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INVESTIGATION OF HYDRODYNAMIC CHARACTERISTICS OF AN AUV BY USING A NEW DEVELOPED CFD ANALYSIS MODEL

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ABSTRACT

Hydrodynamic coefficients are the main significative factors that strongly affect the performance, controllability and maneuverability characteristics of an autonomous underwater vehicle (AUV). These coefficients are generally obtained by different methods such as experimental, numerical and empirical. Although the experimental methods are the most reliable one among these, hydrodynamic coefficients are not generally obtained experimentally; due to financial problems, time-related problems and deficiencies of model basins. Another approach by which these coefficients can be obtained is the numerical methods, such as computational fluid dynamics (CFD). In this project, all hydrodynamic coefficients of an AUV are calculated in six degree of freedom (6 DOF), by using computational and empirical methods. Firstly, a new hydrodynamic calculation model for underwater vehicles is created and verified. After the verification of CFD solution model, hydrodynamics database of an AUV is constituted and then stability and performance characteristics are determined.

INTRODUCTION

In recent years, intensive efforts are being concerted towards the development of Autonomous Underwater Vehicles (AUVs) and AUVs have become a main tool for surveying below the sea in the scientific, military and commercial applications because of the significant improvement in their performance. Despite the considerable improvements in AUV performance, however, AUV technologies are still attractive to scientist and engineers as a challenging field. Some of AUV designs, which are used for different purposes, are shown in Figure 1.

Figure 1: *Types of Various AUVs [7,10,11].*

In order to design an AUV, it is usually necessary to analyze its hydrodynamics performance, maneuverability and controllability characteristics. A useful tool for gaining an understanding of the performance of an AUV is a dynamic simulation of the equations of the motion of the vehicle. To perform these simulations, the hydrodynamic coefficients of the vehicles must be calculated. These coefficients are specific to the vehicle and provide the description of the hydrodynamic forces and moments acting on the vehicle in its underwater environment. The hydrodynamic coefficients may be classified into 2 main groups. These are static hydrodynamic coefficients and dynamic hydrodynamic coefficients. Static hydrodynamic coefficients occur while the AUV have steady cruise conditions without any maneuvering. However, dynamic hydrodynamic coefficients are more complex than the

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statics, and dynamic coefficients may be classified into 3 subgroups such as; linear damping coefficients (maneuvering coefficients), linear inertial force coefficients (added mass, inertia coefficients) and nonlinear damping coefficients. These coefficients may be obtained by different ways. These are experimental methods, numerical methods and empirical methods. The most reliable one in these calculation methods is the experimental methods. Vertical Planar Motion Mechanism (VPMM), Rotating-Arm Mechanism and Coning Motion Mechanism are the most common experimental techniques to measure the hydrodynamic coefficients. VPMM and Rotating-Arm Mechanism are shown in Figure 2.

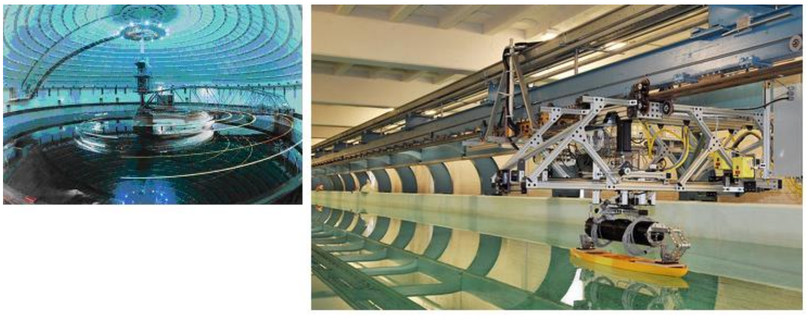

Figure 2: *Rotating Arm Mechanism and VPMM [2,12].*

In spite of the fact that the most reliable methods to calculate hydrodynamic coefficients are the experimental techniques, also these are the most expensive ones to determine the hydrodynamic coefficients. Because of this reason, experimental methods cannot be used in every design steps of the AUVs. Instead of experimental methods, numerical (computational fluid dynamics) and empirical techniques can be used. To calculate the hydrodynamic coefficients, new CFD calculation models and empirical methods can be developed by using test-case documents, which have experimental datum to compare and verify the solutions.

DEFINITION OF THE HYDRODYNAMICS COEFFICIENTS

In the hydrodynamic coefficients, which mostly affect the maneuverability of an AUV, are static and the linear damping coefficients. A rectangular cartesian coordinate system, attached to the center of gravity of vehicle, is used in the project. The three components of the hydrodynamic force along the directions x, y, z are denoted by X, Y, Z respectively, and the three components of the hydrodynamic moments by L, M, N. This is illustrated in Figure 3.

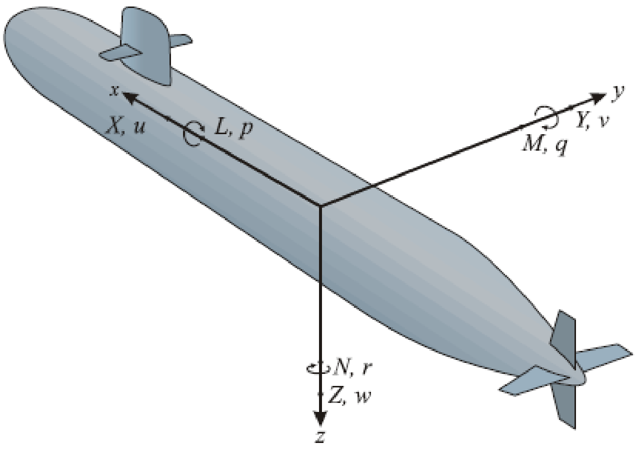

Figure 3: *Schematic of the cartesian coordinate system [6].*

The path of the vehicle is then assumed to be intentionally altered slightly by deflection of various control surfaces on the vehicle. The three components of force X, Y, Z and the three components of the moments L, M, N are expanded up to second order terms in the linear velocities u, v, w and the angular velocities p, q, r where these velocities now represent perturbations to the equilibrium condition of steady state forward motion. The expression for the forces and moments are derived from "*Standard Equations of Motion for Submarine Simulations*" [4] and then take the form:

$$\sum X = X_{qq}{}'q^2 + X_{rr}{}'r^2 + X_{rp}{}'rp + X_{\dot{u}}{}'\dot{u} + X_{vr}{}'vr + X_{wq}{}'wq + X_{uu}{}'u^2 + X_{vv}{}'v^2 + X_{ww}{}'w^2 + X_{\delta e\delta e}{}'\delta e^2 + X_{\delta r\delta r}{}'\delta r^2 + X_{\delta a\delta a}{}'\delta a^2 \tag{1}$$

$$\sum Y = Y_{\dot{r}}{}'\dot{r} + Y_{\dot{p}}{}'\dot{p} + Y_{p|p|}{}'p|p| + Y_{pq}{}'pq + Y_{qr}{}'qr + Y_{\dot{v}}{}'\dot{v} + Y_{vq}{}'vq + Y_{wp}{}'wp + Y_{wr}{}'wr + Y_r{}'r + Y_p{}'p + Y_{|r|\delta r}{}'|r|\delta r + Y_{v|r|}{}'v|r| + Y_v{}'v + Y_{v|v|}{}'v|v| \tag{2}$$

$$\sum Z = Z_q{}'\dot{q} + Z_{pp}{}'pp^2 + Z_{rr}{}'rr^2 + Z_{rp}{}'rp + Z_{\dot{w}}{}'\dot{w} + Z_{vp}{}'vp + Z_{vr}{}'vr + Z_q{}'q + Z_{|q|\delta e}{}'|q|\delta e + Z_{w|q|}{}'w|q| + Z_{|w|}{}'|w| + Z_{ww}{}'ww + Z_{vv}{}'v^2 + Z_{\delta e}{}'\delta e + Z_{\delta a}{}'\delta a \tag{3}$$

$$\sum K = K_{\dot{p}}{}'\dot{p} + K_{\dot{r}}{}'\dot{r} + K_{p|p|}{}'p|p| + K_{pq}{}'pq + K_{qr}{}'qr + K_{\dot{v}}{}'\dot{v} + K_r{}'r + K_p{}'p + K_{vq}{}'vq + K_{wp}{}'wp + K_{wr}{}'wr + K_v{}'v + K_{v|v|}{}'v|v| + K_{vw}{}'vw + K_{\delta r}{}'\delta r \tag{4}$$

$$\sum M = M_q{}'\dot{q} + M_{pp}{}'pp^2 + M_{rr}{}'rr^2 + M_{rp}{}'rp + M_{q|q|}{}'q|q| + M_{\dot{w}}{}'\dot{w} + M_{vp}{}'vp + M_{vr}{}'vr + M_q{}'q + M_{|q|\delta e}{}'|q|\delta e + M_{w|q|}{}'w|q| + M_{|w|}{}'|w| + M_{ww}{}'ww + M_{vv}{}'v^2 + M_{\delta e}{}'\delta e + M_{\delta a}{}'\delta a \tag{5}$$

$$\sum N = N_{\dot{r}}{}'\dot{r} + N_{\dot{p}}{}'\dot{p} + N_{r|r|}{}'r|r| + N_{pq}{}'pq + N_{qr}{}'qr + N_{\dot{v}}{}'\dot{v} + N_{vq}{}'vq + N_{wp}{}'wp + N_{wr}{}'wr + N_r{}'r + N_p{}'p + N_{|r|\delta r}{}'|r|\delta r + N_{v|r|}{}'vr + N_v{}'v + Y_{v|v|}{}'v|v| + N_{vw}{}'vw + N_{\delta r}{}'\delta r \tag{6}$$

There are many kind of hydrodynamic coefficients which could be evaluated to describe the dynamics of the vehicle [3]. In this project static, linear damping, and nonlinear damping coefficients are calculated by using CFD methods and linear inertia coefficients are calculated with empirical methods. Firstly, CFD analysis process would be investigated.

METHODOLOGY OF THE CFD ANALYSES PROCESS

In this project, fundamental hydrodynamic coefficients in six degree of freedom such as surge, heave, sway forces and pitch, yaw and roll moments are calculated for different cruise conditions. Also, stability and performance characteristics of an AUV are determined. In order to calculate these coefficients, linear and nonlinear steady state computational fluid dynamics (CFD) analyses are done. But before this step, CFD solution model of hydrodynamic calculations must be verified, to get correct results from CFD analyses. In order to verify the solution methods of CFD calculation model, test-case documents are studied. These documents include geometry of any underwater vehicle, test conditions and test results. For the verification study, hydrodynamic test results and geometry of Autosub Autonomous Underwater Vehicle Model is used. In order to start the hydrodynamic analysis process firstly, solid model of an AUV must be created. The solid model is created in CATIA 3D modeling software and then fluid domain is constituted. In order to constitute the grid of the AUV GAMBIT 2.4 software is used. Edge mesh, surface and volume meshes of the geometry are created in GAMBIT software. Also, to define the boundary layer over the geometry TGRID 5.0 software is used. At the end of this process, fluid domain and grid files of an AUV gets ready to perform hydrodynamic analyses in CFD analysis software. Flow chart of the preparation of hydrodynamic database of any AUV is shown in Figure 4.

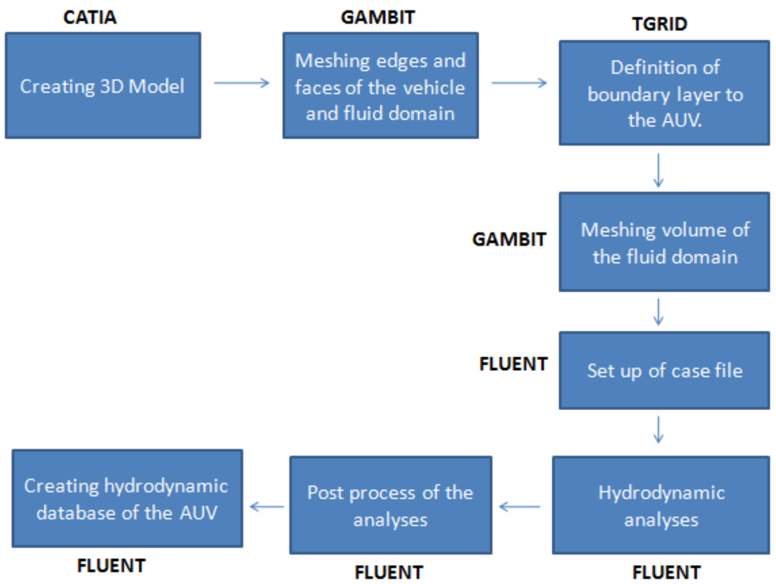

Figure.4: *Flow chart of the hydrodynamic analysis process.*

In the CFD analysis processes ANSYS Fluent 13.0 software is used. Some characteristic features for hydrodynamic analyses as a solver model, turbulence model, boundary conditions, Y+ values, characteristic features for the fluid and solution techniques are defined in Fluent 13.0. After the complementation of setup case for hydrodynamic analyses, lots of CFD analyses are carried out for different cruise conditions and hydrodynamic database is constituted.

VERIFICATION OF HYDRODYNAMICS ANALYSIS MODEL

In this study, a comprehensive study has been made to validate the CFD tools for the hydrodynamic analysis of the underwater bodies such as autonomous underwater vehicles. In order to evaluate the capabilities and accuracy of the tools used in this project, Autosub autonomous underwater vehicle (AUV) model has been selected as a test case, because of the availability of extensive validation data for field variables as well as for integral quantities. The experimental data of Autosub AUV is available at National Oceanography Centre, Southampton, UK.

Autosub Autonomous Underwater Vehicle Model

Autosub is a large AUV developed by a team of engineers and oceanographers at the National Oceanography Centre, Southampton, UK. Autosub Project was initiated firstly in 1988, in order to develop unmanned autonomous underwater vehicles for its future marine science programs and for global monitoring [9]. Autosub is controlled by four movable control surface mounted at the rear of the vessel in a cruciform arrangement. The control surfaces' cross sections consist of NACA 0015 hydrofoil [9].

Autosub's principle dimensions and hydrofoil are listed below [9]:

- Length: 7 meter
- Diameter: 0,9 meter

Naca 0015 Hydrofoil;

- Chord of the hydrofoil: 0,294 meter
- Thickness of the hydrofoil: 0,02 meter

Autosub model is composed of an axisymmetric body and four appendages in plus configuration. Picture and 3D drawing of the full model is given in Figure 5.

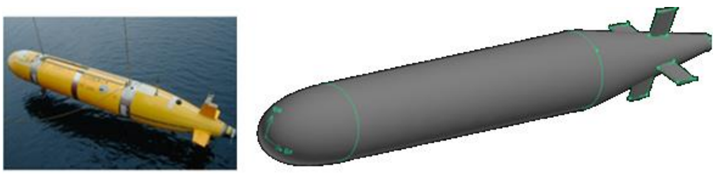

Figure.5: *Autosub Autonomous Underwater Vehicle [11].*

Test and Analysis Conditions

The data used in the present study are based on the experiments which were performed in the National Oceanography Centre, Southampton, UK by engineers and oceanographers at the National Oceanography Centre. Towing tank tests of Autosub are performed for 2/3 scaled model with 2.69 m/s linear velocity and between ±10 degree angle of attacks with 2 degrees intervals. As the result of the experimental studies, drag force, heave force and pitch moment of Autosub is calculated. Tests are achieved at different angle of attacks and a model speed of 2.69 m/s which correspond to a Reynolds number of about 12 million. In the calculation of Reynolds Number, dynamic viscosity of the water is accepted as 0,001003 kg/m.s and the density is accepted as 998 kg/m^3.

Grid Generation of Autosub AUV

In order to perform hydrodynamic analysis, firstly fluid domains and solution grids of Autosub must be created. . In order to constitute the grid of the AUV, GAMBIT 2.4 software is used. Edge mesh, surface mesh and volume mesh of the geometry is created in a hierarchical order, so edge mesh of the model is constituted in first step. Grids are created in appropriate density to be use in Navier-Stokes equations. Some surface grid pictures are shown in Figure 6.

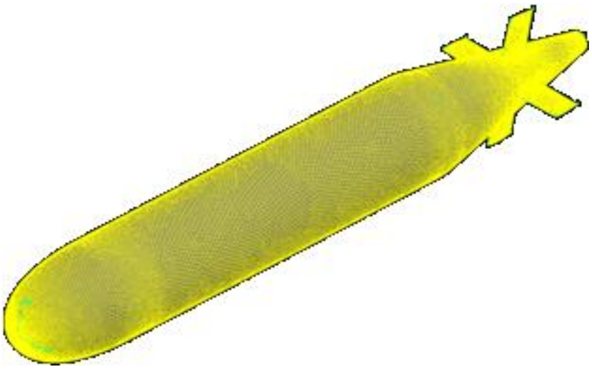

Figure 6: *Surface grids of Autosub AUV.*

Additionally to define the boundary layers over the Autosub geometry, TGRID 5.0 software is used. The boundary layer is created as two zones. These are inner zone and outer zone. To specify the zone thickness, Reynolds number is calculated and Y+ is chosen. Reynolds Number of Autosub model is calculated as 12 million at 2,69 m/s velocity and kinematic viscosity is accepted as 1,38e-06. Then Reynolds Number is put into Y+ formulations and Y+ is chosen as 1. In this way first thickness of the boundary layer is calculated and defined. Boundary layers are created in compatible with turbulence models, which are used in CFD analyses. Boundary layers of Autosub model are shown in Figure 7.

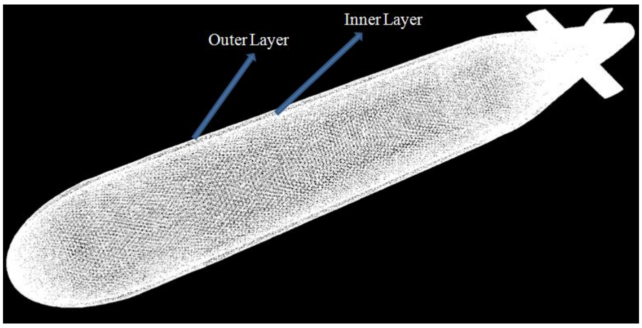

Figure 7: *Structure of Boundary Layers of Autosub AUV.*

At the end of meshing process, vehicle's grid and fluid domain's grids are completed, and the geometry gets ready to make hydrodynamic analyses in CFD software. Some pictures of the fluid domain are shown in Figure 8.

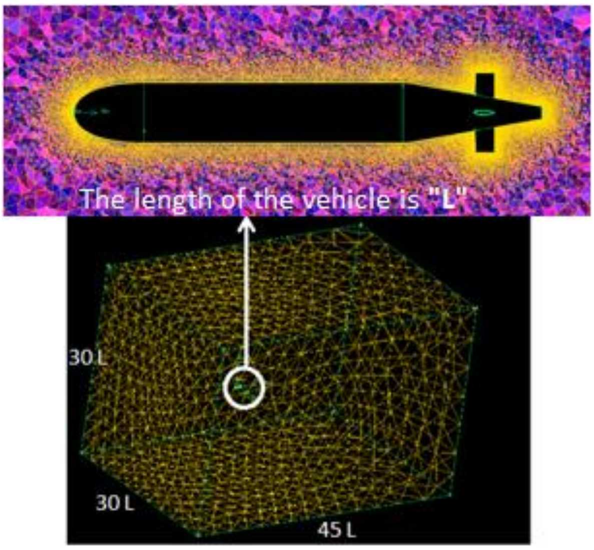

Figure 8: *Grids of Fluid Domain of Autosub AUV.*

Fluid domain of Autosub is created large enough, not to be exposed to blockage effects in the CFD analyses. At the end of the preparation of the fluid domain, CFD analyses process is started by using Fluent Version 13.0 software.

Results and Verification of CFD Analysis of Autosub AUV

In the test case study of Autosub, hydrodynamic analysis results are existing for 2/3 scaled model with 2.69 m/s linear velocity and between ±10 degree angle of attacks with 2 degrees intervals. So that, Autosub hydrodynamic model is constituted in the same condition with test case document and the calculated results are compared with the test case data's. Comparisons are accomplished with dimensionless terms. Hydrodynamic forces and moments are converted to dimensionless form with length of the model (L), velocity of the vehicle (V) and the density of the fluid (ρ). For this study, hydrodynamic modeling infrastructure is setup by using Segregated solver model, and Navier-Stokes Equations are solved in Implicit, steady conditions. Moreover in hydrodynamic analyses, *K-ε* turbulence model is used in Realizable, Enhanced Wall Treatment turbulence conditions.

$$w' = \frac{w}{U} \tag{1}$$

$$C_D = \frac{\text{Drag Force}}{1/2\rho V^2 L^2} \tag{2}$$

$$C_Z = \frac{Z}{1/2\rho V^2 L^2} \tag{3}$$

$$C_M = \frac{M}{1/2\rho V^2 L^2 L} \tag{4}$$

Comparative graphics for the experimental and CFD results of drag, surge forces and pitch moment are shown in Figure 9,10 and 11.

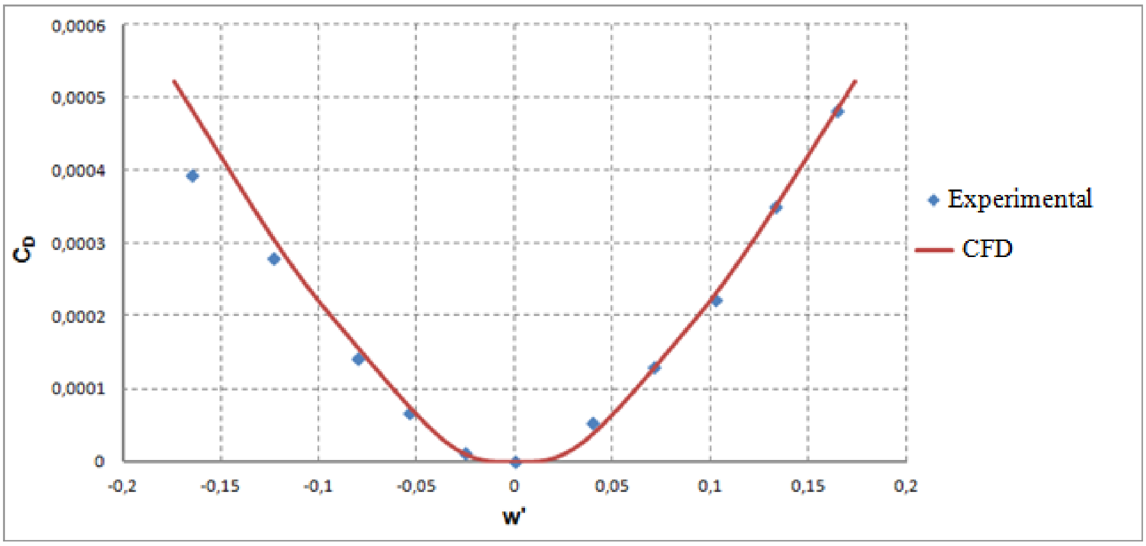

Figure 9: *Variation of Drag Force Coefficients according to w'*

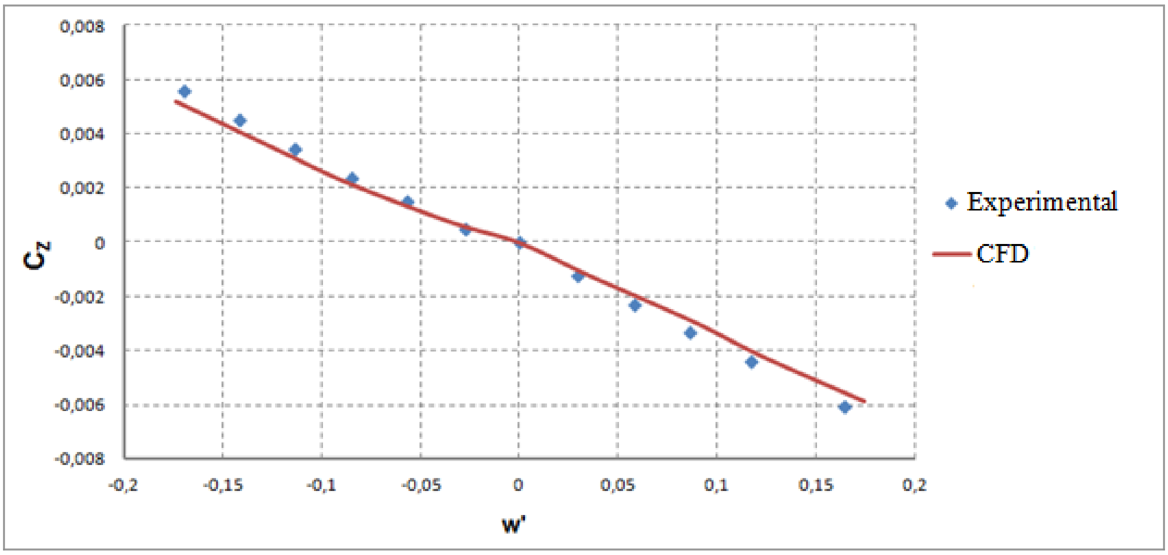

Figure 10: *Variation of Surge Force Coefficients according to w'*

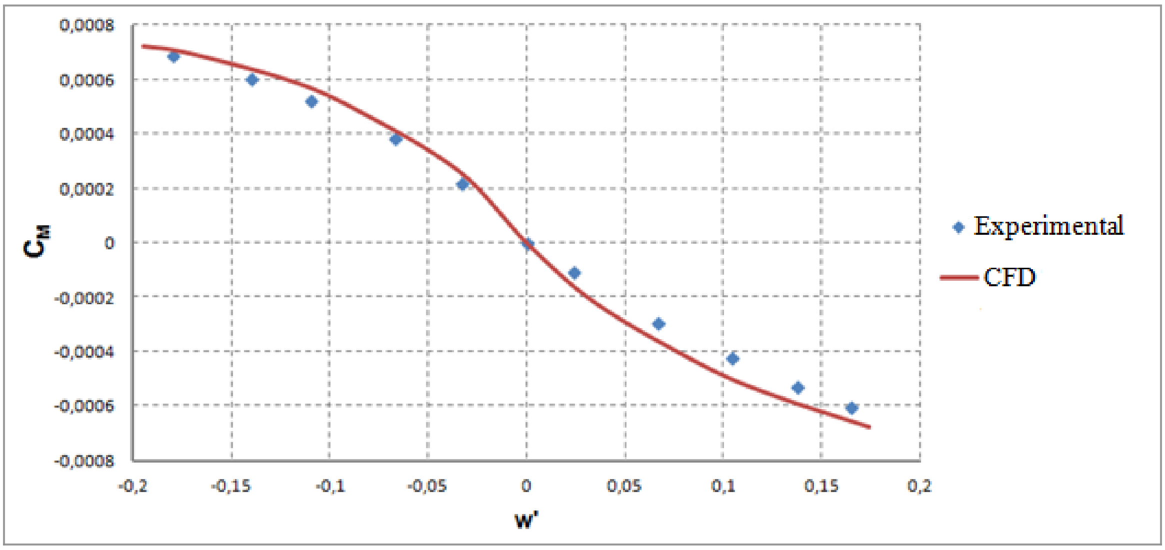

Figure 11: *Variation of Pitch Moment Coefficients according to w'*

As shown in the figures, CFD analysis result are compatimle with experimental test results. In this study, verification of hydrodynamic analysis model for underwater vehicles is performed. Through this verification study, hydrodynmaic characteristic of an AUV can be determined by computational methods, without having any experimental facilities. In the next step, hydrodynamic database of Autosub is constituted in six degree of freedom by using verified hydrodynamic analysis model.

HYDRODYNAMICS ANALYSES OF AUTOSUB UNDERWATER VEHICLE

In this study, a comprehensive study has been made to constitute hydrodynamic database of Autosub AUV in six degree of freedom (6DOF). Different static and dynamic hydrodynamic analyses are performed of Autosub for different cruise conditions. In static hydrodynamic analyses, cruise speeds, control surface deflections and angle of attacks in different planes are variable parameters. However, rotational and acceleration maneuvering conditions are simulated in dynamic hydrodynamic analyses.

Calculated hydrodynamic forces and moments for different cruise conditions can be used in conceptual design process of Autosub AUV model. According to pitching moment coefficients versus angle of attack graphics for different velocities, longitudinal static stability of the vehicle is discussed. Center of pressure locations of the vehicle for different angle of attacks is determined and normal forces distribution of each part of the vehicle, which cause to pitching moment, is extracted and static stability of Autosub is discussed. For the hydrodynamic analyses in 6DOF, verified CFD (computational fluid dynamics) methods are used.

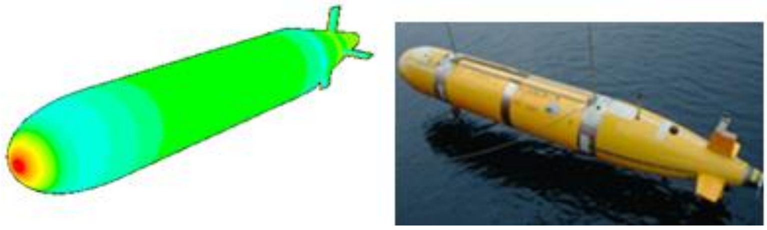

Figure 12: *Autosub autonomous underwater vehicle [11].*

Analysis Conditions of Autosub AUV

In the present study; X, Y, Z forces and K, M, N moments of Autosub is calculated for different maneuvering conditions. Velocity levels in the analyses are 5, 10, 15, 20 and 25 knots. The analyses are done in nine different angle of attacks and sideslip angle levels; these are -10, -7, -5, -2, 0, 2, 5, 7, and 10. Also Autosub's hydrodynamic analyses are performed in nine different elevator and rudder deflection angles configurations such as, 0, ±5, ±10, ±15, ±20 degrees. Additionally dynamic hydrodynamic analyses are performed for three turning radius such as; 20, 30, 40 meters. All the hydrodynamic analyses are performed in both pitch and yaw planes. Operating Reynolds Number is changed between 1,27e+07 and 6,52e+07. In these hydrodynamic analyses, kinematic viscosity of the water is accepted as 1,38e-06

Hydrodynamic Analysis Results of Autosub AUV

In this study, hydrodynamic database of Autosub AUV is constituted in 6DOF by using verified CFD calculation model for underwater vehicles. In this scope firstly, drag forces of Autosub is calculated for different velocities. The calculated drag force versus velocity graphic is shown in Figure 13. In the graphic, units of the velocities are knot and it is seen that, increment of drag force is compatible with velocities.

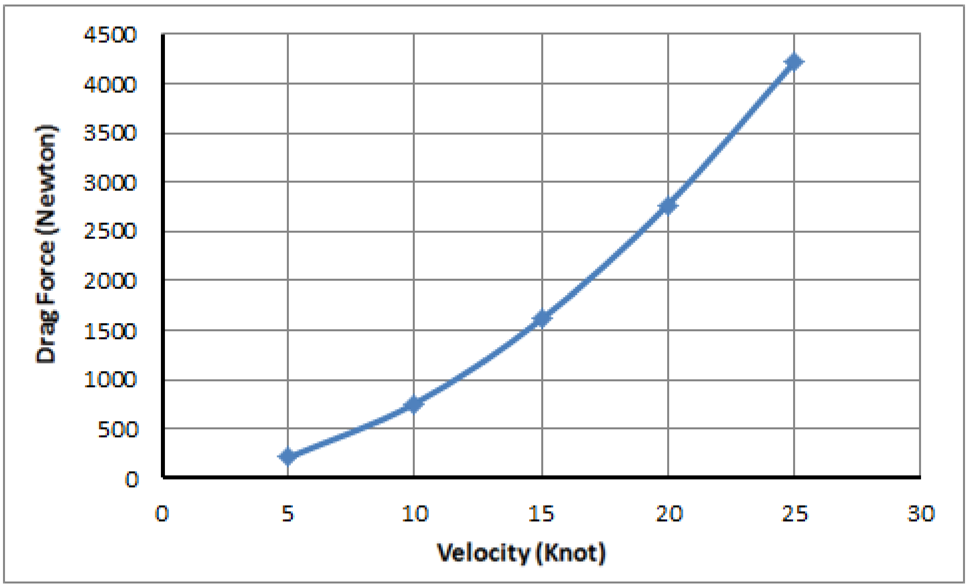

Figure 13: *Drag Forces vs. Velocity Graphics of Autosub.*

As shown in the Figure 14, drag coefficient is decreasing with Reynolds number regularly. Around the critical Reynolds number, the stability characteristic of fluids is unstable. This instability causes unexpected behaviors of the fluids and also, controllability of underwater vehicles in these flow regimes is very hard. So that, stability characteristic of fluid where the AUVS cruise in, is very important. It is shown that in Figure 14, the flow regime where Autosub cruise in is far away from the critical Reynolds number and stable.

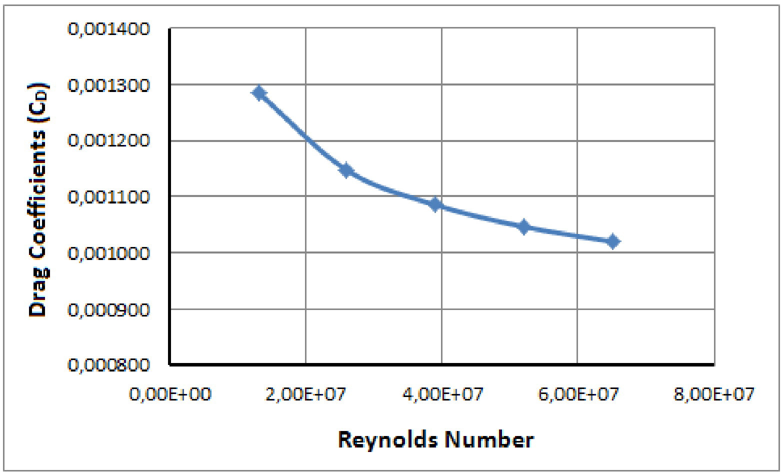

Figure 14: *Drag Coefficient vs. Re Number Graphic of Autosub.*

Autosub's Reynolds number start from 1,27e+07 in the calculations, and this point stays at the right of the critical point so that, there is not any decrease in Re-C_d graphic of Autosub because of the critical point.
Axial forces are also calculated for different angle of attacks in different velocities, as shown in Figure 15. In the graphic, units of the velocities are knots and it is seen that, increment and decrement of axial forces are compatible with angle of attack and cruise velocity. Variation of the axial forces with angle of attacks is too much in high speeds and very little in low speeds.

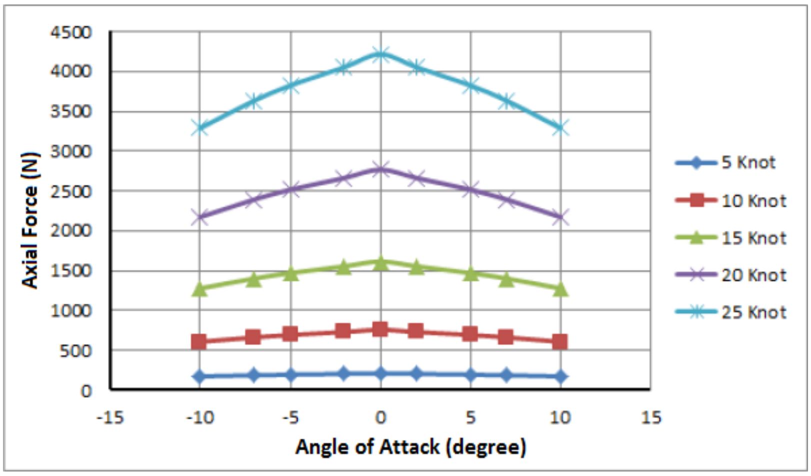

Figure 15: *Drag Forces - Angle of Attack Graphic for Different Velocities.*

Except of axial forces, yaw forces and pitching moments of Autosub are also investigated. Variation of yaw force versus sideslip angle at different velocities graphics are shown in Figure 16.

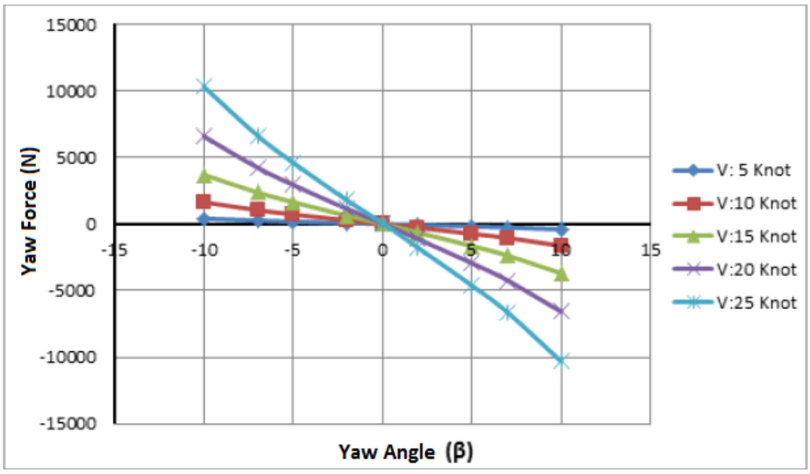

Figure 16: *Yaw Force vs. Sideslip Angle Graphic for Different Velocities.*

As shown in the graphics, yaw force decrease with sideslip angle according to velocity levels. In hydrodynamic simulation and modeling calculations, square of the vehicles length is accepted as a reference area and the length of the vehicle is accepted as a reference length.
In addition to drag and yaw forces, pitching moment values and pitching moment coefficients (C_M) of Autosub AUV are also calculated by using CFD methods. Hydrodynamic analyses are done in different angle of attacks and velocity levels to investigate static stability characteristic of Autosub. Pitching moments versus angle of attack at different velocities are shown in Figure 17 and pitching moment coefficient versus angle of attacks in 10 knots cruise speed shown is in Figure 18.

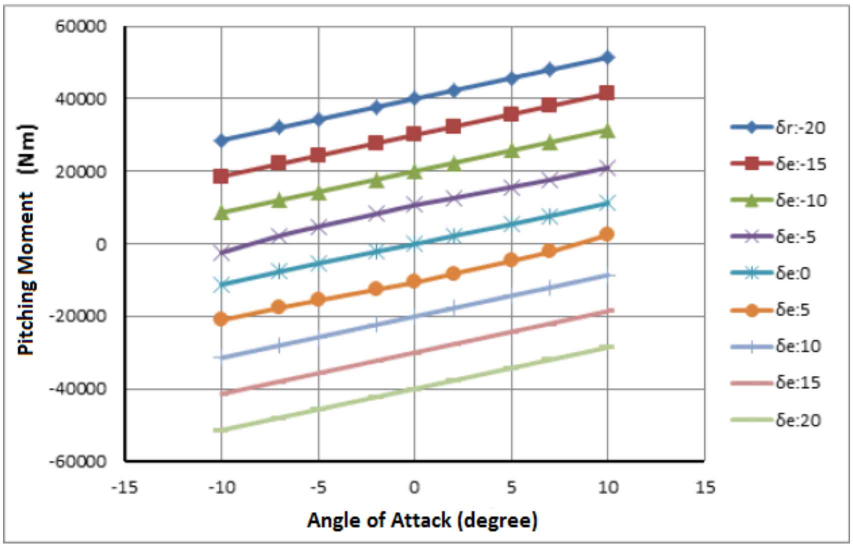

Figure 17: *Pitching Moment vs. Angle of Attack Graphic for Different Velocities.*

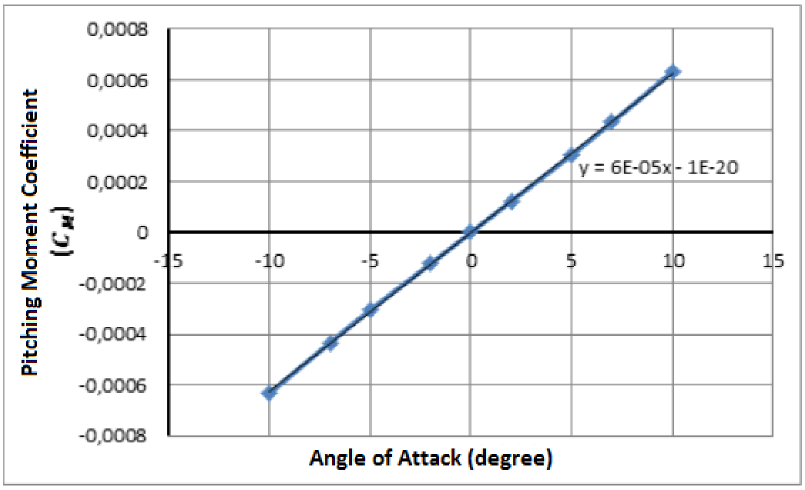

Figure 18: *Pitching Moment Coefficient (CM) vs. Angle of Attack Graphic for 10 Knots Cruise Speed.*

As shown in the graphics, pitching moment and pitching moment coefficient increase with angle of attack according to velocity levels, for different velocities. Pitching moments levels depend on cruise velocities because of dynamic pressure.

$$Pitching\ Moment = C_M \frac{1}{2} \rho V^2 {L_{ref}}^3$$

Dynamic pressure includes velocity term ($\frac{1}{2}\rho V^2$) and dynamic pressure changes with velocity as exponential. So, pitching moments change with velocity levels.
Also, longitudinal static stability can be investigated according to C_M-α graphics (Figure 18). In the flight dynamics equations, if the slope of C_M-α graphic is negative, it can be said that the vehicle is statically stable.

$$Static\ Stability\ Criteria => \quad \frac{\partial C_M}{\partial \alpha} < 0$$

However, in the opposite situation it is said that, the vehicle is statically unstable. If it is investigated the C_M-α graphic of Autosub, it can be seen that, the slope of the graphic is positive ($\frac{\partial C_M}{\partial \alpha} > 0$) . So, Autosub has statically unstable geometry. This is because of; the center of gravity point is the behind of center of pressure point of Autosub. Center of gravity point distance to the nose of the geometry is 3.159 meter but, the resultant hydrodynamic force point is in front of the center of gravity, as shown in the Figure 19.

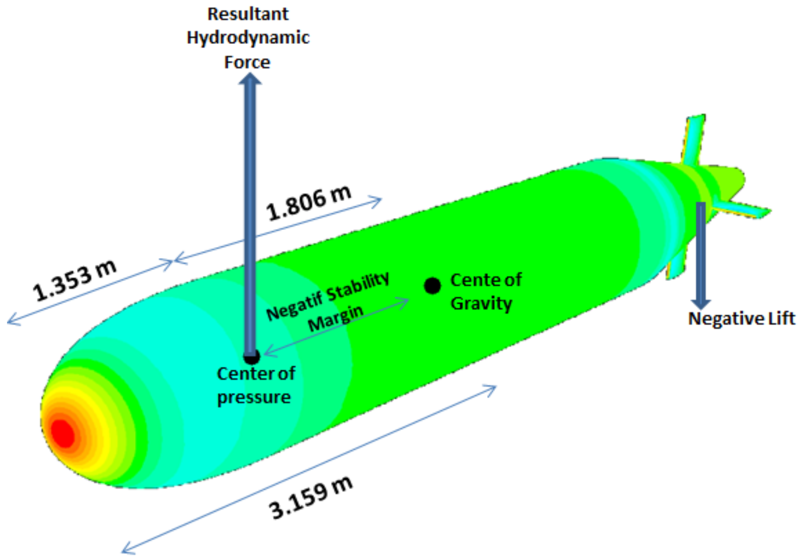

Figure 19: *Center of Pressure and Center of Gravity Locations of Autosub.*

In the Autosub geometry, aft-body part produces a negative lift; in this situation the center of the pitch moment moves to front of the vehicle and this situation pushes forwards the center of pressure point in front of the center of the gravity point, so that the geometry becomes unstable.
Except of force and moments results of Autosub, also pressure distribution over the body in 10 knots cruise conditions is studied. The pressure distribution of Autosub is shown in Figure 20.

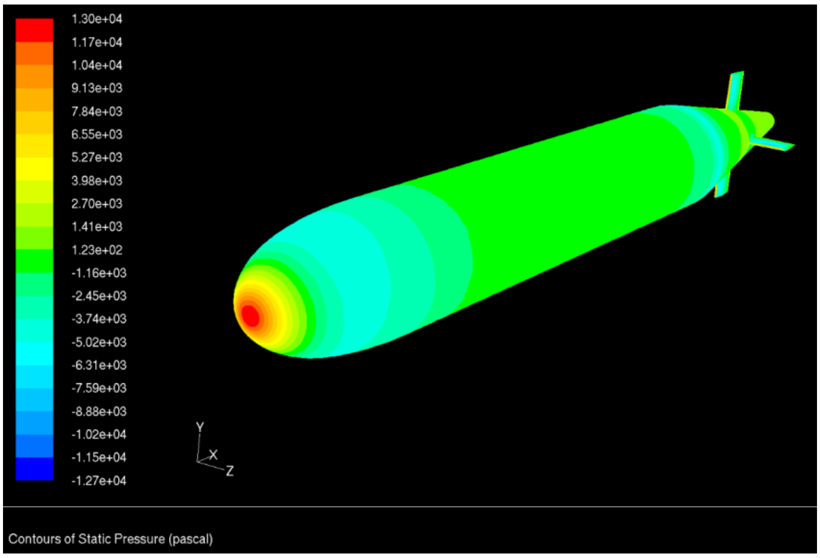

Figure 20: *Pressure distributions over Autosub AUV in 10 knots.*

As shown in the figure static pressure is maximum over the nose and it is approximately 1,3e+04 Pascal. A high pressure region is observed in the fore region of the AUV due to the effect of stagnation pressure. But, static pressure is approximately zero over the middle body, because the velocity is parallel to the middle body and pressure vectors are parallel to the middle body.

In the scope of this study, dynamic stability analyses and performance analyses of Autosub are also performed. After the stability analyses, it can be said that, these underwater geometries such as Autosub are usually statically unstable but dynamically stable. Because of the specific damping effects of underwater worlds such as added mass terms and munk moments, underwater vehicles stability characteristics get stable.
In the hydrodynamic analyses, it can be said that; Reynolds Averaged Navier Stokes (RANS) equations are solved without any problem and the verified CFD calculation models can be used to calculate any of hydrodynamic coefficients in 6 degree of freedom, in the next steps of the project.

CONCLUSION

In this project; a new numerical and empirical hydrodynamic calculation method is developed to calculate hydrodynamics coefficients of Autosub AUV in 6DOF. Analyses are done in different cruise and maneuvering conditions. However, before achieving of hydrodynamic analyses of Autosub, hydrodynamic calculation model, which is done by CFD methods, is verified with test-case studies. In the verification studies, test cases for Autosub AUV model are used. Full appendages model of Autosub is used in the verification studies. Calculated numerical results are compared with the experimental results and it is seen that, calculated results are close to experimental results adequately, to rely on performing hydrodynamic analyses with CFD methods. After the verification of CFD modeling methods, 6DOF hydrodynamic database of Autosub is constituted. Using hydrodynamic force and moment results, static and dynamic stability analyses and performance calculations of Autosub are performed. According to results, it is seen that Autosub has statically unstable but dynamically stable geometry.
In this project, a new hydrodynamic analysis method is developed and verified for underwater vehicles. By using the verified analysis models, hydrodynamic performance and characteristic of any underwater vehicles can be investigated and determined.

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