A PRELIMINARY PROPOSAL FOR A FLOATING, PHASE CONTROLLED WAVE ENERGY CONVERTER WITH HYDRAULIC MACHINERY FOR OPTIMUM CONTROL AND PRODUCTION OF USEFUL ENERGY

by

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ABSTRACT

In this report a proposal for a new wave energy converter (WEC) is given, incorporating such ideas as phase and amplitude control and force compensation. The WEC consists of a semi-submerged spherical buoy, which can perform heaving oscillations relative to a strut connected to a submerged plate, against which the vertical wave force on the buoy can react. The sphere and the plate are also interconnected by a pair of pistons and cylinders, which work as hydraulic pumps. The hydraulic system is used to obtain both phase and amplitude control for the buoy's motion, and to extract useful energy from the system. Electric power is produced by an electric generator, run by a hydraulic motor. Gas accumulators are used to smoothen the output energy on a short time scale.

A description of force compensation, based on the long-wavelength approximation, is given. On this basis the dimensions of the sphere and plate are chosen so that force compensation is obtained for the desired wave periods. This means that the vertical wave force on the sphere and on the plate are approximately equal, but in opposite directions.

Based on previous design work, on other WECs, a description of the different components is given, and realistic dimensions are proposed. A description is also given of the hydraulic system, and several different ways to implement it are discussed.

Moreover, a WEC without the submerged plate is proposed. Here the strut is connected to the sea floor through a universal joint and an anchor.

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1 INTRODUCTION

During the last 20 years considerable theoretical and experimental work has been done on wave energy conversion in several countries. At the Norwegian Institute of Technology (NTH) this work started in late 1973, and has led to a large number of different ideas for wave energy converters (WECs).[1,2] Some of the proposals were abandoned after a short time, while others were given a more thorough investigation. For some of the WECs preliminary designs were made, and model experiments were carried out.

It is our intention to combine the best ideas from these earlier proposals, to incorporate recent developments and the experience which has been gathered, in order to come up with a proposal for a cost-efficient WEC. Three concepts, in particular, are interesting. Model E is a cylindrical buoy with a hemispherical bottom, and the buoy is moored to the sea floor by a pretensioned cable.[3] Hydraulic machinery is used to extract energy from the motion of the buoy relative to the pretensioned cable, and it is also used to control the phase and amplitude of the buoy's motion. This project was a collaboration between Kværner Brug A/S (Kvaerner) and Institutt for Eksperimentalfysikk (NTH).[4] Model M2 is a cone-shaped buoy,[5] moving along a strut which is connected to the sea floor through a universal joint and an anchor. Energy is extracted by a pneumatic pump, and phase control is obtained by means of a mechanical latch.[6] Model N2 differs from model M2, in that the hull of the buoy is spherically shaped with an opening to the sea at its lower end. The water surface inside the buoy is used as a kind of piston, forcing air through a system of rectifying valves and an air-turbine.[7]

The WEC we propose here is, as the three concepts mentioned above, a point absorber.[8,9] That means the extension of the absorber is short compared to the typical wavelength. An advantage with point absorbers is that the maximum amount of converted wave energy, relative to the size of the absorber, is large compared to larger types of absorbers. However, the smaller the size of the absorber, the narrower is its resonance bandwidth. This can be compensated for by using phase control.[10,11] This means installing a system to control the oscillatory motion of the WEC, in order to obtain optimum phase and optimum amplitude for a broader band of frequencies. The system must be able to control the motion so that the WEC will work well in irregular waves. This can be obtained by a high-efficiency hydraulic system, which is also utilized for power take-off. It is important that the system has high conversion efficiency, since it might be necessary for the WEC to reradiate energy during certain intervals, and losses will then lead to low overall efficiency. Alternatively, approximate optimum phase control may be achieved by latching the motion during certain time intervals of the oscillation cycle.[9]

One of the main problems in wave energy research is to establish a frame against which the conversion mechanism can work. This can be done by a method called force compensation,[12] which works as follows. A passive floating structure consists of a floating body fixed to a fully submerged body. These bodies are designed in such a way that the vertical force on the floating body is compensated by the force on the submerged one. Hence, although the structure may have to endure a large internal force, the resultant force on the structure is small. In the WEC the relative motion between the floating body and the submerged body is utilized. Since the forces on the two bodies are in opposite directions, the relative motion is large, and a conversion mechanism can work between them.

2 DESIGN BASED ON HYDROSTATIC AND HYDRODYNAMIC CONSIDERATIONS

A sketch of the proposed WEC is shown in figure 1. The main body of the converter is a semi-submerged spherical hull, connected to a submerged plate by a strut and two pistons and cylinders. The spherical hull is allowed to move along the strut, with the pistons damping the motion. A spherical hull is chosen[2,7] because model tests have shown that this shape gives less bending moments on the strut, thus drastically reducing the weight of strut, compared to for instance a vertical cylinder with hemispherical bottom. Moreover, due to the doubly curved surface of the hull, it is a relatively stiff structure, and an improved economy of construction material is obtained. The diameter of the sphere is chosen to be 10 m, as this is considered to be an efficient size for a point absorber when the wave periods are from 6 to 12 seconds.[9]

The size and submergence of the plate must now be chosen so that force compensation is obtained for the desired range of wave periods. How this can be done is described in Appendix A. It is found that if the plate has a radius of 9.5 m and a submergence of 16 m, reasonably good force compensation is obtained for wave periods between 5 and 10 seconds. These calculations are estimates, based on a long-wavelength approximation. An additional force on the plate is due to viscous drag. This is not taken into consideration here. When this force is included the desired effect can probably be obtained with a somewhat smaller plate.

Let us next consider the masses in the system. When the sphere is floating alone, its lowest part should be submerged no more than 2 m below the water surface. This gives a submerged volume of 52.5 m^3, and the mass of the sphere should be approximately 54 Mg (tonnes). A vertical oscillation amplitude of 3 m (considered to be the buoy's design amplitude) is then possible without loosing the tension in the piston rods.

When the whole system is combined the sphere should be semi-submerged. The volume of the hemisphere is approximately 257 m^3. This means the rest of the WEC (the strut and the plate) should have a net weight (gross weight minus buoyancy) of 2.05 MN.

3 COMPONENTS

We have now determined the main dimensions of the WEC. The next step in the design process is to consider each of the components in the system, and check whether our choice of dimensions is practically feasible. The most important components are listed in table 1 and 2, with descriptions and approximate masses.

According to table 2 the spherical hull, including machinery, has a total mass of approximately 60 Mg, without ballast. This is approximately 6 Mg more than desirable. If the masses of the components cannot be reduced, there are two other ways of solving the problem, either increasing the radius of the sphere, which allows more weight, or alternatively some of the machinery might be removed from the sphere and placed elsewhere, as indicated in the next section.

Provided the rest of the WEC (including ballast) has a mass of approximately 349 Mg, and a submerged volume of 136 m^3, then the net weight has the desired value

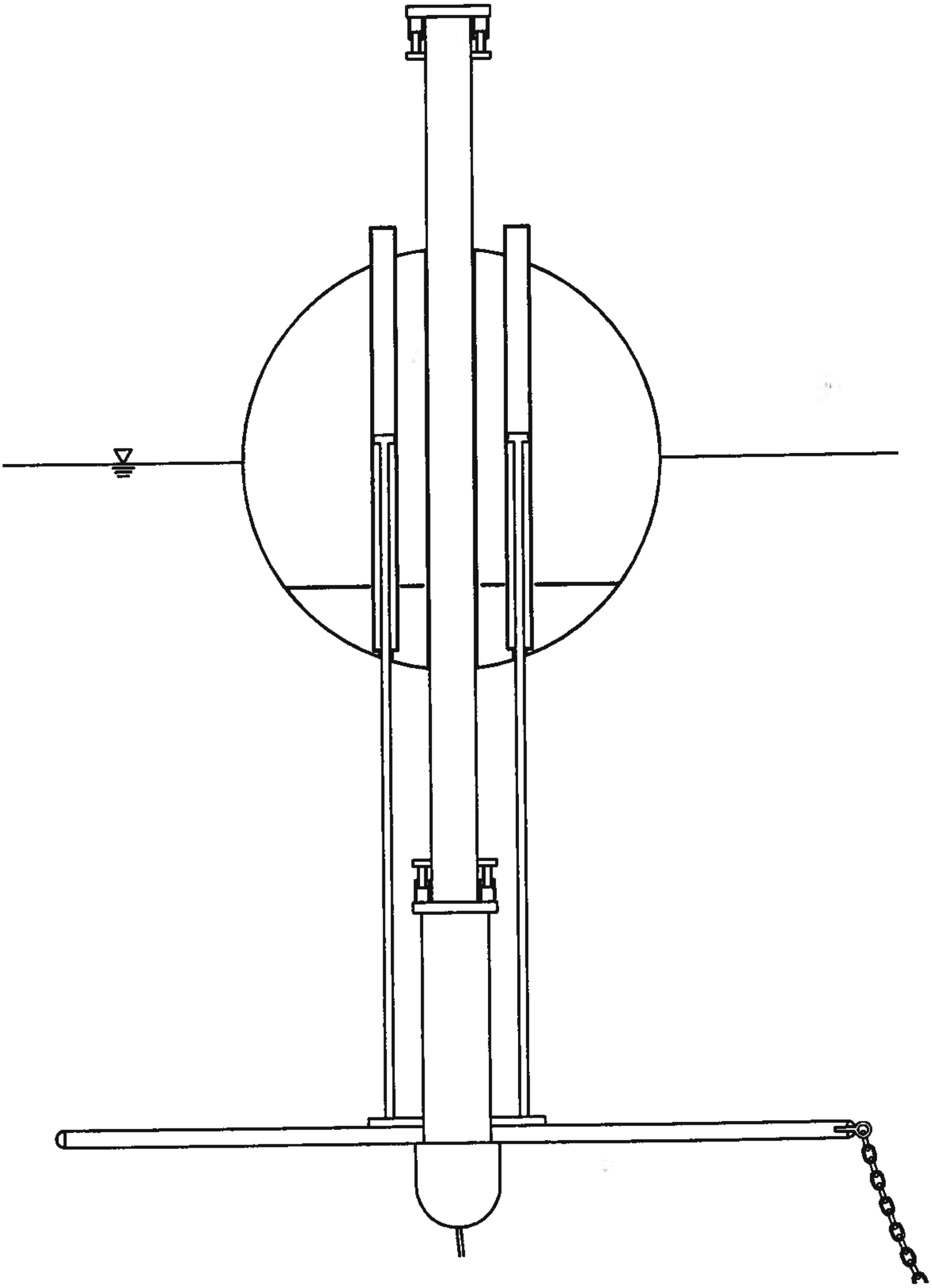

Figure 1. *Sketch of the proposed WEC. It consists of a semi-submerged spherical hull interconnected to a submerged plate by a strut and two pistons and cylinders. Energy is extracted from the system by a hydraulic system and the oscillation of the sphere is restricted by two end-stop devices. The submerged plate is used as a frame of reference, against which the vertical wave force on the sphere can work.*

COMPONENT	DESCRIPTION	MASS Mg (tonne)
Anchor		
Mooring chain		
Stabilising mass/Keel	steel/concrete	24
Plate	reinforced concrete diameter 19 m 0.40 m thick 2.5 Mg/m^3	284
Strut, upper[7]	steel length 21.1 m diameter 1.1 m 30 mm thick walls 800 kg/m	17
Strut, lower	steel length 5.5 m diameter 1.65 m 30 mm thick walls 1250 kg/m	7
End-stop devices[6]	Standard shock absorbers can be used	2 x 4
Piston rods[13]	steel diameter 200 mm 30 mm thick walls length 17 m	2 x 2.5
Pistons[13]	steel diameter 550 mm	2 x 2

Table 1. *A list of the main components of the strut and plate, with descriptions and approximate masses. The descriptions for most of the components, as well as the indicated masses, are based on previous design work for other WECs.*

2.05 MN. The weight of the mooring chain is not included in this calculation.

The choice of dimensions for most of the components is based on components used in earlier projects, and should give realistic values. However, the plate has not been proposed previously and no calculation has, as yet, been made to see how the plate should be designed.

During the last decades developments in material technology has been rapid, and most probably steel may be substituted by other materials in several of the components.

COMPONENT	DESCRIPTION	MASS Mg (tonne)
Spherical hull[7]	steel diameter 10 m 7 mm thick walls 56 kg/m^2	17.5
Ballast in hull	steel or concrete	0
Guiding cylinder[6]	steel diameter 1.1 m length 10 m 30 mm thick walls 800 kg/m	8
Support ribs for the spherical hull	steel	2.5
Machine room floor[7]	steel 60 kg/m^2	1.5
Ladders etc.[7]		1
Hydraulic system[13,14]		
- Cylinders		2 x 3
- Gas accumulators	10 m^3	10
	1.5 m^3	2 x 2
- Valves		1
- Hydraulic motor		0.2
- Pipes		1
- Hydraulic oil	7 m^3	6
Generator	200 kW	1

Table 2. *A list of the main components of the sphere, with descriptions and approximate masses. The descriptions for most of the components, as well as the indicated masses, are based on previous design work for other WECs.*

This can save weight, and lower the construction costs. This possibility has not yet been examined.

4 THE HYDRAULIC SYSTEM

A diagram of the hydraulic system is shown in figure 2. This system is based on discrete control of the motion (latching), and not continuous control.[10] How the system is supposed to control the motion of the buoy, and produce energy, is described earlier.[3]

Phase control is obtained by means of an operable valve which closes or opens the connection from the cylinders to a gas accumulator placed inside the hull of the buoy. Amplitude control is achieved through two check valves (or operable valves) between the cylinders and two gas accumulators, one high pressure accumulator and one low pressure gas accumulator. The pressure difference between these accumulators is used to run a hydraulic motor, and produce useful energy. Alternatively those two gas accumulators could be placed outside the buoy and they could be common for a group of buoys.[4] These accumulators could then be placed on shore, on the sea floor or in a floating structure. In that case the connection between the two gas accumulators and the two valves could be accomplished by means of a pair of hoses. At this point there are two considerations to be made. The volume flow from the cylinders to these gas accumulators is large and occurs only in short periods. This means the hoses will have to have large cross-section, if losses are to be kept at a minimum. It is also desirable to use the gas accumulators for short-time energy storage, in order to smooth out the output electric energy. This means the gas accumulators will have to be large, and it will not be desirable to place them inside the hull. These problems can be solved by having smaller gas accumulators placed inside the buoy, connected to larger external accumulators, which are common for a group of buoys. The accumulators inside the buoy smooth out the volume flow over one wave period, and reduces the maximum instantaneous fluid flow through the hoses. The larger accumulators outside the buoy store energy over several wave periods. It has been suggested that it is desirable to store energy corresponding to the energy production during one hundred seconds,[15] in order to give an electric output that is not varying rapidly.

The pistons shall at equilibrium carry a net weight of 2.05 MN. Assuming an equilibrium pressure of 5 MPa, we suggest the following specifications for the hydraulic system.

Piston rod	diameter 0.20 m
	length 17 m
Cylinder	diameter 0.55 m
	net piston area 0.20 m^2
	length 10 m
	volume 2 m^3
Gas accumulators	high pressure 1.5 m^3
	low pressure 1.5 m^3
	accumulator for storage of reactive energy 8 m^3
Tank	2 m^3
Motor	$\Delta p = 5$ MPa
	1800 rpm
	displacement volume / revolution = 0.0015 m^3
	P = 200 kW

It is not yet clear what kind of hydraulic motor is preferable. It has previously been proposed to use a Pelton turbine. If the pressure difference between the gas accumulators is large the efficiency can be good. It is then necessary to use a nozzle to control the liquid flow.

There are also other kinds of hydraulic motors that have the desired qualities. It has to have variable displacement volume, high efficiency and be able to work at the

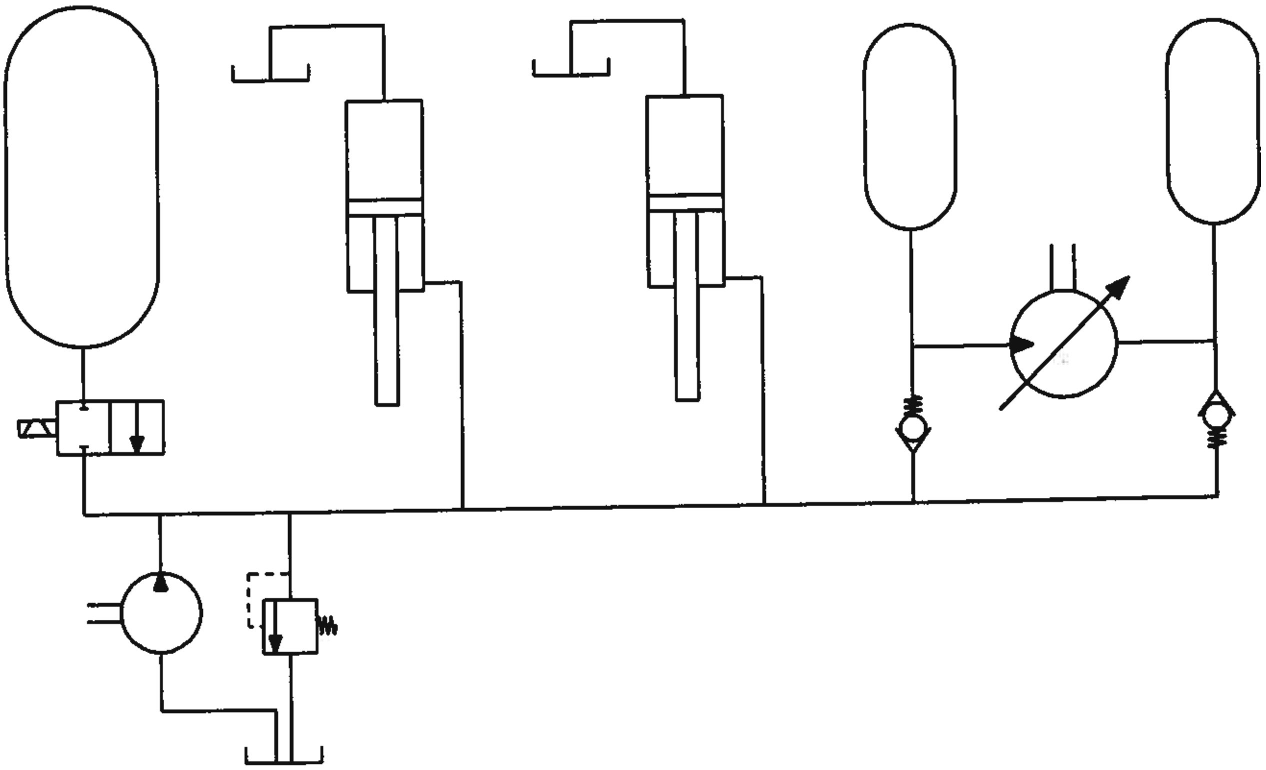

Figure 2. *Sketch of the hydraulic system proposed for phase control, amplitude control and power take-off. In addition to the components shown, filters have to be added and all the valves will have to have some sort of control mechanism.*

desired pressure and volume flow. For this purpose axial piston motors and wing motors seem most suitable. When a motor is chosen it might be necessary to change the specifications of the hydraulic system, so that the pressure over the motor and the liquid flow gives the best possible efficiency.

When the capacity of the hydraulic motor and the electric generator is to be decided, economic considerations have to be taken. The motor should run at full capacity for as much of the time as possible. Calculations will have to be done giving the percentage of time of the year in which the absorbed power exceeds indicated values, and on this basis it will be possible to determine the most cost efficient size of motor and generator.

5 AN ALTERNATIVE PROPOSAL

Figure 3 shows an alternative to the previously proposed WEC. Here the semi-submerged sphere is moving along a strut which is connected to the sea floor through a universal joint and an anchor. The hydraulic system and the sphere are equal in the two proposals, but here the piston rods are connected to a plate together with the lower end-

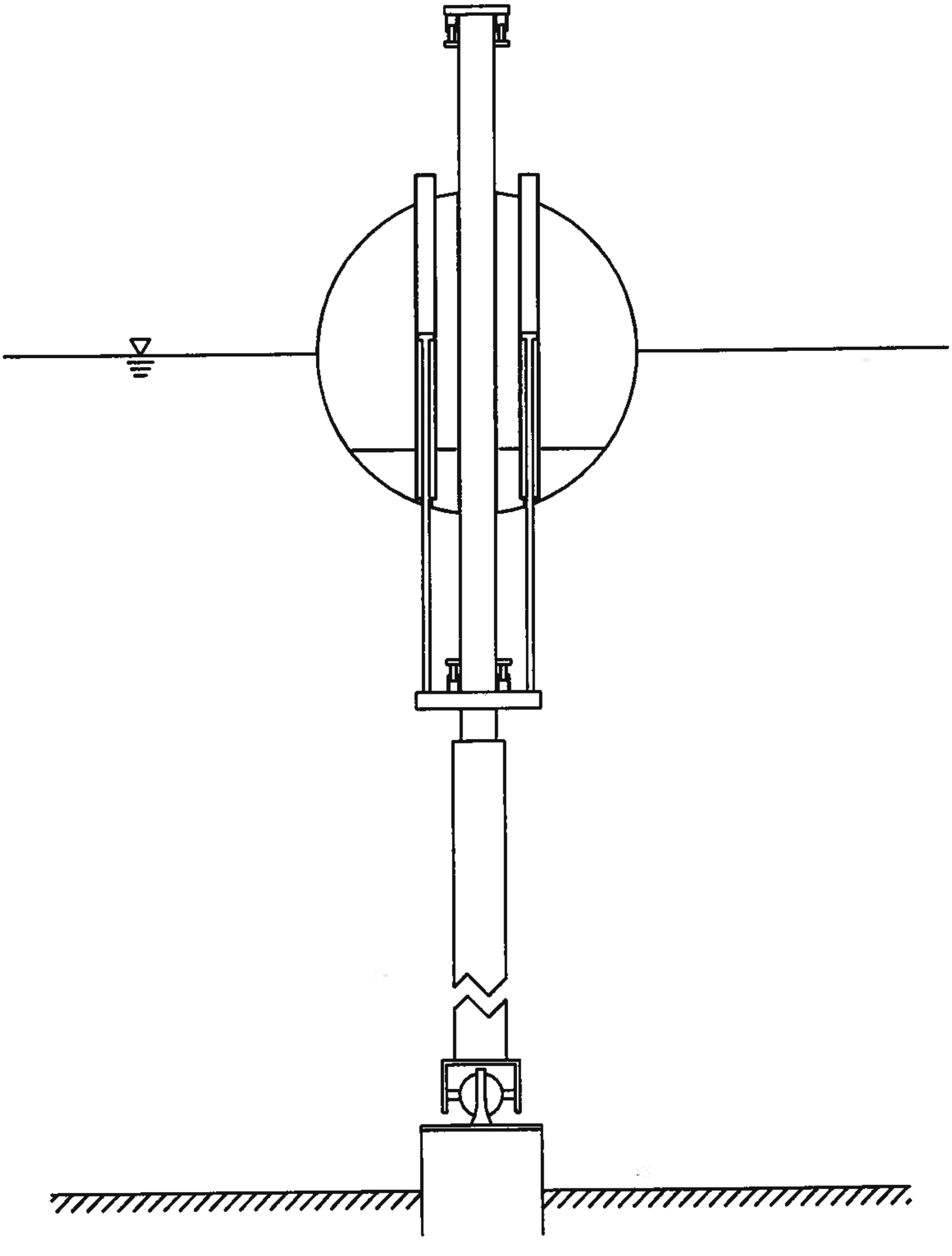

Figure 3. *An alternative proposal for a WEC with phase and amplitude control. The strut is here connected to the sea floor through a universal joint and an anchor, and there is no plate for force compensation.*

stop device. This plate is connected to the upper part of the strut. The advantage with this system is that the mooring is simpler, compared to the floating WEC. Moreover, the weight of the system is not so critical. However, the bending moments in the strut might become larger than with the submerged plate, and this WEC must be adapted to a specific water depth, and can not easily be moved once it is installed.

Problems occur if the difference between high and low tide is large. In this case some kind of arrangement has to be made so that the upper part of the strut adjusts itself vertically, so that the sphere always has its equilibrium position at the same point on the upper strut, independently of the water level. This might for instance be achieved by a hydraulic cylinder connecting the upper and lower part of the strut. When the water level rises the mean pressure in the cylinders rises, and the hydraulic cylinder connecting the two parts of the strut extends. When the water level decreases, the mean pressure in the cylinders is reduced, and the hydraulic cylinder contracts. There are probably also several other ways of solving this problem of tidal compensation.

6 ACKNOWLEDGEMENTS

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7 APPENDIX A FORCE COMPENSATION

A main problem in wave energy research is to establish a frame against which the wave forces can work. A floating structure which follows the elevation of the sea, and hence has no relative motion to the waves, cannot absorb any wave energy.

Force compensation is obtained in the following way.[12] A passive floating structure consists of a floating body fixed to a fully submerged body. These bodies are designed in such a way that the vertical force on the floating body is compensated by the force on the submerged one. Hence, the resultant force on the structure is small. As a consequence, only small vertical motions are induced.

We shall here exploit this effect in our WEC, although for a somewhat different purpose. The WEC consists of a semi-submerged sphere connected by a strut to a fully submerged circular plate. The sphere is allowed to oscillate along the strut, and energy can be extracted from the relative motion.

In order to determine, approximately, the dimensions of the structure that give force compensation for the desired frequency interval, a simplified mathematical description of the wave forces on the structure is used.[12] We apply the long-wavelength approximation (small-body theory), which is valid when the extension of the body is much shorter than the wavelength.

Let us first consider the force on the floating sphere. The vertical force amplitude is[16]

$$F_s = (\rho g S_w - \omega^2 \rho V_s (1+\mu_{33s}))A \tag{1}$$

where ρ is the density of water, S_w is the water plane area, ω is the angular wave frequency, V_s is the volume of the displaced water, μ_{33s} is the added-mass coefficient and A is the wave amplitude.

The heave force on the submerged, horizontal circular plate is

$$F_p = -\omega^2 \rho V_p (1+\mu_{33p}) \exp(-kz_p) A \tag{2}$$

where z_p is the submergence of the plate, μ_{33p} is the added-mass coefficient of the plate and V_p is the volume of the plate. It is assumed that the separation between the bodies is so large that hydrodynamical interaction effects are negligible. An additional force on the plate is due to viscous drag. This is not taken into consideration here. There is also viscous drag on the sphere, but this is considered less important then for the plate.

The added-mass coefficient for the semi-submerged sphere is approximately[17,18,19]

$$\begin{aligned}
\mu_{33s} &= (1+k_0)\mu_G - k_1 - 0.01\,k_2 \\
\mu_G &= 0.5 + \frac{\pi 0.56^2 - kR_s \ln(3.6(kR_s)^2/0.56)}{(3.6(kR_s)^2+0.56)\,2\pi} \\
k_0 &= 0.065\exp(-40kR_s/(10+kR_s)) \\
k_1 &= 0.07/(1+4(\ln(kR_s/1.4))^2) \\
k_2 &= \{1+(kR_s-3)^8\}^{-1} - \{1+(2kR_s-2)^8\}^{-1} + \{1+(20kR_s-3)^8\}^{-1}
\end{aligned} \tag{3}$$

where R_s is the radius of the sphere and k the wave number. For the added mass coefficient of the submerged plate we adopt a formula given by Patton[20]

$$\mu_{33p} \approx \frac{8R_p}{3\pi t} \approx 0.85\,\frac{R_p}{t} \tag{4}$$

where t is the thickness of the plate and R_p the radius of the plate.

The point is now to make

$$F_e = F_s + F_p \tag{5}$$

as small as possible over the frequency interval where energy absorption shall occur. Then $F_p \approx -F_s$, and the buoy's heave force F_s has a reference against which it can work. An example of this is shown in figure 4, where the forces are normalized with respect to $\rho g S_w A$. It is then possible to install a conversion mechanism between the two bodies to extract energy from the relative motion.

However, the long-wavelength approximation is valid only for kR_s up to approximately 0.5. Fortunately it is possible to find a better approximation for the excitation force on a semi-submerged sphere, using the exact reciprocity relation between the radiation resistance and the excitation force.[21] The excitation force can then be expressed as follows

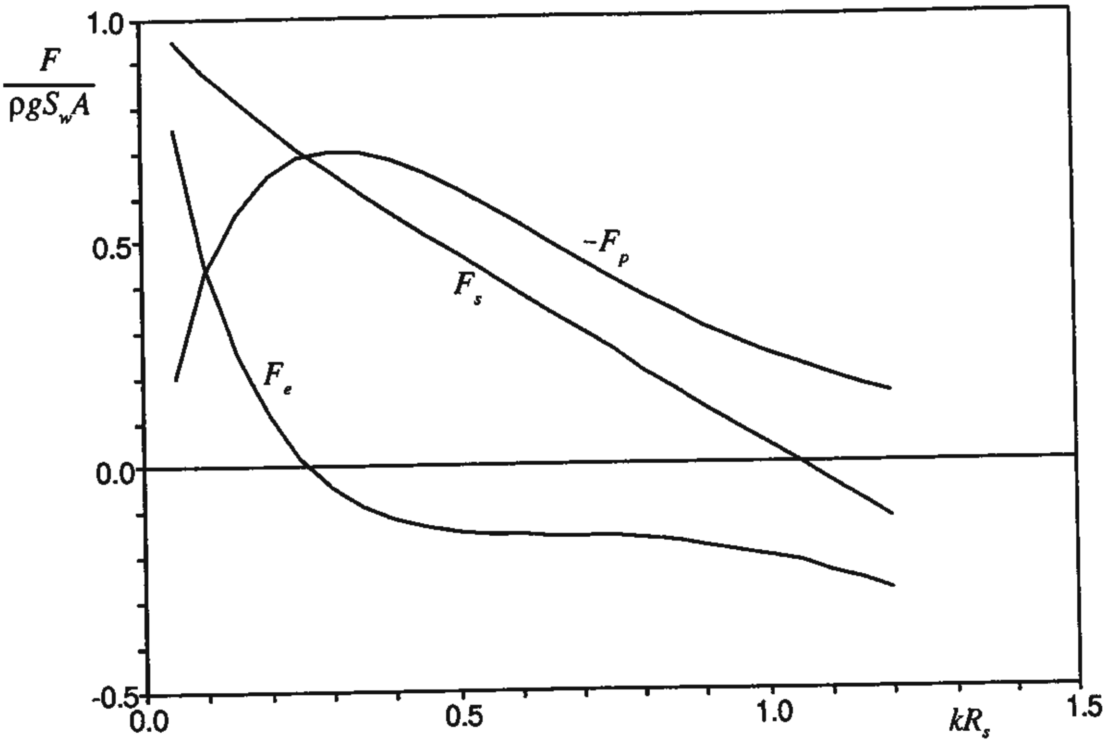

Figure 4. *Normalized excitation force on a semi-submerged sphere with radius* $R_s = 5$ *m, on a submerged circular plate with radius* $R_p = 9.5$ *m, thickness* $t = 0.4$ *m and submergence* $z_p = -16$ *m and the sum of the two forces.*

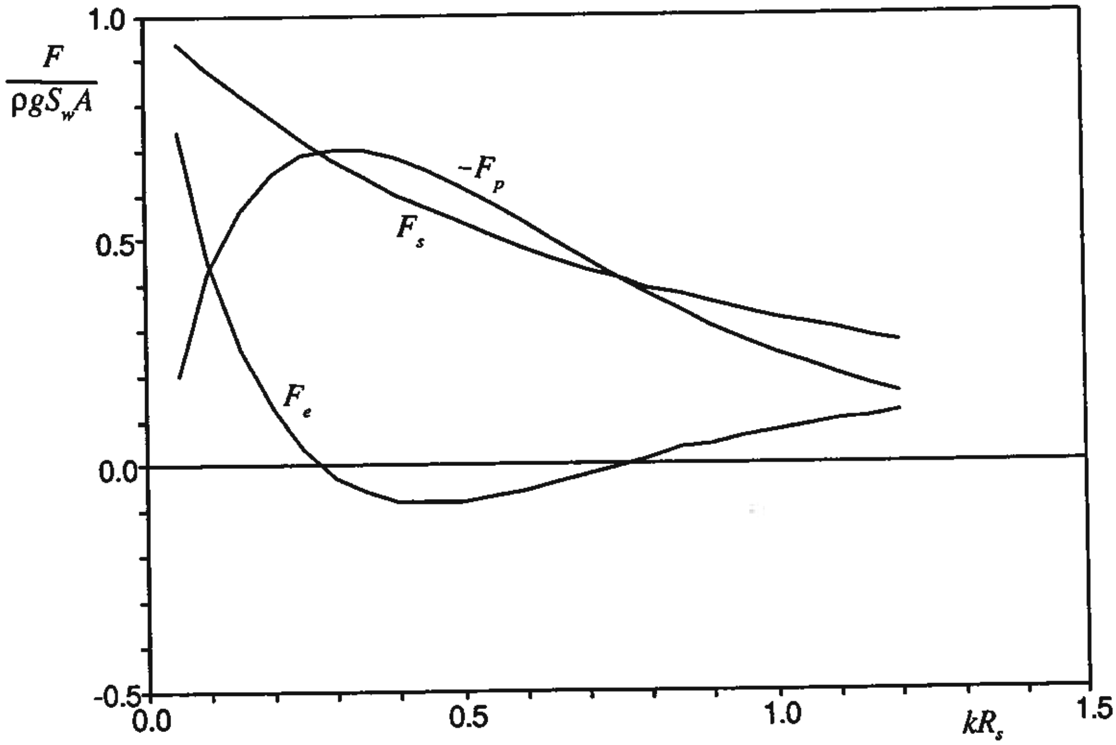

Figure 5. *Normalized excitation force on a semi-submerged sphere with radius* $R_s = 5$ *m, on a submerged circular plate with radius* $R_p = 9.5$ *m, thickness* $t = 0.4$ *m and submergence* $z_p = -16$ *m and the sum of the two forces. The excitation force on the sphere has been found by a different method, compared to the results shown in figure 4.*

$$|F_s| = \sqrt{\frac{4\varepsilon}{3\pi kR_s}}\ \rho g S_w\, |A| \tag{6}$$

where ε is the known added-damping coefficient.[17,18,19] We further note that this relation does not give the phase of the force. However, for small kR_s the excitation force is closely in phase with the wave elevation.[22]

Further, for large values of kR_s, the actual force on the submerged plate is overestimated by the long-wavelength approximation (2). Since the long-wavelength result goes rapidly to zero when kR_s increases, the error introduced should be small. Figure 5 shows the excitation force on the semi-submerged sphere obtained from equation (6) when the values for the added-damping coefficient found by Hulme[19] are used. In addition, the excitation force on the plate obtained by using the long-wavelength approximation, and the sum of the two forces are shown.

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