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LONGITUDINAL MOVEMENT MODELING AND SIMULATION FOR HYBRID UNDERWATER GLIDER

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Abstract

An autonomous underwater vehicle is a vehicle that can move in water, which is also known as an unmanned undersea vehicle. One type is the hybrid underwater glider where the vehicle is designed in such a way that it is able to carry out missions in the water with less power consumption so that it can last a long time in carrying out missions. In this research, a mathematical design is carried out in the form of a nonlinear model with the aim of being able to produce a model in the longitudinal movement of the HUG vehicle which will be tested limited to a simulation using the MATLAB/Simulink program. The parameters used in the model for this longitudinal movement are obtained by the computational fluid dynamics method so that it has been simulated with various movements according to the mission of the vehicle. In the simulation, input is given in the form of variations in the value of the actuator force to be able to carry out movements according to the mission and the simulation is open loop so that the vehicle's response is in the form of position and speed of translation and rotation.

Keywords: hybrid underwater glider, longitudinal motion, nonlinear model, matlab/simulink, computational fluid dynamics.

1. INTRODUCTION

The At this time, the research area cannot be limited, not only on land, in the air, and under the sea. It has also become a necessity for various scientific developments. Conducting research in various areas, of course, cannot be separated from the need for adequate tools to support better and more accurate results. Therefore underwater research is generally used, commonly known as an Autonomous Underwater Vehicle (AUV) [1]. The application of this underwater vehicle provides many benefits for the military, industry, and academic fields, which are commonly used as research needs [2]. In general, AUV has a shape like a torpedo. This has the aim of efficient force, volume of space and can also be steered better [3].

AUV has many types, one of which is the Hybrid Underwater Glider (HUG) [4]. This vehicle is designed to be able to carry out gliding missions like dolphins and, in general, the AUV movement. The general design of this vehicle has a buoyancy engine actuator to make the vehicle sink and is equipped with a moving mass for roll and pitch movement when carrying out missions [5]. The design from the outside of this vehicle has wings on the right and left sides of the vehicle, which serve to reduce the drag effect of the vehicle. On the tail of the vehicle, there is a fin as a steering wheel for maneuvering movements. For mission needs, one of which is mapping and the need for underwater data retrieval, sensors are used, which will be sent through the antenna installed on this vehicle when it appears on the surface [6].

The movement of the HUG vehicle is divided into two parts, namely the movement in the longitudinal and lateral planes [7]. In this study, a nonlinear mathematical model of the HUG vehicle will be derived which is limited to longitudinal movement according to the variables from the specifications of the modeled vehicle. The purpose of this study is to model the longitudinal movement of the HUG vehicle which will then be tested by simulation using the MATLAB/Simulink application with movements that are in accordance with the vehicle's mission.

2. RESEARCH METHOD

Basically, there are two important things needed to analyze this vehicle, namely the axis system consisting of Earth Fixed Frame and Body Fixed Frame, as shown in figure 1 [8]. The model of this

Table 1. General notation of movement 6 DOF

DOF		Force and Momentum Force	Linear and Angular Velocity Linear Velocity	Position dan Euler's Angle Position
1	Surge	X	u	x
2	Sway	Y	v	y
3	Heave	Z	w	z
		Momentum	Angular Velocity	Euler's Angle
4	Roll	K	p	φ
5	Pitch	M	q	θ
6	Yaw	N	r	ψ

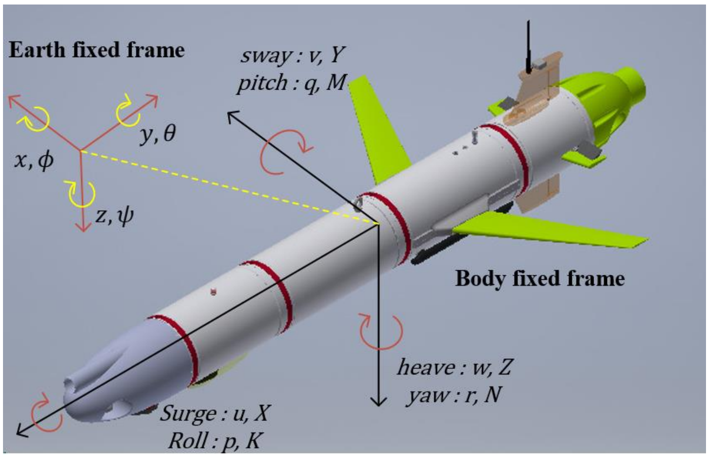

Fig. 1. The axis of movement of the HUG vehicle

HUG vehicle refers to the AUV model in general. For the longitudinal movement of the mathematical model, the resulting mathematical model is derived from the derivation of the kinematics and hydrodynamic mathematical model for the movement of 6 degrees of freedom (6DOF) with the notation that can be seen in Table 1.

2.1. Equations for vehicle movement

Several elements will be used in this hybrid glider equation, including kinematics equations, rigid-body dynamics, and mechanical equations [9]:

- Kinematic equations: Geometric aspects of vehicle movement (Jacobian Matrix)
- Rigid-body Dynamics: Inertia Matrix Vehicles
- Mechanical Equations: Force and Momentum that cause the movement of the vehicle.

2.2. Kinematic equations

The movement that refers to the skeleton of the vehicle is related to inertia or refers to the point frame of the earth [10]. Where the general motion of the AUV vehicle in 6 DOF can be described by vectors as follows Equation (1):

$\eta_1 = [x\ y\ z]^T; \quad \eta_2 = [\varphi\ \theta\ \psi]^T$

$v_1 = [u\ v\ w]^T; \quad v_2 = [p\ q\ r]^T$

$$\tau_1 = [X\ Y\ Z]^T; \quad \tau_2 = [K\ M\ N]^T \tag{1}$$

η is the position and orientation of the vehicle which refers to the point of the earth, v is the translational and rotational speed of the vehicle, which refers to the point of the vehicle frame, and τ is the total force and momentum of the vehicle which refers to the point of the skeleton of the vehicle. As seen in the view of the axis coordinates of the vehicle and the coordinates of the earth above.

The following is a matrix transformation on Equation (2) that changes the translational velocity of the vehicle from a fixed point of the vehicle frame to a fixed point of the earth.

$$J_1(\eta_2) = \begin{bmatrix} cos\psi\ cos\theta & -sin\psi\ cos\varphi + cos\psi\ sin\theta\ sin\varphi & sin\psi\ sin\varphi + cos\psi\ sin\theta\ cos\varphi \\ sin\psi\ cos\theta & cos\psi\ cos\varphi + sin\psi\ sin\theta\ sin\varphi & -cos\psi\ sin\varphi + sin\psi\ sin\theta\ cos\varphi \\ -sin\theta & cos\theta\ sin\varphi & cos\theta\ cos\varphi \end{bmatrix} \tag{2}$$

Note that J is orthogonal on Equation (3):

$$(J_1(\eta_2))^{-1} = (J_1(\eta_2))^T \tag{3}$$

This second coordinate transformation changes the rotational speed of the vehicle from a fixed point of the vehicle frame to a fixed point of the earth as show in Equation (4) [11].

$$J_1(\eta_2) = \begin{bmatrix} 1 & sin\varphi\ tan\theta & cos\varphi\ tan\theta \\ 0 & cos\varphi & -sin\varphi \\ 0 & sin\varphi/cos\theta & cos\varphi/cos\theta \end{bmatrix} \tag{4}$$

2.3. AUV motion dynamics equation

This equation represents the dynamics of the motion of the AUG which is affected by the displacement of the mass distribution, the force, and the working momentum. This dynamic equation consists of translational equations of motion and rotational equations of motion.

The dynamics equation of motion of AUV is derived using the Newtonian method. This method uses the second law of Newton's equation in formulating the dynamics of the system [12]. Mathematically Newton's second law Equation (5) can be written as follows:

$$\sum F = ma \tag{5}$$

Where F is the net force, m is the mass of the object, and a is the acceleration.

The following Equation (6a – 6f) is a derivation of the translational and rotational equations of motion on a hybrid glider vehicle [13]:

$$m[\dot{u} - vr + wq - x_G(q^2 + r^2) + y_G(pq - \dot{r}) + z_G(pr + \dot{q})] = \sum X_{ext} \tag{6a}$$

$$m[\dot{v} + ur - wp + x_G(pq + \dot{r}) - y_G(p^2 + r^2) + z_G(qr - \dot{p})] = \sum Y_{ext} \tag{6b}$$

$$m[\dot{w} - uq + vp + x_G(pr - \dot{q}) + y_G(qr + \dot{p}) - z_G(q^2 + p^2)] = \sum Z_{ext} \tag{6c}$$

$$I_x\dot{p} + (I_z - I_y)qr + I_{xy}(pr - \dot{q}) + I_{yz}(q^2 - r^2) - I_{xz}(pq + \dot{r}) + m[y_G(\dot{w} - uq + vp) - z_G(\dot{v} + ur - wp)] = \sum K_{ext} \tag{6d}$$

$$I_y\dot{q} + (I_x - I_z)pr - I_{xy}(qr + \dot{p}) + I_{xz}(p^2 - r^2) + I_{yz}(pq - \dot{r}) + m[z_G(\dot{u} - vr + wq) - x_G(\dot{w} - uq + vp)] = \sum M_{ext} \tag{6e}$$

$$I_z\dot{r} + (I_y - I_x)pq - I_{yz}(pr + \dot{q}) + I_{xy}(p^2 - q^2) + I_{xz}(qr - \dot{p}) + m[x_G(\dot{v} + ur - wp) - y_G(\dot{u} - vr + wq)] = \sum N_{ext} \tag{6f}$$

The first three equations represent translational motion, and the second three equations are rotational motion equations. Due to the symmetrical shape of the vehicle, the product of inertia is I_{xy}, I_{xz}, dan I_{yz} can be ignored. As for the value of $y_g = 0,$ so that the equation for the dynamics of the AUV motion can be simplified into the following Equation (7a – 7f):

$$m[\dot{u} - vr + wq - x_G(q^2 + r^2) + z_G(pr + \dot{q})] = \sum X_{ext} \tag{7a}$$

$$m[\dot{v} + ur - wp + x_G(pq + \dot{r}) + z_G(qr - \dot{p})] = \sum Y_{ext} \tag{7b}$$

$$m[\dot{w} - uq + vp + x_G(pr - \dot{q}) - z_G(q^2 + p^2)] = \sum Z_{ext} \tag{7c}$$

$$I_x\dot{p} + (I_z - I_y)qr + m[-z_G(\dot{v} + ur - wp)] = \sum K_{ext} \tag{7d}$$

$$I_y\dot{q} + (I_x - I_z)pr + m[x_G(\dot{w} - uq + vp) - z_G(\dot{u} - vr - wq)] = \sum M_{ext} \tag{7e}$$

$$I_z\dot{r} + (I_y - I_x)pq + m[x_G(\dot{v} + ur - wp)] = \sum N_{ext} \tag{7f}$$

2.4. Mechanical equations

In the equation (8) of motion of the vehicle, there are external forces and momentum as follows:

$$\sum F_{ext} = F_{hydrostatic} + F_{lift} + F_{drag} + F_{control} \tag{8}$$

- Hydrostatic

AUV vehicles will experience hydrostatic force and momentum (HS) as a form of combination due to the weight and buoyancy of the vehicle [14].

$$F_{HS} = \begin{bmatrix} X_{HS} \\ Y_{HS} \\ Z_{HS} \\ K_{HS} \\ M_{HS} \\ N_{HS} \end{bmatrix} = \begin{bmatrix} (W - B)sin\theta \\ -(W - B)cos\theta sin\phi \\ -(W - B)cos\theta cos\phi \\ -(y_gW - y_bB)cos\theta cos\phi + (z_gW - z_bB)cos\theta sin\phi \\ (x_gW - x_bB)cos\theta cos\phi + (z_gW - z_bB)sin\theta \\ -(x_gW - x_bB)cos\theta sin\phi - (y_gW - y_bB)sin\theta \end{bmatrix} \tag{9}$$

Note that in Equation (9) the hydrostatic moment stabilizes the pitch and roll, which means that the hydrostatic moment resists the deflection in the direction of the angle.

- Axial, crossflow dan rolling drag

The following Equation (10) are the drag parameters of the hybrid glider vehicle, where the parameters are obtained by considering the drag that occurs around the vehicle at every movement caused by water currents [14].

$$D1 = \begin{bmatrix} X_{u|u|} & 0 & 0 & 0 & 0 & 0 \\ 0 & Y_{v|v|} & 0 & 0 & 0 & Y_{r|r|} \\ 0 & 0 & Z_{w|w|} & 0 & -Z_{q|q|} & 0 \\ 0 & 0 & 0 & K_{p|p|} & 0 & 0 \\ 0 & 0 & M_{w|w|} & 0 & M_{q|q|} & 0 \\ 0 & N_{v|v|} & 0 & 0 & 0 & N_{r|r|} \end{bmatrix} \tag{10}$$

- Added mass

This parameter is a measurement of the mass of the moving water when the vehicle is accelerating [14]. Ideally, the equations (11) of force and momentum of a liquid can be written in matrix form as follows:

$$M_A = \begin{bmatrix} X_{\dot{u}} & 0 & 0 & 0 & 0 & 0 \\ 0 & Y_{\dot{v}} & 0 & 0 & 0 & Y_{\dot{r}} \\ 0 & 0 & Z_{\dot{w}} & 0 & Z_{\dot{q}} & 0 \\ 0 & 0 & 0 & K_{\dot{p}} & 0 & 0 \\ 0 & 0 & M_{\dot{w}} & 0 & M_{\dot{q}} & 0 \\ 0 & N_{\dot{v}} & 0 & 0 & 0 & N_{\dot{r}} \end{bmatrix} \quad (11)$$

3. RESULT AND ANALYSIS

3.1. HUG dynamics model

The control model or mathematical model of the actuator used on the HUG vehicle represents the actuator's mathematical equation for the 6 DOF movement. Part of the translation equation includes the surging movement represented by the main motor of the thruster, the swaying movement of the rudder coupling, front and rear thrusters, the heave movement of the buoyancy engine, which is represented by the equation, and the actuator model containing the elevator mathematical equation. The existence of elevator and rudder actuators on the fins of the vehicle can be used with the condition that the vehicle has a minimum speed of forward movement (surge = u).

For the rotation equation, the roll movement is generated from the mathematical equations of the coupling results of the rudder, front and rear thrusters, the pitch movement is the equation of the elevator, and main thruster coupling and yaw movements are the results of the coupling from the rudder, front and rear thruster equations. This actuator in Equation (12) is generated with the addition of the simulation results from CFD.

$$F_C = \begin{bmatrix} X_C \\ Y_C \\ Z_C \\ K_C \\ M_C \\ N_C \end{bmatrix} = \begin{bmatrix} \%T_{main} \\ (0.5\rho L^2)(0.666{V_B}^2)\delta_r + T_{stern} + T_{bow} \\ (0.5\rho L^2)(-0.34{V_B}^2)\delta_e \\ -z_{cg}Y_T(\delta_r) + (z_{cg} - z_{T_{stern}})Y_T(T_{stern}) + (z_{cg} - z_{T_{bow}})Y_T(T_{bow}) \\ (0.5\rho L^3)(-0.248{V_B}^2)\delta_e - (z_{cg} - z_{T_{main}})X_T(T_{main}) \\ (0.5\rho L^3)(-0.6{V_B}^2)\delta_r + (x_{cg} - x_{T_{stern}})Y_T(T_{stern}) + (x_{cg} - x_{T_{bow}})Y_T(T_{bow}) \end{bmatrix} \quad (12)$$

3.1.1. Nonlinear model 6 DOF hybrid glider in the form of mathematical equations

The following Equation (13a – 13f) is a nonlinear 6 DOF equation for the HUG vehicle in the form of a mathematical equation derived from the above equation so that the following equation is obtained:

$$(m - X_{\dot{u}})\,\dot{u} + mz_g\dot{q} - my_g\dot{r} = my_gpq + mz_gpr - mx_gq^2 + mwq - mx_gr^2 - mvr - Z_{\dot{w}}wq - Z_{\dot{q}}qq + Y_{\dot{v}}vr + Y_{\dot{r}}rr + X_{u|u|}|u|u + (W - B)sin\theta + \%T_{main} \quad (13a)$$

$$(m - Y_{\dot{v}})\dot{v} - mz_g\dot{p} + (mx_g + Y_{\dot{r}})\dot{r} = -my_gp^2 - mwp + mz_gqr + mx_gqp - my_gr^2 + mur + Z_{\dot{w}}wp + Z_{\dot{q}}pq - X_{\dot{u}}ur + Y_{v|v|}|v|v + Y_{v|v|}u|r - (W - B)cos\theta sin\phi + (0.5\rho L^2)(0.666{V_B}^2)\delta_r + \%T_{stern} + \%T_{bow} \quad (13b)$$

$$(m - Z_{\dot{w}})\dot{w} + my_g\dot{p} - m(x_g + Z_{\dot{q}})\,\dot{q} = -mz_gp^2 + mvp - mz_gq^2 - muq + mx_grp - Y_{\dot{v}}vp - Y_{\dot{r}}rp + X_{\dot{u}}uq + my_grq + Z_{w|w|}|w|w + Z_{q|q|}u|q| - (W - B)cos\theta cos\phi + (0.5\rho L^2)(-0.34{V_B}^2)\delta_e \quad (13c)$$

$$(I_x - K_{\dot{p}})\dot{p} - I_{yx}\dot{q} - I_{zx}\dot{r} - mz_g\dot{v} + my_g\dot{w} = -I_{yz}q^2 - I_{xz}pq + I_{zz}qr + I_{yz}r^2 + I_{xy}pr - I_{yy}qr - my_guq - mz_gur + my_gvp + mz_gwp - Z_{\dot{w}}vw - Z_{\dot{q}}vq + Y_{\dot{v}}vw + Y_{\dot{r}}wr + Y_{\dot{v}}vq + Y_{\dot{r}}qr + M_{\dot{q}}qr + Z_{\dot{w}}wr + K_{p|p|}|u|p - (y_gW - y_bB)cos\theta cos\phi + (z_gW - z_bB)cos\theta sin\phi + -z_{cg}Y_T(\delta_r) + (z_{cg} - z_{T_{stern}})Y_T(T_{stern}) + (z_{cg} - z_{T_{bow}})Y_T(T_{bow}) \quad (13d)$$

$$(I_y - M_{\dot{q}})\dot{q} - I_{yx}\dot{p} - I_{yz}\dot{r} + mz_g\dot{u} - m(x_g + M_{\dot{w}})\dot{w} = I_{yz}pq + I_{xz}p^2 - I_{zz}pr - I_{xz}r^2 - I_{xy}qr + I_{xx}pr + mx_guq - mz_gvr - mx_gvp + mz_gwq + Z_{\dot{w}}uw + Z_{\dot{q}}uq - X_{\dot{u}}uw + N_{\dot{v}}vp + N_{\dot{r}}rp - K_{\dot{p}}pr + M_{w|w|}|w|w + M_{q|q|}u|q| + (x_gW - x_bB)cos\theta cos\phi + (z_gW - z_bB)sin\theta + (0.5\rho L^3)(-0.248{V_B}^2)\delta_e - (z_{cg} - z_{T_{main}})X_T(T_{main}) \quad (13e)$$

$$(I_z - N_{\dot{r}})\dot{r} - I_{zx}\dot{p} - I_{zy}\dot{q} - my_g\dot{u} + (mx_g + N_{\dot{v}})\dot{v} = -I_{yz}pr - I_{xy}p^2 + I_{yy}pq + I_{xz}qr + I_{xy}q^2 - I_{xx}pq + mx_gur + my_gvr - mx_gwp - my_gwq - Y_{\dot{v}}uv - Y_{\dot{r}}ur + X_{\dot{u}}uv - M_{\dot{q}}qp - Z_{\dot{w}}wp + K_{\dot{p}}pq + N_{v|v|}|v|v + N_{r|r|}u|r| - (x_gW - x_bB)cos\theta sin\phi - (y_gW - y_bB)sin\theta + (0.5\rho L^3)(-0.6{V_B}^2)\delta_r + (x_{cg} - x_{T_{stern}})Y_T(T_{stern}) + (x_{cg} - x_{T_{bow}})Y_T(T_{bow}) \quad (13f)$$

Note that:

$V_B = \sqrt{u^2 + v^2 + w^2}$

$W = m\ x\ g$

$B = p\ x\ g\ x\ \Delta V$

The longitudinal movement includes the translational movement of the surge, heave and pitch rotational motion so that the 6 DOF equation can be simplified into forces and momentum for longitudinal movement using mathematical equations (13a, c, and e).

3.1.2. Moving Mass Representation for Pitch

The following is a mathematical equation (14) to represent moving mass as a pitch motion actuator which is derived according to the moving mass design for this HUG vehicle.

$$x_G = \frac{m_{mm}(l_{mx}+\Delta l_{mx})+m_{hx}l_{hx}}{m_{tot}} \quad (14)$$

Tabel 2. Moving mass representation parameters for pitch

Notation	Value	Description
m_{mm}	4 kg	Weight of moving mass
l_{mx}	0.1 m	The distance of the moving mass to the COG in the x plane
Δl_{mx}	0.15 ~ -0.15 m	Shift displacement of moving mass
m_{hx}	71 kg	weight of the vehicle without moving mass
l_{hx}	0.087 m	Place cg on the x plane
m_{tot}	75 m	Total weight of mass

3.1.3. Buoyancy Engine Representation

The following Equation (15) is a mathematical equation to represent the buoyancy engine as the heave movement actuator which is derived according to the buoyancy engine design used for this HUG vehicle.

$$\Delta B = \sqrt{\frac{\Delta V g}{C_D A}} \quad (15)$$

3.2. Parameters Used

Based on the derivation of the formula that has been carried out for the longitudinal movement of the HUG vehicle, various parameters that will be used in the HUG simulation, both geometric and physical parameters, as well as hydrodynamic parameters and control parameters for each movement are shown in Table 4-6.

3.3. Movement Simulation

For the simulation, it is assumed that the vehicle is moving in still water. The initial conditions are given: all positions, Euler angle, rotational and translational speeds equal 0. Simulation results can be displayed in 3D and side view to see the vehicle's movement in the longitudinal plane and depth. has been achieved as shown in figures 4 and 5.

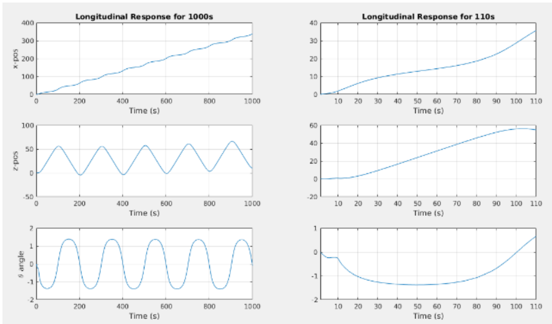

Fig. 2. Vehicle position response for longitudinal movement

Table 3. Parameters Representation of Buoyancy Engine

Notation	Value	Description	Notation	Value	Description
m	70.2 kg	The total mass of the vehicle	x_B	0.087 m	Vehicle volume shift
g	9.8 m/s^2	Gravitational acceleration	y_B	0 m	
L	2.3 m	Vehicle length	z_B	-	
d	0.24 m	Vehicle diameter	I_x	100.2	Momentum of Inertia
p	1000	Density	I_y	0.005	
$z_{T_{main}}$	0	Position the main thruster on the z-axis	I_z	0.081	
x_G	0.087 m	Center of mass	I_{xz}	-0.076	
y_G	0 m		I_{xy}	0	
z_G	0.0113 m		I_{yz}	0	

Table 4. HUG hydrodynamic coefficient

Notation	Value	Description	Notation	Value	Description
$X\dot{u}$	-1.44	Added Mass	X_{uu}	-8.9	Crossflow Drag
$Z\dot{w}$	-12.92		Z_{ww}	-307-360uw	
$Z\dot{q}$	293.79		Z_{qq}	-863.86	
$M\dot{q}$	30.05		M_{ww}	57.911	
$M\dot{w}$	293.79		M_{qq}	4.85	

Table 5. Control variable on HUG

Notation	Value	Description
ΔB	0 ~ 1 N	Buoyancy change
δ_e	0 ~ 20°	The deflection angle of the elevator
$\%T$	0 ~ 1	Thruster Force

Table 6. Parameters Representation of Buoyancy Engine

Notation	Value	Description
ΔV	0~1.5 L	Changes in bladder volume
g	9.8 m/s^2	Gravitational acceleration
C_D	0.14	Drag coefficient
A	46.47 m^2	The area of the buoyancy engine

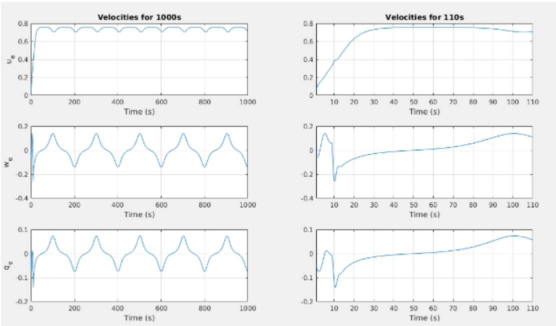

Fig. 3. The translational and rotational speed response of the vehicle for longitudinal motion

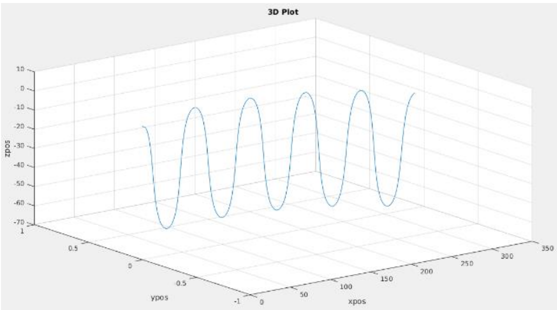

Fig. 4. HUG movement response in the longitudinal plane in 3D

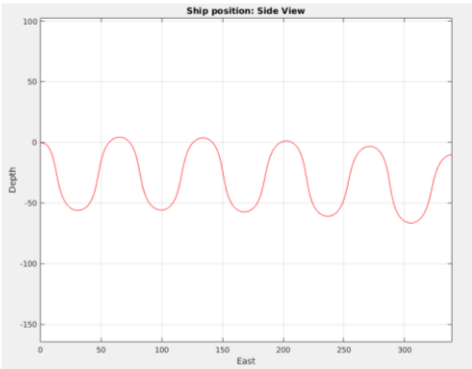

Fig. 5. HUG movement response in longitudinal plane side view

In figure 4 there are axes that are given the names xpos, ypos, zpos are descriptions of the results of the movement of the vehicle on the x, y and z axes so that it can be simulated in 3D in carrying out movement missions according to the input from the actuator that has been given in the MATLAB/Simulink program. While in figure 5 a visualization of the image of the vehicle is visualized to see its depth, Depth is the y-axis which describes the depth, while East is how far the vehicle can go with side view.

3.4. Simulation result analysis

The control parameters given are delta_B = 1, main thruster = 1 and elevator = 20 degree. The simulation duration given is 1000 seconds. Delta_B functions to activate the buoyancy engine to produce sinking motion, then the main thruster is used in the surge movement to move forward and the elevator is used to produce pitch movement in the longitudinal movement.

From the given control parameters, the lateral movement is a stable sinusoidal wave in the water. One wave is generated for 300 seconds, and this can be seen in figure 2.

With the primary thruster input given at 100% (1), the vehicle's maximum speed reaches 0.79 m/s in 20 seconds and experiences an up and down condition up to 100 seconds, as shown in figure 3. At the heave speed and angular rate, it can be seen that the vehicle had experienced instability for the initial 10 seconds of movement. This was because the simulations carried out on this vehicle had not been given any control, and the model used was still a nonlinear equation model with a high order of rank. In performing calculations, it became complex and vulnerable to imbalances from the calculation results [15].

To produce a gliding movement, as shown in figures 4 and 5, the input given to the simulation of the vehicle is moving mass which has positive and negative values, so that the pitch movement produces an angle of ±21°.

4. CONCLUSION

This paper represents a nonlinear equation for the longitudinal movement of the HUG vehicle, where the design of this vehicle already has fixed-wing and controllable fins. In the equation that has been derived, there are various parameter values obtained from the analysis results using the CFD method. With the CFD method, simulations are carried out with various coupling movements to produce hydrodynamic parameters following the vehicle design.

The location of CoG and CoB of the vehicle is stable, where CoB is at point 0.0 which is the center of mass of the volume transfer and is in accordance with the variables presented in Table 4 that the value of $z_G = 0.0113$ which describes the point CoG is below CoB with the z-axis defined. positive pointing downwards. This can be one of the reasons the simulation of the nonlinear mathematical model of the HUG vehicle produces a fairly good response for longitudinal movement even without any control.

For further research, the mathematical model of the longitudinal movement of the HUG can be linearized, so that the navigation, guidance and control systems can be applied.

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