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Original article

An Advanced Electric Power Generator for Offshore Autonomous Stations

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Abstract
Purpose. The research is purposed at substantiation of the design of floating marine stations with a wave energy generator. The proposed construction is of higher efficiency as compared to the known designs due to the application of roll oscillations and resonance operating mode.
Methods and Results. The resonance method of converting wave energy into electrical energy~~,~~ as well as the design of an autonomous station based on the resonance conversion of the station hull roll oscillations into the electrical energy are described. The method implies adjusting the frequency of natural angular oscillations of the floating station hull to the significant wave frequency. It has been theoretically proved that the conversion of roll oscillations energy is more effective than the conversion of vertical oscillations. This is due to the fact that the amount of damping during vertical vibrations of a cylindrical body in water exceeds the amount of damping during angular oscillations of such a body. Besides, the proposed method is shown to be effective for applications in the development of measurement systems and storage devices. The design of a floating station is proposed for implementing the resonance method for converting wave energy. It is shown that adjusting the frequency of natural onboard oscillations of the station hull to the significant wave frequency can be done using the additional filled tanks. The algorithm for adjusting the hull roll oscillations to the resonance with significant wave frequency is described. The kinematic scheme for a mechanical converter of roll energy into electrical one is proposed.
Conclusions. The results of theoretical studies were validated experimentally using the device test model in a wave experimental basin. They show that the hydrodynamic efficiency of the proposed wave converter increases as the wave heights decrease.

Keywords: energy, waves, conversion, mechanical, electrical energy, floating stations, roll oscillations

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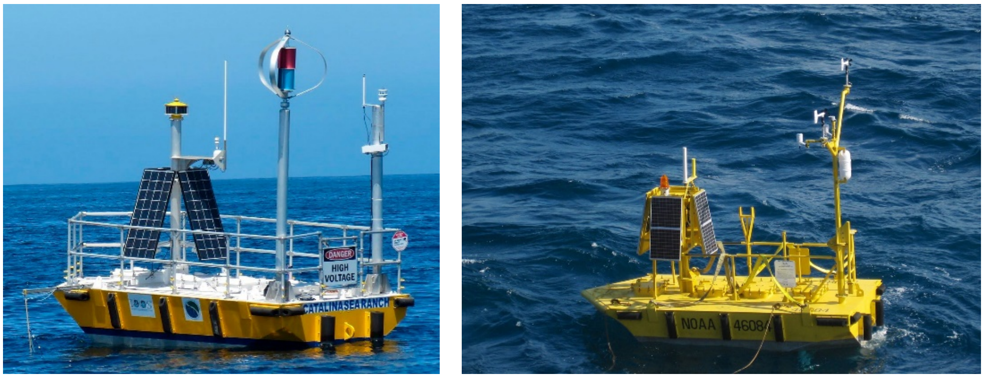
Introduction

As a result of rapid development of marine engineering, a category of offshore autonomous stations has appeared. They are used for collecting hydrophysical information on the shelves of the seas and the World Ocean for real-time oceanological studies and for charging the batteries of underwater unmanned autonomous vehicles (UAVs). These stations are floating vessel-like structures up to

10 m long, with the displacement up to 50 tons; they are equipped with hydrophysical [1], [2] [1, p. 151–152] or other target equipment as well as power sources, the capacity of which determines the endurance of their operation. These stations are developed and manufactured mainly in the US where these works as well as other defense projects are funded by DARPA and the Department of Energy. The stations are equipped with renewable energy sources such as solar panels and wind-powered generators to recharge the batteries and increase the endurance of equipment operation (Fig. 1).



a *b*

Fig. 1. Offshore floating stations for real-time ocean monitoring owned by the *Catalina Sea Ranch* Company (*a*) and the US Coast Guard (*b*)

It should be noted that in recent years UAVs have been actively developing for defense missions, sea bed mapping, underwater surveillance [3] [2] and geological exploration [4]. They support distributed monitoring of the hydrological parameters of aquatic environment [5]. UAV batteries are recharged at special offshore autonomous stations. The British company *AVS Global* holds the leadership in the development of such systems; the results of their research [3] were used for creating a number of surface vehicles and their functional systems. The Russian designers follow the same

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[1] Defense Visual Information Distribution Service, 2013. *Coast Guard, NOAA Return Weather Buoy to Service in Southeast Alaska.* [online] Available at: https://www.dvidshub.net/image/1000279/coast-guard-noaa-return-weather-buoy-service-southeast-alaska [Accessed: 21 April 2024].

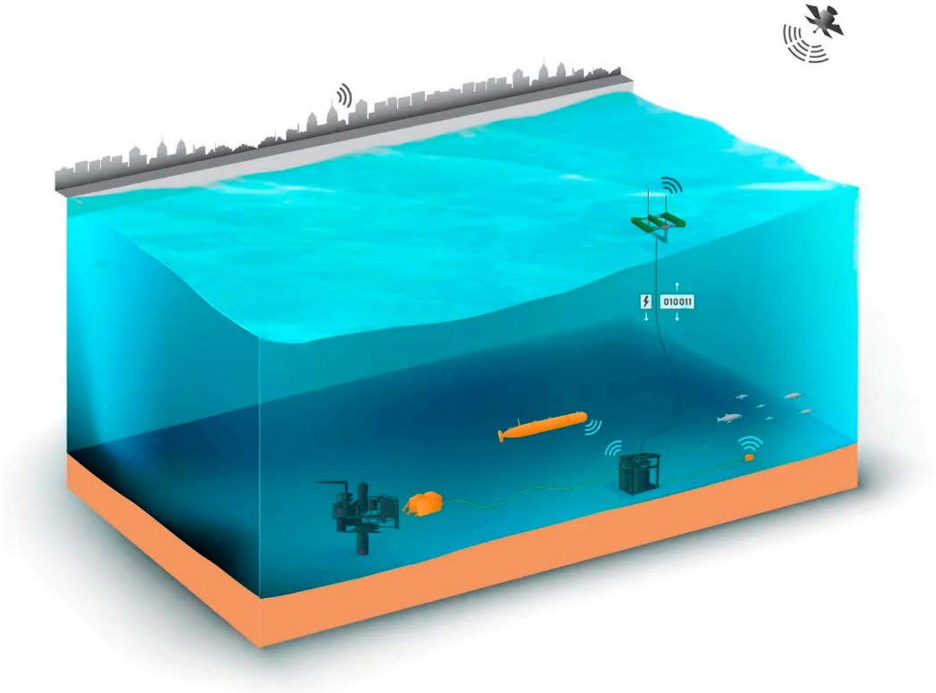
[2] AXYS Technologies Inc., 2024. *Ocean Sentinel NOMAD™ MetOcean Buoy*. [online] Available at: https://axys.com/ocean-sentinel-nomad-metocean-buoy [Accessed: 21 April 2024].

[3] NauticExpo.ru., 2024. *Hydrographic Survey Marine Drones*. [online] Available at: https://www.nauticexpo.ru/proizvoditel-sudno/morskoj-bespilotnik-gidrograficeskih-issledovanij-42947.html [Accessed: 21 April 2024].

[4] Korabel.ru., 2018. [*The Use of Underwater Gliders for Exploration*]. [online] Available at: https://www.korabel.ru/news/comments/primenenie_podvodnyh_glayderov_dlya_geologorazvedki.html [Accessed: 31 January 2024] (in Russian).

[5] Boyko, A., 2021. [*Catalog of Underwater Robots*]. [online] Available at: http://robotrends.ru/robopedia/katalog-podvodnyh-robotov [Accessed: 21 April 2024] (in Russian).

way [6], however, the use of wave energy as a renewable power source is no less efficient. Since the hull of the floating station is directly involved in the power generation process, it becomes a wave-activated power generator (WPG) also known as a wave absorber. Such a generator has been implemented in the *SeaRAY* system designed by *Columbia Power Technologies* [7] (Fig. 2, 3).



F i g. 2. UAV battery recharge station *SeaRAY* desined by the *Columbia Power Technologies* company

It is much more difficult to collect the wave energy in the open sea than in the coastal zone. The reason is that in the former case it is necessary to ensure high reliability of the WPG operation under a wide range of disturbing effects without any additional maintenance which requires proven engineering solutions to be applied. Their design should be simple and maintainable. There are well-known structures of a buoy with WPG employing the vertical oscillations of the buoy designed by *Ocean Power Technologies* [8], however, the efficiency of wave energy

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[6] Boyko, A., 2022. [*Catalog of Solar-Powered Surface Robots*]. [online] Available at: http://robotrends.ru/robopedia/katalog-nadvodnyh-robotov-na-solnechnyh-batareyah [Accessed: 31 January 2024] (in Russian).

[7] Garanovic, A., 2020. *SeaRAY Autonomous Offshore Power System Set for Sea Trials*. Available at: https://www.offshore-energy.biz/searay-autonomous-offshore-power-system-set-for-sea-trials [Accessed: 21 April 2024].

[8] Ocean Power Technologies, 2011. *Company Presentation*, 36 p. [online] Available at: https://oceanpowertechnologies.gcs-web.com/static-files/212d7a27-1fee-40cc-92e2-ca600045c8a0 [Accessed: 03 August 2024].

collection in these converters depends strongly on the amplitude and frequency response of their vertical oscillations.

It should be noted that the amplification factor of the response characteristics for the oscillations of floating objects is affected by damping forces considerably. Since the values of these forces are smaller during the roll oscillations than during the vertical ones, it is the rolling of marine stations that is advisable to use for collecting the wave energy. This feature is explained by the fact that during vertical oscillations of a floating object, the damping forces depend mainly on the intensity of waves propagating from the oscillating object and are proportional to the area of its waterline. All other components, such as vortex damping and skin friction damping which depend on the shape and roughness of the underwater part, are usually much smaller. When a vessel-like object without protruding parts is rolling the level of damping depends primarily on the vortex component while the wave and friction damping play a secondary role. Improving the WPG energy efficiency is obviously an urgent task. To ensure the maximum efficiency, a station with WPG should apparently work in the controlled resonance mode, i.e. adjust the frequency of its own oscillations to the frequency of sea waves.

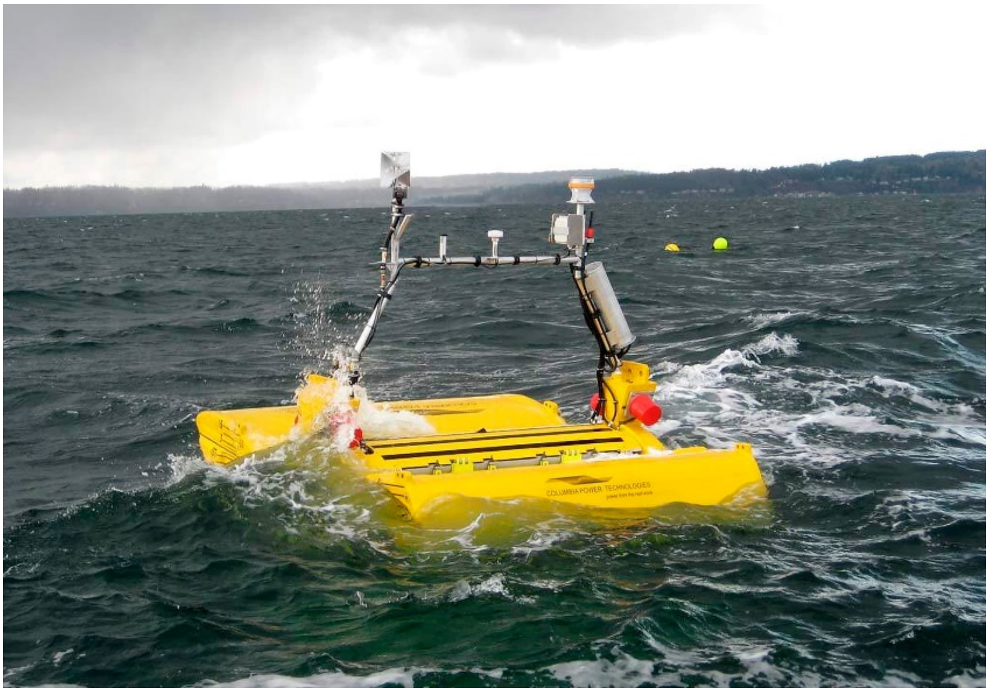

Fig. 3. Wave absorber within the *SeaRAY* system

The objective of the proposed research is to provide rationale for the design of a station with WPG operated in the open sea, the efficiency of which is higher than in the existing designs due to the use of roll oscillations and resonance operation mode.

Resonance-based method for wave energy conversion by floating stations

The wave energy can be converted into the electric power required for recharging the batteries of a floating station by converting the energy of oscillations of the station with WPG into electric power by means of onboard generators. Buoy oscillation on a wave is used for energy conversion by such WPGs as *SEAREV* [7] [4, 5] and *PeWEC* [6]. For example, *Searay* consists structurally of a block that includes several cylindrical floats installed parallel to each other and having separate rotation axes relative to the load frame (Fig. 3). A pendulum body is installed inside each cylindrical float. The rotation of the pendulum with the angular deflection of each float generates mechanical energy when the cylindrical body performs angular oscillations under the influence of waves. The highest operating efficiency of such converters is achieved when they operate in a controlled resonance mode. That is why it is necessary to control the system for converting mechanical energy into electrical energy [7]. Research into operation of onboard resonance-based converters of buoy oscillation energy into electric power has led to the registration of patents [9, 10].

To create a station with WPG which uses controlled resonance is a challenging task since the frequency of the spectral maximum of wave elevations depends significantly on the wave intensity. Moreover, depending on the time of wind activity, the waves can be developing, fully-developed or decaying. The developing waves are typically shorter, i.e., having a smaller period, while the decaying waves are longer, with a larger period. In addition, waves of small intensity may have a bimodal spectrum. Considering these specific features, the characteristics of the station with WPG should be restructured for operating in resonance mode with the waves having different average periods.

One of the examples of such systems is *AquaHarmonics* [8] comprising an anchored floating buoy, power generator of which is installed in the anchor. The rotor of the electric machine is connected to the buoy via the anchor rope and has a spring mechanism. The buoy performs orbital oscillations on the front and back slopes of the waves and the rope is slack enough to separate the buoy and the anchor. Horizontal components of these oscillations are used for power generation. When the buoy approaches the anchor the rope slack is compensated by winding it onto a pulley by means of the spring mechanism and when the buoy moves in the opposite direction the pulley spins the rotor of the electric machine. The eigen frequency of the system of the generator, rope and buoy is controlled by damping the multidirectional rotation of the rotor. This system can operate only in shallow water and is not designed for oceanographic instruments installation. There

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[9] Gryazin, D.G. and Velichko, O.O., 2016. *Installation for Recovery of Energy of Sea Buoys*. Russian Federation Patent No. RU2577924C1. Concern “SCRI “Elektropribor”, JSC (in Russian).

[10] Gryazin, D.G. and Epifanov, O.K., 2018. *Installation for Battery Energy Replenishment of Small Marine Autonomous Equipment and Buoys*. Russian Federation Patent No. RU2658713C1. Concern “SCRI “Elektropribor”, JSC (in Russian).

are also other known designs of buoys with WPG working in the controlled resonance mode and collecting the energy of the buoy vertical oscillations [11].

The maximum use of the wave front energy for converting it into the energy of oscillations should be made by combining the period of the station free roll oscillations with the dominant period of the waves. The reason is that the damping forces determined by the resistance coefficients are much smaller during the angular oscillations of floating bodies than those during their vertical oscillations. The resistance coefficients are not constant; they are velocity functions and have a nonlinear dependence. They are determined experimentally for the weight and size of the floating bodies. For example, the expression for the resistance coefficient in the case of its linear approximation for the vertical oscillations of a floating body can be found from formula [12]

$$W_{\mathrm{vert}} = \frac{4}{3\pi} \rho C_Q S r \omega_V , \tag{1}$$

where ρ is density of water, C_Q is quadratic coefficient of resistance determined experimentally; r is wave amplitude, S is area of the waterline and ω_V is frequency of its vertical oscillations. This expression is convenient for practical calculation of the resistance coefficient (function) which evidently depends on the variables $r\omega$, i.e., on the velocity.

resistance coefficient can be obtained for the angular oscillations of a floating body according to the method proposed in [13] from expression

$$W_{\mathrm{ang}} = 0.85 \omega_F r_A K_W , \tag{2}$$

where ω_F is frequency of free angular oscillations of the floating body, r_A is amplitude of angular oscillations, $K_W = C_W \left(J_{\mathrm{AIR}} - J_{\mathrm{ADD}} \right)$, C_W is quadratic coefficient of resistance depending on the velocity, J_{AIR} is body moment of inertia in the air, and J_{ADD} is added mass moment of inertia of water.

The analysis of expressions (1) and (2) shows that in the case of vertical oscillations of a floating body, the resistance coefficient depends on the area of the floating body waterline while in the case of angular oscillations it depends only on its moment of inertia and added mass moment of inertia of water. Thus, we observe less resistance during roll oscillations than during vertical ones. This is most clearly manifested on spherical or cylindrical floating objects which have the lowest resistance to roll oscillations.

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[11] Korobkov, V.A., 1986. *Ocean Energy Conversion*. Leningrad: Shipbuilding, 280 p. (in Russian).

[12] Berto, G.O., 1979. *Oceanographic Buoys*. Leningrad: Shipbuilding, 215 p. (in Russian).

[13] Blagoveshchenskiy, S.N. and Kholodilin, A.N., 1976. [*Reference Book on Statics and Dynamic Behaviour of Ships. V. 2. Dynamics (Rolling) of the Ship*]. Leningrad: Shipbuilding, 176 p. (in Russian).

To adjust the rolling mode of the station with WPG to the resonance mode in which the amplitudes of its rolling oscillations will be maximal, the eigen frequency of rolling should correspond to the frequency of the maximum spectral density of incident waves. At the same time, variation in the eigen frequency of rolling ω_R of the station with WPG is achieved by varying correspondingly transverse metacentric height *h*, i.e., its stability margin in accordance with known formula [14]

$$T = 2\pi\sqrt{\frac{I}{Dh}}, \tag{3}$$

where *T* is period of free oscillations of the station during rolling; *I* is moment of inertia of the station mass (relative to the longitudinal axis passing through the center of gravity) calculated with the added mass moment of inertia taken into account; *D* is station draught; *h* is transverse metacentric height, i.e. the transverse metacenter elevation above the center of gravity.

It is known that in the absence of developed stern or bow superstructures, a free-drifting vessel turns into a position when its side is almost parallel to the wave and experiences mainly vertical and roll oscillations. This makes it possible to use the rolling conversion and in this case the cylindrical shape of the WPG hull will be most efficient to practically remove the wave and vortex components of damping and to ensure the minimum resistance to roll oscillations, thus reaching the significant amplitudes at resonance that are much greater than the amplitude of the wave slope angle. As a result, the employment of roll energy is expected to considerably increase the efficiency of wave energy harvesting even when the station with WPG has a small draught. In practical implementation, certainly, it is necessary to take relevant design measures against the deck flooding and the WPG overturn during resonance rolling on storm waves.

To convert the roll energy into electric power, it is advisable to use the mechanical energy storage units that would ensure the rotation of the generator rotor of the electric machine at a uniform angular rate similarly to the solution described in [15]. At the same time, the rotation of the electric machine rotor should be unidirectional rather than alternating, during which significant reactive power is generated [9]. It is this sequence of technological solutions that should be implemented in the design of a station with WPG.

It should be mentioned that the maximum use of the roll energy is achieved by combining the period of free oscillations of the generator moving proof mass with the WPG rolling period (Fig. 4). In this case, as soon as the resonance is achieved, the pendulum will decline from the vertical in the opposite direction, i.e., with

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[14] Nogid, L.M., 1967. [*Design of Marine Vessels. Part 2. Vessel Stability and Behavior in Rough Seas*]. Leningrad: Shipbuilding, 72 p. (in Russian).

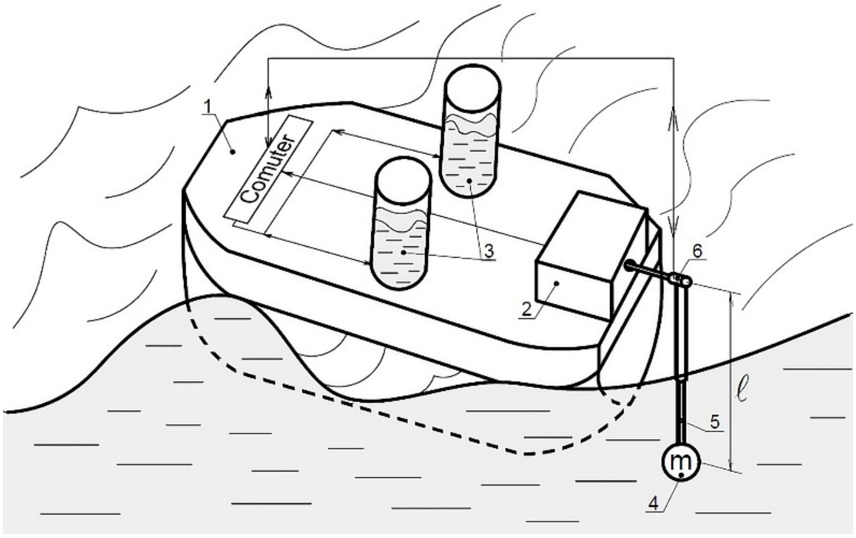
[15] Temeev, A.A., 1995. *Float Wave Power Station*. Russian Federation Patent No. RU2037642C1. (in Russian).

a phase shift by 90° relative to the roll oscillations. Among the advantages of the proposed method is the fact that such a generator will collect the wave energy in a wide range of wave periods.

Design of advanced floating station

A station with WPG (Fig. 4) consists of hull *1* with positive buoyancy, energy conversion mechanism *2*, ballast tanks *3*, pendulum with moving proof mass *4* and computer. The station hull should be close to cylindrical shape because it has the least resistance to roll oscillations. The pendulum can change the length of suspension by varying length *l* of extendable rod *5* by means of extendable rod drive *6*. Ballast tanks *3* should be equipped with level gauges and the water should be supplied into and discharged from the tanks using a pump and drain valves which are not shown in Fig. 4.

The energy conversion mechanism (Fig. 5) consists of two parts: a roll energy converter (REC) and an accumulator — mechanical energy converter (AMEC). The computer (Fig. 4) comprises a microprocessor unit generating control commands, a memory with a recorded control algorithm, analog-to-digital and digital-to-analog converters as well as amplifiers of analog signals for controlling the pump and the valves of the ballast tanks as well as extendable rod drive *17* (Fig. 5). The computer processes the measurement data received from sensor *3* of input shaft *1* twist angle (Fig. 5), the level gauge of ballast tanks *3* (Fig. 4) and multi-turn angle sensor *24* (Fig. 5).



F i g. 4. Design of the station hull with WPG: *1* – floating hull; *2* – energy conversion mechanism; *3* – ballast tanks; *4* – pendulum moving proof mass; *5* – extendable rod; *6* – extendable rod drive

The station with WPG operates as follows. Floating hull *1* of the station (Fig. 4) performs wave-induced roll oscillations relative to the position of pendulum *4* which is close to vertical. The pendulum is damped by water and has mass *m* commensurate with the buoy draught. In order to use the wave front energy to the maximum extent in terms of its conversion into the kinetic energy of rolling by combining the period of free roll oscillations of the floating buoy with the prevailing period of waves, the period of free roll oscillations of the station floating buoy is changed using expression (3) by changing the metacentric height of the buoy. It is changed by filling or draining ballast tanks *3* (Fig. 4). The amplitude and period of roll oscillations are measured by sensor *3* twist angle (Fig. 5) and the computer (Fig. 4) calculates forced oscillations of the station hull.

The algorithm for tuning the hull roll oscillations in resonance with the prevailing frequency of the waves after arbitrary filling of the ballast tanks includes:

1) record of oscillations over the 900 s interval during which the rolling process is considered stationary;

2) determining maximum range of oscillations Θ_{max};

3) determining the region of secondary oscillations Θ_H making 20% of the maximum range;

4) determining the ranges of oscillations caused by prevailing waves $\Theta_{Pi} > \Theta_H$, their number N and average value $\overline{\theta}_P = \frac{\sum_{N}^{i=1} \theta_{Pi}}{N}$;

5) calculation of the period of prevailing waves $T_{Pi} = 900/2N$;

6) filling the ballast tanks to 10% of the volume;

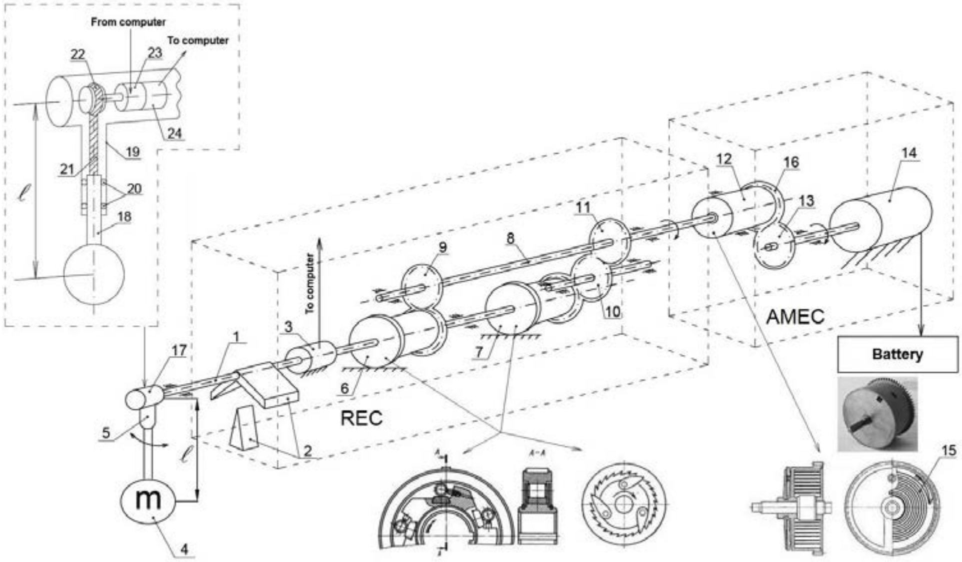
7) repeating the sequence of operations 1 to 5;

8) analysis of values $\overline{\theta}_\Pi$ obtained before and after filling the ballast tanks;

9) if value $\overline{\theta}_P$ obtained after filling is larger than the value before filling the ballast tanks, the latter should be filled according to point 6, and if it is less, it is necessary to start reducing the water level in the tanks by 20% for the first time and then by 10%;

10) as soon as next obtained value $\overline{\theta}_P$ is less than the previous one, it is necessary to restore the water level in the ballast tanks as it was with the previous value.

The ballast tanks are adjusted in accordance with the algorithm depending on whether the waves are decaying, developing or stationary. This adjustment is done programmatically, in the time intervals from 1 to 12 hours. All values of oscillations are calculated by the algorithm in the computer (Fig. 4).



F i g. 5. Mechanism for converting roll energy into electric power: *1* – input shaft; *2* – twist stop; *3* – angle sensor; *4* – pendulum; *5* – extendable rod; *6* and *7* – unidirectional rotation freewheel couplings, e.g., ratchet or freewheel clutches, with tooth rims; *8* – output shaft; *9*, *10* and *11* – gear wheels; *12* – spring drum; *13* – gear wheel of electric machine; *14* – electric machine; *15* – flat spiral spring; *16* – tooth rim; *17* – extendable rod mechanism; *18* – extendable rod; *19* – drive housing pipe; *20* – extendable rod bearings; *21* – rope; *22* – pulley; *23* – motor with gearbox; *24* – multi-turn angle sensor

The period of oscillations of the pendulum installed in the lower part of the station with WPG and water-damped will be less than Schuler period equal to 84.4 minutes, therefore, it will be perturbed by the oscillations during rolling; in addition, its perturbation will also depend on the orbital displacement of the buoy hull oscillating on the waves. Thus, the pendulum will perform some forced oscillations relative to the vertical position with a frequency of this perturbing force. To convert the kinetic energy of roll oscillations into electric power efficiently, the period of free oscillations of the moving proof mass is matched with the period of the buoy rolling. To do so, length l of pendulum 4 is selected and set using the extendable rod 5 (Fig. 5). The resonance frequency of the pendulum oscillations is determined from expression [16]

$$\omega_P = \sqrt{\omega_0^2 - 2K_D^2},$$

where $\omega_0^2 = \dfrac{mgl}{J}$ is eigen frequency of the pendulum oscillations; $K_D = \dfrac{Wl_I}{J}$ is damping coefficient. Here, m is mass of the pendulum; l is length of its suspension;

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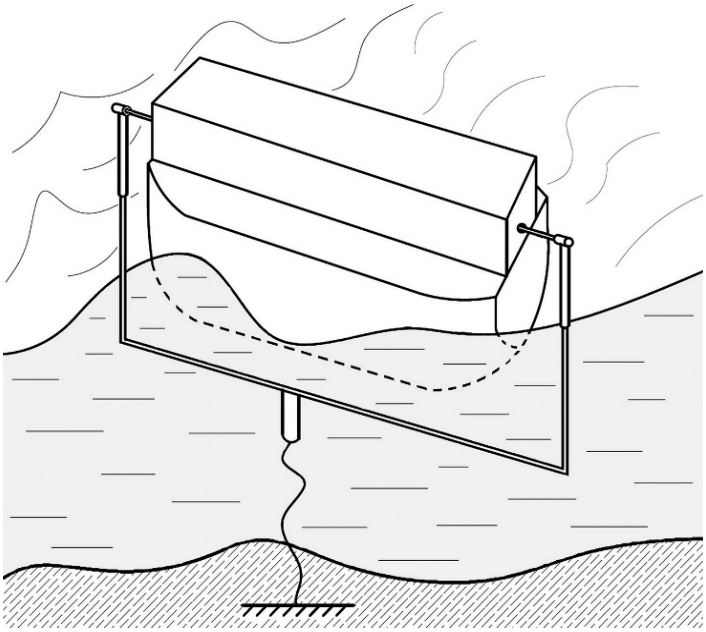
[16] Kuchling, H., 1985. *Paperback of Physics*. Moscow: Mir, 520 p. (in Russian).

J is moment of inertia of the system; l_I is arm of the integral force of resistance including the resistance of both moving proof mass and its suspension rod; W is quadratic coefficient of resistance to the motion of pendulum and its suspension in water depending on the pendulum motion velocity and the cross-section of the pendulum and suspension rod determined experimentally. The period of oscillations is found by known formula $T_P = \frac{2\pi}{\omega_P}$. Length l is calculated in the computer (Fig. 4).



F i g. 6. Design of a station with WPG for installation at an anchor

It should be noted that due to the changed phase of oscillations in the resonance region when the periods of the station hull rolling are close to the periods of its free oscillations the pendulum will decline at a small angle to the side opposite the angle of the buoy hull inclination and twist shaft *1* of the energy converter (Fig. 5) at an additional angle. In order to prevent the hull overturn in the case of stability loss caused by the resonance phenomena, this input shaft of the energy converter is equipped with twist stop *2* (Fig. 5) which will limit the angle of twist and prevent the buoy overturn. The design of the mechanism has been patented [17].

The energy conversion mechanism (Fig. 5) works as follows. During rolling, the station hull turns relative to the vertical position of pendulum *4* with extendable

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[17] Gryazin, D.G., Mashoshin, A.I. and Pashkevich, I.V., 2022. *Mobile Distributed Underwater Surveillance System*. Russian Federation Patent No. RU2767384C1 (in Russian).

rod *5*, and input shaft *1* twists at the same time. The shaft twist is converted into the output signal of angle sensor *3* which is transmitted to the computer.

When the station hull turns counter-clockwise relative to moving proof mass *4* with rod *5*, the moment is transferred from shaft *1* by unidirectional rotation freewheel coupling *6* which can be of various designs such as ratchet or freewheel clutch as described in Fig. 5 (coupling hereinafter) and when the hull turns clockwise, this is done by coupling *7*. Coupling *6* converts the twist of shaft *1* into the counter-clockwise turn of the coupled gear wheel while coupling *7* does the same in clockwise direction; these couplings are connected opposite each other. Owing to gear wheel *9*, intermediate shaft *8* turns clockwise. Owing to the pair of gear wheels *10* and *11*, the coupled gear wheel of coupling *7* also turns shaft *8* clockwise. The gear ratio of the gear wheels connected to couplings *6* and *7* is increasing and equal in relation to shaft *8*. Thus, the REC converts the alternating turn of the station hull relative to the pendulum into the clockwise turn of shaft *8*. Rotation of shaft *8* involves the flat spiral spring of the AMEC located in drum *12*. The torque of the spring is less than the moment of restoring forces during the station hull rolling which maintains its stability. Tooth rim *16* of drum *12* turns wheel *13* when the flat spiral spring is untwisting. Wheel *13* transfers the torque to the rotor of electric machine *14* functioning as a DC generator. The spiral spring has a normal characteristic and almost constant torque when untwisting which ensures small variation in the number of the electric machine rotor revolutions [18]. The current is supplied from generator *14* to recharge the battery. To set the mechanical part of the generator in resonance with the frequency of the station hull free oscillations, pendulum suspension length l is changed by extending rod *18* with load *4* from pipe *19*. Rod *18* is put into a required position by moving it vertically, for which purpose the rope fixed in the upper part of the rod and winded on pulley *22* is driven by motor *23*. To bring the rod into a specified position, multi-turn angle sensor *24* connected to the computer is calibrated in accordance with the turn of pulley *22* and the length of rope *22* wound on it. The pendulum length is changed on command from the computer in accordance with the functional dependence of the pendulum length on the eigen frequency of the station hull rolling. This dependence is determined experimentally, based on the recorded free oscillations of the station with the tanks filled to different levels and with the pendulums of different lengths against the criterion of the largest range of free oscillations achieved by the station hull. The functional dependence mentioned above is determined experimentally at tranquil sea in the absence of external perturbing forces.

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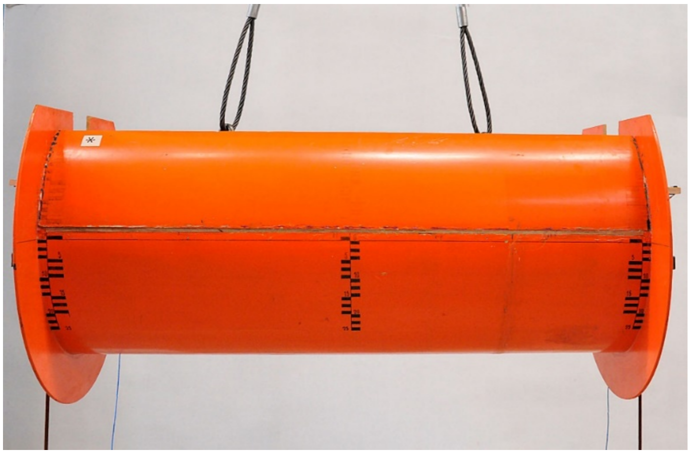
[18] Ponomarev, S.D. and Andreeva, L.E., 1980. [*Design of Elastic Elements in Machines and Devices*]. Moscow: Mechanical Engineering, pp. 64-66 (in Russian).



F i g. 7. Model tested in a wave experimental basin

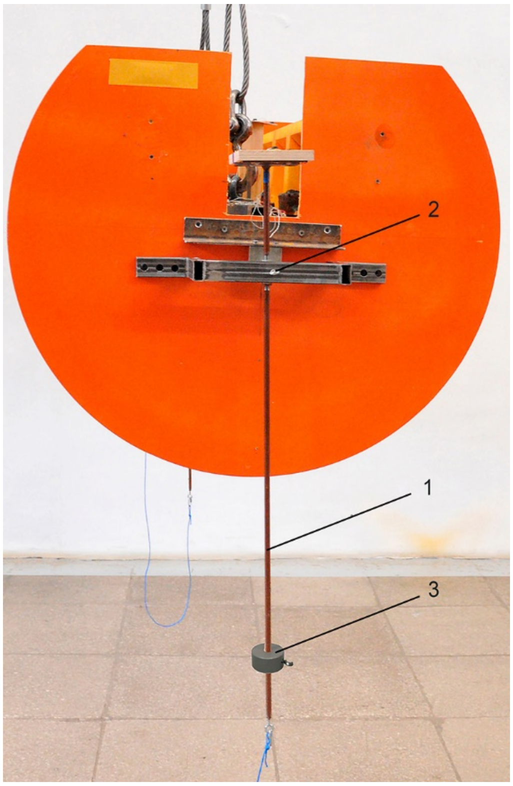
It should be noted that the achievements of modern mechanics make it possible to design the energy conversion mechanism based on other elements; however, their purpose will be the same.

In the case of an anchored station with WPG, a structure shown in Fig. 6 can be used. In this structure, it is proposed to install two energy converters (Fig. 5), connect the extendable rods to each other with an additional horizontal rod and connect an anchor system in the center of the latter. In this case, the position of rod *5* (Fig. 5) will be controlled by the anchor and may be different from vertical; nevertheless, this will not affect the power generated by electric machine *14*. Due to this structure, the station with WPG will be able to turn its side towards the direction of the waves.

Validation of the proposed method

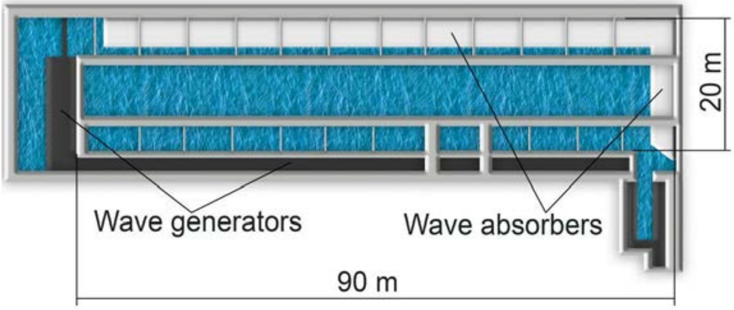
The proposed method was validated by the experimental study of a schematized model of a station with WPG (Fig. 7) in the wave basin at Krylov State Research Center.

The cylindrical model was 1650 mm long, its hull diameter was 640 mm and the mass was 172 kg. The sides of the model were made high in order to keep the waterline area unchanged at large inclination angles. Two pendular systems (Fig. 8) were installed using ball bearings on both side plates of the model hull, at the level of the model center of gravity. The pendular systems comprised rods *1* with a length of 0.9 m fixed on rotation shafts *2* on the axis of the center of mass on the side faces of the model; the position of the axis of the center of mass was identified during the model preparation. The pendular systems were made in the form of rods; there was load *3* on each suspension which could be moved along the rod, thus changing the length of the pendulum. The loads were fixed on the rod using a screw stop.



F i g. 8. One of two pendular systems fixed on the model sides: 1 – rod; 2 – rod rotation shaft fixed on the axis of the model center of mass; 3 – load with a screw stop moving along the rod

The model was tested in a wave basin (Fig. 9) 90 m long, 20 m wide and 4 m deep. The waves were formed by wave generator located at the end of the tank; it could generate regular (harmonic) waves with a length ranging from 0.6 to 12 m and a height from 20 to 240 mm or waves within a specified frequency band.



F i g. 9. Scheme of the wave experimental basin in Krylov State Research Center

Angular positions of the model and rods of the pendular system were captured by an optical tracker *Optotrak Certus HD* [19]; side inclinations of the model hull and rods were measured independently. To do this, triangular frames with three LEDs were installed on the model and on the platforms attached to the rods for the optical system to measure roll angles relative to the horizontal plane. Wave elevations were recorded by an electrolytic wave-recorder. In the course of the experiment, the measured processes were registered with a sampling interval of 0.01 s.

During the experiment, the model was positioned across the basin to model the position when the side faces the incident waves. The model heading was maintained by means of a retention system (Fig. 10) of two thin nylon ropes with elastic elements, one end of which was fixed to the model side at the height of its center of gravity and the other end — to basin structures. The rigidity of the elastic elements in the model retention system was to meet the requirement for the period of free sway oscillations of the retained model to differ enough from both the period of free roll oscillations and the average period of incident waves. This approach minimized the influence of the retention system on the model rolling.

Before the experimental study, the period of the model free roll oscillations and the moment of inertia with the added mass moment of inertia were identified, which were 1.89 s and 10.7 kg·m^2, respectively. Regular waves and bands of irregular waves were selected in accordance with the identified period.

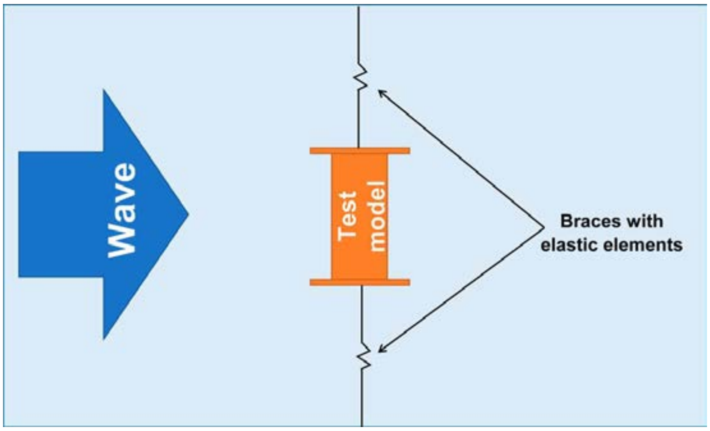


Fig. 10. Scheme of the system for model retention at the wave selection point in the experimental basin

The regular waves were selected before installing the vessel model in the wave basin; they had a period of 1.89 s, a height of 60 mm and a wave slope angle of 1.9°. Under these wave conditions, the angle of the model rolling was about 35°. Fig. 11

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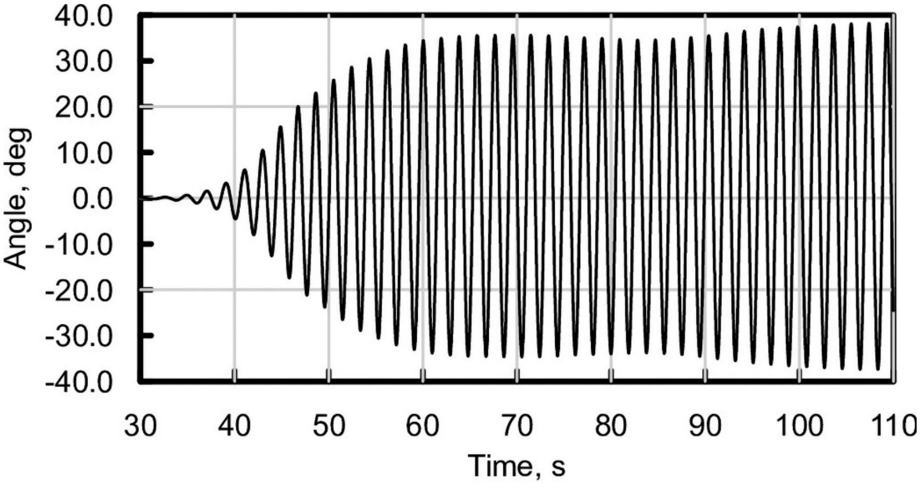
[19] NDI, 2022. *Legacy Products: NDI's 40-Year History and Transition*. [online] Available at: https://www.ndigital.com/products/legacy-products [Accessed: 21 April 2024].

shows a fragment of the video of the model rolling and Fig. 12 presents the realization of roll oscillations measured by the optical system.

F i g. 11. Model during wave tests in the experimental wave basin



F i g. 12. Fragment of recorded realization of model rolling oscillations on regular waves of 0.06 m high with the period 1.89 s in real time

The record of the model roll in Fig. 12 shows the growing resonance effect which consists in increasing amplitude of oscillations when the wave frequencies coincide with the frequency of the model free oscillations. In this case, the model had performed about 15 oscillations before the amplitude became more than 30°. The maximum amplitude of the model steady-state oscillations was 38° while the wave slope angle was just 1.9° which is 20 times less. Obviously, when the wave height changes, its period remains the same, i.e., when the wave steepness changes, the maximum amplitude of rolling and the time of achieving significant amplitudes of oscillations will change as well. The greater wave steepness is, the larger rolling amplitude is and the faster significant amplitudes are achieved. This is due to the fact that energy of wave E_W depends on its amplitude [20]:

$$E_W = \frac{1}{2}\rho g a^2 ,$$

where ρ is density of water; g is gravity acceleration; and a is wave amplitude.

At the next stage of the experimental study, the angular oscillations of the pendular system were measured. For this purpose, a load and its position on the rod were selected so that the difference of phases was 135°. Based on the obtained results, the hydrodynamic efficiency of this object was calculated. The hydrodynamic efficiency is the percentage ratio of the power of model angular oscillations to the power of wave [10]. According to [21], average power N_w of a regular wave crest per the crest length corresponding to the length of the object under study (the model) can be calculated by the formula:

$$N_w = \frac{\rho g^2 h^2 \tau l}{32\pi},$$

where h is wave height; τ is wave period; and l is wave crest length equal to the length of the model.

For the wave generated in the wave basin and experimentally selected to have parameters $h = 0.06$ m, $\tau = 1.89$ s, $l = 1.65$ m, the average corrected power over one period per one meter of the wave crest length was 6.26 W/m.

The power of model angular oscillations N_m can be found from the kinetic energy of angular motion, acquired by the model during angular oscillations. The power of angular motion is equal to amount of work performed by the model over a time unit $\frac{J}{s} = W$:

$$N_m = \frac{A_m}{\Delta t} , \tag{5}$$

where A_m is work performed by the model, and Δt is sampling rate.

Work A_m (J) performed by the model over time unit Δt is equal to the variation in the model kinetic energy over this time unit Δt:

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[20] Lugovskii, V.V., 1976. *Sea Dynamics*. Leningrad: Shipbuilding, 200 p. (in Russian).

[21] Kochin, N.E., Kibel, I.A. and Roze, N.V., 1964. *Theoretical Hydromechanics.* New York – London – Sydney: Interscience Publishers, 577 p.

$$A_m = \frac{\Delta E_{km}}{\Delta t},$$

where E_{km} is kinetic energy of the model angular motion, its J is equal to

$$E_{km} = \frac{1}{2}(J + \Delta J)\dot{\theta}^2,$$

where J is moment of inertia of the model; ΔJ is added mass moment of inertia, $\dot{\theta}$ is angular velocity of the model roll oscillations.

Then, knowing the kinetic energy of the model at each time point, we find power of the model angular oscillations N_m (W):

$$N_m = \frac{\Delta E_{km}}{\Delta t}.$$

The power of angular oscillations can be found from the torque generated by the model angular oscillations, which is equal to the product of the moment of inertia and the added mass moment of inertia by the angular acceleration:

$$M = (J + \Delta J)\ddot{\theta},$$

where M is moment, $\frac{kg \cdot m}{s^2} m = Nm$; $\ddot{\theta}$ is angular acceleration.

We find the work from expression:

$$A_m = M \Delta \alpha,$$

where A_m is work, $Nm = \frac{kg \cdot m}{s^2} m = \frac{kg \cdot m^2}{s^2} = J$; $\Delta\alpha$ is variation in the model angular position in radians over sampling interval dt.

Then the power of oscillations is determined by equation (5).

Using the proposed method and the recorded realizations of the model roll with a sampling rate of 0.01 s, the average power of the model rolling over one period was calculated; it was equal to 54.98 W. The power value per one meter of the model length was 33.32 W/m. Taking into account the normalized power of the selected wave equal to 6.26 W/m, the hydrodynamic efficiency calculated in accordance with the definition proposed in [10] was 532%. Such a large value can be explained by several factors. First, the model roll amplitude is 20 times larger than the amplitude of the wave slope angle. Second, the power of the model roll energy is considered in the steady-state mode of resonance oscillations. Thus, the calculations do not take into account the quantity of energy consumed for building up the model oscillations to the maximum roll angles. Moreover, if we consider only the first oscillations of the model, the angular deviation of which does not exceed the wave slope angle, then the normalized power developed by the model under these conditions will be just 0.08 W/m and the hydrodynamic efficiency will be just 1.33%.

Besides the studies on regular waves, the hydrodynamic efficiency was also studied on irregular waves. For this purpose, two Pearson – Moskowitz spectra were selected with the same periods of the spectral maximum τ_p equal to 1.89 s and significant heights of waves h_s equal to 87.71 mm and 44.69 mm. Figs. 13 and 14 show the records of the model rolling realization in time in the selected spectra of irregular waves at the sampling rate of 0.01 s.

Since the wave spectrum contains a number of harmonics, calculation of power by formula (4) appears to be difficult because this expression has been derived for one harmonic. Therefore, to assess the hydrodynamic efficiency of the model under the conditions of irregular wave spectrum, the power of waves was calculated as average spectral power of waves N_{sp} (W/m) per length unit of the wave profile by formula [11]:

$$N_{sp} = 490\tau_E h_s^2,$$

where τ_E is energy period of waves equal to $0.9\,\tau_p$ for *JONSWAP* spectrum and $0.86\,\tau_p$ for Pierson – Moskowitz spectrum.

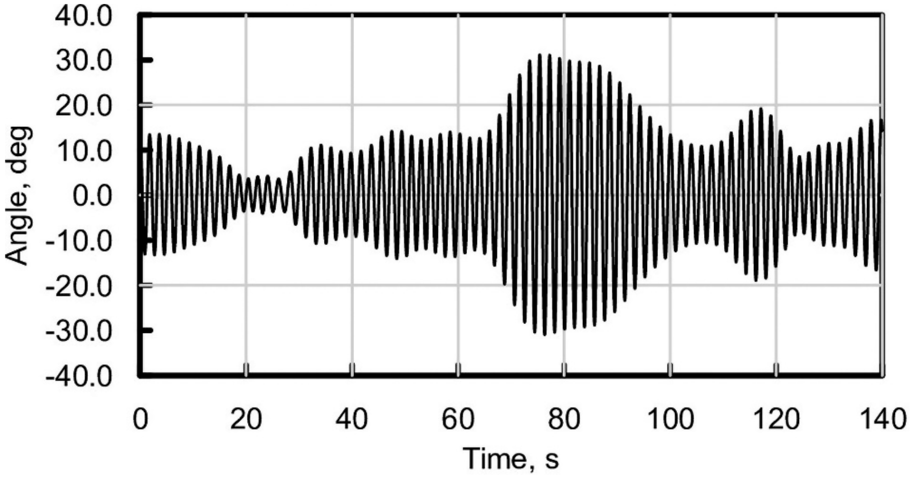
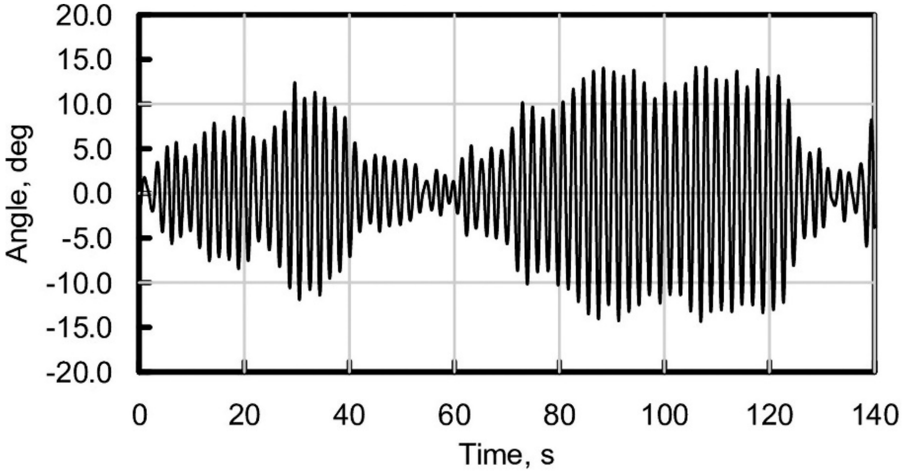


Fig. 13. Fragment of recorded realization of the model rolling in real time on irregular waves generated in the wave basin with spectrum No. 1 (τ_p = 1.89 s, h_s = 87.71 mm)



F i g. 14. Fragment of recorded realization of the model rolling in real time on irregular waves generated in the wave basin with spectrum No. 2 (τ_p = 1.89 s, h_s = 44.69 mm)

In accordance with the realizations shown in Figs. 13 and 14, the power per a unit of wave crest length was 4.90 and 1.30 W/m for spectra Nos. 1 and 2 of irregular waves, respectively. The normalized power of the model angular oscillations was 5.81 W/m for spectrum No. 1 and 1.91 W/m for spectrum No. 2. The hydrodynamic efficiency was 119% and 148%, respectively. Based on these results, it can be concluded that the hydrodynamic efficiency increases with reducing heights of the waves and invariant period of the spectral maximum peak.

The obtained values of hydrodynamic efficiency for irregular waves proved expectedly to be lower than the values obtained for the regular waves, but still amounted to more than 100%. This can be explained by the fact that the period of the spectral maximum of both spectra of selected waves corresponded to the period of free oscillations of the model. This means that the spectra included a large number of waves, the periods of which were close to or coincided with the period of the model free oscillations. These waves caused strong roll oscillations due to the resonance effect which can be clearly seen in Fig. 13 at the 80th second, when the angle of roll oscillations reached 30°.

It should be noted that the hydrodynamic efficiency of resonance-based WPG will reduce even more in the case of irregular waves with the periods of the spectral maximum differing from the period of the model free oscillations since the resonance effect will be minimal or missing at all. The model rolling will reduce considerably because the model will tend to perform angular oscillations in conformity with the angles of the incident wave slopes. Hydrodynamic efficiency on the waves with the periods differing from the period of the model free oscillations will depend on the quality of the model oscillations, i.e., on the peak height and the resonance bandwidth.

Based on the experimental hydrodynamic efficiency results, it is possible to compare a resonance-based WPG to the well-known Salter’s duck [10] which is believed to be one of the most efficient designs of a wave energy converter. The advantage of the Salter’s duck is that it is of cylindrical shape with a protruding part with a large damping coefficient, due to which it can perform angular oscillations under the effect of waves and create a large torque between its sections to transfer it to the generator. At the same time, the cylindrical part has the minimal resistance in water and does not hinder the wave-induced angular rotation of the duck, so it can collect the maximum energy of the incident waves. However, this design is also a disadvantage since the duck follows the wave slope angle and the resonance effect hardly manifests itself in this structure. Therefore, its efficiency determined by the method applied in [10] cannot exceed 100% while the efficiency of a resonance-based WPG can be higher.

Conclusions

As can be seen from the above discussion, the energy of waves, even low-intensity ones, is quite significant. It depends largely on the wavelength and low-frequency waves make the main contribution in the total energy of the waves. Since the hull of a station with WPG is the primary converter of the wave energy, its linear dimensions will determine the power of the collected energy which depends on the wave profile length. Oscillations of the station with WPG are converted into electric power and it is advisable to use resonance-based energy converters in order to increase the efficiency of such conversion.

Under the conditions of resonance oscillations, it is more efficient to use roll oscillations of the wave buoys and floating stations rather than their vertical oscillations because the angular oscillations can be much greater in resonance than the slope angles of the incident waves. The principle of controlled resonance used in the wave absorbers improves significantly their performance efficiency. Hydrodynamic efficiency of the proposed device increases with reducing heights and periods of waves which is extremely important for collecting energy in low-wave conditions.

Increased efficiency of power generation by stations with WPG will inevitably lead to the need for increasing the strength of its hull since the load of incident waves will grow. The increase in strength will, in turn, result in greater mass of the station. In addition, when determining the WPG efficiency, it is necessary to take into account the electric generator loads which may introduce significant damping and reduce the intensity of roll oscillations.

Thus, to ensure the maximum efficiency of power generation, it is essential to select the parameters of stations with WPG for each area of operation considering the average parameters of the waves. On the other hand, adjustment of the frequency of the station free oscillations will increase the range of efficiency coefficients for the wave energy conversion.

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The authors have read and approved the final manuscript.
The authors declare that they have no conflict of interest.