NUMERICAL STUDY OF DEPTH CONTROL OF AN INNOVATIVE UNDERWATER VEHICLE HAVING FOUR BALLAST TANKS

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Abstract:Underwater vehicle has been an active area of research for a long time. Design and control of such underwater vehicle is very much challenging. Here an innovative design of underwater vehicle has been proposed with an innovative placement of four ballast tanks. The dynamics behavior of heave motion has been obtained by solving the governing equation using Matlab-Simulink frame. Open loop depth control has also been achieved by proper control of water flow in and out of the ballast tanks.

***Index Terms*–Underwater vehicle, Diving Dynamics, Ballast tanks**

I. INTRODUCTION

Research on unmanned systems has gained notable development in the last few decades. Beginning with operation in the air these unmanned systems are continuously showing new possibilities on the ground and even underwater. With the first prototype in 1980s Unmanned Underwater Vehicle (UUV) started to spread its amazement in many areas in our daily life viz. in military field [1]; for proper utilization of oceanic resources, mapping as well as predicting underwater optical properties and visibility [2,3]; chemical pluming tracing [4] and many other applications. With the advancement of autonomous underwater vehicles, various shapes and sizes of AUVs have been developed. In most cases, the hull shapes have been of torpedo-like with streamlined body [5] and also smaller in size [6,7]. Design of “small size” AUV is a real challenge from various aspects viz. external hull shape design [8,9], pressure and shear stress distribution over external hull [10]. Besides, control of autonomous underwater vehicles is also a big challenge while executing operation under dangerous environments. Among various control-related problems, depth control plays an important role. For example, when seabed mapping is being done, it is required to keep the AUV at a constant depth from sea level. Many researchers have been working on depth controlling method of Unmanned Underwater Vehicles (UUV) and different techniques of depth control method has been studied. In 2017 Sayedet. al. [11] worked on different depth controlling methods of Unmanned Underwater Vehicle (UUV). In this work various depth control techniques viz. discrete quasi-sliding mode control, adaptive fuzzy logic and hybrid PID control system have been analysed in details and finally it has been found that for depth control the hybrid fuzzy PID control method can said to be the most suitable technique in UUV application. Based on several assumptions on the motion of submarine basically the diving dynamics has been derived. Among them main restriction has been imposed on pitch angle in diving plane which has been assumed to be small and another assumption is that the pitch motion dynamics could be described as a linear equation. These assumptions calls for many modelling errors making itinapplicable for practical cases. In 2005, Ji-Hong Li and Pan-Mook Lee [12]worked on this problem and found out a solution for eliminating these above said hindrance by considering the submarine to take any pitch angle. Besides,the diving dynamics of submarine has been taken as SISO system where the input has been taken as stern plane angle and the depth of the submarine as the output. Finally it has been found that the proposed scheme is more effective than existing method.

Till date for controlling the depth, yaw, roll and pitch motion mainly the control surfaces has been used. The novelty of the present study is that, herefour ballast tank mechanism has been proposedfor controlling of depth, pitch and roll motion of a model submarine. The four ballast tanks can be placed at the four bottom corners of the submarine as show in Fig. 1. Such an innovative placement of these ballast tanks would reduce the number of control surfaces of the submarine. In this present study only the depth control and diving dynamics have been studied for predicting the dynamics of the submarine model with the pitch and rolling motion studies being kept as future scope of work.Main principal for controlling depth of a submarine is to play with the buoyancy force. When the buoyancy force will be equal to the total weight of the submarine, the submarine will be in equilibrium and it will float either on water surface or it will float under fully submerged condition. Now when it is floating under fully submerged condition the submarine can be placed anywhere under water irrespective of the depth from free surface of water. That can be done by properly operating the pumps used for controlling the flow rate in and out of the ballast tanks. In this study four different depths has been obtained by controlling the overall weight of the submarine by controlling the pump activity for filling up or emptying the ballast tanks.

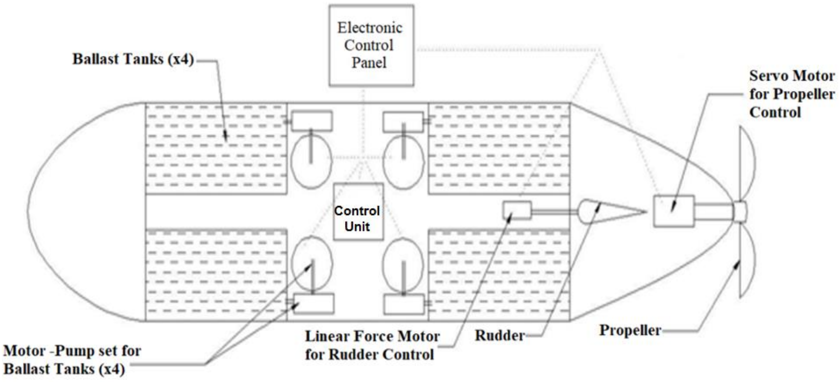


Figure 1 Schematic diagram of the submarine (plan view)

II. MATHEMATICAL MODELING

While modelling the mathematical equation for heave or pitch motion it has been assumed that the flow rates at which the water is flowing in or out of the ballast tanks is equal and due to small size of this submarine added mass effect is neglected. Based on the above said assumptions the dynamics of heave motion on submarine becomes

$$\text{mass} \times \text{acceleration} = F_w + F_b + F_{hd} \tag{2.1}$$

The first term on right hand side of Eq. (2.1), F_w is the force due to the weight of submarine which is the product of mass of submarine and gravity of earth (g). Now mass of the submarine has been divided in two parts. One is dead mass M of submarine and the other is the mass due to change of water volume in ballast tank, Δm. Though the value of gravity changes with position, but that change is very small and hence in this study the value of gravitational acceleration is taken as $9.81\ m/s^2$. So, the force due to weight of submarine becomes

$$F_w = (M + \Delta\text{m})\text{g} \tag{2.2}$$

The second term in Eq. (2.1), F_b is the buoyancy force term which is responsible for upward (heave) motion of the underwater vehicle as is given by,

$$F_b = \rho \times \forall_s \times g \tag{2.3}$$

Where, $\forall_s$ is the submarine volume and ρ is the density of water.

Under equilibrium and fully submerged condition total weight of the submarine is equal to the buoyancy force. From this condition, to acquire higher depth all the ballast tanks will be filled with water to increase the overall weight of the submarine which is more than the buoyancy force. Similarly for surfacing the submarine the ballast tanks are emptied to decrease the overall weight of the submarine.

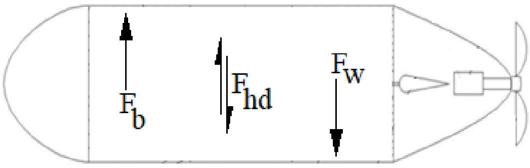


Figure 2 Forces acting on submarine during heave motion

The third term is the hydrodynamic resistance F_{hd}. This motion always acts in the opposite direction of the motion (heave) of the submarine just like a break and decreases the speed of the submarine. So, when there is no motion this force will be zero. The expression of the force is given as

$$F_{hd} = \frac{1}{2} \times C_d \times \rho \times A_s \times \dot{z}^2 \tag{2.4}$$

Here, C_d is the co-efficient of drag, A_s is the projected surface area of the submarine with $\dot{z}$ being the velocity of submarine during heave motion.

As the heave motion includes the vertical movement of the submarine in both directions, Eq. (2.4) need to be modified as the velocity is squared. So for getting the resisting force during up and down movement of the submarine $\dot{z}^2$ is replaced by $\dot{z} \times |\dot{z}|$. So, the final equation for hydrodynamic force becomes

$$F_{hd} = \frac{1}{2} \times C_d \times \rho \times A_s \times \dot{z} \times |\dot{z}| \tag{2.5}$$

After substituting the values from equation (2.2), (2.3), (2.5) in equation (2.1) finally the dynamics for heave motion of the system is obtained as

$$(M+\Delta\mathrm{m})\ddot{z} = (M+\Delta\mathrm{m})\mathrm{g} - (\rho \times \forall_s \times g) - \left(\frac{1}{2} \times C_d \times \rho \times A_s \times \dot{z} \times |\dot{z}|\right) \quad (2.6)$$

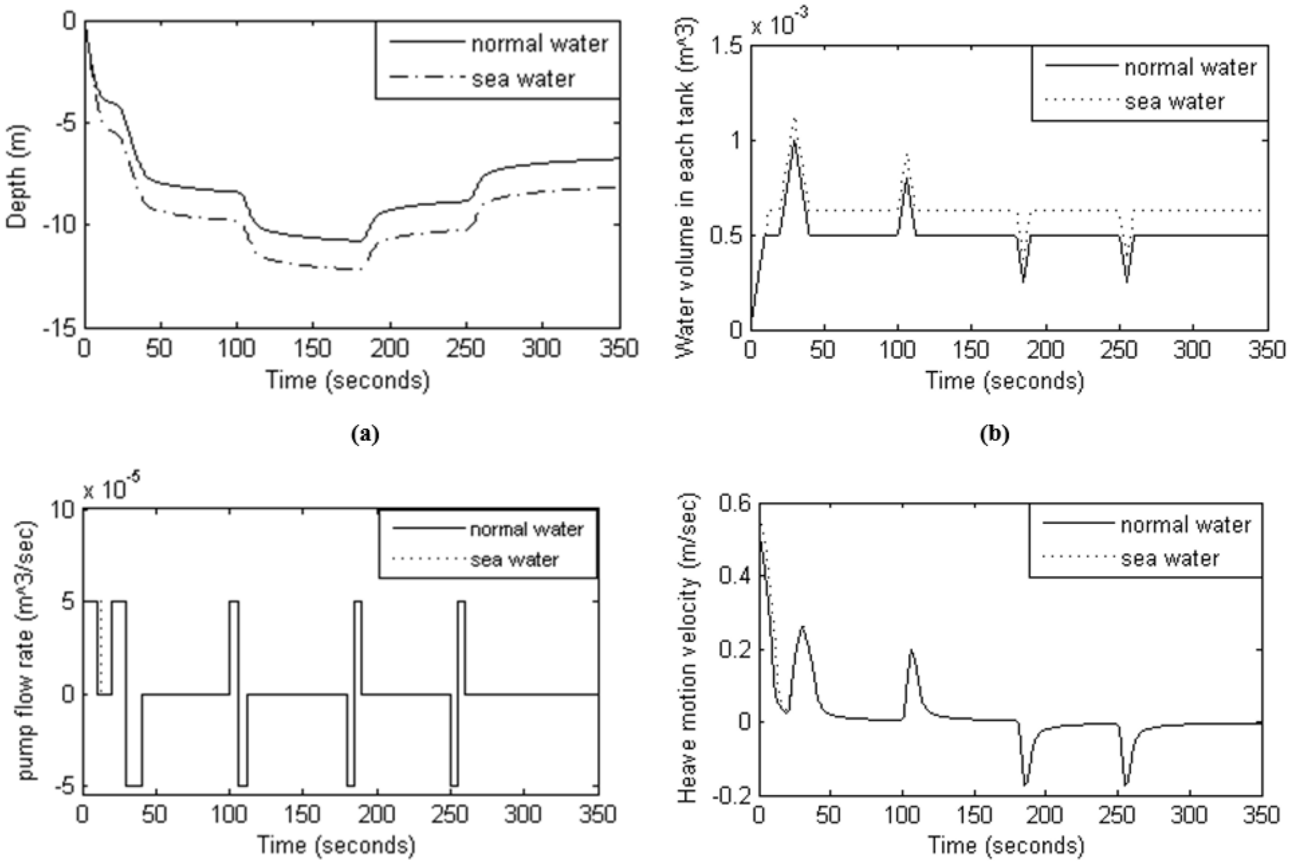
where, $\ddot{z}$ is the acceleration of submarine during heave motion. During downward motion the velocity of submarine has been taken as positive and during upward motion, the velocity is taken as negative. Based on this proper sign convention has been used in Eq. (2.6).

III. RESULTS AND OBSERVATIONS

For finding out the dynamics of heave motion of the submarine the governing equation Eq. (2.6) is solved using Runge-Kutta method in Matlab-Simulink frame. The parameters used for solving the governing equation have been listed in Table 3.1. Besides, the volume of each ballast tank has been taken as 1.3 liters and flow rate of each pump as 50 ml/sec.

Table 3.1 Parameters used for analytical calculation

Parameter	Value	Unit
M	17.6	Kg
g	9.81	m/s^2
ρ (normal water)	1000	kg/m^3
ρ (sea water)	1029	kg/m^3
$\forall_s$	0.02	m^3
C_d	1	-
A_s	0.1393	m^2



(a) (b)

(c) (d)

Figure 3 (a) Depth of submarine versus time; (b) Water volume in each ballast tank versus time; (c) Flow rate of each working pump versus time; (d) Heave motion of submarine versus time

In this study two different liquid has been taken, one is normal water having a density of 1000 kg/m^3 and another is sea water having density of 1029 kg/m^3 and four different depth of the submarine has been achieved which is shown in Fig 3(a) and corresponding the velocity of the submarine is also shown in Fig 3(d). For this present study it has been considered that at the beginning the submarine is partially submerged and in equilibrium condition. Now when the pumps are switched on they start to flood the ballast tanks causing the increase of the total weight of the submarine. As a result the submarine starts to sink and simultaneously the buoyancy force is also increased. This process would continue till the total submarine got immerse in liquid and produced maximum buoyancy force. From Fig 3(b) it is clear that for achieving the equilibrium condition (when buoyancy force and total weight of submarine are equal) the ballast tanks has been filled with some water (for normal water which is 500 ml and for sea water that is about 626.8 ml). From this result it is also possible to predict the suitable size of ballast tank for achieving a given range of depth.

It is also observed from Fig 3(b) that in case of sea water ballast tanks are filled more for achieving the equilibrium condition as buoyancy force is more in sea water than normal water. Now for achieving the next depth the pumps are operated in such a manner that the amount of water which has been fed into ballast tank for getting that particular depth, the same amount of water must has been taken out of the ballast tanks after achieving that depth and here is the main challenge for controlling the pumpsthat has been shown in Fig 3(c).

IV. CONCLUSION

Equation of motion of an underwater vehicle having an innovative arrangement of four ballast tanks, has been obtained for its movement in the vertical direction i.e. for obtaining different depths underwater. Open loop data of control of water flow from the four ballast tanks for achieving different depths have also been obtained.

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