ACTIVE CONTROL OF SURFACE ROBOT POSITION

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Nowadays ships are mostly used to provide seismic measurements in the ocean. But their own magnetic field does not allow to achieve a high accuracy of such measurements. The lack of reliable and accurate data on the structure of the seabed and seismic activity in the area of interest in the ocean is the main limiting factor that does not allow to increase the oil deposit ratio of wells in offshore. Nowadays this ratio is equal to 32% meanwhile oil deposit ratio in shelf is equal to 45%. Increasing by 1% of this ratio allow to increase oil well productivity by 20 million barrels. Marine surface robots can help to increase this ratio as they are able to operate in the water for a long time. They are cost and energy effective tool to provide seismic data in operating regime 24/7. This article briefly describes the construction and functionality of wave gliders. Considered robot consists of two modules - surface and underwater. They are connected by means of a cable. Robot underwater part consists of wing elements which convert the energy of the surface wave into the translational movement of the whole robot. Such robot construction leads to dependence of the robot on the waves. Waves cause undesirable movement of the whole robot, and as a result, the instability of robot motion, position and their accuracy. Such continuous disturbances do not allow to robot to hover on the water surface. Kinematics and dynamics models allow to design a reliable and robust control system to allow robot to hover on the water surface at a given point. A simplified two-links model is proposed in this paper for dynamic model development. Disturbances were considered in form of sinusoidal, progressive, flat and regular waves. The Stewart platform was used to simulate wave perturbations. Experimental test bench was developed to test provided control system and to estimate its accuracy.

Keywords: surface robot glider, active control, disturbances, position

1. Introduction

About three quarters of the Earth's surface is covered with water in the form of lakes, rivers, seas or oceans. The humanity actively explore near and far space, while 95% of the world's oceans of the Earth and 99% of its fauna remain unexplored [1].

Nowadays, the underwater world is studied by using unmanned underwater vehicles, which are subdivided into simple data acquisition devices and complex autonomous underwater vehicles (AUVs). Such AUVs have a solid frame where one can mount any measuring equipment capable of collecting scientific data concerning the aquatic environment state, such as temperature, electrical conductivity or speed and direction of underwater streams. Due to the high autonomy, the ability of carrying various sensors and the possibility of intelligent control, the AUVs have become the main robotic mobile devices for solving the problems of water ecology, sampling, solving research problems with little or no human participation [2].

The most important criteria for assessing all AUVs are high autonomy and cruising range. Nowadays, there is an AUV class that meets these requirements - surface robots (wave gliders). Surface robots have operational attractiveness due to their low cost, high autonomy (about 1 year) and the possibility of long-term research, high cruising range, high accuracy of work and minimal human participation [3,4].

The robot consists of two modules - surface and underwater, which are connected by a cable through which data is exchanged (Figure 1).

Figure 1: Wave glider

The surface module provides continuous communication between the robot and the operator through the satellite communication and/or radio communication, and this module also supplies the AUV with additional energy (in addition to solar panels the AUV also have batteries). Such energy module provides uninterrupted power for all electronic equipment on board the robot throughout its life without any additional charge. The AUV underwater part includes wing elements that transform the wave motion energy of the AUV surface module into the translational motion of the entire robot. Wave gliders have virtually unlimited lifetime (the average real lifetime can be estimated at 5-7 years before scheduled maintenance).

There is always a cable pulling force between the underwater and surface AUV modules. When the surface module rises due to the presence of a waves, the tension force changes, which leads to the fact that the sum of the cable tension force and the buoyancy force becomes greater than the sum of the gravity forces acting on both bodies (cable gravity force can be neglected) and the hydrodynamic drag force of the AUV underwater module. The underwater wings articulated cantilevering allows to convert the vertical displacements of the surface module into the translational motion of the entire robot. Thus, the wave kinetic energy is transformed into the wave glider kinetic energy (Figure 2).

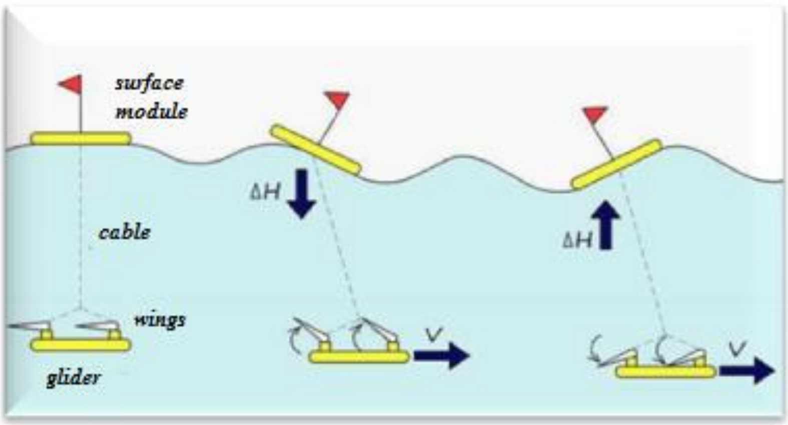

Figure 2: Glider operation principle

This robot type moves continuously due to the constant presence of a wave. Therefore, despite the obvious advantages of this robot type, there is a significant problem associated with the glider hanging at a certain point. This problem does not allow obtaining accurate data on the bottom structure and seismic activity in the zones of interest. The availability of these data is the main limiting factor that determines the oil recovery ratio in the open sea at 32% instead of the 45% achieved on the shelf. The increase of this factor by 1% will allow to increase oil production by 20 million barrels.

To solve this problem, present wave gliders can use propellers. They provide traction opposite to the wave perturbation acting on the glider, thereby compensating the disturbances of the whole system. The disadvantage of this method is the need to place compensating propellers on all robot sides, which complicates its design, as well as propellers constant power consumption in the hang mode.

This paper presents a new method for surface robot active position monitoring based on its kinematics and dynamics. The proposed method allows the groups of such AUVs to be held in one place under the influence of winds and streams.

2. Method description

The surface robot can be represented in simplified form as a two-section converter (Figure 3). The proposed method is based on the control of mass m_2 oscillations by controlling the spring elements K2 and a dampener D (cable tension force) via setting a disturbing effect on the system using an element K1. The cable tension force is naturally formed when the surface waves are perceived by the AUV surface module. In general, it is co-directional or opposite to the gravity vector.

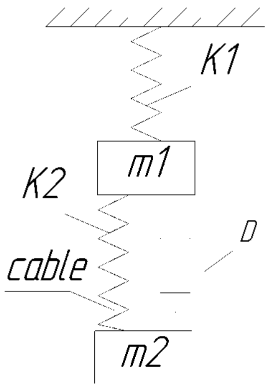

Figure 3: Two-section converter

It is necessary to develop system dynamic and kinematic models to solve this problem. Wave glider motion modeling is a complex hydrodynamic task, since for the accurate calculation of the system it is necessary to consider all perturbations acting on the wave glider.

There are a lot of works devoted to the topic of system active control. The most common is the inverse pendulum model with active control [5-7]. The fact is that this two-mass model depicts a variety of real systems - from the orientation of spacecraft to various robots. This model was used as an efficiency test, starting with the methods of control theory based on PID controllers and ending with FNN- Fuzzy Neural Networks technologies [8].

3. The system kinematic model

In order to find the displacement and speed of the surface and underwater AUV modules, it is necessary to know the position and speed of the system mass center, as well as the rotation matrix. Figure 4 shows the coordinate systems which are necessary to describe the motion kinematics of the entire robot and its individual parts:

- index ^{F} – coordinate system associated with the AUV surface module;
- index ^{G} – coordinate system associated with the AUV underwater module;
- index ^{O} – coordinate system associated with the AUV mass center;

- XOY – global coordinate system, which is used to find the AUV final location in the underwater space.

In many works, the X axis is oriented to the east, but in this paper the X axis is oriented positively to the north, and Y is oriented positively to the east.

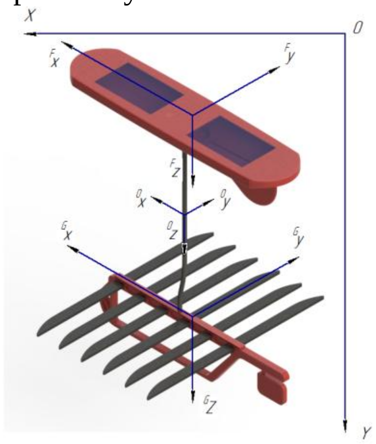

Figure 4: The glider coordinate systems placement

In order to represent the resulting motion equations in a coordinate system associated with the AUV mass center, it is necessary to use the rotation matrix

$$ {}_{F}^{0}R = \begin{bmatrix} c(\theta)c(\Delta\psi) & c(\Delta\psi)s(\theta)s(\phi) + s(\Delta\psi)c(\phi) & -s(\theta)c(\phi)c(\Delta\psi) + s(\Delta\psi)s(\phi) \\ s(\Delta\psi)c(\theta) & c(\Delta\psi)c(\phi) + s(\Delta\psi)s(\theta)s(\phi) & s(\Delta\psi)s(\theta)c(\phi) + c(\Delta\psi)s(\phi) \\ s(\theta) & -s(\phi)c(\theta) & c(\theta)c(\phi) \end{bmatrix} \quad (1) $$

$$ {}_{G}^{0}R = \begin{bmatrix} c(\theta) & s(\theta)s(\phi) & -s(\theta)c(\phi) \\ 0 & c(\phi) & s(\phi) \\ s(\theta) & -s(\phi)c(\theta) & c(\theta)c(\phi) \end{bmatrix} \quad (2) $$

where C и S - abbreviation of cosinus, sinus;

$\Delta\psi$ - the angle between the surface module attachment point and the underwater module in the OG coordinate system;

The glider speeds and displacements can be represented in the global coordinate system. To do this, it is necessary to use the rotation matrix:

$$ {}_{0}^{XOY}R = \begin{bmatrix} c(\theta)c(\psi^{G}) & -s(\psi^{G})c(\phi) + s(\theta)s(\phi)c(\psi^{G}) \\ s(\psi^{G})c(\theta) & c(\psi^{G})c(\phi) + s(\phi)s(\theta)s(\psi^{G}) \end{bmatrix} \quad (3) $$

The transition from the coordinate system associated with the AUV gravity center to the global coordinate system concerns only the components along the X and Y axes. This is because the global coordinate system component Z_0 is not determined from the motion equation, but is assigned as a periodic sinusoid. General motion equations are obtained using the Newtonian mechanics equations.

4. The system dynamic model

The general form of the wave glider dynamic model for six degrees of freedom is as follows:

$$ M\dot{v} + C(v)v + D(v)v + g(\eta) = \tau \quad (4) $$

where

M - inertia matrix;

C(ν) - Coriolis matrix including centripetal components;

D(ν) - attenuation matrix;

g(η) - gravitational forces and moments vector;

τ - perturbation vector;

$\eta = [x, y, z, \phi, \theta, \psi]^{T}$ - displacement matrix;

$v = [u, v, \omega, \rho, q, r]^{T}$ - speed matrix;

u, v, w - x y z axis speeds;

p, q, r - roll, pitch and yaw angular speeds respectively.

Before considering the wave glider dynamic model, it is necessary to take some assumptions. The AUV surface module is floating, therefore it does not affect gravity forces. In addition, it is assumed that both surface and underwater modules have a slight difference in the location of the gravity center and the buoyancy center. Thus, the last two terms in the gravitational forces and moments matrix completely disappear (that is, the hydrostatic forces on the glider do not affect either the surface or the underwater modules).

Taking into account the above notation, the equation (4) will be as follows:

$$\begin{bmatrix} m^0 & 0 & 0 & 0 & 0 & 0 \\ 0 & m^0 & 0 & 0 & 0 & 0 \\ 0 & 0 & I_{xx}^0 & 0 & 0 & 0 \\ 0 & 0 & 0 & I_{xx}^0 & 0 & 0 \\ 0 & 0 & 0 & 0 & I_{zz}^F & 0 \\ 0 & 0 & 0 & 0 & 0 & I_{zz}^G \end{bmatrix} \begin{bmatrix} \dot{u}^0 \\ \dot{v}^0 \\ \dot{p}^0 \\ \dot{q}^0 \\ F_{\dot{r}}F \\ G_{\dot{r}}G \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & -m^0 v^0 \\ 0 & 0 & 0 & 0 & 0 & -m^0 u^0 \\ 0 & 0 & 0 & 0 & 0 & -I_{xx}^0 q^0 \\ 0 & 0 & 0 & 0 & 0 & I_{xx}^0 p^0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} u^0 \\ v^0 \\ p^0 \\ q^0 \\ F_r F \\ G_r G \end{bmatrix} +$$

$$+ \begin{bmatrix} {}^0X & 0 & 0 & 0 & 0 & 0 \\ 0 & {}^0Y & 0 & 0 & 0 & 0 \\ 0 & 0 & {}^0K & 0 & 0 & 0 \\ 0 & 0 & 0 & {}^0M & 0 & 0 \\ 0 & 0 & 0 & 0 & {}^FN & 0 \\ 0 & 0 & 0 & 0 & 0 & {}^GN \end{bmatrix} + \begin{bmatrix} {}^0X_{HS}{}^G \\ -{}^0Y^G{}_{HS} \\ -{}^0Y_{HS}^G \left|{}^{0T}G0\right| \\ {}^0X_{HS}^G \left|{}^{0r}G0\right| \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} {}^0X_{Thurst}{}^{+0}X_{u\delta}^G(\delta) \\ {}^0Y^G{}_{Thurst} + {}^0Y_{u\delta}^G(\delta) \\ -({}^0Y_{Thurst}^G + {}^0Y_{u\delta}^G(\delta))\left|{}^{0r}G0\right| \\ ({}^0X_{Thurst}^G + {}^0X_{u\delta}^G(\delta))\left|{}^{0r}G0\right| \\ 0 \\ {}^GN_{uu}^G \end{bmatrix} \quad (5)$$

where

m^0 - whole system mass;

I^0_{xx} - the whole robot inertia moment relative to the X axis (above index G refers to the AUV surface module, index F for AUV underwater module);

${}^0X$, ${}^0Y$, - the total force acting along the X and Y axes, respectively;

${}^0K$, ${}^0M$, ${}^FN$, ${}^GN$ - the forces moments sum relative to the roll, pitch and yaw angle;

${}^0X^G_{HS}$ - hydrostatic forces acting on the AUV surface module;

${}^0X^G_{Thurst}$ - glider thrust along the X axis;

${}^GN^G_{uu\delta}$ - the force deflecting the AUV rudder;

Equation (5) is a set of nonlinear dynamical motion equations of the wave glider for six degrees of freedom. Consider the right-hand side of this equation, namely the matrix of perturbation effects:

$$\tau = \begin{pmatrix} {}^0X_{Thurst}^G + {}^0X_{u\delta}^G(\delta) \\ {}^0Y_{Thurst}^G + {}^0Y_{u\delta}^G(\delta) \\ -({}^0Y_{Thurst}^G + {}^0Y_{u\delta}^G(\delta))|{}^0r_{G0}| \\ ({}^0X_{Thurst}^G + {}^0X_{u\delta}^G(\delta))|{}^0r_{G0}| \\ 0 \\ {}^GN_{uu\delta}^G \end{pmatrix} \quad (6)$$

Figure 5 shows a developed surface AUV control system based on the kinematic and dynamic models:

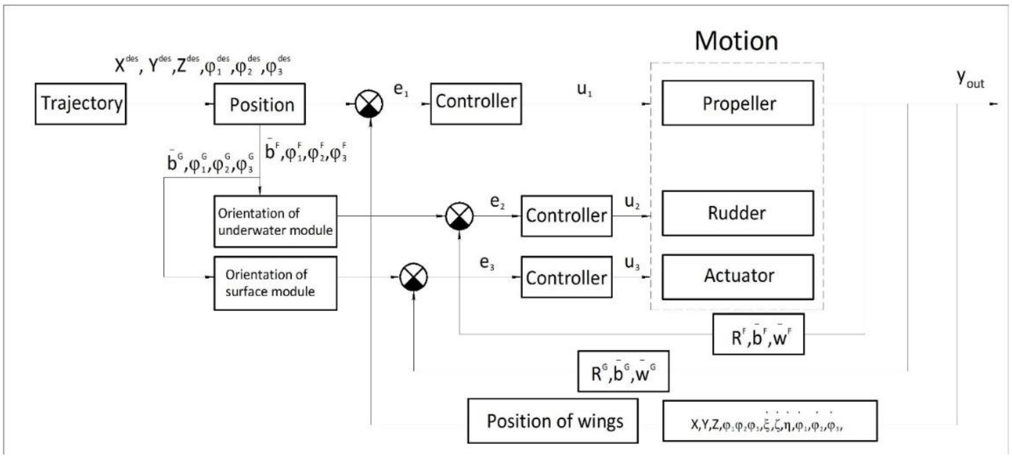

Figure 5: The AUV control system scheme

Figure 5 shows that the error in AUV position and orientation arises from the influence of waves on it. The disadvantage of this surface glider dynamics model is that perturbing effects of wind, streams and waves are neglected. Only two input perturbations, which are added to the speeds in the global coordinate system are taken into account - the thrust and AUV rudder deflection angle (δ) [9].

To realize the AUV hanging, it is necessary to control the cable traction force. Due to the presence of a surface wave, this force is always present. The essence of the proposed method is the active control of this force. To control the traction force, it is necessary to know the AUV surface module position and the waves amplitude.

To take into account wave perturbations, as well as perturbations caused by the streams, one can assume that the wave is progressive, flat, regular and sinusoidal. The wind perturbation effect can be neglected due to the lack of sailage in this type of AUV.

Sinusoidal waves movement affects only the glider movement along the Z axis. The stream is taken into account as a term in the perturbation matrix. In [10] the authors also take into account the AUV vertical rocking. Then the wave perturbation acting on the whole glider will be as follows:

$$A\ddot{\psi} + B\psi + C\psi + A\ddot{\xi}_g + B\dot{\xi}_g + C\xi_g = Pexp(i\omega t), \tag{7}$$

where ξ_g– vertical amplitude of the AUV gravity center, – trim angle at pitching, A,B,C – coefficients of inertia, damping and restoring forces, respectively, P – complex amplitudes of perturbation forces and moments, ω – pitching reduced frequency, equal to the waves apparent frequency.

Then the matrix of perturbation effects (6) will be as follows:

$$\tau = \begin{pmatrix} {}^{0}X^{G}_{Thurst} + {}^{0}X^{G}_{u\delta}(\delta) + X_{stream} \\ {}^{0}Y^{G}_{Thurst} + {}^{0}Y^{G}_{u\delta}(\delta) + Y_{stream} \\ -({}^{0}Y^{G}_{Thurst} + {}^{0}Y^{G}_{u\delta}(\delta) + Y_{stream})|{}^{0}r_{G0}| \\ -({}^{0}X^{G}_{Thurst} + {}^{0}X^{G}_{u\delta}(\delta) + X_{stream})|{}^{0}r_{G0}| \\ A\ddot{\psi} + B\psi + C\psi + A\ddot{\xi}_g + B\dot{\xi}_g + C\xi_g = Pexp(i\omega t) \\ {}^{G}N^{G} \end{pmatrix} \tag{8}$$

5. Task solving method

To design the proposed control system, it is necessary to use theoretical and experimental methods for system setting up. This paper describes the test bench that allows to implement the position active control of a two-section surface AUV.

Figure 6 shows the developed test bench scheme.

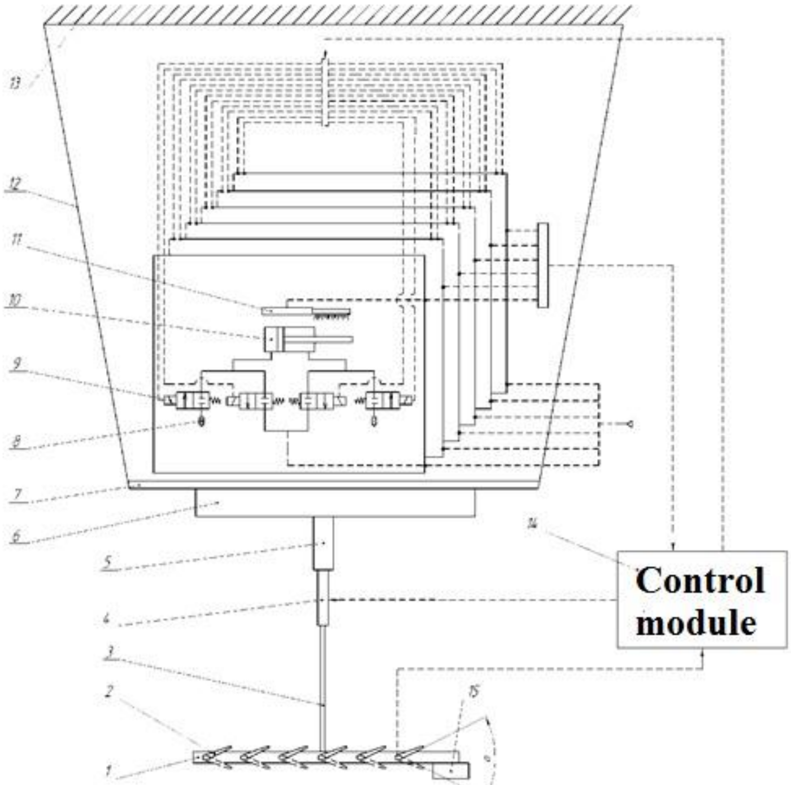

Figure 6: Test bench scheme.

AUV underwater module 1 with wing elements 2, where the angle of rotation sensors 15 are situated, are rigidly connected through a cable 3 with actuator 4. The actuator in turn is rigidly attached to AUV surface module 6. The surface module is fixed to the moving part 7 of Stuart platform 12, which has six pneumatic cylinders 10 as actuators, these cylinders are connected by hinges to a moving part 7 on one side, and with a fixed base 13 of Stuart platform 12 on the other side. The pneumatic cylinders 10 are connected by respective inputs and outputs through the pneumatic distribution valves 9 to the compressor or other air sources and are also equipped with rod position sensors 11. Electrical contacts of rod position sensors 11 for pneumatic cylinders 10 and angle sensors of wing elements 2 are connected to the corresponding electrical inputs of the control unit 14, while its electrical contacts are connected to the corresponding electrical inputs of pneumatic distribution valves 9 and actuator 4.

6. Test bench operating principle

The Stewart platform can be used to simulate wave perturbations on land. The Stewart Platform is a movable mechanical system, whose output link can travel with six degrees of freedom. It is possible to use a pneumatic platform to simulate the waves movement, since the accuracy of positioning (low for a compliant working substance - air) is not a priority, because the main task is imitation of movement trajectory [11].

The parameters of generated waves - amplitudes, phases and frequencies (A, φ, ω) - are preset in the control unit. The pressure from the air source is fed to the platform proportional pneumatic valves, which in turn alternately open and close, thereby providing the necessary movement trajectory of the Stewart platform movable part. The position control of the pneumatic cylinders rods is monitored by the rod position sensors. In order to keep the wing elements in a neutral position, a linear actuator that connects the surface and underwater AUV units is required. By adjusting to the waves amplitude, it protrudes and retracts in antiphase, thereby being the dampener of this system.

The waves simulation on the Stewart platform with given parameters (A, φ, ω) allows to obtain the value, which is necessary for controlling the linear actuator in the antiphase of waves.

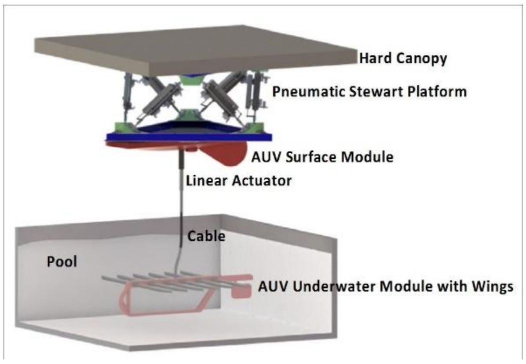

Figure 7: The test bench view

7. Conclusion

Nowadays, there is an acute problem of collecting reliable and accurate data on the structure of the ocean bottom and seismic activity in the zone of interest, as well as natural disasters accurate forecasting. Such kind of devices as wave gliders allow to cope with these tasks. This paper presents a dynamic model of underwater gliders which takes into account the perturbing effects of wind, streams and waves. The analysis of the obtained new perturbation matrix was carried out, for the theoretical and experimental research of the obtained dynamic model a test bench was developed; this test bench consists of a control system, a pneumatic Stewart platform and a wave glider, which allows to carry out research of wave oscillations active damping. It is planned to assemble this test bench and carry out full-scale tests by means of it to study the active control system for damping the wave oscillations.

8. Acknowledgements

This work was supported by the Ministry of Education and Science of the Russian Federation (Grant # 01v-R200-201).

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