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Experiment on the Energy Gain of Floats-Type Wave Generator

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Key Words: wave energy conversion, movable-body type, floats and counterweight, One-way clutch, multiple sets.

Abstract: Results of performance test of multi-floats type wave energy converter is presented. This system consists of several sets composed of a float and a counterweight attached at both ends of wire hanged from a pulley placed above water surface. Results of experiments performed in a water pool showed that this system works for the waves from various directions and showed total efficiency greater than 20% for wave period 2−3 seconds, wave height about 15cm. Also rough estimation of the energy gain to be expected in the actual sea has been done. As a result, energy gain is expected as 7.68kw when an energy converter of the present type with one float of 4m diameter is used at wave height 2m and wave cycle 4 second, and the value changes in proportional to the product of (float diameter)^2×(wave height)^2 ／(wave period).

INTRODUCTION:

As the living standards of human beings go up, the use of energy continues to grow. This is causing a variety of serious problems in global environment. In such a circumstances, much is expected of clean energy. Though wave energy has not been effectively used so far, it has various advantageous properties to other natural energy. Sea waves are generated by wind and propagate to other sea areas, thus transports the energy, and therefore reduces the temporal variations of energy. The density of wave energy is high near the water surface. So we only have to place energy converter linearly near the sea surface. There have been designed a variety of wave energy conversion systems among which OWC (Evans (1982), Malmo et al. (1985)) and movable body type (Hadano et al. (1998), Watabe et al. (1999)) are considered to be promising.

Authors (Hadano et al. (1998)) have developed a movable body type wave energy converter free from the problem of structural strength popular to this type, which utilizes the rotational motion of movable body as power intake. The concept of the authors' system is as below. A float and a counterweight are attached to both ends of the wire rope suspended from a pulley placed above the water surface. If the float is located on the water surface, the pulley will turn alternately by water wave motion. This alternate rotational motion is converted into a pair of opposite unidirectional rotational motions of the two shafts by one-way clutches. This is a basic element of energy conversion, and multiple basic elements are connected. The connection of multiple basic elements is done by setting chain coupling at the junctions of the shafts of individual basic elements of energy conversion. Each power of the two rotational motions of the shafts is summed up by all basic element of energy conversion, and then is combined to form a unidirectional rotational motion. The resultant rotational motion is accelerated by transmission, and then turns a generator. In this system each pair of a float and a counterweight independently moves vertically according to the change in water surface elevation at the location of each float. Since the system has a part transmitting the power by only a tension of the wire, it works flexibly responding to a complicate motion of water in wavy sea areas. Further, since the mechanical part is located above water surface and the system separates the part of energy intake and mechanical part structurally, maintenance has become much easier. Though this system is logically supposed to work irrespectively to the direction of incident wave, the evidence has not been shown.

In this paper workability of this system is examined for various directions of incident wave through laboratory experiments. Furthermore energy conversion by this system is roughly estimated by static balance consideration.

EXPERIMENT:

Experiments were performed in a water pool at Marine Engineering Experiment Site in Nippon Bunri University. The water pool has a wave maker and the test section of 40m long, 15m wide and 1m deep. The experimental model was set 17m apart from the wave maker. Fig.1 shows a simplified plan view of the model. Weight of each counterweight was set 40kg, and two types of floats were used; the one was quadratic prism type of 0.5m wide×1.1m long×0.45m high and the other was circular cylinder type of 0.7m diameter and 0.45m high. Since this model has a problem that there is fair amount of mechanical loss of the gears which sums up the torques of a pair of shafts in opposite unidirectional rotational motions in each other into a unidirectional rotation of a shaft at the last stage, all experiments were conducted without summing up the powers of two rotational motions of the shafts, i.e. only one component of the unidirectional rotational motions of the shafts was picked up. In this state the model always turns a generator utilizing the power obtained by two pairs of float and counterweight. Wave height was changed in the range about 2cm to 20cm, the period of wave cycle as 2 to 8 seconds, the water depth 0.6m. In order to test the workability of the model for various wave directions, the angle of incident wave was set at 0, 30, 60 and 90 degrees. Experimental Conditions are indicated in Tables 1 and 2.

Temporal variations of water surface elevation and the obtained electric power were examined in the experiments. In the experiments using quadratic floats, water surface was measured at point C in Fig.1, i.e. the relative position of the measurement to the model was fixed. While it was measured 2.70m apart laterally from the center of the model in the experiments using circular cylinders. Electric power was obtained from the potential difference between both ends of a resistor connected to both terminals of a direct current motor reversibly used as a generator. Electric power P at every time was obtained using the following relation:

$$P = V^2/R \tag{1}$$

Where, V is the measured potential difference, R is the electric resistance.

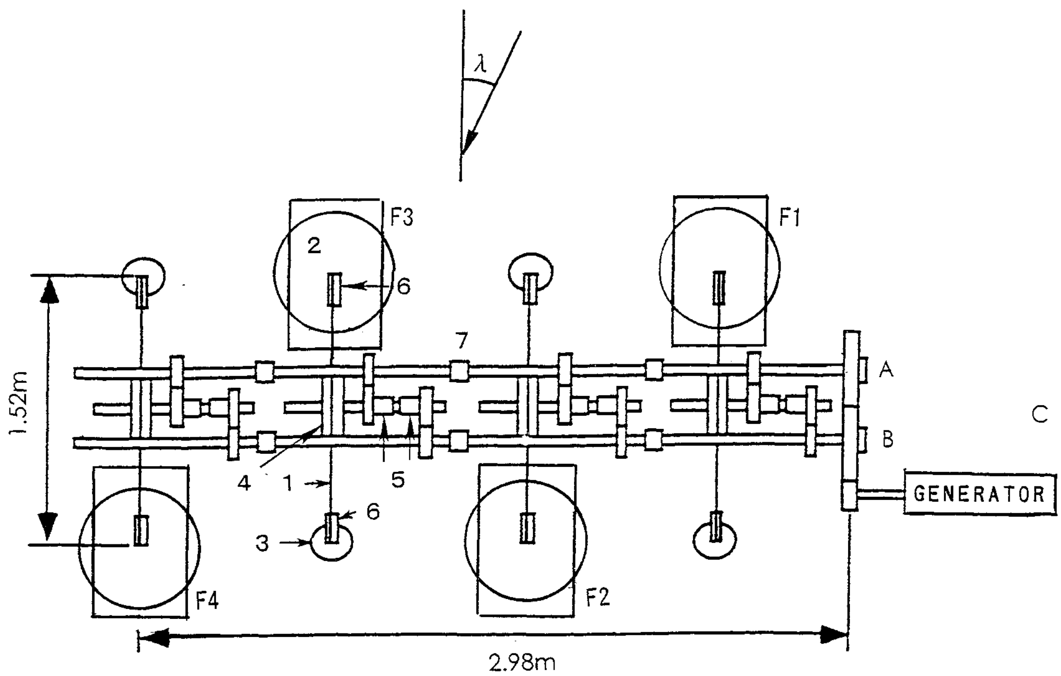


Fig.1 Simplified plans view of an experimental model. 1:wire, 2:float, 3:counter- weight, 4:pulley to extract wave power, 5:one-way clutches, 6:free pulley, 7:chain coupling, F1～F4 : floats.

Table 1 Wave condition

period (sec)	wave height(cm)	
	quadratic float	circular float
2	7.42～19.02	4.50～13.20
3	8.86～20.30	7.98～14.34
4	9.20～19.84	8.95～15.29
5	4.80～8.19	4.03～8.49
6	5.10～9.26	4.80～8.19
7	7.81～15.70	10.47～13.79
8	2.77～6.70	2.62～4.54

Table 2 Weight of the float.

λ (deg.)	float weight(kg)	
	quadratic	circular
0	71,80,100	60,80,100
30,60,90	80,100	80,100

EXPERIMENTAL RESULTS AND DISCUSSION

Fig.2 shows the examples of the temporal variations of water surface level and obtained power for the case using quadratic prism floats at T=3sec, H=11.3cm－15.0cm, weight of the float 80kg. In Fig.2(b), real line, broken line, dotted line and chain line indicate the results for λ=0, 30, 60 and 90 degrees, respectively. The change in obtained power for each angle of incident wave shows various patterns reflecting the different phase shifts of water surface elevation at the positions of individual floats. From the figure as λ increases the time during which obtained power shows zero become short, but the maximum and mean values of obtained power reduce. This reduction of obtained power reflects the situation that only the frontal two floats can effectively extract wave energy at large values of λ since other floats come to locate in the lee. In order to indicate this situation quantitatively, the distance from the point of water level measurement to individual floats taken in the direction of wave propagation(Δx) and the time lag estimated from the time when an arbitrary particular wave crest line passes the point of water level measurement to the time when the same wave crest line passes a float in question(Δt) are calculated. The results are indicated in Table3. Minus value in the table indicates that the floats locate beyond the point of water level measurement from the viewpoint of wave propagation. The maximum time shift of passage of the same crest line experienced by 4 floats is 0.22T when λ=0degree and 0.345T when λ=90gegree. Since the direction of the rotation is complicate, further consideration along this logic does not seem so meaningful at present.

Fig.3 shows the relation between the time averaged obtained power and wave height in the case λ=0degree, where numbers near the plot indicate wave period. As was reported in the previous paper (Hadano et al. (1998)), for each cases of wave period and float type, gained energy increases as the wave height increases. The result obtained in the experiment using the quadratic prism type floats shows the larger values of gained energy reflecting a large value of the cross-sectional area Further results in the case of wave period of 2 to 3 seconds show high values of obtained power when compared to other cases with almost the same wave height. While in the case of wave period 4 seconds obtained power implies the least efficient performance. Fig.4 shows results of total efficiency. Similar to Fig.3 efficiency increases as wave height increases. This seems to indicate that as wave height increases wave energy is effectively transferred into electric energy overcoming mechanical loss.

Table 3 Distance and time lag of individual floats from the point of water level measurement along the wave propagation.

		Float1	Float2	Float3	Float4
λ (deg.)	Δx(m)	-0.760	0.760	-0.760	0.760
0	Δt(s)	-0.329	0.329	-0.329	0.329
λ (deg.)	Δx(m)	0.542	2.258	1.342	3.058
30	Δt(s)	0.235	0.978	0.581	1.324
λ (deg.)	Δx(m)	1.698	3.151	3.084	4.537
60	Δt(s)	0.735	1.364	1.335	1.964
λ (deg.)	Δx(m)	2.400	3.200	4.000	4.800
90	Δt(s)	1.039	1.385	1.732	2.079

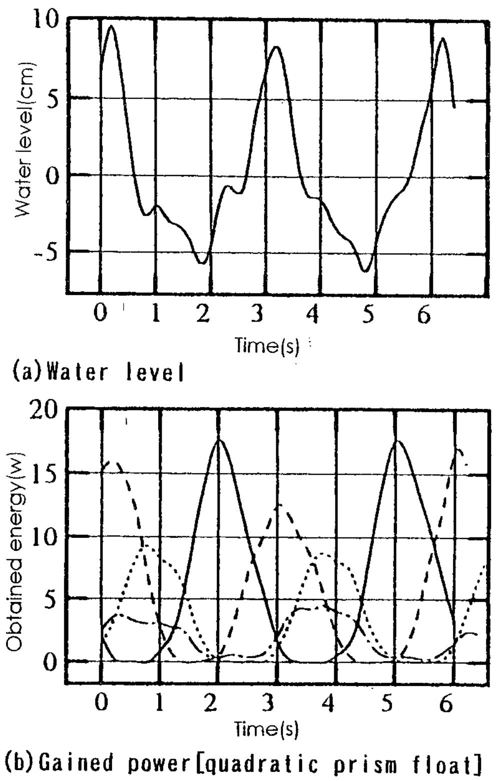


Fig.2 Temporal variations of water level and obtained energy. In (b) real line, broken line, dotted line and chain line denote the results of λ=0,30,60and 90degrees respectively.

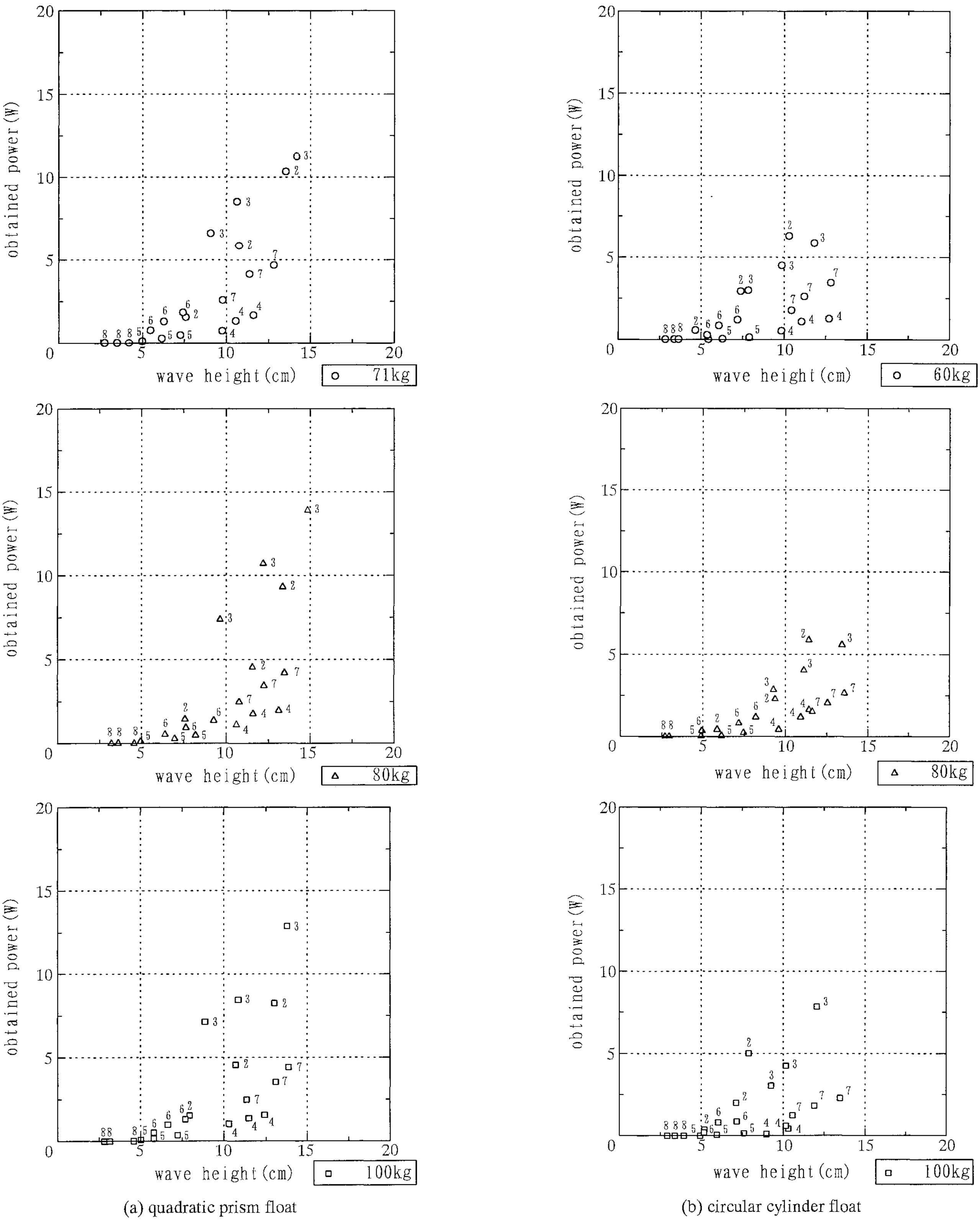
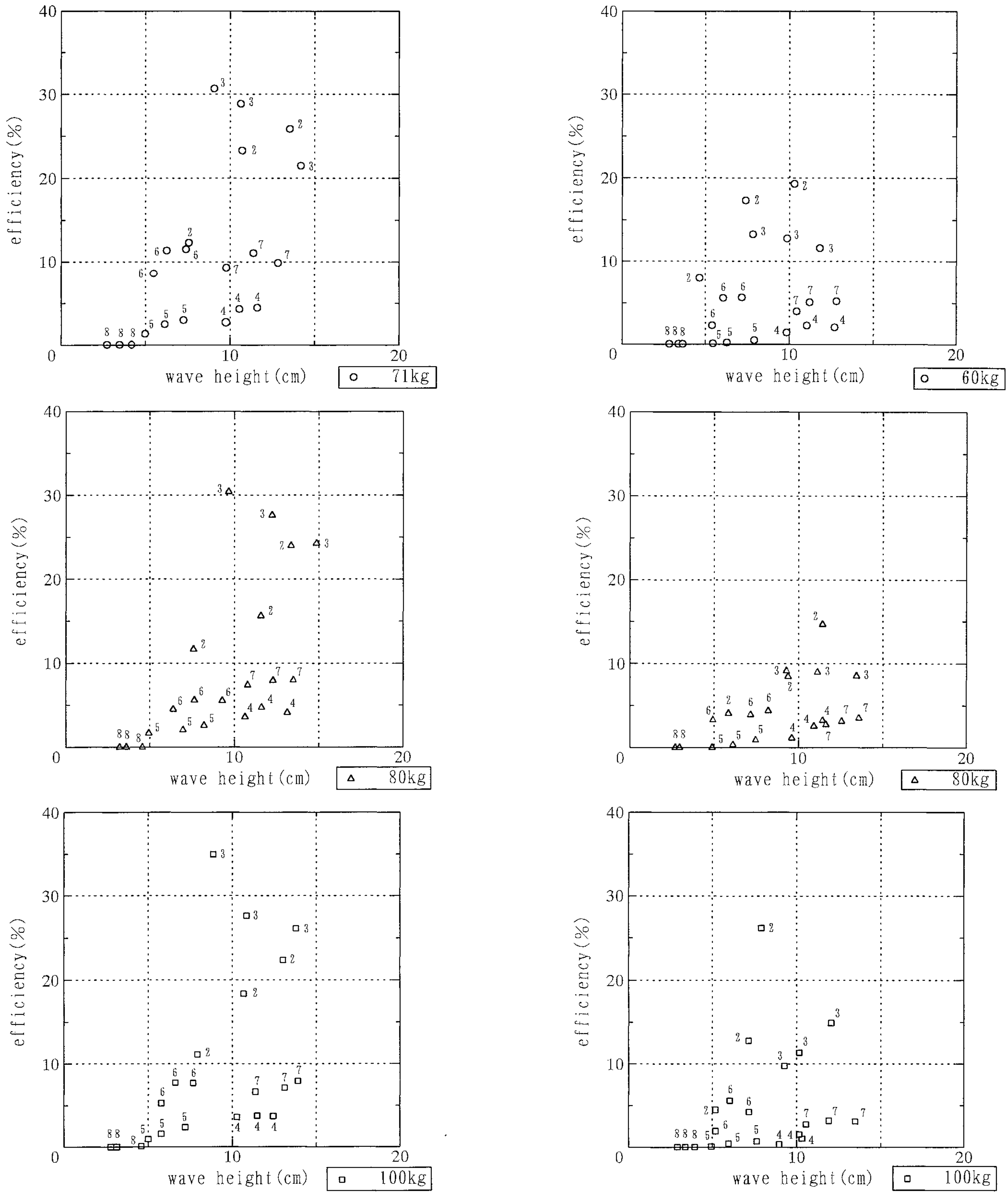


Fig.3 Relation between obtained energy and wave height for λ =0degree.



(a) quadratic prism float

(b) circular cylinder float

Fig.4 Relation between total efficiency and wave height for λ =0degree.

CONSIDERATION OF MODEL IMPROVEMENT FOR PRACTICAL USE

Fundamental performance of the system has been examined by water pool experiment. The most serious problem of the experimental model shown in Fig.1 is that when the torques of the two shafts are summed up, the resultant total power obtained becomes lower than that obtained for one shaft case. Indeed power that can be extract is twice that of the one shaft case. This contradiction must have resulted from the mechanical loss due to the rust on the cog of the gears at the last stage. The gear should be enveloped in the casing. Further it is complicate to construct the system with two shafts, particularly misalignment will easily arise when connecting several energy converting elements. So we design the system connecting multiple energy conversion elements each of which creates a unidirectional rotational motion of one shaft and whose gear part is enveloped by casing. A brief sketch of the improved energy converting element is indicated in Fig.5. Pair of one-way clutches is set on the axis so as to rotate gear and sprocket in the same direction finally.

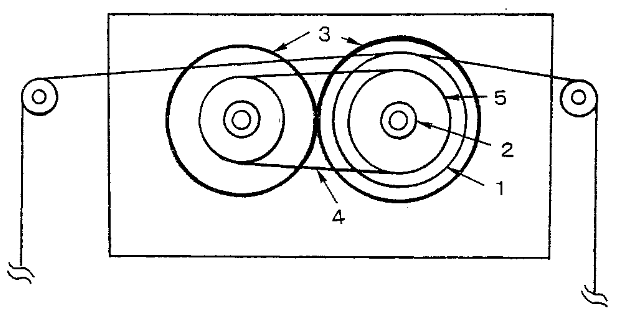


Fig.5 Improved energy converter element. 1: pulley to intake wave power, 2:one－way clutches, 3:gears, 4:chain, 5:sprocket

RELATION BETWEEN DIMENSIONS OF THE PARTS

Relation between dimensions of the parts, particularly the relation between weights of float and counterweight is important in designing the system. Here we attempt to give a rough estimation of the relation and expected energy gain. Fig.6 shows the simplified sketch of the model.

Let us put the volume and weight of a float as Vf and Wf, weight of counterweight as Wc, buoyant force acting on the float as B, radius of the pulley as R, torque needed to rotate generator at

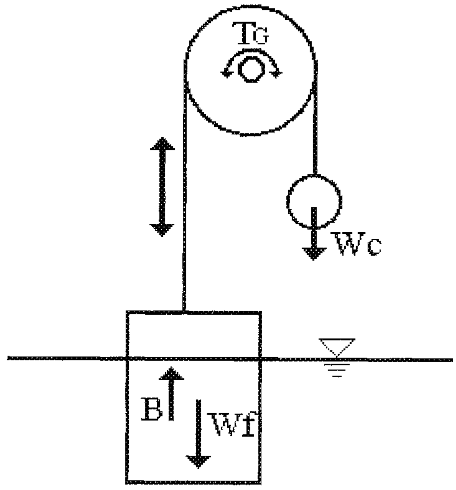


Fig.6 A sketch to evaluate expected energy gain.

pulley point as TG, unit weight of the water as w, specific gravity of the float S, ratio of submerged volume of the float to total volume of the float as α. Further suffix 0 is attached to the value at free state that only gravity and buoyancy forces acting on the float balance the gravity force acting on the counterweight. Balance of forces in this state is

$$W_f - W_c - B_0 = W_f - W_c - \alpha_0 w V_f = 0 \qquad (2)$$

Now we consider the situation in which system works as an energy converter. In this situation amplitude of the vertical motion of each float is smaller than that of water level variation. This difference corresponds to energy conversion. Evaluation of the energy conversion of this system requires mechanical dynamical consideration (for example Saito et al. (1999)), which takes into account of the inertial forces of float, counterweight, fluid around the float etc. In a rough estimation of the relations between the relevant physical quantities such as weight relation between float and counterweight etc., however, such precise evaluation may not be needed. Therefore a simple static consideration may be used here. When water level is falling, balance of forces is approximated as

$$W_f - W_c - B = W_f - W_c - \alpha w V_f = T_G / R \qquad (3)$$

When water level is rising, balance of forces is approximated as the above equation with T_G negative value.

Combination of Eqs.(2) and (3) leads to the following form:

$$B_0 - B = (\alpha_0 - \alpha) w V_f = T_G / R \qquad (4)$$

This equation indicates that the change in the volume of submerged part of the float from the free state forms the torque to rotate generator. The value of α varies between α_0 and α min when water level is going down, and it varies between α_0 and α max when water surface is going up. The forms of α min and α max are given as

$$\alpha_{\min} = \alpha_0 - \frac{T_G/R}{wV_f} \quad \alpha_{\max} = \alpha_0 + \frac{T_G/R}{wV_f} \quad (5)$$

The weight of a counterweight to be set may be obtained as below.

$$W_c = W_f - B_0 = w(S - \alpha_0)V_f \quad (6)$$

EXPECTED ENERGY GAIN

Next wave power that can be obtained will be roughly estimated. As was referred to in the previous chapter various dynamical forces should be taken into account for precise evaluation of energy gain. But all relevant physical quantities are not determined at present and sufficient dynamical evaluation is difficult. Therefore we make a rough estimation that neglects the dynamical effects, which means the neglect of the phase shift between the vertical motion of the float and the variation of water level. The estimation given here is valid only when the period of the free mode of oscillation of the system that corresponds a response to pulse external force such as water level change is short compared with the period of incident wave. Let us put the rise of water level and float from the stationary state as η and Sf respectively, velocity at which water level and float go up as vs and vf respectively. Thus they are expressed as below.

$$\eta(t) = -0.5H\cos(2\pi t/T), \quad v_s = H\pi/T\sin(2\pi t/T) \quad (7)$$

$$S_f(t) = -S_m\cos(2\pi t/T), \quad v_f(t) = 2\pi Sm/T\sin(2\pi t/T) \quad (8)$$

Since energy extracted in this system is estimated as the work done by a wire moving against the tension exerting the wire, i.e. torque load needed to turn generator, energy gained per unit time Pf is evaluated as the time average of the absolute value of the product of the tension TG/R and the velocity of the wire running. TG/R may be evaluated as

$$T_G/R = w(\eta(t) - S_f(t))A \quad (9)$$

Where A is the cross-sectional area of a float cut by horizontal plane. And wire running velocity may be evaluated by vf. Thus the energy gained per unit time Pf may be evaluated as

$$w(0.5H - S_m)S_m A/T \quad (10)$$

This is the quadratic equation with respect to Sm, which varies by controlling the excitation voltage of a generator. When excitation voltage is set so that Pf would have the maximum value, Sm becomes 0.25H ; i.e., vertical displacement of the float is a half that of water level. Then the maximum value of Pf, Pfm, is expressed as follows:

$$P_{fm} = 1/16 \cdot wH^2A/T \quad (11)$$

Note that even if control of the excitation voltage is not completely done the value of Pf is expected to be near the maximum value Pfm. On the other hand , energy gain has an upper limit, i.e. the energy flux which the wave brings out. So energy gain expected in the ideal state may be evaluated as follows:

$$P = Min(P_{fm}, Fe \cdot D) \quad (12)$$

where, Min is a function indicating the minimum value, Fe the energy flux of wave estimated as the energy transferred per unit time per unit length in the direction of wave crest line, and D the width of a float projected to the that direction.

Fig. 7 shows the values of P evaluated for a circular cylinder of 4m diameter at various combinations of wave height H and the period of wave cycle T. In this example, energy gain is restricted by the value of Pfm i.e., by the work due to vertical motion of float not by the energy flux of the wave. Restriction from energy flux occurs only at short wave period such as 1second or less and at large of float diameter. It is shown that energy gain not less than 1KW is expected from a energy converting element composed of one pair of a float of 4m diameter and a counterweight for the wave with wave height 1m and wave period 2 to 8seconds. Since energy is proportional to D^2, Fig.7 gives a measure of the energy gain for other diameter. A fair amount of energy gain is expected.

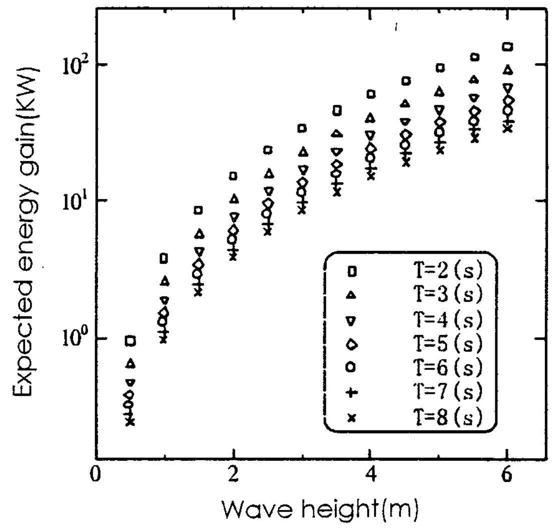


Fig.7 Expected energy gain. Float diameter 4m.

CONCLUSION

So far performance of the wave energy converting device that the authors are developing has been examined experimentally. And the energy gain has been roughly estimated based on the static consideration with the vision of practical use. It has been made clear that the device works when waves come from various directions. The gained energy decreases with the increase of the angle of the incident wave reflecting the situation that though the frontal float effectively extracts wave energy the other floats in the lee can not face to original wave of big wave height. The energy gain expected in the practical use may be estimated by Fig.5 considering the fact that energy gain of this device is proportional to the cross-sectional area of the float in the range of interest condition in practice. The estimation given in this paper, however, neglects the effects of dynamical factors such as inertial forces. We should determine various relevant physical quantities of parts for prototype structure then evaluate the energy gain based on the dynamical equations.

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