Over the past decade the revolutionary in all industries have been made, primarily due to the wide dissemination of the robotic solutions. Industries associated with the development of the Ocean were not an exception. A new class of underwater robots with a hydrostatic principle of motion provides a long-term monitoring of the water area. Such robots have a great scientific and technical potentials. Nowadays, five types of buoyancy variation systems are known. All of them allow robot to vary its mass or volume. Hydraulic buoyancy variation systems with gear pumps and bladders have been shown to be the most wide spread and reliable systems. The focus of this paper was made on the designing of such systems and on theoretical investigations of its performances to analyze its energy characteristics and the influence of the buoyancy variation system on the whole robot behavior and its stability. This paper describes a test bench developed to conduct the experimental investigations. The buoyancy variation system was simulated in SimScape software to estimate its dynamic characteristics, and the influence of the working process on the accuracy of underwater robot motion. Obtained theoretical approach allows to fully simulate the working processes of underwater gliders at a various operating regimes to estimate its dynamics and vibroacoustics

Keywords: AUV, buoyancy variation, dynamics, test bench, simulation

1. Introduction

During the last three decades, autonomous underwater gliders have transitioned from a concept to an extremely powerful tool for oceans exploration worldwide [1]. This achievement is based on significant efforts that are being made for underwater gliders developing: a number of investigations have been carried out on glider dynamics [2], [3], performances, path and motion control [3], [4], [5], [6], [7], [8]. Nonlinear dynamic equations, feedback control laws equilibrium points were obtained in [9]. Estimation of the glider energy consumption for a number of operating depth was discussed in paper [10].

However, there is a lack of information about the influence of glider internal systems on its dynamics and produced fluid-borne noise. The noise produced by the exploration robot during the motion often exceeds 1/3-octave frequency bands above the recommended levels by 20-22 dB in the frequency range below 200 Hz and 10 dB in frequencies above 500 Hz [1]. In such a manner, this paper investigates the influence of the buoyancy variation system of the underwater glider on its motion
accuracy. The underwater glider Mariam is supposed to operate up to 500 m depth. Firstly, in this paper the development of hydraulic buoyancy variation system is described. Development was based on mathematical model of a buoyancy engine: steady flight equilibrium analysis gives the vehicle volume for buoyancy control, depth, speed and response time also can be derived; an analysis of glider motion was made to discuss the relationship between buoyancy variation system and accuracy of motion.

2. Mariam glider configuration

Autonomous underwater glider Mariam specification is presented in Table 1. It has a modular architecture. The hull has three sections: the attitude and steering control system is located in the nose section, electrical and main control system is located in the middle section, buoyancy control system and data acquisition system are placed in the aft section. Mariam has three functional layers: organization, coordination and execution layers. Modular construction of the glider allows other equipment to be integrated into the existing system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body length</td>
<td>2.1 m</td>
</tr>
<tr>
<td>Wing span</td>
<td>1.2 m</td>
</tr>
<tr>
<td>Diameter</td>
<td>1.2 m</td>
</tr>
<tr>
<td>Mass</td>
<td>50 kg</td>
</tr>
<tr>
<td>Buoyancy engine displacement</td>
<td>600 ml</td>
</tr>
<tr>
<td>Endurance</td>
<td>60 days</td>
</tr>
<tr>
<td>Depth</td>
<td>500 m</td>
</tr>
</tbody>
</table>

The analysis of Figure 1 shows that buoyancy variation system is the most complex and working processes inside it determine the accuracy of underwater motion, its dynamic and vibroacoustic state. The more higher pressure pulsations and vibrations inside the system, the less accurate motion a robot has. Pressure pulsations inside the glider hydraulic system and its elements vibrations are transmitted through the glider body. This leads to increasing of the acoustic impact of the glider on the environment.

Figure 1 – Flowchart of Mariam system
3. **Simplified mathematical model of buoyancy engine**

At the very beginning stage, we will consider the glider as a blunt ended rigid cylinder which is able to move in a vertical direction (Figure 1). The standard Cartesian coordinate xyz system is used with z-axis oriented downward. The forces acting on the considered are shown in Figure 2. Summing forces one gets,

\[ W - \frac{dF_{\text{buoyant}}}{dt} \pm F_{\text{drag}} = \frac{dM}{dt} \cdot \frac{d^2 z}{dt^2} \]  

(1)

where, \( F_{\text{buoyant}} \) is the buoyant force, [N]; \( F_{\text{drag}} \) is the drag force, [N]; \( W \) is the weight of the vehicle in the air, [N]; \( M \) is apparent mass of the vehicle, [kg]; \( z \) is the position of the vehicle along z direction, [m/s\(^2\)]; \( t \) is time [s].

Note that the apparent mass of the vehicle is given by,

\[ M = m' + m \]  

(2)

where, \( m' \) is the added mass due to the acceleration of the vehicle, [kg].

\[ F_{\text{buoyant}} = \rho f g \frac{dV}{dt} \]  

(3)

where, \( \rho f \) is the density of water, [kg/m\(^3\)]; \( V \) is the total volume of water displaced by the vehicle [m\(^3\)].

\[ F_{\text{drag}} = -\rho f \pi d^2 C_d \frac{dz^2}{dt} \]  

(4)

where,
- \( d \) is the diameter of the vehicle, [m];
- \( C_d \) is the coefficient of drag force, acting on blunt ended cylinder at a certain angle of attack.

![Figure 2: Forces acting on a buoyancy engine: a – positive z-direction, b – negative z-direction](image)
The final equation has the following form,

\[
 m \cdot g - \rho_f g \frac{dV}{dt} \pm \frac{-\rho_f \pi d^2 C_d}{8} \frac{dz^2}{dt} = \frac{dM}{dt} \cdot \frac{d^2 z}{dt^2}
\]  

Equation allows to analyze the glider dynamics. Figure 3 represents the estimation of position and velocity of the glider for a given variation of volume as a function of time.

![Figure 3 - Glider velocity (a) and position (b)](image)

Increasing of the vehicle volume leads to increasing of its terminal velocity and more rapid changing of position. These results allowed to choose the value of volume variation – 500 ml.

4. Buoyancy engine

A wide success of underwater gliders as a tool for ocean exploration is determined by its long-term exploitation period: they are able to move in the water autonomously during a long period of time due to their the principle of motion which is provided by buoyancy engine [11]. Buoyancy engine allows the glider to vary its net buoyancy by sucking in/out the water or by varying the volume of the vehicle. This variation in combination with the control surfaces lead to the tooth-like up-and-down motion of the glider in the vertical plane. Existing legendary gliders SLOCUM [12], Seaglider [13] and Spray [14] have single buoyancy engine and a movable mass for pith and roll angles control.

The structure of the designed buoyancy variation system is shown in Figure 4a. The variation of glider volume is realized by an internal and external bladders which are inflated and deflated by an oil gear pump. Hydraulic accumulator 4 simulates external bladder with pressure load equivalent immersion depth pressure. Pneumatic-hydraulic accumulator 7 simulates internal bladder. Work fluid pumping from external bladder into internal bladder produces negative buoyancy, reverse pumping provides positive buoyancy. This system has several disadvantages such as oil leakage, high pressure ripples and vibrations. The mechanical structure of the buoyancy variation system is shown in Figure 4.
Previous analysis \cite{15} has shown that the main sources of vibration are pumps, electric motors, and hydraulic valves at all operating regimes. Vibrations origin due to fluid pressure pulsations at the pump inlet caused by the hydrostatic effect during the first 2 seconds after a cold start. Discussed hydraulic system was simulated in MATLAB/Simulink to investigate the dynamics of mass transferring and as a result the variation of the robot volume. The simulation time is supposed to be 86 seconds for the cycle emersion-immersion.

Obtained simulation results (not shown here in this paper) allow to investigate the influence of working processes inside buoyancy variation system on the accuracy of the glider motion by combination of this model and simplified model of the buoyancy engine.

![Semi-natural test bench hydraulic system](image1)

![Semi-natural bench exterior view](image2)


Figure 5 – Simulink/Simscape simulation of the buoyancy control system
CONCLUSION

This paper shows only approach for complex design of underwater gliders. This approach allows to take into account the most important subsystems of the glider, their dynamic characteristics and interaction. This approach can be useful for engineer who are dealing with underwater unmanned vehicles. Our further investigation will focus on analysis of the obtained results to theoretically and experimentally estimate glider dynamics and vibroacoustics.

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REFERENCES

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