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Autonomous observation buoy: evaluation of concept

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Content

1. Introduction

NORCE Norwegian Research Centre AS has been invited to contribute to the development of the observational buoy by WaveCo AS. The work is supposed to be a part of the program “Forsker til låns” which assumes that a single researcher works on the project.

WaveCo develops an autonomous buoy that utilizes wave energy (eventually solar energy) to supply own machinery as well as the measurement equipment. Energy harvesting should be sufficient that the buoy always preserves actively its location resisting to wave and current forces and supplies the installed equipment.

WaveCo has supplied a detailed description of the preliminary concept in documents and drawings. WaveCo has also provided a few previous works evaluating various aspects of the concept.

“Svardal, Ramstad, Helgesen: Development of brake systems for a wave power turbine – bachelor thesis” describes a towing tank experiment that considers the development of the braking system for a wave-powered turbine in order to simulate the generator load. The work considers the overall efficiency of the turbine at different turbine speed, mean moment and rotation of the blades. The formula for rotation power on page 16 is incorrect (must be Power = RPM (1/s) * Torque (N*m)) which might lead to lower estimate for the power production and the overall efficiency.

Strømsem (Global Maritime): Concept Evaluation for Torpedeo Wave Turbin. The report compares the wave energy against the production by the turbine at different sea states. It is concluded that most probable sea states carry typically less energy.

Olsen: Dynamic Positioning of Power Generating Buoy. The report presents a numerical model of the system dynamics and the optimal solutions. The energy production is not evaluated.

In this report we assess the system in terms of force balance and the overall energy balance. The objective is to find out if the system is able to produce enough energy for its own needs.

2. Analysis

The purpose of the analysis is to estimate all external forces acting on both the turbine and the floater and find out if the turbine can provide enough power to withstand those forces. Rough analysis gives an indication of the overall energy production-and-demand balance.

The shape of the floater is unknow as up to this date. For analysis, it is sufficient to suggest only basic parameters as width, length, draft, weight. In principle, the floater will adjust its heading for minimal resistance. It should be taken into account that the attached turbine contributes to the force balance. In fact, the sea current may change its direction at certain depth. In such case, the floater should adjust the heading accordingly. In some cases, the heading may not be optimal with respect to wave direction which leads to larger wave drift force. Below, the contributing forces are explained.

2.1. Description of the assembly

The assembly consists of a floater and a turbine attached below the floater with an umbilical cable. The upper deck of the floater can be covered with solar panels for extra energy production.

The turbine is attached to the floater with a long umbilical cable. The cable should satisfy the following requirements:

- It should be long enough that the effect of the waves on the turbine is minimal,
- The length should also be minimized to reduce the weight,
- The cable should be strong enough to bear both the weight of the turbine and the dynamic load caused by drag, added mass, resistance of the propellers, etc.
- The cable should be thin for minimal drag,
- The cable should consist of both high-power lines and steering signal wires.
- The cable should be attached through the slip ring to allow free rotation.

The turbine has two propellers that rotate in opposite directions to compensate each other's moment. The moment of the propellers is adjusted independently by changing the angle of attack of the propeller blades. We acknowledge the idea of putting a few vertical flaps on the turbine axis for more steering (flaps 4,7,10 on fig. 1).

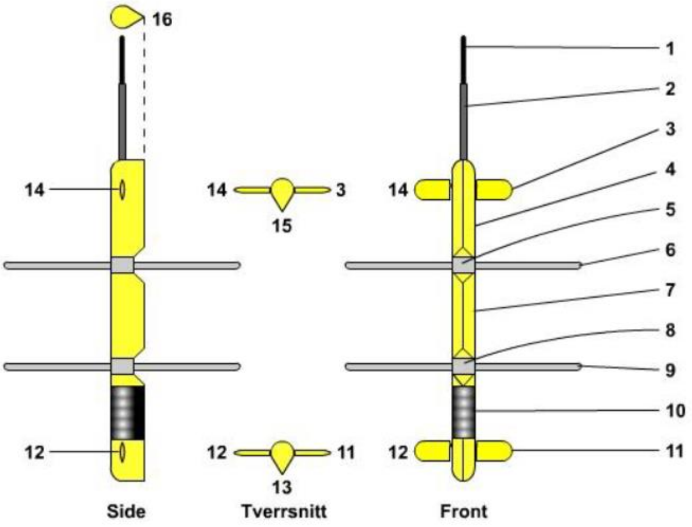

Figure 1. Assembly of the turbine (illustration from WaveCo).

WaveCo suggested also putting flaps (3,14,11,12) that control the horizontal position of the turbine with respect to the floater while moving up and down. This ensures that the turbine is always located right below the floater and the turbine is always vertically oriented. Though we acknowledge the idea, we would like to point out that it is effective only in large waves, and in calm weather the structure will be drifted out by the sea current lacking energy at the same time. We suggest that the turbine can be inclined by the sea drag. There are two options in this case:

1. The propellers remain parallel to the horizontal plain and the effect of the sea current is minimized. This complicates the construction by adding to specifically designed constant velocity joints that would transfer torque.
2. The propellers rotate in the plane always perpendicular to the turbine's axes of symmetry. In such case, the propellers are exposed to the sea current, adding more resistance. Excess energy produced by the propellers is used for more propulsion to withstand the additional resistance.

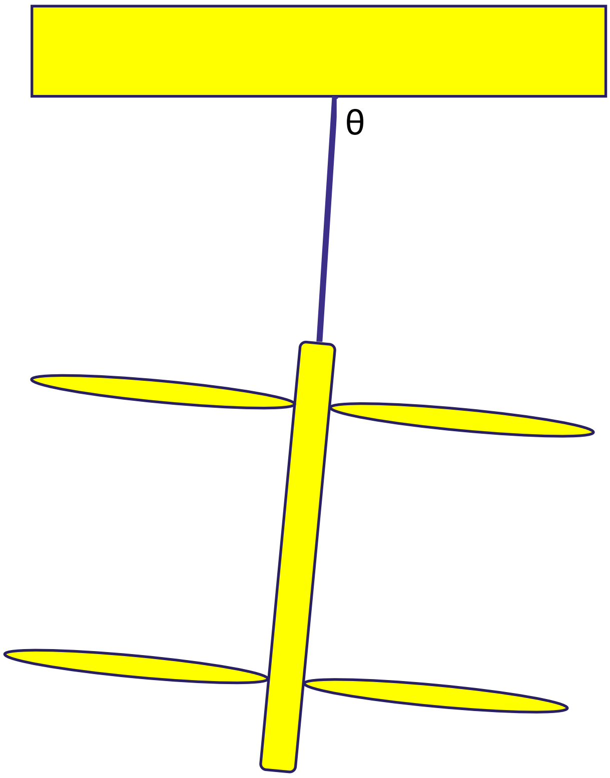

Figure 2. Proposed design.

2.2. Environmental conditions

Sea waves. For the reference data, we consider the most frequent sea state in the North Atlantics [2]:
Significant wave height: 2m
Peak period: 8 s

For simplicity, we assume periodic motions in a sinusoidal wave with amplitude 1 meter and period 8 s.

Available wave energy per meter wave crest can be approximated by [4]:

$$P_w = \frac{\rho g^2}{64\pi} H_s^2 T_p \tag{1}$$

ρ is the density of water (1030 kg/m^3),
g is the gravity acceleration (9,81 m/s^2),
Hs is the significant wave height,

Tp is the wave peak period.

Sea current. Water mass motion is generated by general sea currents, tidal and wind induced components. Tidal and wind components decay at larger depth, but this dependence can be omitted taking into account that the contribution of the latter two components is not big. Other current components [1] are omitted for simplicity. In some places, the sea current close to the surface may have a totally different direction than the current at some depth. Such situation is very unfavorable as this results in forces acting in all directions significantly increasing the transversal components. For simplicity, all current components are merged into two values: the current speed at the depth of the wave turbine and the current speed at the surface.

The impact of currents is estimated by the drag force component:

$$\boldsymbol{F_D} = \frac{1}{2} C_D \rho A_T \boldsymbol{u} |\boldsymbol{u}| \tag{2}$$

C_D is the drag coefficient,
A_T is the cross-section area transversal to the velocity vector,
u is the velocity vector.

For the reference, we choose the sea current to be 0,3 m/s [2,3].

2.3. Forces and motions

Wave drift. Wave drift force is highly dependent on the floater shape. In principle, the response amplitudes must be calculated using CFD, but some estimations can be made. Wave drift force is approximated according to [1]:

$$\begin{gathered} F_{wx} = \frac{2}{3} \rho g \zeta_a^2 d \cos \alpha \\ F_{wy} = \frac{2}{3} \rho g \zeta_a^2 l \sin \alpha \end{gathered} \tag{3}$$

F_w is a wave force vector in x (longitudinal) and y (transversal) directions,
α is heading with respect to the wave direction,
ζ_a is the wave amplitude (half the height),
d is the transversal dimension of the vessel,
l is the longitudinal dimension of the vessel.

Sea current force is calculated with (2).

Vertical motion. Vertical motion is due to waves and buoyancy of the floater. As for the wave drift, heave depends on the shape of the vessel. When resonance occurs, the effect of vertical oscillations may increase improving the energy efficiency. But if resonance occurs at some more probable sea states, other states may be not so good. Therefore, it is more desirable that the response is maximal at the most sea states. Thus, the best-case response amplitude for heave motion is 1. This means that the floater follows the wave shape and damping is minimal. Thus, the vertical driving force is given by the submerged volume of the floater and its mass:

$$F_B = \rho g V_{sub} - M_F g \tag{4}$$

This force should be compensated by the pulling force of the turbine.

The size of the floater is defined by the maximum pulling force and the weight of the floater. The umbilical cable must be tight at all times. This means that the weight of the turbine should be big enough to compensate for the propeller resistance plus the maximum acceleration due to wave motion. Vertical coordinate, velocity and acceleration due to wave motion are given by:

$$\begin{gathered} z = \zeta_a \sin \omega_p t \\ \dot{z} = \zeta_a \omega_p \cos \omega_p t \\ \ddot{z} = -\zeta_a \omega_p^2 \sin \omega_p t \end{gathered} \tag{5}$$

For simplicity, we assume that inclination of the turbine is so small that the turbine moves almost vertically. In practice, this means that the weight of the turbine is much larger than the drag force acting in the transversal direction. Thus, in some cases, smaller transversal components may be omitted.

Added mass and inertia of the turbine. Added mass of the turbine is the force acting in the direction opposite to the motion as a result of the fluid mass inertia when the body accelerates [3]:

$$F_A = C_A \rho V_t \ddot{z} \tag{6}$$

C_A is the added mass coefficient depending on the turbine body shape; for cylindrical shape, C_A=1 [3],
V_t is the turbine displaced volume.

Inertia of the turbine contributes in the same way due to the turbine mass:

$$F_I = M_t \ddot{z} \tag{7}$$

And the submerged weight of the turbine:

$$F_G = M_t g - \rho g V_t \tag{8}$$

Turbine drag. Drag force acts on the turbine due to fluid viscosity. It has both the vertical component due to the periodic vertical motion and the horizontal component due to the sea current [3]:

$$\begin{aligned} F_{DTx} &= \frac{1}{2} C_{Dx} \rho A_x u^2 \cos\theta \\ F_{DTz} &= \frac{1}{2} C_{Dz} \rho A_z (u^2 \sin\theta + \dot{z}^2) \end{aligned} \tag{9}$$

C_D is the drag coefficient: C_{Dx} = 1 for a cylinder and C_{Dy} = 1 for a rounded nose section [3],
A_x and A_z are the cross-sections in x and z directions,
u is the sea current speed,
θ is the inclination angle with respect to the vertical axis,
$\dot{z}$ is the vertical velocity and is a function of time.

Resistance of the propellers and energy production. Ideal power produced by the propellers is defined as

$$W = F_R(\dot{z} + u \sin\theta) \tag{10}$$

Where F_R is the resistance force of the propellers. Here we assume the turbine design where the propellers are always perpendicular to the turbine axes. Thus, the produced excess energy is used to compensate the increased resistance due to sea current.

According to Betz's law, there exist a theoretical maximum of 59% for the energy that the rotors can produce.Thus, the efficiency of the rotors cannot exceed this maximum. In our calculations, we set the efficiency to 40%. The energy production by the rotors can be estimated as

$$P_{rot} = \rho S u_t^3 \tag{11}$$

Where S is the cross-section area of the rotor. For the given power requirement (10), the rotor's diameter can be found from (11).

Propulsion is one of the major concerns for the energy independency of the system. If the buoy is in free sailing, the external forces will lead to a constant drift. Thus, the forces will be compensated by the drag force

$$F_{DF} = \frac{1}{2} C_{DF} \rho A_T u_F^2 \tag{12}$$

And the required energy to keep the floater in place is

$$P = F_{DF} u_F \tag{13}$$

u_F is the equivalent drift velocity of the float or the velocity with which the float would drift without any propulsion.

Balance of forces gives the requirements for the dimensions and the energy production. The equations above assume that the inclination angle is small. This simplifies the calculations, but the forces may be overestimated. We believe that this is conservative for the concept evaluation.

For the balance of forces, vertical components must be calculated at their maximums to satisfy the requirement that the connecting cable must always be tight.

Balance of vertical components leads to the requirements for the size of the float, maximum pulling force must be compensated by the buoyancy:

$$F_B = F_A + F_I + F_G + F_{DTz} + F_R \tag{14}$$

Balance of the horizontal components lead to the requirements for energy production by the turbines:

$$F_{Wx} + F_{Dx} + F_{DTx} + F_R \sin\theta = F_{DF} \tag{15}$$

Energy balance:

$$W = P + P_E \tag{16}$$

Where P_E is the excess power drawn by the equipment onboard.

3. Solution

The above equations lead to a system of 3 equations (14,15,16). For simplicity, we assume that the inclination angle is small and can be omitted in some cases, where the contributing force is small, i.e. in (9). Calculations are performed in an Excel table. The system of equations leads finally to a cubic equation for the equivalent velocity u_F, which is solved iteratively in Excel. The table is attached with this report and can be modified. Values in grey cells are calculated and should not be modifies. Other parameters, such as the floater width (sum for both parts of the catamaran) or draft can be changed. In the final result, the inclination angle must be larger than 0, otherwise the solution is not valid, and the configuration cannot be used.

Table 1. Calculation example used for the concept evaluation.

Wave drift						
Wave height, m		2,00				
Wave amp, m	ζa	1,00				
Wave period, s	Tp	8,00				
Theoretical energy, W	Pw	26819				
Efficiency		40 %				
Available energy		10728				
Wave frequency, rad/s	ωp	0,79				
Max vertical velocity, m/s		0,79				
Max vertical acceleration, m/s²		0,62				
Sea current on surface, m/s	u	0,30				
Sea current at 3m, m/s	u	0,30				
Turbine				Floater		
Mass, kg	Mt	4000		Mass, kg	M_F	2000
Radius, m		0,25		Heading, deg	α	0,00
Vertical drag coef	C_Dz	1,00		Width, m	d	1,70
Length, m		4,00		Length, m	l	4,30
Horizontal drag coef	C_Dx	1,00		Draft, m	h	0,90
Displaced volume, m³	Vt	0,79		Displaced volume, m³	$Vsub$	6,58
Added mass coefficient	CA	1,00		Displaced mass, kg		6776
Max vertical drag, N	$\boldsymbol{F\_DTz}$	62,38		Vertical force, N	$\boldsymbol{F\_B}$	46856
Max horizontal drag, N	$\boldsymbol{F\_DTx}$	92,70		Drag coefficient	C_DF	1,00
Max inertial force, N	$\boldsymbol{F\_I}$	2467		Drag exposed area, m²	A_T	1,53
Submerged weight, N	$\boldsymbol{F\_G}$	31304		Wave drift force, N	$\boldsymbol{Fwx}$	5726
Displaced mass, kg		808,96		Drag sea current, N	$\boldsymbol{F\_Dx}$	70,92
Max added mass, N	$\boldsymbol{F\_A}$	499,01		Excess power, W	P_E	300,00
Max resistance of the propellers, N	$\boldsymbol{F\_R}$	12523		Equivalent speed, m/s	u_F	2,30
Cross-sectional area (Betz), m²		19		Power required, W	W	9923
Rotor diameter, m		4,9		Turbine inclination, deg	θ	1,33

Another issue that should be taken into account for calculations is that the cable should also be tight when the turbine goes down. Resistance of the propellers may affect the descent and thus, must be properly compensated by the turbine submerged weight. The contribution of added mass, drag and inertia is also important. In principle, the submerged weight may be lower, however in such case, the propeller resistance must be reduced on the descent (by changing the angle of attack). It is also required that the projected power production should be physically possible at the suggested sea state. The above requirements are formulated as

$$\begin{gathered} \theta > 0 \\ F_G > F_R + F_I + F_A + F_{DTz} \\ W < P_w \end{gathered} \tag{17}$$

4. Conclusions

The above calculations show that the balance of forces is possible, and the produced energy is enough to supply the floater for propulsion. In the solution, we used the most probable sea state in the North Atlantics. Other scenarios can be also be replayed using the attached calculation Excel sheet.

We suggest that the floater is designed such that the heave response to waves remains stable (close to 1) for the most of wave periods. This assures that the system will function at all sea states.

Since the inclination angle is rather small, we suggest that installation of the transversal flaps is not necessary, and the rotors do not need specific joints. The analysis shows that it is completely fine to have the turbine slightly inclined. The increased resistance by the sea current can be compensated by the propulsion.

In terms of excessive energy that is drawn by the onboard systems, we observe that it is very hard to deliver much. Thus, alternative sources should be considered for better energy balance, such as solar panels.

Finally, we conclude that the concept proposed by WaveCo is physically feasible, and there is a room for fine adjustments. Thus, it will be possible to find the most suitable solution both in terms of production and efficiency.

The future work can be continued by considering the system dynamics in more details. Energy production must be assessed at various sea states and each component can be studied more thoroughly.

5. References

[1] O. Faltinsen. Sea Loads on Ships and Offshore Structures. Cambridge University Press, 1993.
[2] DNVGL-CG-0130 Wave Loads. Class guideline, 2018.
[3] DNV-RP-H103 Modelling and Analysis of Marine Operations. Recommended practice, 2014.
[4] Herbich, John B. Handbook of coastal engineering. McGraw-Hill Professional, 2000.