INTERNATIONAL JOURNAL OF RENEWABLE ENERGY RESEARCH
K. Sholanov and Zh. Issaeva, Vol.9, No.3, September, 2019

SUBMERGED FLOAT WAVE ELECTRIC POWER STATION ON THE BASIS OF THE MANIPULATOR CONVERTER

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Received: 10.06.2019 Accepted: 15.08.2019

Abstract- The article presents a new float wave power station (WPS). A characteristic feature of the float WPS consists in a six-position parallel manipulator used to convert the water mass energy into six translational movements of manipulator actuators and in a float that is used with an aerodynamic profile in section. The article gives rationale for the choice of parallel manipulator and float shape. Demonstrational model is described. Dynamic model of the apparatus has been designed for the study and calculation of float WPS parameters. An algorithm for calculating design parameters of WPS is presented. These parameters include working tool from the floater with mast, manipulator converter design. Technology for converting energy of all special movements of the floater and location of the floater under the water provide the new WPS with higher productivity and service life compared to its equivalents.

Keywords- wave power station; parallel manipulator; float, actuator, dynamic model.

1. Introduction

It is known that surface waves of large water spaces (oceans, seas, large lakes) have an enormous amount of energy [1,2]. To extract and use this energy, various wave energy sources are applied [3,4]. The theory of wave energy conversion, applied technologies and WPS devices are described, for example, in [5-11]. As the analysis of these works shows, mainly cylindrical floats are used to extract the energy of moving water masses, and stem and cylinder-shaped structures are used as energy converters. It should be noted that these technologies and technical facilities do not allow obtaining high efficiency since only the energy of water masses vertical movement is used [12,13]. Successful development of wave power engineering and its widespread use are hampered by a number of problems; among them, WPS low performance and their susceptibility to damage from wave dynamics and corrosion are significant [14].

It is known that in most float WPS, the process of converting wave energy into electrical energy occurs in 2 stages: at the first stage, the wave energy is extracted and converted into mechanical energy of the “organized” movement; in the second stage, the energy of mechanical movements is converted into electrical energy. Due to the fact that known devices are used for power extraction at the 2nd stage, this work focuses only on the technology and technical facilities used to extract and convert energy of water mass motion. The article sets the goal of creating and justifying the new design for the new float wave power station (FWPS), creating an apparatus for numeric calculations and selection of submerged FWPS parameters. At the same time, from the experience of using floating offshore platforms [15-18], it was proposed to convert the float motion energy into movement of six manipulator actuators, use a six-motion manipulator [19]. Also, the article gives substantiation and proposes to use a new ellipsoid float with an aerodynamic profile in section. The article *considers su*bmerged location of the float WPS as this will prevent the power station from destructive actions of waves. WPS is installed in the coastal zone so that the float is located a short distance below the water surface. By choosing the installation depth, the required amplitude of the float movement is provided. To ensure the required position of the float by depth, a mast or frame structure rigidly connecting the float and the upper manipulator platform is used.

2. Justification of the WEPS design

As noted above, the primary converters of the existing WPS transform the vertical movement of water mass into a translational motion. However, during commotions, water masses make more complex movements. For example, according to the trochoidal theory of waves [20], water particles move along a circular orbit, the parameters of which are determined by the wave parameters. In addition, it is known that the orbit radius at the lower boundary of water surface is equal to $r_0 = H/2$, *a)* where H is wave height. With the change of distance (h) from the surface downward, the orbit radius of water particles movement (r) decreases exponentially.

$$r = r_0 e^{-2\pi h/\lambda}. \tag{1}$$

Here λ is wave length.

The plane of a closed orbit is located vertically to the water surface and perpendicular to a wave crest. Since the direction of wave advance can change over time, position of closed orbit plane also changes. If WPS float is located under water, it will be captured by the water mass moving in a closed orbit. In fact, the float moves along a spatial closed trajectory performing a two-dimensional motion in different directions that in general represents spatial movements with six degrees of freedom. In this case, it requires expanding the manipulator converter function, since it must convert the spatial movements of the float into six "organized" mechanical movements.

2.1. Choice of manipulator converter

In order to convert the energy of all spatial movements of the float into "organized" mechanical movements, a six-motion parallel manipulator was chosen as a converter. Out of the manipulators, Gough-Stewart [21] and SHOLKOR parallel manipulators have a large bearing capacity as their upper platform can be rigidly connected with the float. In these models (Fig. 1), the lower platform 1 is connected to the upper platform 2 by means of six actuators 3. The models differ by the actuators interconnection schemes.

a)

b)

Figure 1. Manipulators of platform robots

Comparative analysis of models showed that the SHOLKOR manipulator has several advantages compared to the Gough-Stuart manipulator. These advantages are listed below.

1. Each of the six actuators can move independently from others. For example, one actuator can be moved and its length can be changed without changing the lengths of other actuators.
2. Moving and changing the length of a certain set of actuators in a predetermined way can give any desired spatial position of the mobile platform or its simplest movements relative to the lower one.
3. Each spatial position of the mobile platform corresponds to a certain length of the

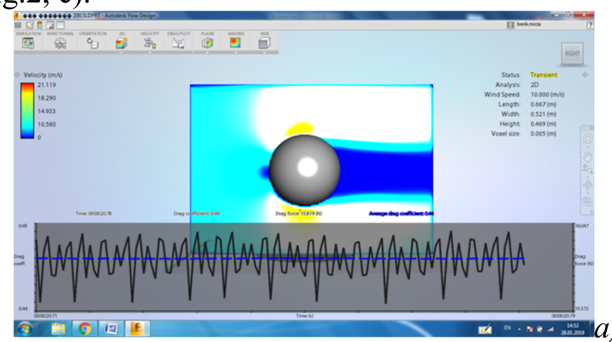
actuators. From this, it follows that the mobile platform can be moved, and the lengths of the actuators will unambiguously change.

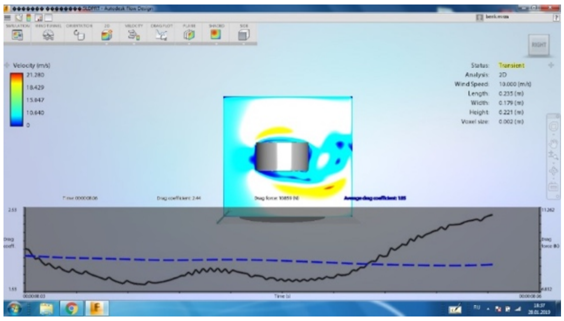
It is also known from the analysis of kinematics [22] that the direct and inverse kinematics problem is explicitly solved in the SHOLKOR parallel manipulator.

In this regard, the parallel SHOLKOR manipulator was chosen as the manipulator converter for the new WPS. At the same time, to protect the joint from corrosion in the aggressive environments, multi-mobile spherical connections of the actuators with the platforms are replaced with flexible cable (wire rope) connections [23], as shown in Figure 1.

2.2. Choice of the float shape

The WPS design [24] consists of a manipulator converter, a working body (WB) and additional devices intended for converting mechanical energy of actuators into electrical energy, i.e. electric power generation systems that is not considered in this article. It is accepted that the WB consists of a float, a structure (mast) holding the float, and the manipulator upper platform. The efficiency of wave energy conversion in the FWPS is largely dependent on the float shape, captured movement of water mass. To select the most effective float configuration, computer simulation of airflow around a variety of floats with different shapes was performed using Autodesk Flow Design that is a virtual wind tunnel. When simulating, any resistance force and resistance factor are determined automatically. The float models with the same volume but different in shape were investigated: a ball (Fig.2, a), a cylinder (Fig.2, b), an ellipsoid with an aerodynamic section profile (Fig.2, c).


a)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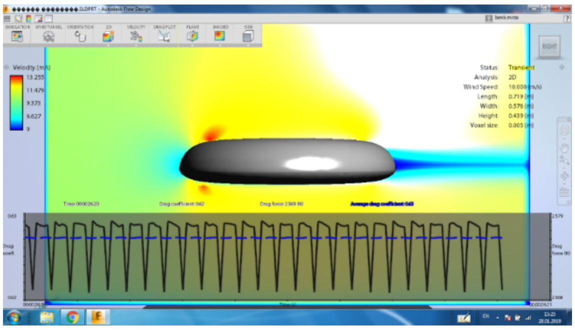
c)

Figure 2. Simulation of flow-around of floats with various shapes

As a result, the modeling has defined velocity field and pressure characteristics for each of the models. The obtained averaged values of resistance factor and the resulting resistance force are summarized in Table 1.

Table 1. Simulation Results

No.	Float Shape	Resist.force, H	Resist. factor
1	Sphere	15.752	0.44
2	Cylinder	10.859	2.44
3	With aeroprofile	2.577	0.628

Comparative analysis of the simulation results showed that the float shape with an aerodynamic section profile provides the least resistance forces with an acceptable resistance factor. The float of this form is characterized by the absence of cavitation (emptiness behind the model), there is also presence of lifting force observed due to the profile features. In this regard, according to the simulation results, a float of a shape similar to an ellipsoid of rotation with an aerodynamic section profile was selected. It should be noted that the resistance factor obtained by simulation allows, during preliminary calculations, to establish the volume of the float surface at a given power and speed of water particles movement.

2.3 Description of the WPS demonstration model

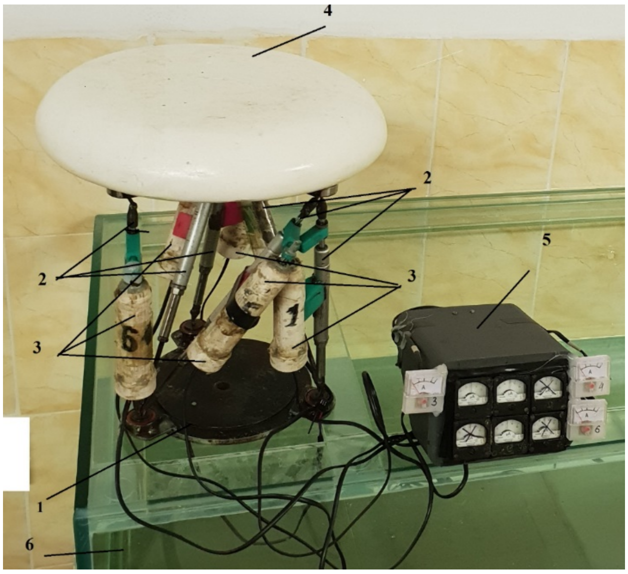

Figure 3. Demonstration sample of WPS

Functionality of the WPS using the technology of more efficient wave energy conversion, is confirmed by demonstration model WPS (Figure 3). Figure 3 shows: 1-bottom manipulator platform; 2-six actuators representing the connection "stem - cylinder"; 3-six linear electric current generators, rotors of which move along with the actuator stems; 4- float with aerodynamic profile; 5-unit amperemeter; 6 aquarium for testing. Under the wave action, the float is captured by moving water and actuators 2 (stem-cylinder connections) are brought into translational motion. When the stems movement moves the rotors of the linear generators 3 producing electric current measured by amperemeter 5. In order to verify the declared WPS capabilities, a demonstration sample of a wave power station in an aquarium and in a natural reservoir was tested. Tests have confirmed that the demonstration sample produces electric current under the action of moving water.

3. Designing of a submerged WPS dynamic model

The object of this work research is a new technical device, WPS that uses the technology of converting spatial movement of water mass into electrical energy. In this regard, the task is to create a mathematical apparatus for studying and selecting design parameters of the WPS. When designing WPS of a given power, first, the geometrical dimensions of the float are determined, and then the design parameters of the

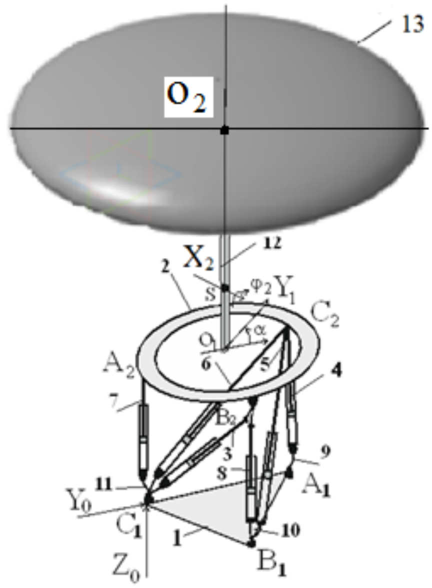

Figure 4. WPS design model.

manipulator converter are found and the actuators are selected. To solve the problem, a dynamic model of WB is formed. For this purpose, design diagram of the WPS presented in Figure 4 is used. It consists of the bottom 1 and upper 2 platforms of the manipulator connected by actuators 4-8 by means of flexible connections: 10- two links; 9 -three links; 11 - four links. Mast 12 rigidly connects the float 13 and the upper platform 2 of the manipulator,

3.1. Designing of a working tool dynamic model

It should be noted that the WB motion occurs in underwater environment, therefore it is required to consider a complex non-linear mathematical model that takes into account multiply-connected non-linear dependencies among various components of spatial motion with six degrees of freedom. On the other hand, it is known that the assessment of hydrodynamic effects on the part of the underwater environment is generally a very labor intensive task. At the same time, there is still no convenient mathematical model for the float of the new form. In this regard, designing of a dynamic model makes a number of assumptions aimed at creating an adequate simplified model of WB. Firstly, it is assumed that the WB float is captured by water mass particles and moves in a closed orbit. Secondly, it is assumed that the WB moves in the water particles orbit plane on long coastal waves. Thirdly, to take into account the hydrodynamic effects of the underwater environment, the force effect of water on the underwater vessel body is considered as analogues. Taking into account these assumptions, and that the float has an axis of symmetry, we believe that all distributed external force factors acting on the float can be reduced to the corresponding resultant forces and moments located in the plane of the water particles orbits in the direction of wave advance (wave ray) and passing through the axis of WB symmetry.

Based on these assumptions, it is assumed that the WB performs a two-dimensional motion with three degrees of freedom in the orbit plane passing the float vertical axis of symmetry.

For the designing of a WB dynamic model, two coordinate systems are used (Fig. 4). Fixed coordinate system $C_1X_0Y_0Z_0$ associated with a fixed manipulator platform, axis C_1Z_0 that is directed vertically up to the water surface (plane $C_1X_0Y_0$),and axis C_1Y_0 is located in the original direction of the wave ray. Movable system $O_1X_1Y_1Z_1$ begins in the center of the platform and axis, in the initial position parallel to the corresponding axes of the system $C_1X_0Y_0Z_0$. Mass center S of the working tool is located on the axis O_1Z_1 at the distance of $O_1S = L_S$. In case of two-dimensional movement, the WB moves with the plane $O_1Y_1Z_1$ and rotates around the axis SX_2 parallel to the axis O_1X_1. WB dynamic model designing takes into account the fact that this model is later used to create a WB model as a control object, the input for which is an external effect. In the theory of nonlinear systems control [25], dynamic model is formed using parameters of conditions, first derivatives of which are included in the equations of condition. These equations are useful for further linearization. In this regard, we make the equations of state, taking the vector of coordinates as the state parameters$\mathbf{X}_1$=[X_{11} X_{12} X_{13}]^T= [$y_S z_S \varphi_2$]^T and velocity vector $\mathbf{X}_2$ =[X_{21} X_{22} X_{23}]^T= $[\dot{y}_S \quad \dot{z}_S \quad \dot{\varphi}_2]^T$. Here (y_S, z_S) - coordinates of mass center. of WB in a fixed system,·φ_2 - angle of WB rotation around the axis SX_2 . The equations of state has the form of

$$\begin{aligned} \dot{\mathbf{X}}_1 &= \mathbf{X}_2, \\ \dot{\mathbf{X}}_2 &= \mathbf{M}^{-1}(\mathbf{F} - \mathbf{D}\mathbf{X}_2 - \mathbf{C}\mathbf{X}_1). \end{aligned} \quad (2)$$

Here $\mathbf{M}$ is (3x3) mass inertia characteristics matrix; $\mathbf{D}$, $\mathbf{C}$ are (3x3) matrices of, respectively, damping and stiffness. The external action vector is

$$\mathbf{F} = \mathbf{A} + \mathbf{G} + \mathbf{F}_W + \mathbf{F}_R. \quad (3)$$

Here are matrices (1x3) vectors: $\mathbf{A}$ - of Archimedes forces, G - of gravity, $\mathbf{F}_W$ - hydrodynamic forces from wave action and $\mathbf{F}_R$ - reaction forces.

The values included in equations (2 and 3) are discussed in more detail below.

It is well known that at low motion speed of air and liquid particle movement, laws of aerodynamics and hydrodynamics coincide. Therefore, to determine the float surface area S we will use functional connection [26] for power

$$S = \frac{2N}{\eta \cdot \rho \cdot v_W^3} \quad (4)$$

Where ρ is water density. The calculation is done with minimal water speed w with set power N of the WPS. Tentatively efficiency factor is considered to be η=0.5.

3.1.1. The matrix of WB mass inertial characteristics

The influence of the underwater environment on the WB mass inertial characteristic is taken into account using the matrix of the added masses Λ. When two-dimensional motion in the orbits water particles plane of the orbits with a plane $O_1Y_1Z_1$, provided that the float moves like water particles near the float, the kinetic energy of the fluid is determined by the expression [27]:

$$T_F = \frac{1}{2}\mathbf{X} \cdot \Lambda \cdot \dot{\mathbf{X}}, \quad (5)$$

where the matrix of added masses is

$$\Lambda = \begin{pmatrix} \lambda_{11} & 0 & 0 \\ 0 & \lambda_{22} & 0 \\ 0 & 0 & \lambda_{33} \end{pmatrix}. \quad (6)$$

Here it is taken into account that the axes of coordinates are the float axes of symmetry, and the kinetic energy of the liquid is invariant with respect to the coordinate system. The matrix of mass inertial characteristics is obtained by adding the matrix Λ mass and moment of inertia of the float relative to the axis SX_2 to the corresponding elements, i.e.

$$\mathbf{M} = \begin{pmatrix} m_B + \lambda_{11} & 0 & 0 \\ 0 & m_B + \lambda_{22} & 0 \\ 0 & 0 & J_{BS} + \lambda_{33} \end{pmatrix}, \quad (7)$$

where m_B is float weight in the initial state; $J_{BS} = J_{BX3}+m_B(L_{O3S})^2$ is axial moment of inertia of the float, where J_{BX3} is the moment of inertia of the ellipsoid relative to the axis of the float passing through the geometric center O_2 parallel to the axis O_SX_2(Fig.4); L_{O2S} *is* distance from the geometric center of the ellipsoid to the center of WB mass. We assume that the float has the correct shape of the ellipsoid of rotation, then the added masses of the float depend on the shape of the body in the water and can be determined by analytical dependencies based on the theory of potential flows. To obtain the added mass in three directions of motion, we analyzed the values obtained from the theory of Faltinsen bands [28], as well as Mansouri and Hadidi [29] according to the flat disk approach and the values obtained from hydrodynamic experiments [30] that almost coincide. In this connection, the added mass values for the triaxial ellipsoids of rotation obtained as a result of the experiment were used. If the triaxial ellipsoid of rotation along the axes has dimensions of O_2X_3 –c; O_2Y_3 - b; O_2Z_3 – a, and dimensions b and c are equal to ($b = c$), and dimension is $a=b/4$, *then from the tables coeffitients* K_{11}=0.15, K_{22}=2.5, K_{33} =1.9 can be found. Added masses are equal to $\lambda_{11}= K_{11}/\rho V$, $\lambda_{22}= K_{22}/\rho V$, $\lambda_{33}= K_{33}/\rho V$, where ρ is water density, V is float volume.

3.1.2. External forces

The vector equality (3) gives the forces of external and hydrodynamic effects on the float. The first two components: the force of Archimedes and the force of gravity, are determined by known methods, therefore the expression for these forces will not be given. The third component represents hydrodynamic force and moment caused by waves. Currently, there are no analytical methods for modeling wave dynamics convenient for practical use. In this regard, to determine the components of hydrodynamic forces and moments caused by waves, we use empirical formulas from the theory of ships [31]. However, some values used for ships will be simplified in relation to the float. Such values are the length and width of the float equal to the diameter L = D; the orientation angles of the float with respect to the incident wave, i.e. course, trim and roll angles are assumed to be zero due to the symmetry of the float profile. Before getting the expression for the forces and moment, it is needed to set values for some auxiliary variables. Constant variable depending on water density and gravitational acceleration $C=\rho gD$; wavelength dependent variable (λ) and float dimensions $k(\lambda,D)=-29.95(\lambda/D)^6 + 213(\lambda/D)^5+ +592.7(\lambda/D)^4+814.3(\lambda/D)^3 - 573.8(\lambda/D)^2 + 195.4(\lambda/D) -24.6$.

The value depending on the speed of the float center of mass

$f(v)= 0.12+0.25v -0.004v^2$.

The coefficients taking into account the float orientation in relation to the incident wave

$f_0=4.835e+2.609;\ f_1= 4.24;\ f_2=136.5$.

Taking into account the adopted coefficients, projections of hydrodynamic forces and moments in expression (3) are calculated by the following empirical formulas

$$F_{WY} = C \cdot k(\lambda, D) \cdot f_0 \cdot A^2 \cdot f(\dot{y}_{S1}) = F_{WY}(X_{21}, X_{21}^2),$$

$$F_{WZ} = C \cdot k(\lambda, D) \cdot f_1 \cdot A^2 \cdot f(\dot{z}_{S1}) = F_{WZ}(X_{22}, X_{22}^2), \quad (8)$$

$$M_{WX} = C \cdot k(\lambda, D) \cdot f_2 \cdot A^2 \cdot f(\omega_2) = M_{WX}(X_{23}, X_{23}^2)$$

Here A *is* wave amplitude; the right-hand sides of the equalities mean that the hydrodynamic forces and moments depend on the state parameters.

Dependencies (8) give fairly accurate results [32] provided that $\frac{2A}{\lambda} \le \frac{1}{15}$, i.e. for the case of long waves in the coastal zone, for which a dynamic model is made.

3.1.3. Rigidity matrix

Using expressions derived from the theory of bands in [33], a rigidity matrix is formed; it allows calculating the restoring hydrostatic forces due to the action of water

$$C = \begin{pmatrix} c_{11} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & c_{33} \end{pmatrix}, \quad (9)$$

where $c_{33} = \rho g A_s$, $c_{11} = \rho g A_s L_{O3S}$.

Here $A_s=\frac{\pi D^2}{4}$ is area of midsection; L_{O2S} is distance from the center of mass to the geometric center of the float. The float dimensions are determined reasoning from the relation (4) according to the set power.

3.1.4. Damping matrix

The damping matrix is used to account for the damping forces resulting from the dissipation of the float energy. These forces are divided into wave and viscous forces. In [32], the elements of the damping matrix were adopted; they are used to form a WB dynamic model in the form of

$$D=\begin{pmatrix} d_{11} & 0 & 0 \\ 0 & d_{22} & 0 \\ 0 & 0 & d_{33} \end{pmatrix}, \quad (10)$$

where the diagonal elements are determined by equalities $d_{11}=0.0005\omega_{11}M_{11}$; $d_{22}=0.0026\omega_{22}M_{22}$; $d_{33}=0.0027\omega_{33}M_{33}$. ω_{ii} $(i=1,2,3)$ indicates the natural oscillation frequency of the WB when moving along the axes SY_1, SZ_1 and rotation around the axis SX_1; $M_{ii}(i=1,2,3)$ *are* elements of the matrix of WB mass inertial characteristics (7). Let us assume that frequencies ω_{ii} $(i=1,2,3)$ tend to the frequency of free oscillations of water particles moving in a closed orbit and depend on the wave height and length. For example, at a wave height of 2m, the wave period will be equal to $T=6c$ [32], and circular frequency of free oscillations of wave water particles to $\omega=2\pi/T=1.046$ c^{-1}.

3.2. Analysis of working body dynamic model

The second matrix equality in expression (2) can be represented as a system of three differential equations. The inverse matrix of the mass inertial characteristic (7) is equal to

$$\mathbf{M}^{-1}=\begin{pmatrix} 1/(m_B+\lambda_{11}) & 0 & 0 \\ 0 & 1/(m_B+\lambda_{22}) & 0 \\ 0 & 0 & 1/(J_{BS}+\lambda_{33}) \end{pmatrix}. \quad (11)$$

Let us define the elements of external influence vector (3).

$$\mathbf{F}==\begin{pmatrix} F_Y \\ F_Z \\ M_X \end{pmatrix}=\begin{pmatrix} \rho gV\sin\varphi_2 \\ \rho gV\cos\varphi_2 \\ 0 \end{pmatrix}+\begin{pmatrix} m_B g\sin\varphi_2 \\ -m_B g\cos\varphi_2 \\ 0 \end{pmatrix}+$$

$$+\begin{pmatrix} F_{WY} \\ F_{WZ} \\ M_{WX} \end{pmatrix}+\begin{pmatrix} F_{RY} \\ F_{RZ} \\ M_{RX} \end{pmatrix} \quad (12).$$

Damping forces are equal to

$$\mathbf{DX}_2=\begin{pmatrix} d_{11}\dot{y}_S \\ d_{22}\dot{z}_S \\ d_{33}\omega_2 \end{pmatrix}. \quad (13)$$

The rigidity force is determined by the matrix

$$\mathbf{CX}_1=\begin{pmatrix} c_{11}y_S \\ c_{22}z_S \\ c_{33}\varphi_2 \end{pmatrix}. \quad (14)$$

Let us place the expressions from (11–14) into the second equality (2), we obtain a system of nonlinear equations.

$$\dot{X}_{21}(m_B+\lambda_{11})=\rho gV\sin X_{13}+m_B g\sin X_{13}+ \\ +F_{WY}(X_{21},X_{21}^2)+F_{RY}-d_{11}X_{21}-c_{11}X_{11},$$

$$\dot{X}_{22}(m_B+\lambda_{22})=\rho gV\cos X_{13}-m_B g\cos X_{13}+ \\ +F_{WZ}(X_{22},X_{22}^2)+F_{RZ}-d_{22}X_{22}-c_{22}X_{12},$$

$$\dot{X}_{23}(J_{BS}+\lambda_{33})=M_{WZ}(X_{23},X_{23}^2)+ \\ +M_{RZ}-d_{33}X_{23}-c_{22}X_{13}. \quad (15)$$

Let us consider the system state at the operating point (M) of the float trajectory when the float center of mass is stationary and occupies the most distant position from the bottom, and there are no hydrodynamic forces. In this state $X_{13}=0$. Let us assume that $\dot{\mathbf{X}}_{21}\simeq 0$, then from equations (15) we obtain the components of the WB reaction forces at the operating point

$$F_{RY}|_M=0, \\ F_{RZ}|_M=\rho gV-m_B g, \\ M_{RX}|_M=0. \quad (16)$$

The system of equations (15) is transformed into a form suitable for determining the reaction forces. We assume that the input variables are state parameters, and the output variables are reaction forces. Let us write the equations of dynamics for small deviations from the operating point. After conversion, taking into account (16), we obtain the system

$$\Delta F_{RY} = G_1(\mathbf{X}) = d_{11}X_{21} + c_{11}X_{11} + \Delta\dot{X}_{21}(m_B + \lambda_{11}) - \\ -\rho g V \cdot X_{13} + m_B g \cdot X_{13} - F_{WY}(X_{21}, X_{21}^2),$$

$$\Delta F_{RZ} = G_2(\mathbf{X}) = d_{22}X_{22} + c_{22}X_{12} + \Delta\dot{X}_{22}(m_B + \lambda_{22}) - \\ -F_{WZ}(X_{22}, X_{22}^2),$$

$$\Delta M_{RZ} = G_3(\mathbf{X}) = \Delta\dot{X}_{23}(J_{BS} + \lambda_{33}) + d_{33}X_{23} + c_{22}X_{13} - \\ -M_{WZ}(X_{23}, X_{23}^2). \qquad (17)$$

Here, in view of the small parameter values of X_{13} it is assumed that $\sin X_{13} \approx X_{13}, \cos X_{13} \approx 1$.

The orientation of the orbit plane of water particles movement, in which the WB moves, changes with the wave direction changes. In this regard, it should be noted that equations (17) describe the WB motion in a certain period of time characterized by a certain orientation of the orbital plane. The direction of the plane in which the WB movement occurs is determined by the angle α (Fig.4) between the axis O_1Y_1 of the moving coordinate system and fixed axis C_1Y_0. To solve the system of nonlinear equations (17), we use the method of tangential approximation [25], taking into account that near the operating point, a trajectory of center of mass represents a continuous curve. Then

$$(\Delta F_{RY} \quad \Delta F_{RZ} \quad \Delta M_{RX})^T = \mathbf{J}_{36}(G)|_M \cdot \\ \cdot \left(\Delta X_{11} \quad \Delta X_{12} \quad \Delta X_{13} \quad \Delta X_{21} \quad \Delta X_{22} \quad \Delta X_{23}\right)^T \qquad (18)$$

Where Jacobian at the working point (M) is

$$\mathbf{J}_{36}(G)|_M = \left.\begin{pmatrix} \frac{\partial G_1}{\partial X_{11}} & \cdots & \frac{\partial G_3}{\partial X_{11}} \\ . & . & . \\ . & . & \frac{\partial G_3}{\partial X_{13}} \\ \frac{\partial G_1}{\partial X_{21}} & . & . \\ . & . & . \\ \frac{\partial G_1}{\partial X_{23}} & & \frac{\partial G_3}{\partial X_{23}} \end{pmatrix}\right|_M$$

Once from dependencies (17) ΔF_{RY}, ΔF_{RZ}, ΔM_{RX}, corresponding to the input parameters are determined, the reaction forces of the WB (F_{RY}, F_{RZ}, M_{RX}) are equal to

$$F_{RY} = F_{RY}|_M + \Delta F_{RY}, \\ F_{RZ} = F_{RZ}|_M + \Delta F_{RZ}, \\ M_{RX} = M_{RX}|_M + \Delta M_{RX}, \qquad (19)$$

where $F_{RY}|_M$, $F_{RZ}|_M$, $M_{RX}|_M$ are the values of WB reaction forces components at the operating point. Equations (18, 19) allow making numeric calculations and determining projection of force and moment acting from the converter manipulator on WB according to output parameters (coordinates and speeds in each discretized point of the trajectory of the mass center). Mass center movement trajectory depends on the wave height and length (average annual values are taken at the place of WPS location), as well as on the depth of float location under the water (1).

3.3. 1. Kinematics of the WB

Designing a manipulator converter includes selection of the power of the actuators. Moreover, the initial forces for determining the forces on the actuator stems are the WB reaction forces found above (19). In order to determine the movement speed of the actuator rods, the WB kinematics is examined below. It is known that the WB at the time instant moves in a plane. The task is to determine the position of nodesA_2, B_2, C_2 of the top platform, if the WB position is given by coordinates (y_S, z_S) of the center S and rotation (φ_2) relative to the axis crossing S. To solve this problem, homogeneous transformation matrices are used in robotics [34]. As noted earlier: the reference system $C_1X_0Y_0Z_0$ is motionless; mobile system$O_1X_1Y_1Z_1$*is* associated with the WB presented in the form of a triangular prism SA_2,B_2,C_2. We define the matrix T of a composition of transformations that is obtained as a result of multiplying the transformation matrices for elementary rotations and shifts. Below is a sequence of elementary movements. In parentheses, there are the designations of matrices of elementary transformations:

1. Shift *(A_1)* along the axes of the motionless system up to coincidence of C_1 and O_1.

2. Turn*(A_2)* around the axis O_1Z_1 at the angle until the axis O_1Y_1 forms an angle α with axis C_1Y_0.
3. Shift*(A_3)* by valuey_S,
4. Shift *(A_4)*by valuez_s
5. Shift*(A_5)* by value L_S along the axis O_1Z_1.
6. Turn*(A_6)* around the axis O_1X_1 at an angle φ2.
7. Shift*(A_7)* by value -L_S along the axis O_1Z_1.
8. Turn*(A_8)* around the axis O_1Z_1 at an angle –α.

The matrix T of the composition of transformations is determined by the equality

$T=(A_1)\ (A_2)\ (A_3)\ (A_4)\ (A_5)\ (A_6)\ (A_7)\ (A_8)$,(20)

i.e.

$$T=\begin{pmatrix}1&0&0&x_{O1}\\0&1&0&y_{01}\\0&0&1&z_{O1}\\0&0&0&1\end{pmatrix}\cdot\begin{pmatrix}C\alpha&-S\alpha&0&0\\S\alpha&C\alpha&0&0\\0&0&1&0\\0&0&0&1\end{pmatrix}\cdot$$
$$\cdot\begin{pmatrix}1&0&0&0\\0&1&0&y_S\\0&0&1&0\\0&0&0&1\end{pmatrix}\cdot\begin{pmatrix}1&0&0&0\\0&1&0&0\\0&0&1&z_S\\0&0&0&1\end{pmatrix}\cdot$$
$$\cdot\begin{pmatrix}1&0&0&0\\0&1&0&0\\0&0&1&L_S\\0&0&0&1\end{pmatrix}\cdot\begin{pmatrix}1&0&0&0\\0&C\varphi_2&-S\varphi_2&0\\0&S\varphi_2&C\varphi_2&0\\0&0&0&1\end{pmatrix}\cdot$$
$$\cdot\begin{pmatrix}1&0&0&0\\0&1&0&0\\0&0&1&-L_S\\0&0&0&1\end{pmatrix}\cdot\begin{pmatrix}-C\alpha&S\alpha&0&0\\-S\alpha&-C\alpha&0&0\\0&0&1&0\\0&0&0&1\end{pmatrix}. \quad (21)$$

As a result of matrixes multiplication (21), a transformation matrix T is obtained with elements in the form of

$$t_{11}=S^2(\alpha)\cdot C(\varphi_2)-C^2(\alpha);\ t_{12}=C(\alpha)\cdot S(\alpha)+$$
$$+C(\alpha)\cdot S(\alpha)\cdot C(\varphi_2);\ t_{13}=S(\alpha)\cdot S(\varphi_2);\ t_{14}=x_{01}-$$
$$-y_S S(\alpha)-L_S S(\alpha)\cdot S(\varphi_2);\ t_{21}=-C(\alpha)\cdot S(\alpha)-$$
$$-C(\alpha)\cdot S(\alpha)\cdot C\ (\varphi_2);\ t_{22}=S^2(\alpha)-C^2(\alpha)\cdot C(\varphi_2);$$
$$t_{23}=-C(\alpha)\cdot S(\varphi_2);$$
$$t_{24}=y_{01}+y_S C(\alpha)+L_S C(\alpha)\cdot S(\varphi_2);$$
$$t_{31}=-S(\alpha)\cdot S(\varphi_2);$$
$$t_{32}=-C(\alpha)\cdot S(\varphi_2);\ t_{33}=C(\varphi_2);\ t_{34}=L_S+z_{01}+$$
$$+z_s-L_S C(\varphi_2);\ t_{41}=t_{42}=t_{43}=0;\ t_{44}=1. \quad (22)$$

The coordinates of any WB point can be defind in the fixed reference system by the following equality:

$$\boldsymbol{\rho}^{\mathbf{0}}=T\boldsymbol{\rho}^1, \quad (23)$$

where $\boldsymbol{\rho}$ is homogeneous column vector composed of coordinates in the system with the index shown at the top.

For example the coordinates of the manipulator upper platform nodal pointA_2 corresponding to the platform movement when the coordinates of the WB $[y_{S,}\ z_S\ \varphi_2]^T$ and angle α are determined by matrix equality

$$\begin{bmatrix}x_{A2}^0 & y_{A2}^0 & z_{A2}^0 & 1\end{bmatrix}^T=T\begin{bmatrix}x_{A2}^1 & y_{A2}^1 & z_{A2}^1 & 1\end{bmatrix}^T$$

.

Speed of the nodal points A_2,B_2,C_2 is determined differentiation by time of equality (23)

$$\dot{\boldsymbol{\rho}}^{\mathbf{0}}=\dot{T}\boldsymbol{\rho}^1\ . \quad (24)$$

Wherein

$$\dot{T}=\sum_{i=1}^{3}U_i\dot{q}_i=U_1\dot{y}_S+U_2\dot{z}_S+U_3\omega_2. \quad (25)$$

where

$$U_1=A_1A_2\frac{dA_3}{dy_S}A_4A_5A_6A_7A_8,$$
$$U_2=A_1A_2A_3\frac{dA_4}{dz_S}A_5A_6A_7A_8, \quad (26)$$
$$U_3=A_1A_2A_3A_4A_5\frac{dA_6}{d\omega_2}A_7A_8.$$

Speed, for example, of a nodal point A_2 is determined from (24) using equalities (25), (26)

$$\begin{bmatrix}\dot{x}_{A2}^0 & \dot{y}_{A2}^0 & \dot{z}_{A2}^0 & 0\end{bmatrix}^T=\dot{T}\begin{bmatrix}x_{A2}^1 & y_{A2}^1 & z_{A2}^1 & 1\end{bmatrix}^T.$$

Similarly, they can be defined in the fixed coordinate system of the any WB point velocity.

Change in the position of the manipulator upper platform causes a change in the position of the actuators and, therefore, the directions of the reaction force vectors acting on the upper platform change. In order to determine the position of the actuators, inverse problem of the manipulator kinematics is solved. This task consists in the fact that with a known position of the moving upper platform, coordinates of the nodal points (A_2, B_2, C_2) determine the orientation and length of the actuators [35].

Using the algorithm for solving the inverse problem for a manipulator, we calculated the position of the platform for given positions of the WB center of mass (Fig.5). Based on the dependencies obtained above, an algorithm has been formed and a program has been compiled in Matlab; the program allows determining positions of the upper platform relative to the lower one by WB changes. As an example, Figure 5 shows the graph: *a*) - spherical movement of the platform at a fixed point C_2;*b)* - spacial progressive movement when all actuators work with the same values; c) – movement of the platform with different movements in the actuators.

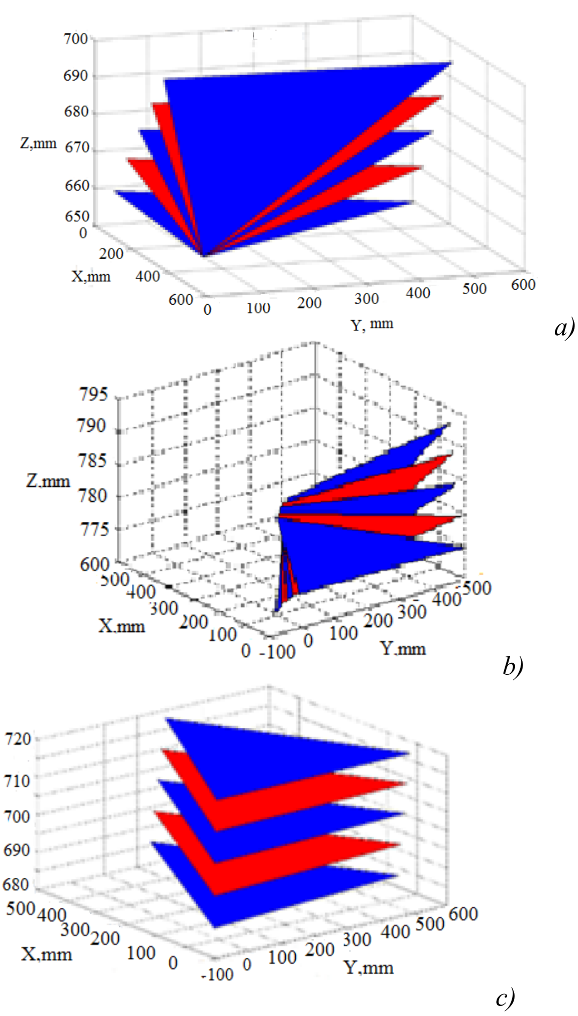

Figure 5. Platform Moves with WB

3.3. Force analysis of the WB

For the design of the WPS and selection of the actuators of a given power, as mentioned earlier, data are required on the forces in the manipulator actuators and the speeds of stems movement. Above (24-26), expressions are obtained for determining the speeds of nodal points. The necessary efforts on the actuator stems are determined as a result of the force analysis of the manipulator upper platform. The basically data are the main vector of the reaction force $\vec{R} = \vec{R}_{WZ} + \vec{R}_{WY}$ attached to the upper platform at the point O_1 and the vector of a pair of forces $\vec{M}_R$ obtained as a result of WB dynamic analysis (19). It should be noted that the force $\bar{R}$ is located (Fig.6) in the plane *Q*, and the moment vector of a couple of forces $\vec{M}_R$ is directed perpendicular to the plane *Q* coinciding with the moving plane $O_1Y_1Z_1$. destructive action of waves, therefore increasing its service life.

For the design and study of the WPS, dynamic model is created. A mathematical apparatus is designed that allows numeric determination and selection of design parameters of the WPS ensuring its effective functioning. The input data for calculations are: required power of the WPS, average annual wave parameters obtained during monitoring of the supposed place of WPS installation.

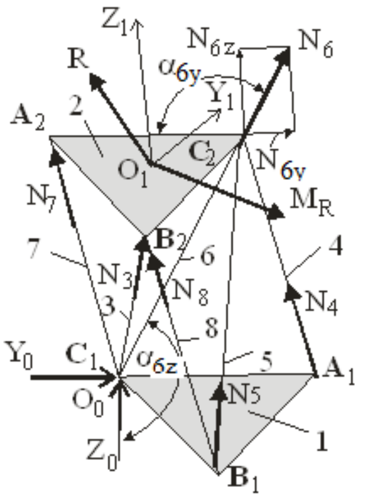

Figure 6. The pattern for force analysis of the manipulator

Thus, for a given direction of the wave ray, $\overline{R}$ and $\vec{M}_R$ are known. In fact, the required forces $\boldsymbol{N}_3$, $\boldsymbol{N}_4$, $\boldsymbol{N}_5$, $\boldsymbol{N}_6$, $\boldsymbol{N}_7$, $\boldsymbol{N}_8$ act on the platform 2 (Fig. 6) and they are directed along axes of actuator stems. As an example, Figure 6 shows angles α_{6y} and α_{6z} between actuator stem 6 and axles C_1Y_0 and C_1Z_0, respectively The directions of the lines of forces action for each actuator are determined by solving the inverse problem of kinematics for a parallel manipulator. In determining the reaction forces, it should be taken into account that the forces acting on the upper platforms are spatial. Therefore, three equations of forces and moments equilibrium written in the system of coordinates $C_1X_0Y_0Z_0$ should be added to the dynamics equations (18) as for the spacial system.

$$\sum_{i=3}^{i=8} N_{ix} = 0;\ \sum_{i=3}^{i=8} M_y(\mathbf{N}_i) = 0;\ \sum_{i=3}^{i=8} M_z(\mathbf{N}_i) = 0. \quad (27)$$

Reaction forces $\overline{R}$ and moment of reaction $\vec{M}_R$ are determined by equalities

$$\sum_{i=3}^{i=8} N_{iy} + R_y = 0;\ \sum_{i=3}^{i=8} N_{iz} + R_z = 0;\ \sum_{i=3}^{i=8} M_x(\mathbf{N}_i) + M_{Rx} = 0. (28)$$

Thus, in the six equations (27,28), the unknown variables are the desired values of the six reaction forces - N_i $(i=3,\ldots,8)$. By the forces acting on the actuator stems and their movement speed, the powers of the actuators are determined, from which the constructive dimensions of the stem-to-cylinder connection and the whole structure of the parallel manipulator are selected.

4. Conclusion

The article provides the rationale and selects the design of a new submerged float wave power station with a manipulator converter and a float with an aerodynamic section profile. With the help of a demonstration sample, it was shown that a new wave power station produces electric current under the action of water mass movement. New WPS has a range of advantages: first, technology for converting all special movements of the float into organized linear movements of the six actuators allows for a 6-fold increase in the productivity of the WPS; second, the float submerged position protects the WPS from the

The further work development is production of a prototype and performance of experimental research for improving the WPS design and methods of their computer analysis and synthesis.

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