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A Novel Mechanism that Harvests Energy via Ideal Hydraulic PTO Units

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Abstract

These days regarding to the importance of the renewable energies, lots of studies are carried out in this field. The density of the ocean wave energy is more than another renewable energy sources. In this study, a novel electro-hydraulic mechanism is presented in order to convert the wave energy into the electricity. Mechanical energy of this mechanism is provided by two plates those are hinged together and are exposed to the ocean waves. Interaction between the ocean waves and plates of the mechanism leads to generate rotational and translational motions. Each rotational motion is converted to the two translational motions, which are transferred to the electro-hydraulic systems. The equation of motion of the mechanism that is connected to ideal hydraulic power take-off (PTO) units is presented and theoretically investigated. Ideal hydraulic power take-off unit parameters effect on the plates motions and wave energy harvesting. Optimized version of this mechanism can be a good breakwater and energy harvester.

Keywords: Ocean wave energy, Energy harvesting, Renewable energy, Hydraulic power take-off unit, Hydraulic PTO, Breakwater.

A. Introduction

These days, importance of renewable energies is not hidden for anyone. There are lots of wave energy converter concepts. They can be classified into several groups based on following criteria: (a) Distance of the device position from the shore, (b) device location relative to the sea level, (c) device size and its orientation relative to the sea waves and (d) principle of wave energy extraction [1]. Breakwaters are barriers in order to protect an area against sea waves. The attached breakwaters orientation is in the direction that storm waves. De-attached breakwaters are suitable for offshore areas and are not connected to the shore [2]. Combination of wave energy converter and breakwater concepts is an intelligent way to decrease costs [3].

B. Mathematical modeling

In this study, a novel electro-hydraulic mechanism is presented in order to convert the wave energy into the electricity. Mechanical energy of this mechanism is provided by two plates which are hinged together and are exposed to the ocean waves. The first plate is hinged to a fixed frame and can only rotate about this side. The second plate is hinged from one side to the first plate and translates by the guided roller on its other side. Translational side of the plate is connected to a spring that is connected to the fixed frame as shown in Fig. 1.

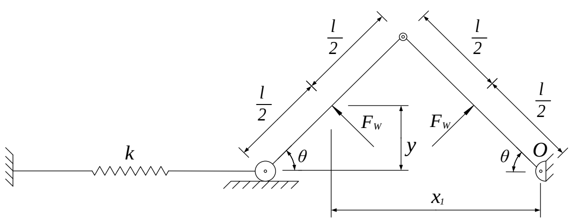

Fig. 1. Schematic of the mechanism from the top view.

Interaction between the ocean waves and plates of the mechanism leads to generate four rotational and one translational motions. Each rotational motion is converted to the two translational motions as shown in Fig. 2, which are transferred to the electro-hydraulic systems. There are two rotational motions in each plate and one translational motion duo the plate's side that is connected to the spring in this mechanism. Two ideal hydraulic power take-off units with different parameters are considered in order to generate electricity from these translational motions as shown in Fig. 3. Equation of motion of the introduced mechanism that can capture energy via PTO units is as follows:

$$\Big(I_0 + \bar{I} + 2ml^2\sin^2\theta + \frac{ml^2}{4} + \frac{4}{3}m_s l^2\sin^2\theta + \frac{5}{64}\rho\pi l^4 + \frac{1}{16}\rho\pi l^4\cos^2\theta + 0.0810\rho\pi a^2 l^2\sin^2\theta\Big)\ddot{\theta} +$$

$$\Big(ml^2\sin 2\theta+\tfrac{2}{3}m_s l^2\sin 2\theta-\tfrac{1}{32}\rho\pi l^4\sin 2\theta+ 0.0405\rho\pi a^2 l^2\sin 2\theta\Big)\dot{\theta}^2+4kl^2\sin\theta- 2kl^2\sin 2\theta+2lF_w\sin^2\theta\ -F_w l+2klpt\sin\theta+ 8F_{PTO}r(1+\tan^2\theta)+2lF'_{PTO}\sin\theta=0 \tag{1}$$

where m, l, a, t, $\bar{I}$ and d are, respectively, each plate's mass, width, length, thickness, moment of inertia about an axis passes through the center of mass and is parallel to the rotation axis of the plates and mean length that is covered by water. In Eq. (1) added masses due to the motion of the plates in fluid are considered. m_s and k are mass and stiffness of the spring and ρ is the water density. F_w is water force due to its accumulation behind the plates and wave force as follows:

$$F_w=\left[\frac{\sinh\left[K\left(h+\frac{H}{2}\right)\right]}{\cosh(Kh)}-\frac{\cosh\left[K\left(h+\frac{H}{2}\right)\right]}{\sinh(Kh)}-\frac{\sinh[K(h-d)]}{\cosh(Kh)}+ \frac{\cosh[K(h-d)]}{\sinh(Kh)}\right]\cos(Kx'-\omega t)+\rho g l\frac{\left(d-\frac{H}{2}\right)^2}{2} \tag{2}$$

where h is water depth (from the seabed to the still water level). Still water level (SWL) is the calm-water position which the Cartesian coordinate system is on it. H, λ, K, ω and g are wave height, wavelength, wave number, wave period and gravitational acceleration, respectively.

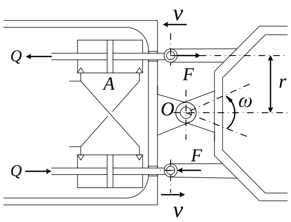

Fig. 2. Schematic of the energy transfer process.

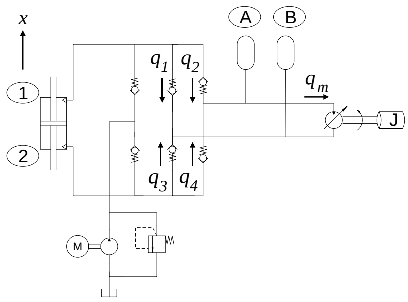

Fig. 3. Hydraulic PTO unit circuit diagram.

The mathematical model of hydraulic PTO unit circuit diagram is as follows [4]:

$$F_{PTO}=(p_1-p_2)A_p$$

$$\text{If sign}(\dot{x})>0\,,\quad A_P\dot{x}-q_1-q_2=\frac{V_1}{B}\frac{dp_1}{dt}$$

$$\text{If sign}(\dot{x})<0,\quad A_P\dot{x}-q_3-q_4=\frac{V_2}{B}\frac{dp_2}{dt}$$

$$q_1=\begin{cases}0, & p_1>p_B\\ -K\sqrt{p_B-p_1}, & p_B\geq p_1\end{cases} \tag{3}$$

$$q_2=\begin{cases}0, & p_A>p_1\\ K\sqrt{p_1-p_A}, & p_1\geq p_A\end{cases}$$

$$q_3=\begin{cases}0, & p_2>p_B\\ -K\sqrt{p_B-p_2}, & p_B\geq p_2\end{cases}$$

$$q_4=\begin{cases}0, & p_A>p_2\\ K\sqrt{p_2-p_A}, & p_2\geq p_A\end{cases}$$

where p_1, p_2, V_1, V_2 are pressures and volume of oil in the piston chambers. Also, A_p and B are the piston area and bulk modulus of the oil and p_A and p_B are accumulator pressures. K is chosen to be very large so that the pressure drop across each check valve is negligible. The flows q_A and q_B to accumulators A and B are given by:

$$q_A=q_2+q_4-q_m\,,\ q_B=q_m-q_1-q_3 \tag{4}$$

Also, q_m which is flow to the motor is obtained by

$$q_m=D_m\omega_m\,,\ \dot{\omega}_m=\frac{D_m(p_A-p_B)-T_g}{J} \tag{5}$$

where D_m, ω_m, J and T_g are the motor displacement, the motor speed, the inertia of the generator and generator torque, respectively, where

$$T_g=C_g\omega_m\,,T_m=(p_A-p_B)D_m\,,P_m=T_m\omega_m \tag{6}$$

where C_g, T_m and P_m are, respectively, damping coefficient of the generator, motor torque and mechanical power produced by the PTO. Eqs. (3)-(13) are presented for a hydraulic PTO unit that harvests energy from translation, where displacement and velocity of the piston are

$$x=2l(1-\cos\theta)\,,\dot{x}=2l\dot{\theta}\sin\theta \tag{7}$$

The mentioned equations for hydraulic PTO unit that harvest energy from rotation are same as Eqs. (3)-(8) but, their parameters are different. Also, displacement and velocity of the piston are as follows:

$$x=r\tan\theta\,,\dot{x}=r\dot{\theta}(1+\tan^2\theta) \tag{8}$$

C. Results

Equation of motion of this mechanism is related to the PTO units equations. These equations can be used to identifying essential parameters that effect on wave energy harvesting and breaking waves. In the absence of hydraulic PTO units and added mass terms, equation of motion of the physical model is verified via Adams software as presented in Fig. 4.

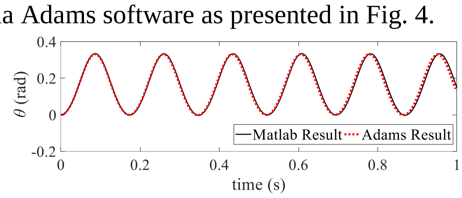

Fig. 4. Verification of results obtained from Matlab and Adams softwares.

D. Conclusion

Optimized version of this mechanism can generate electricity efficiently and protect an area against waves. Results obtained from simulation of a small physical model in Adams software are verified via equation of motion of the mechanism.

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