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DESIGN SOLUTION AND SELECTED RESEARCH RESULTS OF THE SEA-WAVE ENERGY CONVERTER

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Abstract

The paper presents a novel device, a special buoy, for capturing the energy of sea-waves and the design of its model for conducting test in a towing-tank. The paper also presents the research program and general analyses on selecting the turbine and hull form, systems of anchoring and propulsion. In addition, it includes some chosen results of model tests and numerical calculations. Model of the buoy at the scale of 1:5 was tested in the towing tank for some range of wave height and its frequency and for two value of column length, a few states of ballast and tension of the anchor ropes. Numerical calculations were conducted for the same conditions and additionally for several anchor systems as well.

Keywords: *sea- wave energy, wave power device, hydrodynamics model tests*

1. Introduction

Presently over 80% of world production of electric power comes from fuel power station. In view of forecasted farthest increment of request for this kind of energy and shrinking stocks of traditional fuels and threat of adverse climatic changes evoked of their intensive expenditure there is urgent requirement of new finding and improvement of existing methods of utilization of renewable energy sources.

Energy of sea and ocean wave is one of such renewable source. There is enormous energy potential, but diffused on big surface and because of it practically not exploited until now. It is valued for European Union, modestly counting, on 120 – 190 TWh/year for opened reservoirs and additional 34 – 46 TWh/year for coastal zone [1]. Average Atlantic wave bears on meter of width about 70 kW. Somewhat Baltic waves bear less. According to estimates of Marine Institute in Gdansk these capabilities are considerably smaller for polish coastal zone and they amount to 3 – 5 kW /m [5].

Problems of capturing of sea-wave energy are new relatively and investigated during last some tens years mainly by scientific and research centres of seaside highly economically developed countries only. However, it is necessary to note, that last time interest grows this topic fastly. Along with growing request for renewable energy and development of new technology perfecting of existing and working out of new methods of capturing of sea-wave energies are processed. Designing of the objects for commercial use of this kind of energy requires exact researching and knowledge and solutions of many difficult problems [7], [8]. Especially it concerns such problems as hydrodynamics of wavy motion and, in case of floating object, its movement trajectory on wave also so, in order to convert this changeable and spread over sea-wave energy to electric power most effectively.

Mentioned problems have been captivated in topic of research in the Faculty of Ocean Engineering and Ship Technology of Gdansk University of Technology [2,3,4]. From about three years there are conducted research project which title is: Experimental and numerical research of the buoy for capturing of the sea-waves energy. The paper presents an original method of winning of sea-wave energy by means of rolling buoy and it's construction solution based on the general concept contained in the patent of Mr. Sławomir Klukowski [6], and also some chosen results of model research and numeric calculations.

2. Design requirements assumptions

Prior to starting to design any novel structure, especially one mean to work under marine conditions, it is necessary to conduct analysis of the forecasted atmospheric and sea conditions which may occur during operation with emphasis on extreme weather scenarios. Such analysis allows for assessing the character and value of acting loads, as well as of the various hazards and technical problems, allowing for greater accuracy in establishing technical requirements assumptions of the structure and its equipment.

In case of the presented power buoy it was decided that the prototype would be meant to operate on the Baltic Sea in the Polish coastal zone at the depth of about 20 meters. It was also determined that the design and construction of the prototype should be proceeded by model based research in a towing-tank. The decision was made to build at least two models of the buoy at the scale of 1:5.The scale was selected based on the possibility of conducting research tests of the models on the large towing-tank located in the Ship Design and Research Centre in Gdansk, where it is possible to create model conditions close to those found at sea. This fact has significant impact on generalizing the measurement results and employing them for the verification of calculations. The towing-tank has the dimensions of L x B x H = 260 x 12 x 6 m and is equipped with a wave generator, as well as a towing carriage with measuring equipment. The tank allows for conducting tests for a wide range conditions with waves up to 0.7 m in height and 14 m in length for regular wave and even greater height for irregular waves. The large towing-tank dimensions significantly decrease the influence of wall deflection and creation of a shallow-water wave, allowing for conducting longer measuring sessions.

Taking into account the above factors, the following general model buoy design requirements were set:

- transverse buoy hull dimensions – 2.0 to 2.5 m;
- total draught of turbine column – up to 3.5 m;

3. Construction solutions

There were prepared two designs of the buoy models which differed mostly in the shape of the hull, power transmission system, the type of power generator and the buoy anchoring system.

The first designed solution of the model buoy, which more precise description is presented in the paper [3], is shown in fig. 1.

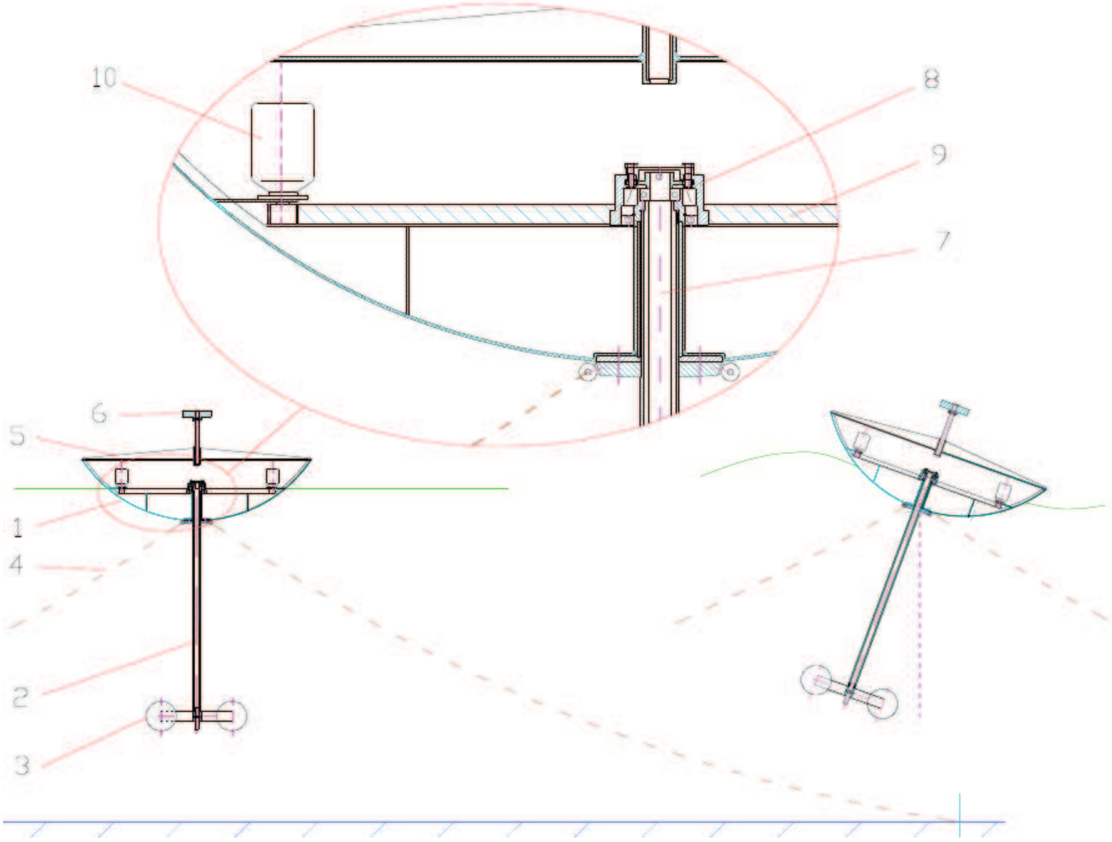

Fig. 1. Conceptual design of the buoy model for towing-tank tests: 1 – buoy body , 2 – column in form of tube, 3 – turbine, 4 – anchoring chain or line, 5 – buoy body cover, 6 – slidable weight for controlling buoy's centre of gravity, 7 - shaft, 8 – unidirectional clutch with bearing system, 9 – main gear , 10 – generator.

The second variant of the buoy was created at a later date following a more extensive theoretical analysis of the behavior of objects a top a wave, as well as after taking into account realistic technical and financial capabilities of the research. In comparison to the previous solution a number of significant changes were introduced. The axially symmetrical hull shape was abandoned in favor of form somewhat similar to “Salter’s duck” with a markedly elongated front and cylindrical rear part, as can be seen in Fig. 3. It was decided that such a shape allows for better use of waves’ kinetic and potential energy. This stems from the fact that the significant power of the hydrostatic lift of the water below acting on the elongated bow part of the hull should increase the angle of buoy’s deflection. In addition, after the crest of the wave passes the bow part above the water surface will increase the torque of the returning motion due to the longer arm of its centre of gravity in relation to the axis of the roll.

Assumed following general model buoy geometric parameters:
- transverse buoy hull dimensions – LxB = 2,03 m x 2,0 m;
- draught of the turbine: - variant 1 – T1 = 2,3 m; - variant 2 – T2 = 3,1 m;
- nominal displacement: - variant 1 – D1 = 0,67 m^3; - variant 2 – D2 = 6,9 m^3;

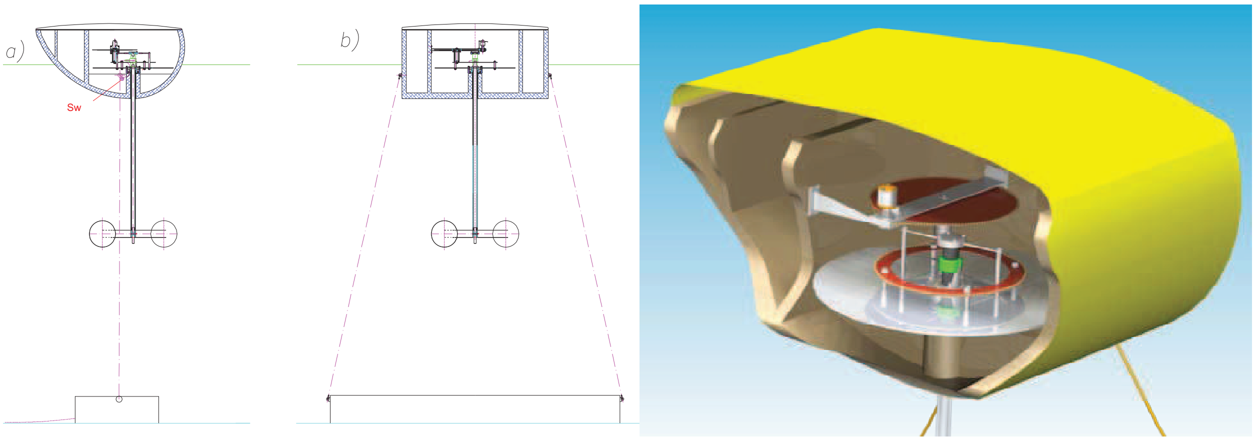

Fig. 2. Construction solution of the buoy: a) – longitudinal section, b) – cross section and on left side – 3 D longitudinal section

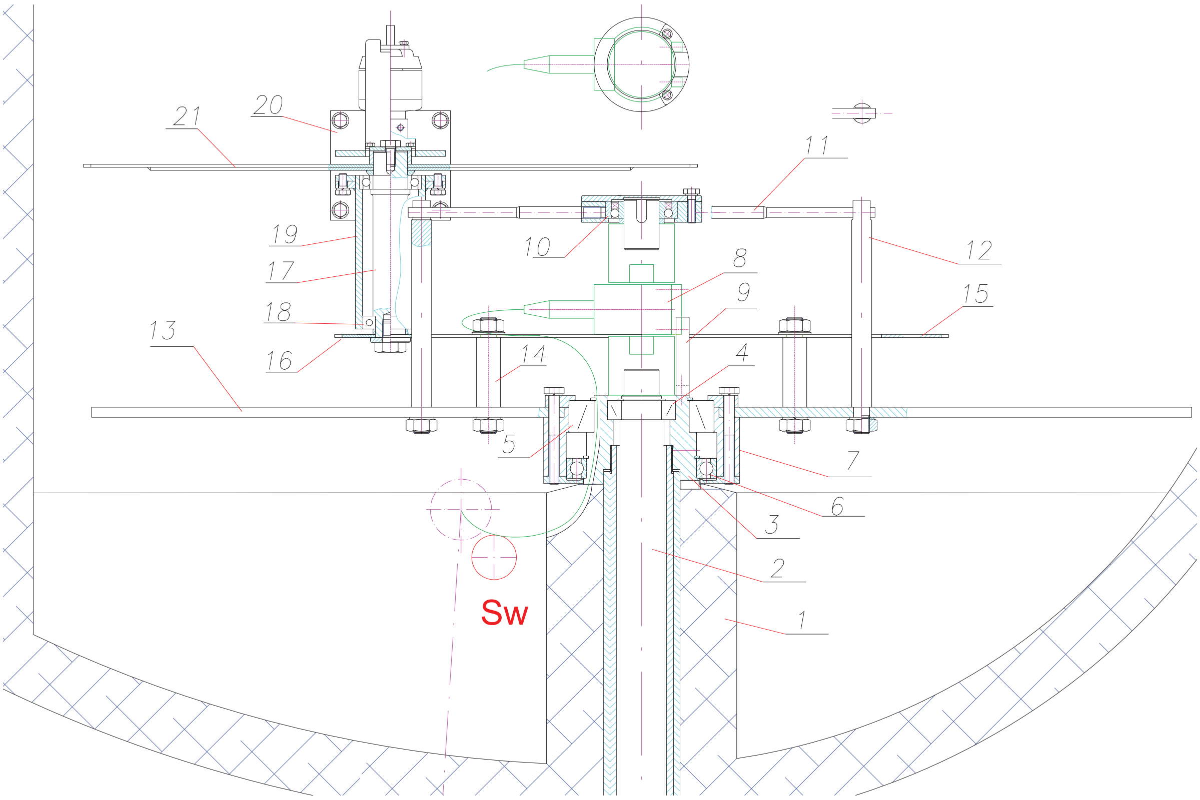

Fig. 3. Power transmission from the turbine shaft to the generator. Nomenclature: 1 – buoy hull, 2 – turbine shaft, 3 – head of column, 4, 5 – tapered roller bearings, 6 – roll bearing, 7 – hub of flywheel, 8 – torque meter, 9 – bracket, 10 – unidirectional clutch, 11 – casing of the clutch with two horizontal rods, 12 – vertical rods, 13 – flywheel, 14 – bolts, 15, 16 – 1st stage chain pulley, 17 – upper shaft journal, 18 – roll bearing, 19 – sleeve, 20 – transmission casing, 21 – 2nd stage chain pulley transmitting power to located above generator

The shaft 1 is placed inside the column on roller bearings. Turbine is attached to the lower end of the shaft. Blades of the turbine are semi-spherical in shape. This shape ensures turbine spin in only one direction independently of any lateral motion of the turbine. Number and diameter of the blades and diameter of their localization was established after model tests of turbines in towing–tank with different number and configuration of the blades. The mentioned parameters are following:

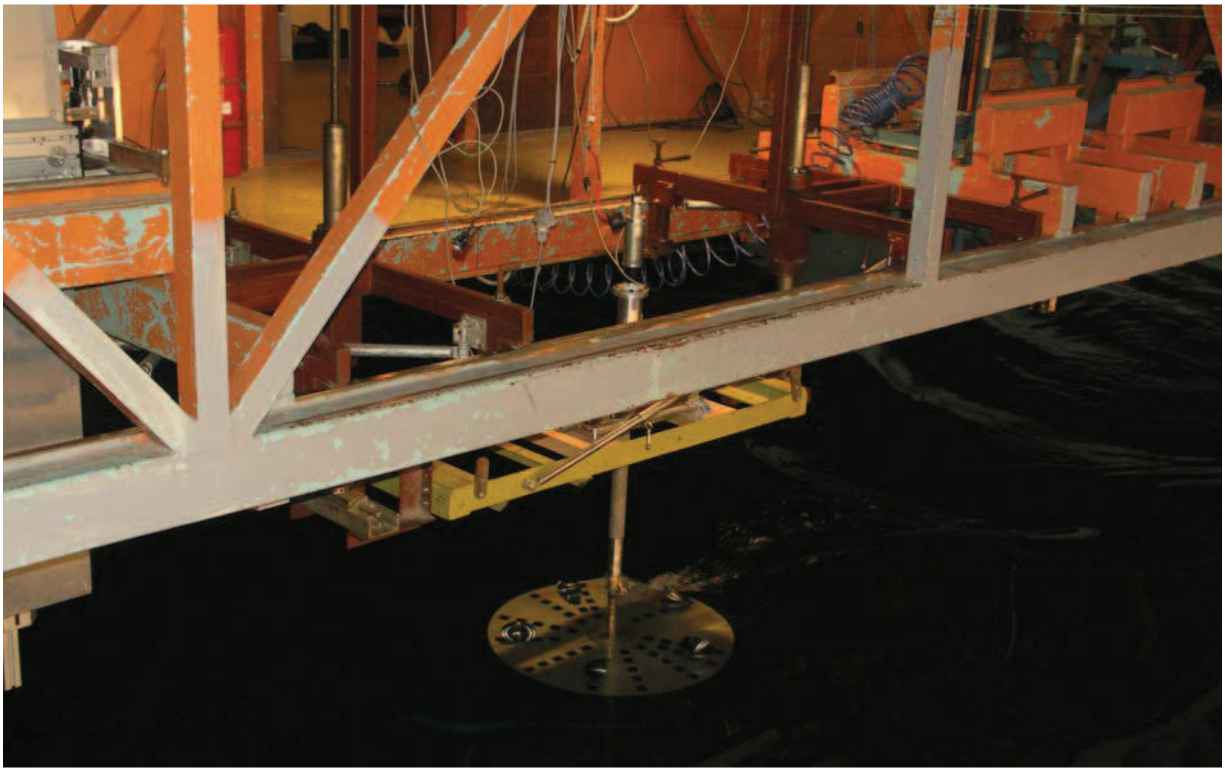

Fig. 4. Photographs of the turbine model tests in the towing tank

- number of blades – $N_{cup} = 3$
- diameter of blade – $D_{cup} = 0{,}36$ m
- diameter of turbine – $D_T = 1{,}08$m

The new buoy hull also required changes to the anchoring system. Two anchoring strands were attached to the flat sidewalls of the hull. Proper selection of the attachment point of the anchoring strands was of high importance. In opinion of the authors' of this paper the attachment point should be located somewhat in front of and at the same time above the buoy's uplift centre. Such location is characterized by a very favorable course of the righting moment in the function of the buoy's angle of deflection. This moment is very small for low deflection angles due to the short arm of the force acting in the anchoring strand and does not interfere with hull's deflection. It increases to large values with high deflection angles, as a result of the uplift center and roll axis shifting away from the point of anchoring strand attachment, which to some degree protects the buoy from turning over and facilitates its returning motion.

The lower ends of anchoring strands are attached to a sinker resting on the bottom which in turn is connected by a separate strand to the bottom anchoring element. The sinker has the form of a box filled with heavy elements. The width of the sinker is substantially larger than the buoy width which protects the turbine from catching onto the anchoring strands during its rolling atop waves. The weight of the sinker in the water is appropriately smaller than total hull displacement, so that in the event of a very high wave the buoy would remain on the surface lifting only the sinker. The length of the anchoring strands was set as the approximate straight line distance between the points of their attachment to the buoy and the sinker. This means that in a certain foreseen range of wave height, the buoy not being able to float freely on the water surface will as the waves swell increase its draught. In doing so it will create increasingly large resistance, taking on growing amounts of wave energy which will manifest itself in increased amplitude of its roll which translates into greater efficiency.

4. The buoy model tests

The buoy model presented above was tested in the towing-tank. The apparatus installed on the model allowed measuring and recording the following parameters:

- linear acceleration in three directions,
- buoy rolling angles,
- heaving height,
- torque on turbine shaft,
- rotation speed and current parameters of the generator.

The measuring system allows for collecting data with constant rotation speed and variable torque or with constant torque and variable rotation speed of the generator.

The prepared program encompassed the following research tasks:

- Establishing favorable shape of the buoy hull depending on the chosen variant of defined or undefined wave direction.
- Preparing efficient anchoring system for both of the above mentioned variants of wave motion.
- Establishing the impact of the location of buoy's centre of gravity and moment of inertia on its rolling characteristic and power generation efficiency.
- Investigating the impact of the moment of inertia of the rotating elements of the system transmitting power from the turbine to the generator, as well as the influence of the gyroscope effect on the effectiveness and parameter stability of the generated electrical power..
- Setting outermost wave parameters:
  - the minimum necessary for starting the process of power generation,
  - the maximum where danger of mechanical or electrical damage appears - if possible to obtain in the towing-tank.
- Setting the general efficiency characteristic of generating power as function of wave parameters.
- Preparing a mathematical model and calculating program for simulating operation of the power buoy.

Verification of calculation results with data obtained during the model-based research phase.

Two photographs of the model buoy are presented in Fig.5 below - before launching in the towing-tank and during tests in regular wave conditions.

Fig. 5. Photographs of the power buoy model - on the left during preparation for launching, on the right during tests in the towing tank

The first series of model tests was conducted for the buoy with short column. Depth of dip of the turbine was 2,3 m. There were measured angles and displacements of the buoy' hull as well as rotary speed and torque of the turbine's shaft for assumed ranges of wave height H_{wM} = 0,35 – 0,5m and it's frequencies f_M = 0,3 – 0,44 Hz. Obtained power and angles of pitch of the buoy for two values of wave height converted on real parameters are presented in fig. 6a and fig. 7a.

Remaining model tests were carried for the buoy with the column extended about 0,8 m. Extension of the column has caused change of mass and dips of draught of the hull about 0,006 m, and consequently displacement in bottom direction of a mass centre of the buoy and change of moment of inertia in respect to pitch movement. After measurements conducted in the same way as in first series the tests were repeated for boosted mass of ballast in the hull about 100 kg, what caused increase draught of the buoy about far 0,032 m and next - for eased anchor ropes about 0,08 m.

Results of this series of the tests are show in fig. 6b and fig. 7b. It is possible to see distinct influence of increase of the column length as well as moment of inertia of the buoy pitch movement on displacement of extremes of pitch angle and power in direction of lower values of wave frequencies

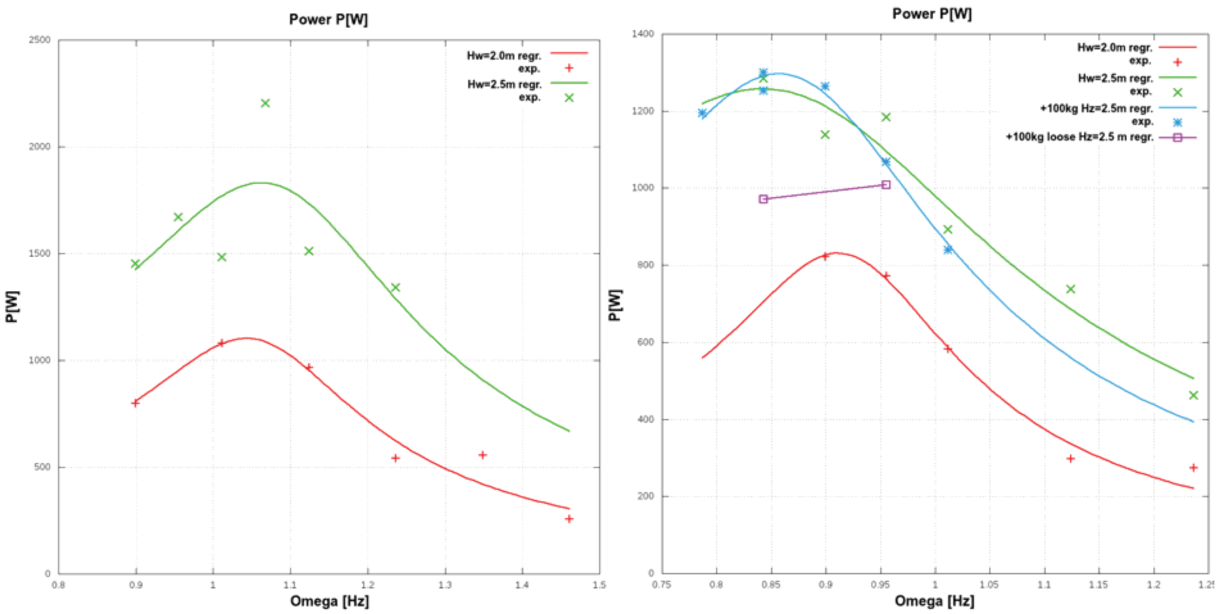

Fig. 6. Power of the buoy: a) – with short column, b) – with long column

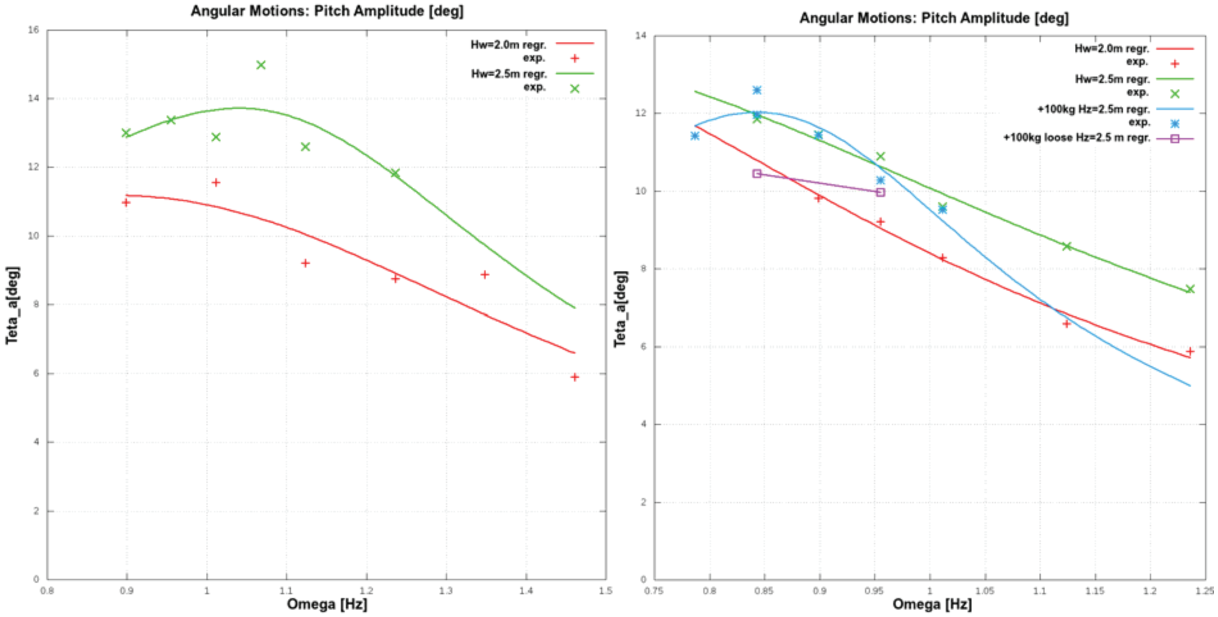

Fig. 7. Pitch of the buoy: a) – with short column, b) – with long column

There is visible also an advantageous influence increased rigidity of the anchoring system on efficiency of tasted device's action. It should be mentioned that received results considerably differ from expected, especially in value of power. These values are smaller than in case of buoy with short column. Reason of this could be for example some technical fault committed during exchange of the column on longest one or any error in measurements. Because of high cost of the model tests and limited financial means on this purpose the tests could not be repeated. Further research of the buoy for different anchoring systems and geometric parameters were conducted with use of numerical simulations only.

5. Numerical simulation

Theoretical model has been developed based on rigid body motion in six degrees of freedom. Forces and moments acting on the buoy are caused by hydrodynamic external reactions according to wave, anchoring system and gravitation. Hydrostatic forces are calculated by integrating the static pressure of the submerged area of hull surface of the buoy. Buoy hull is modelled using quadrilateral panels. During calculation of the hydrostatic forces, acting on the panel, it is checked by algorithm whether the panel is fully immersed. If the panel is immersed partly, the force is calculated only for the wetted area. Hydrodynamic reaction is a sum of two components of frictional resistance and pressure resistance. The resistance of appendages is calculated based on its drag coefficient.

In the presented method water wave motion is modelled using a linear theory of waves. In addition, corrections have been introduced taking into account the impact of the free surface deformation on the value of hydrostatic pressure. Hydrodynamic pressure is calculated from the Bernoulli equation. Impacts, related to the presence of water added masses, is modelled using a simplified method based on the strip theory. Buoy hull is divided into strips with a specified thickness. Each section is associated a mass of water which causes hydrodynamic reaction during accelerated motion. Mass of water around frame depends on its shape and direction of motion.

To calculate the total hydrodynamic reactions the buoy acceleration ought to be known. The acceleration, in turn, depend on the sum of the forces acting on the hull. Therefore, calculation of the forces due to added masses shoud be done by successive approximations.

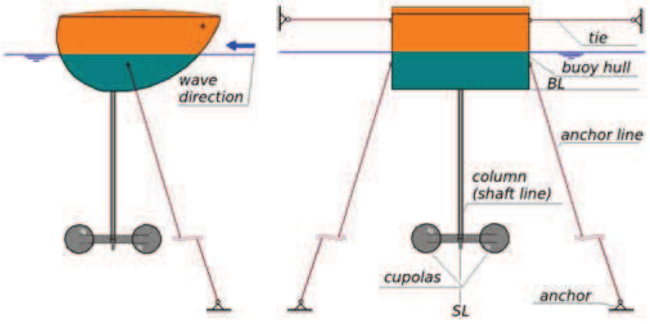

Fig. 8. Sketch of the modelled anchoring system

The first version of anchoring system of the buoy consist of two main ropes and two auxiliary lines. Main ropes are (almost) vertical. The ropes are strained to increase draft of the boy. Auxiliary lines are horizontal, their role is to prevent yawing. The stiffness of vertical ropes is high to prevent heave motions. However horizontal lines are flabby, in order to minimize yawing without reducing pitching. The sketch of the anchoring system is presented at Fig. 8.

The buoy turbine is moving progressive (due to pitch motion) and rotating. Hydrodynamic reaction on rotor is calculated as the sum of forces induced on canopies and additional elements to which the canopies are attached. Hydrodynamic reaction induced on singular (isolated) canopy were calculated after defining and evaluation of the characteristics of drag and lift coefficients using RANSE-CFD method. The total torque of the turbine is the difference between hydrodynamic interactions and torque response to the generator. Torque on the generator is a function of turbine rotational speed. In this model, we have assumed that this is a linear function.

Below some results of chosen examples of numerical calculations for a two variants of the buoy's anchoring systems are presented. The calculations were conducted for following common parameters according to fig. 9:

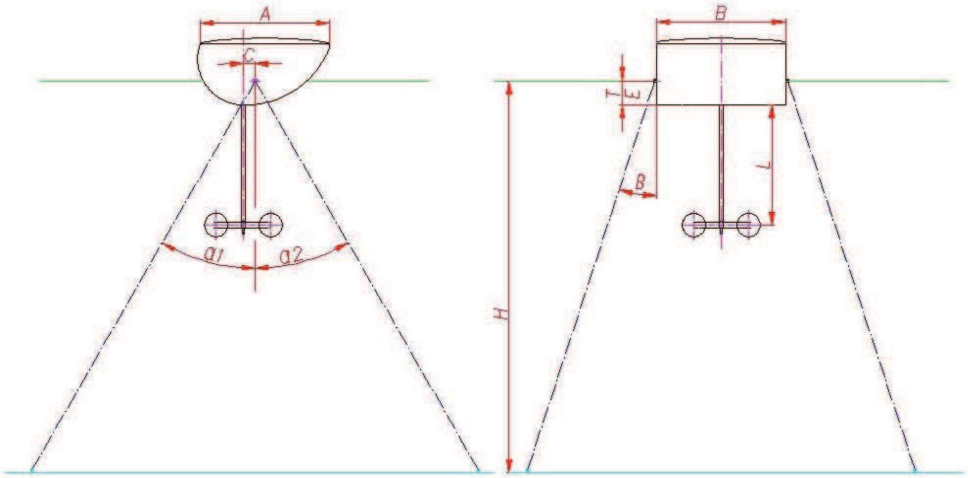

Fig. 9. View of the anchored system of the buoy with shown basic geometrical parameters
A = 2,0 m; B = 2,0 m; C = 0,162 m; L = 1,84 m; E = 0,370 m; H = 6,0 m; α_1; α_2; *b = 18°*

- $T_0 = E = 0{,}320$ *m – draught of the buoy's hull before tensioning of the anchor wire;*
- $T_k = 0{,}370$ *m – draught of the buoy's hull after tensioning of the anchor wire;*
- $d = 0{,}005$ *m diameter of the anchor wire;*
- $H_w = 0{,}4$ *m – height of wave;*

Variant 1 of the anchoring system shown in fig. 2 is the same which was tested in the towing tank. It contains only two anchor wires which, in an end view, in calm water look like vertical line. It means $\alpha_1 = \alpha_2 = 0°$. Captured power, pitch, horizontal and vertical displacement of the buoy calculated for real scale for the same range of the wave angular speed are presented in fig. 10, 11, 12 and 13.

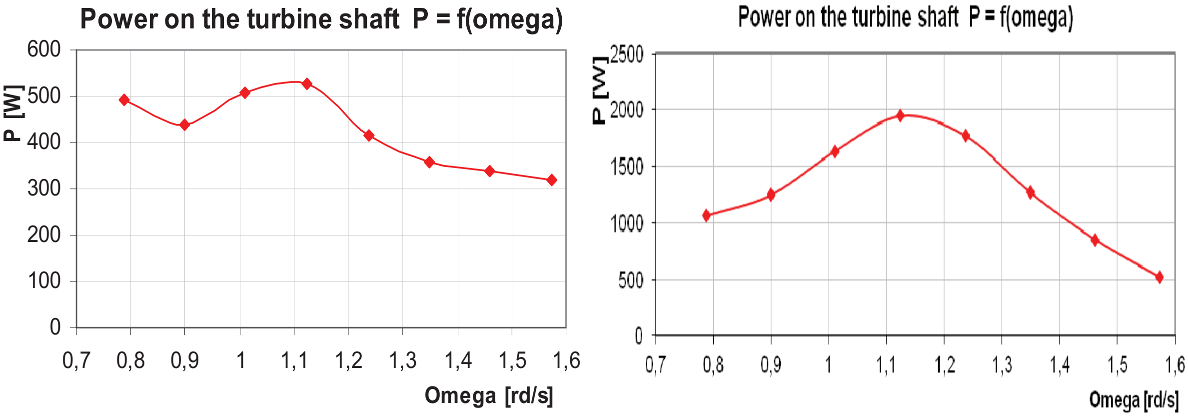

Fig. 10. Power on the turbine shaft calculated for the buoy with a short column (L = 1,84 m) on left side and with a long column (L=2,64 m) on right side.

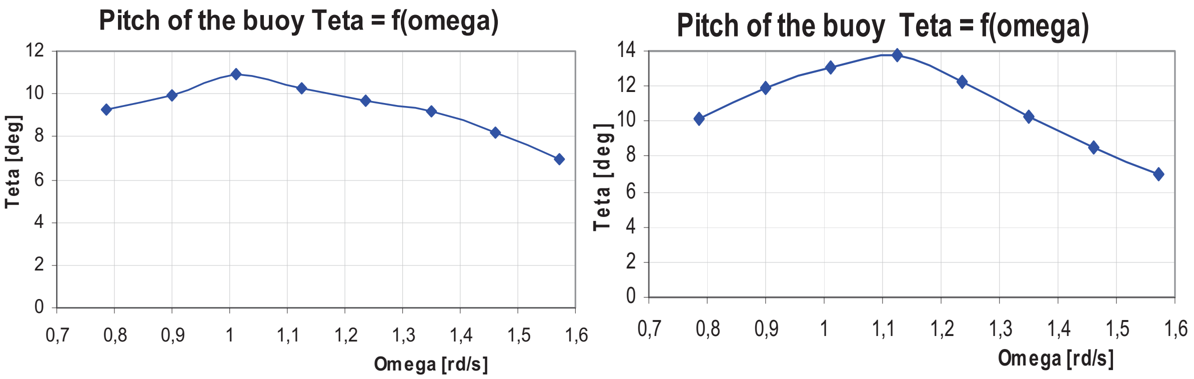

Fig. 11. Calculated pitch of the the buoy: with the short – on the left and long column on the right side.

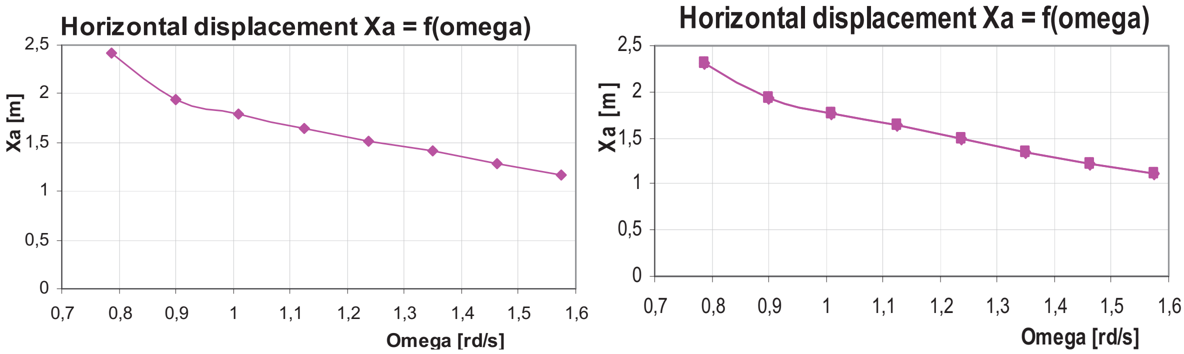

Fig. 12. Calculated pitch of the the buoy: with the short – on the left and long column on the right side.

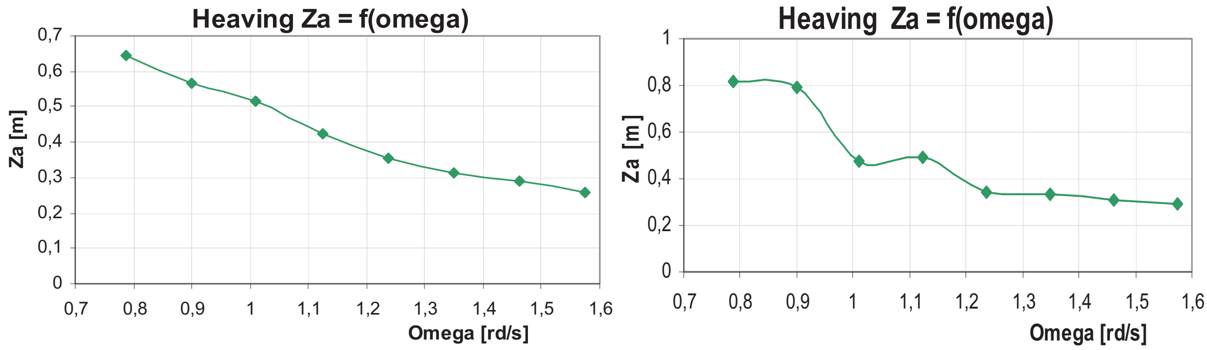

Fig. 13. Calculated heaving of the the buoy: with the short – on the left and long column on the right side.

Comparing the results of model tests shown in Figure 6 with the results of calculations presented in Fig. 10, one can see significant differences in the values. In autor's opinion the results of model tests of the buoy with the short column are the most reliable. It means that theoretical model of calculations gives understated results of captured power by more than half. So it can be concluded that shown below values of calculated power under the real conditions will be more than twice bigger.

Variant 2 of the anchoring system is shown in fig. 9. It consists of four anchor wires, which position are defined by dimensions C,E, H and angles α_1 and α_2. Values of the rest mentioned geometrical parameters are the same as in variant 1. It is possible to create some variation of the system depending on the values of angles α_1 and α_2. Figures 14 ÷ 16 present power, torque and rotary speed on the turbine shaft in function of the wave angular velocity of the sea-wave, calculated for four different configurations of anchoring system. These anchoring configurations differ only by values of angles α_1 and α_2. Presented results are calculated for buoy with long column and 2m of wave height.

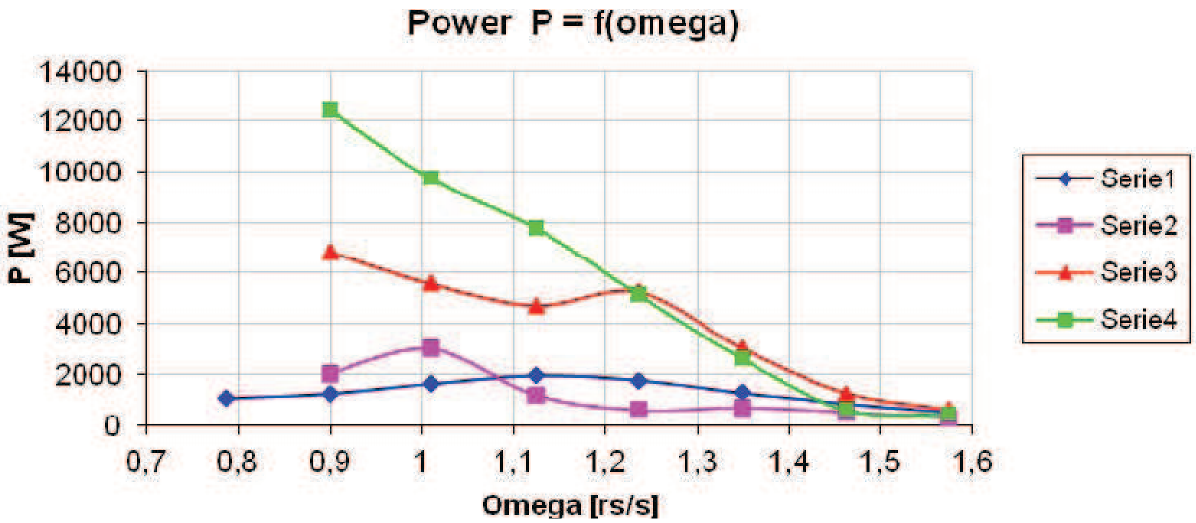

Fig. 14. Power on the turbine shaft calculated for the buoy with a long column:
Serie 1 - $\alpha_1 = \alpha_2 = 0^\circ$; *serie2 -* $\alpha_1 = \alpha_2 = 15^\circ$; *serie 3 -* $\alpha_1 = \alpha_2 = 30^\circ$; *serie 4 -* $\alpha_1 = 15^\circ$; $\alpha_2 = 45^\circ$

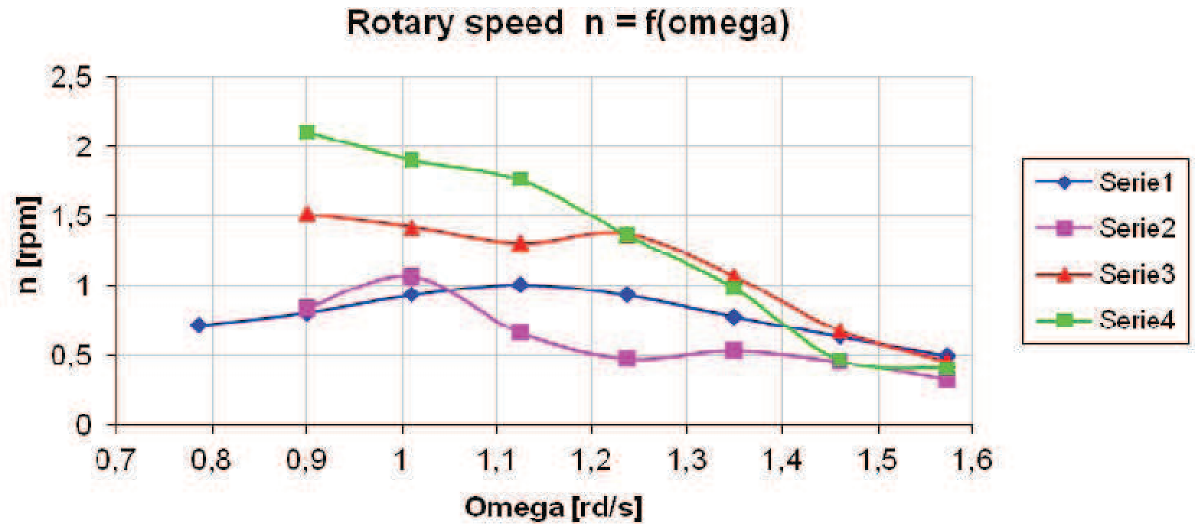

Fig. 15. Rotary speed of the turbine calculated for the buoy with a long column:
Serie 1- $\alpha_1 = \alpha_2 = 0^\circ$; *serie2 -* $\alpha_1 = \alpha_2 = 15^\circ$; *serie 3 -* $\alpha_1 = \alpha_2 = 30^\circ$; *serie 4 -* $\alpha_1 = 15^\circ$; $\alpha_2 = 45^\circ$

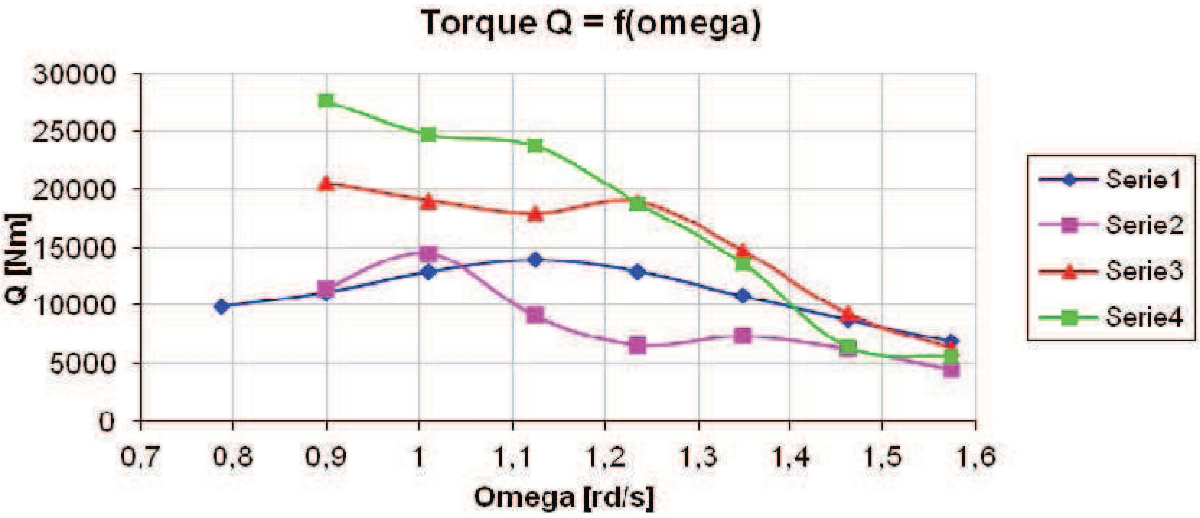

Fig. 16. Torque on the turbine shaft calculated for the buoy with a long column:
Serie 1- $\alpha_1 = \alpha_2 = 0^\circ$; *serie2 -* $\alpha_1 = \alpha_2 = 15^\circ$; *serie 3 -* $\alpha_1 = \alpha_2 = 30^\circ$; *serie 4 -* $\alpha_1 = 15^\circ$; $\alpha_2 = 45^\circ$

6. Conclusions

The design solution of the device for capturing the sea-wave energy as well as the model tests in the towing tank and numerical simulations presented in the paper are the first stage of this subject study, which started over two years ago at the Faculty of Ocean Engineering and Ship Technology of the Gdansk University of Technology. Even if these studies are not completed yet it allowed to determine the impact of various structural and geometrical parameters on the quality and effectiveness of device. Right now we can say, that as expected, one of the most important is the anchor buoy system. The system applied to the model tests was not the most preferred, but was a compromise between the desirable and feasible in the existing technical conditions of the towing tank. With the developed method of calculation it was possible to perform simulations of the device for several variants of this system. Selected results of these simulations are shown in Figures 10 - 15 and they indicate that by changing the anchoring system several times more power from the same device operating in the same sea conditions may be received.

When submitting the paper for publication there are conducted further simulations of the device operating, for determining the influence of other geometrical parameters and the buoy hull shape. We hope that the results of these studies are interesting enough that they were suitable for further publication.

Acknowledgment

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