A Seesaw Shaped Floating Wave Energy Converter

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Abstract— **A floating seesaw shaped Wave Energy Converter (WEC) is proposed, composed of double pontoons and a vertical damping plate deep into water. The double pontoons are shaped in cylinder, and are rigidly connected. A damping plate is placed deeply underwater, connected with the double pontoons by a slender rod. Roll moment will be generated when ocean waves hit surface floated double pontoons, and a generator is placed to convert this roll moment into electricity. The motion model of the WEC is set up to estimate averaged power.**

Keywords——**wave energy converter, seesaw WEC, floating WEC, vertical damping plate, modified Morison's equation**

I. INTRODUCTION

Twin-pontoon typed floating wave breaker is a popular type, used to attenuate oceans waves passing it[1]-[3]. We have proposed a seesaw shaped WEC (wave energy converter) trying to exploit the possibility to harvest wave energy instead of simply attenuate it.

II. THE SEESAW SHAPED FLOATING WEC

The seesaw shaped WEC is illustrated in Fig. 1, it is composed of a twin-pontoon floating body, a submerged vertical damping plate, and a rod is used to connect these 2 parts.

This type of WEC is designed to capture wave energy by its roll motion. When beam waves passing through it, roll motion will be generated, and relative angular movements between the floating pontoons and the vertical damping plate will be created, A PTO device driven by this roll motion is used to generate electrical power.
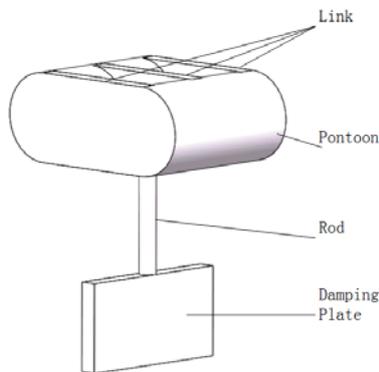
(a)
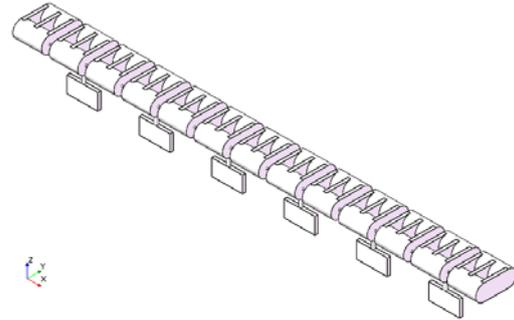
(b)

Fig.1 the Seesaw WEC, (a) individual WEC, (b)WECs in Array

III. GOVERNING EQUATIONS OF THE SEESAW WEC

Following the principles of floating body hydrodynamics, the general governing equation of Seesaw WEC is

$$(M + A)\ddot{x} + B\dot{x} + Cx = F_w \qquad (1)$$

Where M is mass and moment of inertia of the floating body parameter, A, B, C are mostly hydrodynamics parameters, and f_w is wave excitation force. As the WEC is fully symmetry, these parameters are

$$M = \begin{bmatrix} m & 0 & 0 & 0 & 0 & 0 \\ 0 & m & 0 & 0 & 0 & 0 \\ 0 & 0 & m & 0 & 0 & 0 \\ 0 & 0 & 0 & I_{11} & 0 & 0 \\ 0 & 0 & 0 & 0 & I_{22} & 0 \\ 0 & 0 & 0 & 0 & 0 & I_{33} \end{bmatrix}$$

$$A = \begin{bmatrix} A_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & A_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & A_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & A_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & A_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & A_{66} \end{bmatrix}$$

$$B = \begin{bmatrix} B_{11} & 0 & 0 & 0 & 0 & 0 \\ 0 & B_{22} & 0 & B_{24} & 0 & 0 \\ 0 & 0 & B_{33} & 0 & 0 & 0 \\ 0 & B_{42} & 0 & B_{44}+c & 0 & 0 \\ 0 & 0 & 0 & 0 & B_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & B_{66} \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{24} & 0 & 0 \\ 0 & 0 & C_{33} & 0 & 0 & 0 \\ 0 & C_{42} & 0 & C_{44}+k & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

In these matrixes, c is the damping coefficient of PTO, k is the spring stiffness of PTO. B_{22}, B_{42}, C_{22} and C_{42} are due to the existence of the vertical damping plate, their values are related to the PTO parameters k and c.

IV. INVESTIGATION WITH WAVE HYDRODYNAMICS PRINCIPLE

In this section, we will compute the wave force based on a modified Morison's equation[4],[5]. The 2 individual cylinder pontoon force and wave force of 3 links as a whole will be computed firstly, then sway force, heave force and roll moment F_2, F_3, F_4 of the whole WEC will be computed.

TABLE I
GEOMETRY PARAMETERS of Seesaw WEC

Symbol	Name	Value
L	Length	5 m
B	Beam width	6.2 m
B1	Pontoon axis distance	4 m
R	Radius of pontoon	1.1 m
L1	Width of link 1	0.05 m
L2	Width of link 2	0.5 m
L3	Width of link 3	0.05 m
D	Rod Length	10m

We will assume a first order plane progressive deep-water beam waves, wave surface elevation and velocity potential are

$$\eta = A\cos(ky - \omega t) \tag{2}$$
$$\phi = \frac{gA}{\omega} e^{kz} \sin(ky - \omega t) \tag{3}$$

For surface waves, $z = 0$, then

$$\phi = \frac{gA}{\omega} \sin(ky - \omega t) \tag{4}$$

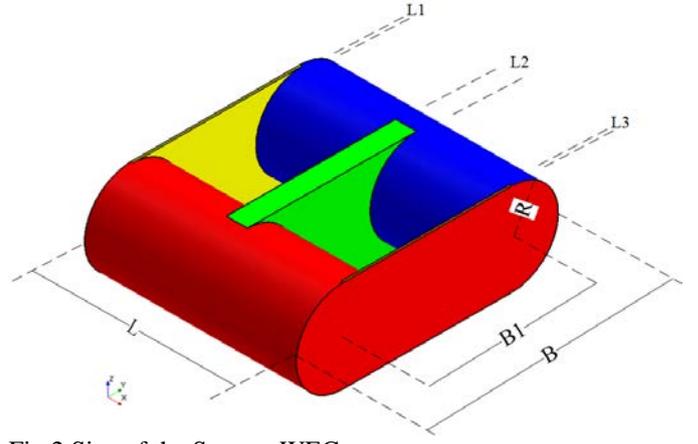Dispersion relation states that

$$k = \frac{\omega^2}{g} \tag{5}$$

Fig.2 Size of the Seesaw WEC

And the water particle velocity and acceleration are

$$u_y = \omega A\cos(ky - \omega t) \tag{6}$$
$$u_z = \omega A\sin(ky - \omega t) \tag{7}$$
$$a_y = \omega^2 A\sin(ky - \omega t) \tag{8}$$
$$a_z = -\omega^2 A\cos(ky - \omega t) \tag{9}$$

For the partially submerged cylinder

$$f_y = \frac{1}{2}\rho C_D A_y(t) u_y \sqrt{u_y^2 + u_z^2} + \rho C_M V(t) a_y \tag{10}$$
$$f_z = \rho C_M V(t) a_z + \rho g[V(t) - V_0] \tag{11}$$
$$A_y(t) = (\eta + R)L \tag{12}$$
$$V(t) = \left[\frac{1}{2}\pi R^2 + R^2 \arcsin\left(\frac{\eta}{R}\right) + \eta\sqrt{R^2 - \eta^2}\right]L \tag{13}$$
$$V_0 = \frac{1}{2}\pi R^2 L \tag{14}$$

where f_y and f_z are the horizontal and vertical components of the wave force, Ay(t) is the instantaneous immersed projected area of the cylinder in the horizontal direction, V_0 and $V(t)$ are the instantaneous and initial immersed volumes of the cylinder. C_D and C_M are the drag and inertia coefficients, the widely used values of $C_D = 1.2$ and $C_M = 2.0$ are adopted in this paper.

For 3 links, similar equations will be utilised based on the same principle. As these 3 links do not face waves directly, F_y component will be omitted.

Wave force will be computed against following parameters: wave amplitude A is 1m, period 6.2832s, and wavelength 61.6380 m. the computed wave induced sway force F2, heave force F3 and roll moment F4 are show in Fig. 3.
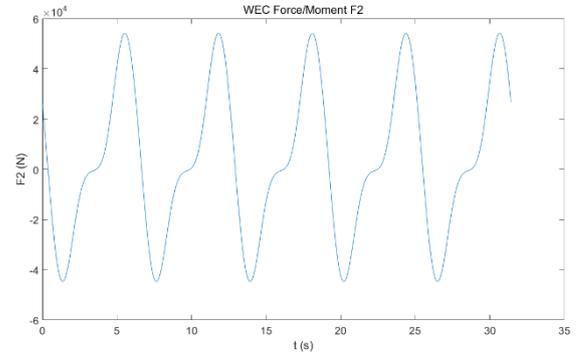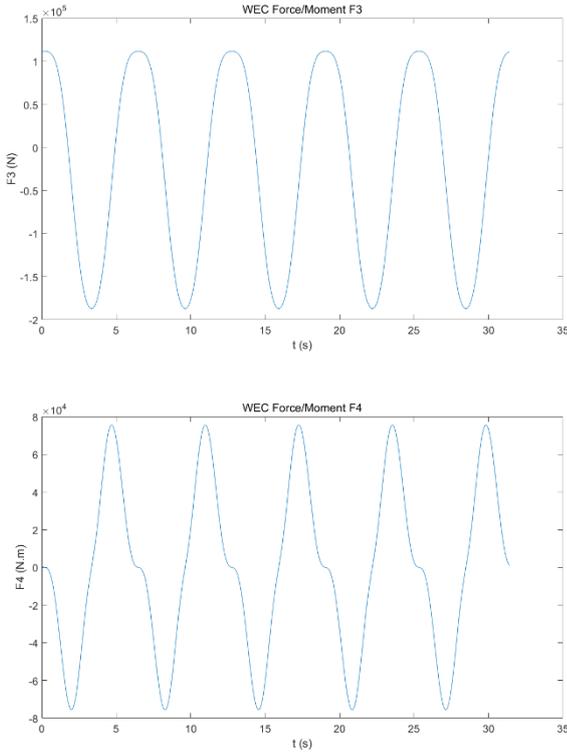
Fig.3 Wave hydrodynamics forces of the Seesaw WEC

The moment F4 can be decomposed into 3 main components with different frequencies:

$$F_4 = -6.1799e^4 sin(1*t) + 1.4678e^4 sin(2*t) + 1.0602e^4 sin(3*t) \qquad (15)$$

V. INVESTIGATION WITH MECHANICAL VIBRATION PRINCIPLE

In this section, we will analyse the WEC performance based on mechanical vibration principle. Roll motion in this device is used for power generation, and sway motion are coupled with it. The governing equation are listed as follows.

Assume

$$x = Xe^{i\omega t} \qquad (16)$$
$$f_w = F_w e^{i\omega t} \qquad (17)$$

then

$$(-(M+A)\omega^2 + B\omega + C)X = F_w \qquad (18)$$

The 2nd and 4th components are listed below. Usually these 2 coupling equations should be solved by numerical method.

$$(-\omega^2(M_{22}+A_{22}) + i\omega B_{22} + C_{22})X_2 + (\omega B_{24} + C_{24})X_4 = F_{w2} \qquad (19)$$
$$(-\omega^2(M_{44}+A_{44}) + i\omega(B_{44}+c) + (C_{44}+k))X_4 + (\omega B_{42} + C_{42})X_2 = F_{w4} \qquad (20)$$

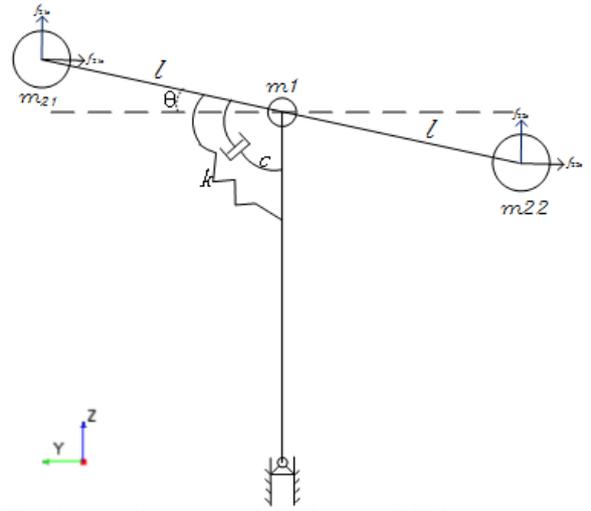Fig.4 the roll motion of the Seesaw WEC

$$M_{44} = 5252 \, kg.m^2$$
$$A_{44} = 30695 \, kg.m^2/rad$$
$$B_{44} = 210 \, N.m/(rad/s)$$
$$C_{44} = 373608 \, N.m/rad$$

The instantaneous and mean power equations are

$$\wp = cRe(\dot{x}_4)^2 \qquad (21)$$
$$\mathcal{P}_m = \frac{1}{\mathcal{T}}\int_0^{\mathcal{T}} \wp dt = \frac{1}{\mathcal{T}}\int_0^{\mathcal{T}} cRe(\dot{x}_4)^2 dt = \frac{1}{2}c|X_4|^2\omega^2 \qquad (22)$$

The amplitude of x_4 should be less than the steepness of ocean waves.

$$|X_4| \le A\frac{\omega^2}{g} = 0.1019 \qquad (23)$$

The coupling matrix element

$$B_{24} = B_{42} = c/D \qquad (24)$$
$$C_{24} = C_{42} = k/D \qquad (25)$$

D is the rod length, and is 10m here.

The coupling element is relatively small compared with the main component of equation,

If we choose

$$C_{44} + k = \omega^2(M_{44}+A_{44}) \qquad (26)$$

Then the roll motion will be in resonant state, then we choose c satisfy

$$\omega(B_{44} + c) = |\frac{F_{w4}}{X_4}| \qquad (27)$$

Ignoring B_{44}, the max power will be is

$$\mathcal{P}_m = \frac{1}{2}\sum(F_4\omega|X_4| - B_{44}|X_4|^2\omega^2) \qquad (28)$$

With the linear system assumption, max $\mathcal{P}_m$ with 3 components is about 6.265kw. This is the upper limit of wave power available; the practical power we can get will be limited due to the efficiency of mechanical transmission, electricity generator, and electricity conversion.

VI. CONCLUSIONS

A seesaw shaped WEC is proposed, and the beam wave hydrodynamics forces are computed based on modified Morison's equation. The max power that the WEC can generate is computed based on mechanical vibration theory.

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