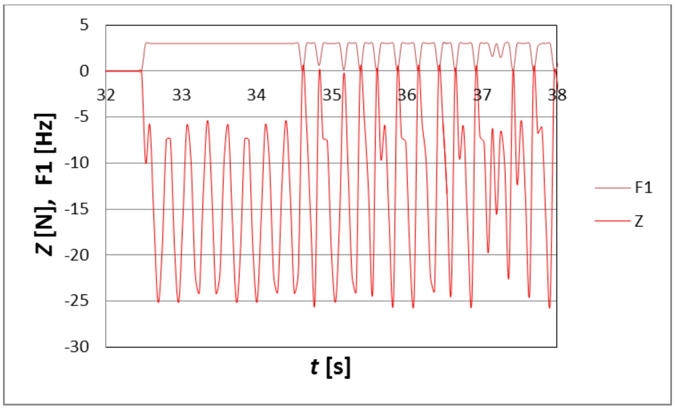

Fig. 9. Changes of oscillation frequency of left side fin *F1* and generated by the two side fins vertical force *Z* during SMC controller operation (zoom in time from 32nd to 38th second of simulation)

In the next Fig. 10, changes of the BUV's trim and the angle of left side fin neutral position are illustrated. The course of these parameters were the same for both controllers: PID and SMC. It is caused by the fact that the same rule of steering angles of neutral position of side fins is used for both controllers. This rule takes into account the momentary value of the trim, which appears, when the side fins start to oscillate (Fig. 10).

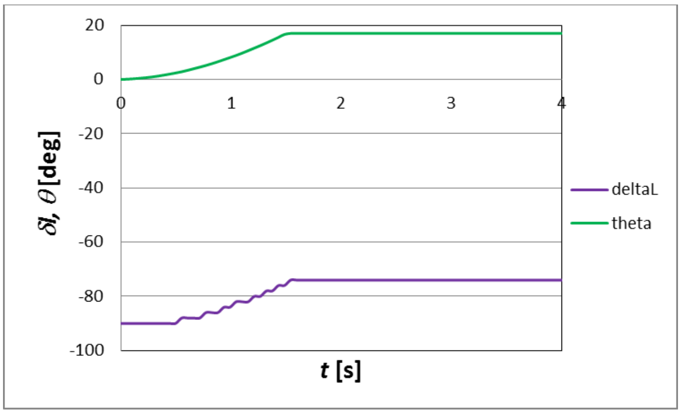

Fig. 10. Changes of the BUV trim and the neutral position of left side fin

Not taking into account the BUV's trim in determination of the neutral position of side fins during the depth stabilization may result in quite large displacement of the BUV in the vertical plane (Fig. 11 – red line entitled "notC"). This displacement cannot be tolerated e.g. during registration of video or sonar signals. Therefore, the neutral position of side fins should be still corrected taking into consideration the BUV's trim.

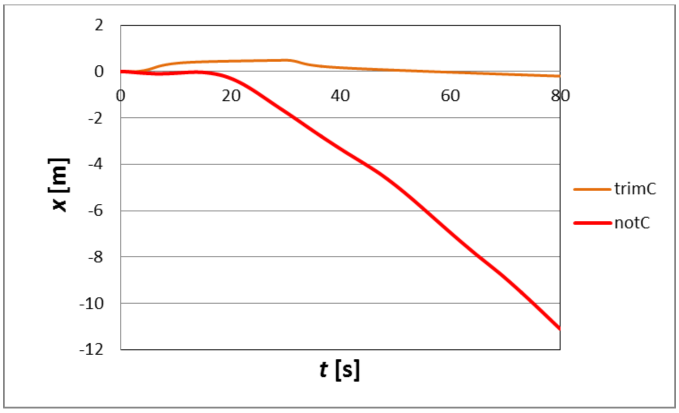

Fig. 11. Changes of the BUV trim and the angle of left side fin neutral position

V. Conclusions

Designed mathematical model of the motion of biomimetic underwater vehicle allows us to design and tune PID and SMC depth controllers of the BUV. SMC controller is more efficient and precise than PID controller. However, SMC controller causes more intensive operation of side fins, i.e. more changes of oscillation frequency is observed. It is worth mentioning that an efficient stabilization of depth requires also proper calculation of the neutral position of side fins taking into account the BUV's trim. During the future research, the depth controller described in this paper and other controllers of the BUV [9] will be verified in tests on real object.

Acknowledgment

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References

[1] J.E. Colgate, K.M. Lynch, "Mechanics and Control of Swimming: A Review", IEEE Journal of Oceanic Engineering, Vol. 29, No. 3, 2004, pp. 660-673.

[2] O. M. Curet, N. A. Patankar, G. V. Lauder, M. A. MacIver, "Mechanical properties of a bio-inspired robotic knifefish with an undulatory propulsor", Bionispiration&Biomimetics, No. 6, 2011.

[3] W.-S. Chu, "Review of Biomimetic Underwater Robots Using Smart Actuators", International Journal Of Precision Engineering and Manufacturing, Vol. 13, No. 7, pp. 1281-1292, 2012.

[4] T. Fossen, "Handbook of Marine Craft Hydrodynamics and Motion Control", Wiley, 2011.

[5] K. H. Low, "Modelling and parametric study of modular undulating fin raysfor fish robots", Mechanism and Machine Theory, Vol. 44, 2009, pp. 615–632.

[6] M. Malec, M. Morawski, P. Szymak, A. Trzmiel, " Analysis of Parameters of Traveling Wave Impact on the Speed of Biomimetic Underwater Vehicle", Trans Tech Publications, Solid State Phenomena, Vol. 210, 2014, pp. 273-279.

[7] P. Szymak, et al., "Autonomous underwater vehicles with silent undulating propulsion for underwater ISR – II part", Report on the second stage of the project No. DOBR-BIO4/033/13015/2013, Polish Naval Academy, in Polish, 2015.

[8] P. Szymak, et al., "Technical Report on SABUVIS project, Report on the Milestones M1-M3 of the project No B-1452-ESM1-GP, Polish Naval Academy, 2015-2016.

[9] P. Szymak, "Simulation and control of biomimetic underwater vehicle with undulating propulsion", WSEAS, Transactions on Systems, Vol. 15, 2016, pp. 180-187.

[10] X. Ye, Y. Su, S. Guo, L.Wang, "Design and realization of a remote control centimeter-scale robotic fish," IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM 2008), pp. 25-30, 2008.