SEMI-NATURAL TEST BENCH FOR BUOYANCY VARIATION SYSTEM OF UNDERWATER ROBOTS INVESTIGATIONS

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Underwater gliders now have become extremely popular and useful tool for ocean observation. They are moved by changing their residual buoyancy. Buoyancy is regulated, as a rule, by means of hydraulic system. Operation of this hydraulic buoyancy variation system is accompanied by large acoustic noise and vibrations due to occurred pressure pulsation inside it. The development of a reliable sampling and testing platform for these robots requires a thorough system design and many costly at-sea trials during which systems specifications can be validated. Semi-natural test bench allows to simulate two the most widespread buoyancy variation systems. Their modeling and simulation provide a cost-effective estimation to carry out preliminary component, system (hardware and software), and mission testing and verification, thereby reducing the number of potential failures in at-sea trials. It is detailed the necessary procedure to allow the conversion of the models from MATLAB/Simulink to LabView code, integration of the control software with the real-time operating system used on the embedded controller (Compact Rio). Developed test bench allow to estimate the vibroacoustic performances of underwater glider buoyancy variation systems such as: pressure pulsations, vibration and noise. In such a manner, it allows to investigate the sources of fluid borne noise, structure borne noise and air borne noise that are present at a variety of glider operational modes. Fluid born noise was estimated by means of hydrophones installed inside hydraulic lines, structure borne noise – by means of vibrational acceleration transducers.

Keywords: underwater glider, test platform, semi-natural bench, hydraulic vibrations, acoustic noise

1. Introduction

Nowadays underwater gliders have become to play a vital role in ocean exploration and allow to obtain the valuable information about underwater environment, such as water's temperature, salinity, conductivity, pH-balance and others. These data collection process doesn't need high speed motion and accurate navigation of underwater robot. The most part of ocean observation tasks requires just a transition from A-point to B-point. It results in that buoyancy driven robots are widely used for ocean observation nowadays [1]. There are some best known underwater gliders projects such as such as Seaglider [2], Spray [3], and Slocum [4]. They can travel autonomously over long distances, gathering water quality data at a reasonable cost [5].

Changing positive and negative buoyancy values provides consecutive upward and downward glides. Such robots have a low level of energy consumption as don't use propulsion system and active aerodynamic surfaces such as rudder or ailerons. Buoyancy driven robots use electro-mechanical or hydraulic buoyancy variation systems. Hydraulic systems are believed to be used in large-scale underwater vehicles, because they can withstand overload from the environment. They have a simple scheme, which consists of internal and external bladders, gear pumps (reversible or irreversible), safe and distributive valves, hydro accumulators. However, these hydraulic schemes have problems with vibration and noise produced by internal aggregates such as gear pumps, valves and others. They are caused by oil pulsation in pipes due to fluid transfer working process.

Development of an underwater robotic system is a challenging task. Unsteadiness of environment and its uncertainties requires a thorough testing of robotic system in a various environment conditions. Generally, development and testing of buoyancy variation system is done separately from the rest part of an underwater robot. The technology of semi-natural testing is known to improve the reliability and operational characteristics of robotic systems. It provides accurate imitations of external loading of buoyancy variation systems and, as a result, allows to estimate pressure pulsations, vibrations and noise produced by robot's systems.

Technical systems used by humans such as wave power plants, ships, submarines, underwater vehicles and others, usually gave a great impact on the underwater environment [6]. The main influence is the noise that is produced by such systems. This fact determines the autonomous underwater vehicles (AUV) to be as silent as possible. The main system in hydraulic buoyancy driven AUV that can produce noise is a propulsion system. The lower pressure pulsations in hydraulic system and vibrations that are occurred in it, the higher quality of the buoyancy variation system's work. Fluid pulsations are unacceptable phenomenon, because of its influence on control system. Moreover, these pulsations lead to insufficient accuracy of navigations.

Acoustic noise in hydraulic systems is known to be caused by two reasons. It is the fluid borne noise, occurring due to fluid flow in pipelines, and the structure borne noise, occurring due to the working process (Fig. 1).

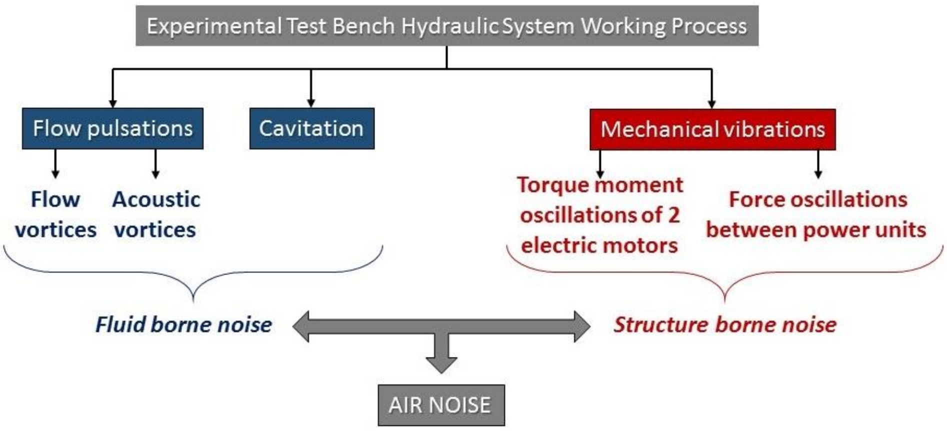

Figure 1: Noise occurring inside a hydraulic buoyancy variation systems

In such a manner, the main focus in this paper was made on decreasing of air borne noise in hydraulic buoyancy variation systems. To do so, a semi-natural test bench was proposed to use. Such test bench is an intermediate solution to develop a hardware-in-the-loop (HIL) test bench. The advantages of semi-natural test bench in relation to underwater robotics are determined by the features of underwater glider testing process:

- test efficiency (as in the financial aspect and the amount of materials and aggregates);
- scheme changing ability (bench design allows to change main units);
- the possibility of adjusting the boundary conditions of the experiment (in conditions of full-scale tests AUV takes all weather conditions, which had a negative impact on the buoyancy variation system working out);
- no risk of robot loss during tests.

Using semi-natural testing technology, the most important parameters of system's work, such as pressure pulsations, vibrations, work fluid flow rate and others can be obtained. But this is not enough for a complete underwater glider modelling, which consists of a number of extra sensors and software for navigation, motion and control. Due to this, semi-natural testing is the first step to the further investigations by means of HIL test bench. HIL can simulate ascends and descends of AUV. In work [7] HIL test bench was used for investigation of navigation accuracy and allowed to estimate an error of positioning. Also, HIL simulation is used for mathematical modelling [8]. In this paper HIL simulations are presented to validate the controller, based on Hybrid Neuro-Fuzzy Network approach for AUV. The aim of HIL simulator architecture is not to provide a set of ‘perfect’ models [9]: HIL could be allow to deal with the problem of heterogeneous coordinated vehicles, under communication constraints. HIL is very useful for integrating testing, because the entire system can be tested as a whole allowing any system integration errors to be detected in advance of real world trials [10].

More detail modelling of AUV motion consists influence of wave effects on underwater glider’s kinematic. To compute the dynamic evolution of the system hybrid simulator was used. The same approach was used in paper [11]. Hybrid simulators consists of the real and virtual systems that are interact between each other in a virtual environment to simulate a real-scale behavior of an underwater glider. The dynamic environment is necessary to simulate to have precise working conditions of robot internal systems.

2. Underwater glider

An underwater glider, considering in this paper, is presented in Figure 2, a. An uni-directional pump is used with the proper flow direction switching valve [12]. The valve is 24-volt solenoid activated and allow to switch the flow direction. Transferring oil between external and internal bladder causes volumetric change, therefore the buoyant force changes. (Fig. 2, b)

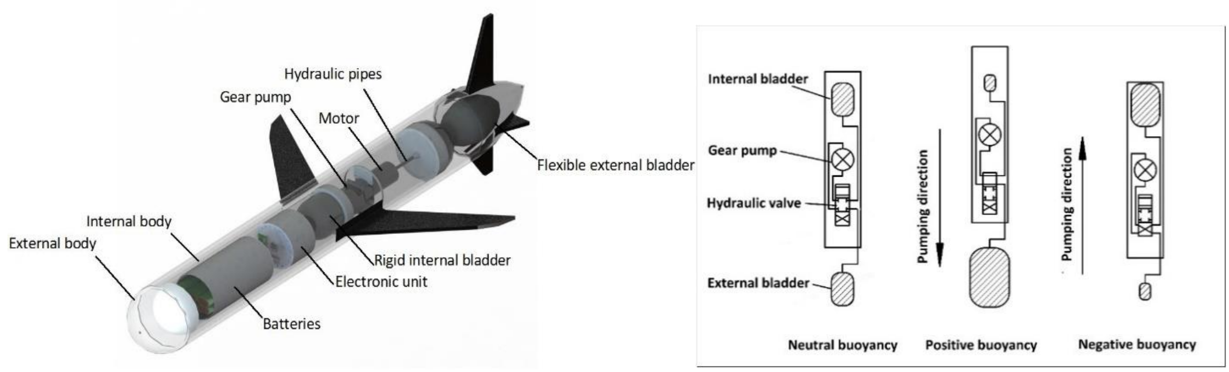

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Fig. 2: a) Hydraulic underwater glider; b) Hydraulic buoyancy variation system

The final speed of the device depends on changes in the volume that occur in the system when the buoyancy changes. Changing the system volume directly affects the stability of the exchange rate system and the correctness of the route. This can be seen from the block diagram in Figure 3. One of the buoyancy change system equations contains the element, which directly affects the trajectory of the glider motion.

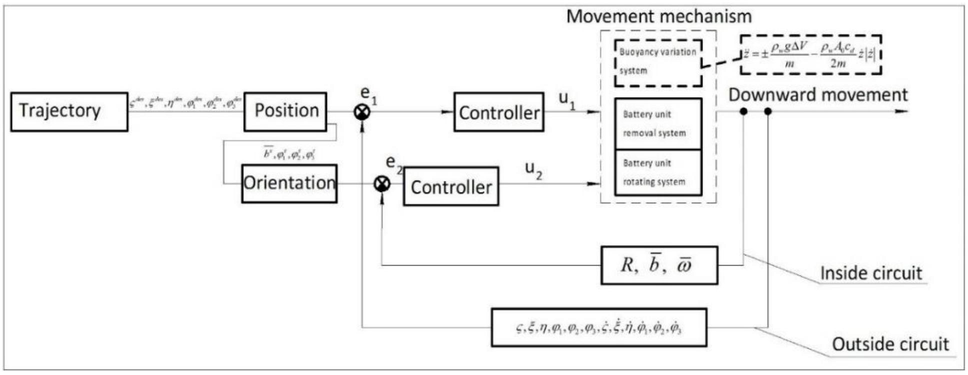

Fig.3: A schematic of underwater glider’s control system

The glider receives information about desired depth from pressure sensors. The relationship between depth and ballast mass is linear [13]. Consequently, it is natural to implement a PID-controller. The depth control system scheme is shown in Figure 4.

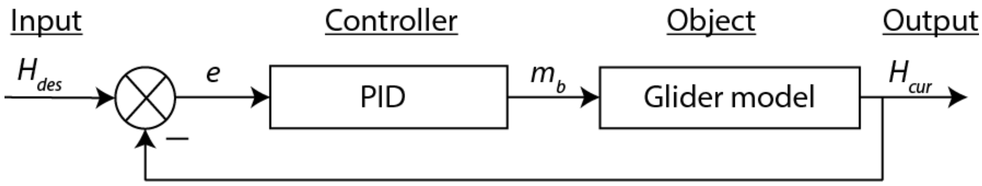

Fig. 4: PID-controller's block diagram

where H_{des} is a desired depth value; e is a depth error; m_b is a variable ballast mass; H_{cur} is a current depth.

3. Semi-natural experimental test bench

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. Therefore, the main task of the present investigation is underwater glider's hydraulic buoyancy variation system modelling. To do so, a semi-natural test bench was developed. It allows to evaluate the influence of glider elements in the overall noise performances during the transfer of working fluid from the external bladder to the internal bladder and back. Semi-natural test bench is designed for periodic, acceptance and certification tests of the buoyancy variation system.

Hydraulic system of the design test bench simulates underwater glider's hydraulic buoyancy variation system work (figure 5). It based on the most widespread hydraulic buoyancy variation systems.

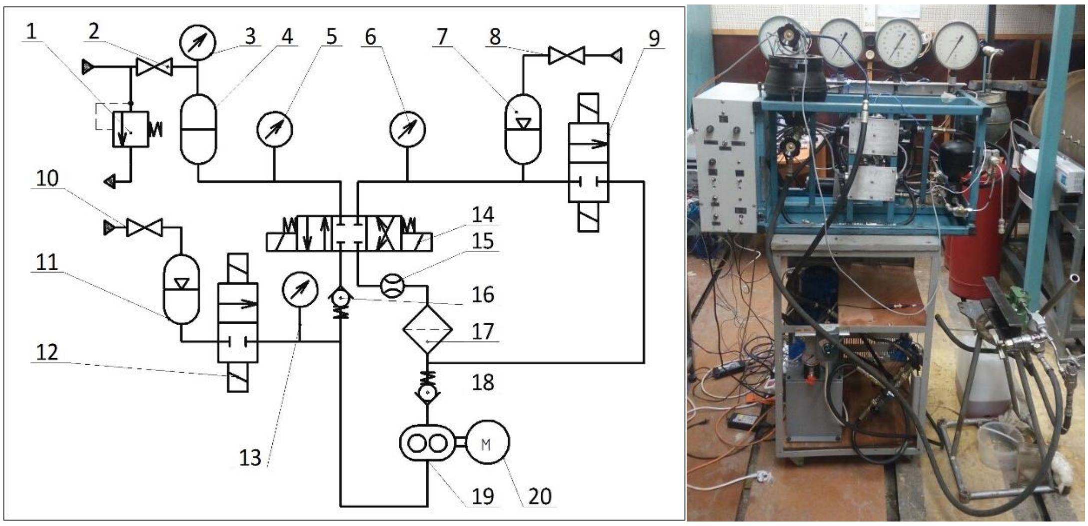

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Fig. 5: a) Semi-natural test bench hydraulic system: 1 – safety valve; 2 – shutoff valve; 3 – manometer; 4 – hydraulic accumulator; 5 – manometer; 6 – manometer; 7 – pneumatic-hydraulic accumulator; 8 – shutoff valve; 9 – 2/2 directional control valve; 10 – shutoff valve; 11 – pneumatic-hydraulic accumulator; 12 – 2/2 directional control valve; 13 – manometer; 14 – 4/3 directional control valve; 15 – flowmeter; 16 – check valve; 17 – filter; 18 – check valve; 19 – gear pump; 20 – electric motor; b) Semi-natural bench exterior view

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.

The basic mathematical model of glider dynamics was converted into a program for the controller (NI Single Board), which in its turn controls the operation of valves, pressure relief valve and the motor. Parameters which recorded and analyzed be the controller are:

- pressure in the three points of the hydraulic system;
- volumetric flow rate;
- speed of the gear pump rotation.

All values of the system can be seen on the computer in a real-time mode. Flow sensor and RPM sensor were installed to control main parameters of the system. Data from sensors is gathered by controller and duplicated in LabView program (fig. 6).

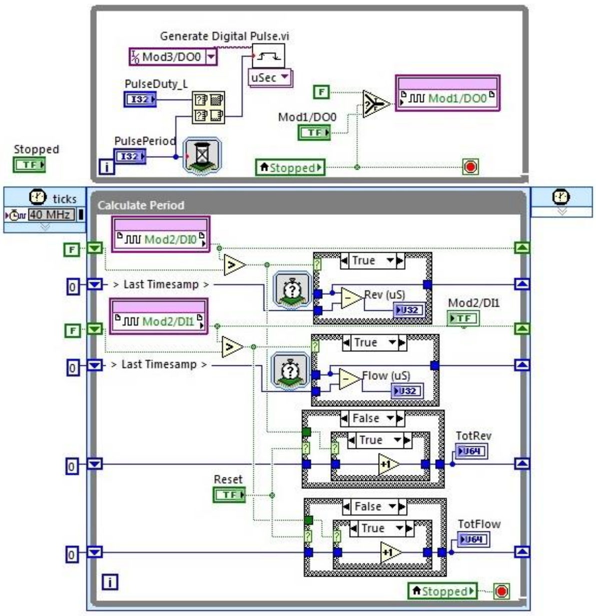

Fig. 6: Semi-natural test bench control system (LabView)

3.1 Experimental results

Semi-natural bench testing program is formed by imitating buoyancy variation system principal work.

First regime is glider's immersion imitation (work fluid pumping from external bladder to internal bladder). Work fluid is pumping from external bladder (hydraulic accumulator 4) to internal bladder (pneumatic-hydraulic accumulator 7). After a series of tests the pump gasket forcing phenomenon was observed. Because of that, there is a hydraulic accumulator 11, which needs to unload trunk-line before gear pump. Work fluid volume, pumping from external bladder to internal bladder, is calculated by flowmeter.

Second regime is glider's emersion imitation (work fluid pumping from internal bladder to external bladder). Work fluid is pumping from internal bladder (pneumatic-hydraulic accumulator 7) to internal bladder (hydraulic accumulator 4).

Third regime is work fluid dropping from internal bladder to external bladder (gear pump crash imitation).

The main aim of these experiments was to determine vibration from basic units and pressure pulsations of the internal and external bladders of hydraulic system during glider's immersion and emersion imitations. Vibration acceleration and pressure pulsation sensors were installed on the hydraulic accumulator 4, pneumatic-hydraulic accumulator 7, 4/3 directional valve 14, 2/2 directional valve 9, gear pump 19 and rechargeable pump, which imitate water pressure on external bladder 9 (hydraulic accumulator) during immersion.

LMS noise analyze ascertained that the sharpest vibrations in hydraulic system was produced by gear pump in both immersion and emersion processes (fig. 7, a,b). The analysis of the graphs shows that, during the pumping operations, the average vibration amplitude of the remaining units increases at least 2 times. Also on the charts is the significant impact of the precharge pump, (simulates the water pressure on the hydraulic accumulator), on all units. The background noise of this precharge pump increases the average vibration of the aggregates by a factor of 1.5.

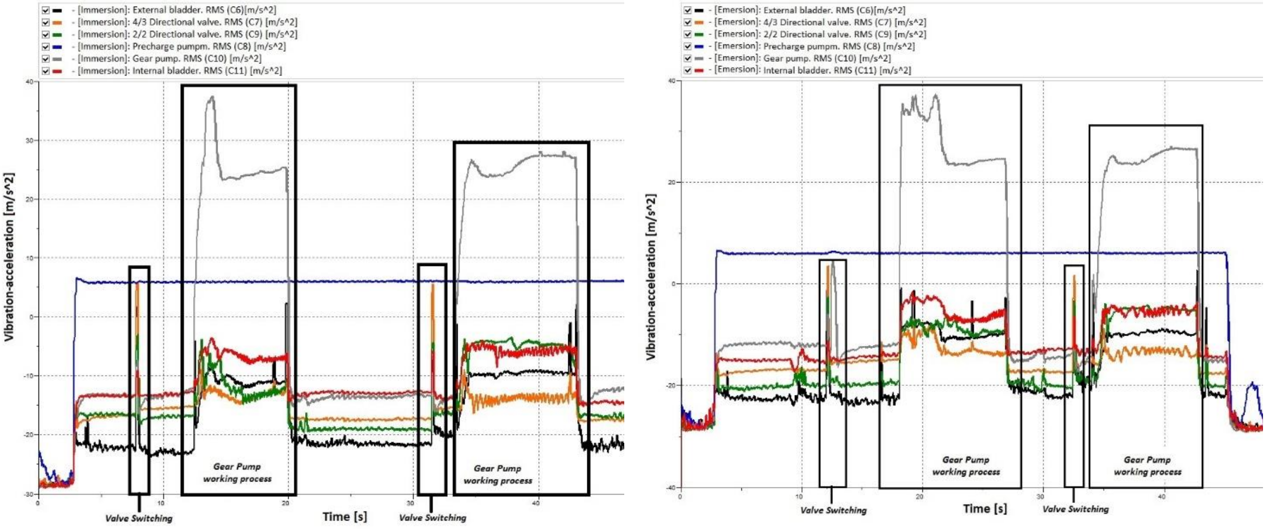

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Fig. 7: a) Vibration-acceleration analyze (Immersion regime); b) Vibration-acceleration analyze (Emersion regime)

It should be mentioned that the vibration amplitude of the main pump has increased significantly during the first switch-on period. The values of these amplitudes are presented in Table 1. It is justified by a hydraulic strike inside the system itself. This is the most significant impact on the hydraulic system, since the vibration amplitude of the remaining aggregates also increased proportionally at this time by about 7-8%. Hence it can be concluded that the most dangerous from the point of view of increasing the vibration amplitude of aggregates is the first moment of starting the main pump.

Table 1: Vibration Accelerations (Root-mean-square Value)

	Immersion regime		Emersion regime	
	Max	*Min*	*Max*	*Min*
Main pump	74,7921	0,03821	70,7726	0,03575
Hydraulic accumulator	1,3034	0,05257	1,35114	0,03799
Control Valve D-1	1,90392	0,04016	1,49432	0,03709
Control Valve D-2	0,71441	0,04227	0,72992	0,03638
Precharge pump	2,00255	0,03937	1,99167	0,04219
Pneumatic-hydraulic accumulator	0,626	0,04236	0,8248	0,0399

Another parameter, which was investigated during the experiment, was the pressure pulsations in the system (fig. 8, a,b). Pressure pulsation sensors were installed in the trunk, connected to both accumulators. When comparing pressure pulsations in the accumulators, taking into account the operation of the pumps, it can be concluded that the pressure pulsations in the system, especially in the pneumatic-hydraulic accumulator, are not associated with the main pump. Hydraulic accumulator after charging by a certain pressure itself absorbs the main pulsations from the pump. While significant pulsations that occur after the pump is switched off are justified by residual ripple of the working fluid in the pipeline during pressure equalization. It can be concluded that the main pump also influences the pressure pulsation in the system.

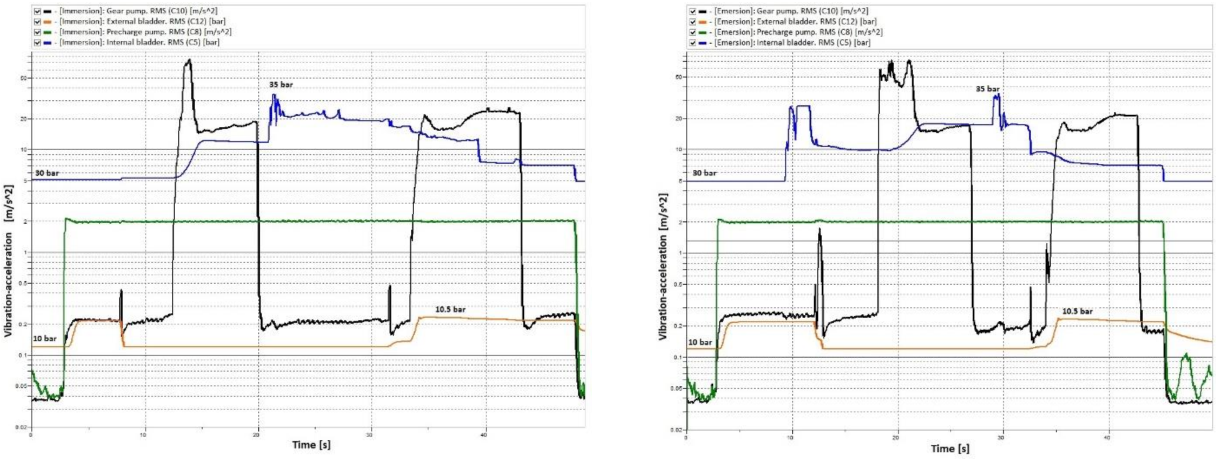

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Fig. 8: a) Pressure pulsations analyze (Immersion regime); b) Pressure pulsations analyze (Emersion regime)

4. Conclusion

The problem of acoustic impact of AUV on the environment still remains actual. In order to identify the main factors generating noise inside the hydraulic buoyancy variation system, the semi-natural test bench was developed. Experimental investigations of buoyancy changing of the underwater glider were conducted by means of the test bench. According to the obtained test results, air borne noise of the glider is mostly caused by the structure borne noise. The influence of pressure pulsations is not so significant. During the experiments, the influence of two pumps on the system was revealed, which significantly increasing the overall background of noise. However, the occurrence of pulsation of the working fluid in the pneumatic-hydraulic accumulator did not depend on the operation of the pump. Consequently, the pressure pulsations that occur because of pump work can be compensated by damping the internal bladder itself. To decrease the vibrations in the hydraulic system vibrations dampeners should be used.

5. Further investigations

In further investigations, we're going to realize HIL test bench based on developed semi-natural experimental bench. New bench will be improved with software based on underwater glider's dynamic model. It will allow to conduct the experiment as close as possible to real conditions with main movement and control systems of the underwater glider.

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