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Introducing a New Mechanism as a Breakwater and Energy Harvester

M. Noroozi [1], M. Tahani [2*] and A. Afsharfard [3]
[1] M.Sc. Student, [2] Professor, [3] Associate Professor
[1, 2, 3] Department of Mechanical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran

*(Corresponding Author: mtahani@um.ac.ir)

Abstract

Ocean wave energy is a renewable, dense, huge and time independent source of energy. In order to protect structures, ports and harbors against waves and converting this energy to useful form of energy, lots of studies are carried out. In this study, a novel mechanism is presented, which can break the waves and convert their energy into the electricity via an electro-hydraulic system. This mechanism consists of two plates with rotational and translational motions, which can be connected to the electro-hydraulic system. A prototype is made to study the system experimentally. The equation of motion of this mechanism is solved numerically and validated by experimental results. Finally, the wave transmission coefficients for different dimensionless incident wave frequency numbers are experimentally obtained. According to the experimental results, it is shown that the wave transmission coefficients of the prototype vary between 0.5151 and 0.7782. Therefore, it is concluded that the presented mechanism is a practical system that not only is an effective breakwater but also is a good energy harvester.

Keywords: Ocean wave, Energy harvesting, Breakwater, Vertical walls, Renewable energy, Offshore platforms.

A. Introduction

These days, regarding increasing global energy demand, limited sources of fossil fuels and their environmental impacts, renewable energies are attracted attentions. Due to the density of renewable energy sources, the first place is devoted to the ocean waves [1]. Lots of Wave Energy Converter (WEC) concepts have been developed, but few of them have been tested in the ocean [2]. According to location of WECs, they are categorized into shoreline, near-shore and offshore devices. WECs can also be classified according to the wave energy harvesting methods into three groups [3]: Oscillating Water Columns (OWCs), Oscillating bodies and Overtopping devices. A breakwater can disrupt the wave energy and protects an area against the ocean waves. There are many types of breakwaters, but they can be classified into two general types [4]: The attached breakwater and the de-attached offshore breakwater. Combining the wave energy converter and the breakwater systems, practical devices can be introduced like LIMPET [1].

B. Mathematical Modeling

In this study, a new mechanism is suggested. This mechanism consists of two plates which are hinged together. 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. When waves interact with these plates, there are four rotational and one translational motions that they can be used to generate electricity.

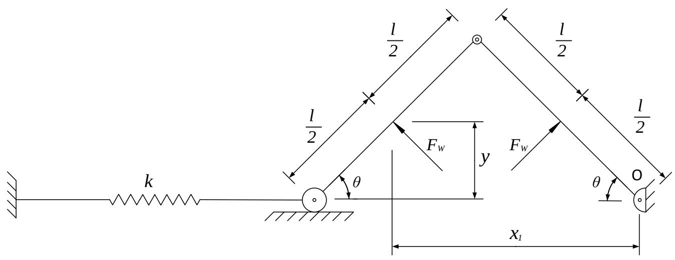

Fig. 1. Schematic of the mechanism from the top view.

Consider two plates of width l, length a, thickness t, mass m, the moment of inertia about an axis passes through the center of mass and is parallel to the rotation axis of the plates $\bar{I}$. A spring is connected to the plate with stiffness k, and one fix frame as shown in Fig. 1. θ is angle of rotation of the plates as shown in Fig. 1 and $\dot{\theta}$ is rotational velocity. x_1 and y are horizontal and vertical coordinates of mass center of the second plate, respectively. The elongation of the spring is x_2.

$$x_1 = \frac{3l}{2}\cos\theta,\ y = \frac{l}{2}\sin\theta,\ x_2 = 2l(1-\cos\theta) \tag{1}$$

Also, potential energy and total work done by external loads are as follows:

$$U = \frac{1}{2}k(x_2 + pt)^2,\ W = -F_w\, x_2 \sin\theta + F_w l\theta \tag{2}$$

where pt is change in initial length of the spring at $\theta = 0$ and F_w is the force on plates. The kinetic energy of the mechanism is due to the kinetic energy of the plates, spring and kinetic energy of added mass [5]. Body motion in a fluid causes motion of some volume of fluid around the body that adds inertia to it. This inertia is named added mess. So, total kinetic energy is

$$T = \frac{1}{2}I_o\dot{\theta}^2 + \frac{1}{2}\bar{I}\dot{\theta}^2 + \frac{1}{2}m(\dot{x}_1{}^2 + \dot{y}^2) + \frac{1}{2}\frac{m_s}{3}\dot{x}_2{}^2 + \frac{5}{8}\rho\pi\left(\frac{l}{2}\right)^4 \dot{\theta}^2 d + \frac{1}{2}\rho\pi\left(\frac{l}{2}\right)^2 \dot{y}^2 l + 0.8154\left(\frac{\rho\pi d^2}{4}\right)\dot{x}_1{}^2 t \quad (3)$$

where d, ρ, t and m_s are, respectively, the mean length of the plate that is covered by water, water density, thickness of the plates and spring mass. Substituting previous equations into the Lagrange equation, the equation of motion of the mechanism is obtained as

$$\left(I_0 + \bar{I} + 2ml^2\sin^2\theta + \frac{ml^2}{4} + \frac{4}{3}m_s l^2\sin^2\theta + \frac{5}{64}\rho\pi l^4 + \frac{1}{16}\rho\pi l^4\cos^2\theta + 0.0810\rho\pi a^2 l^2\sin^2\theta\right)\ddot{\theta} + \left(ml^2\sin 2\theta + \frac{2}{3}m_s l^2\sin 2\theta - \frac{1}{32}\rho\pi l^4\sin 2\theta + 0.0405\rho\pi a^2 l^2\sin 2\theta\right)\dot{\theta}^2 + 4kl^2\sin\theta - 2kl^2\sin 2\theta + 2lF_w\sin^2\theta - F_w l + 2klpt\sin\theta = 0 \quad (4)$$

Since the plates operate such as wall, water accumulates behind them. So, there is calm-water height behind plates and wave force which applies load on plates. Total force is

$$F_w = \left[\frac{\sinh\left[K\left(h+\frac{H}{2}\right)\right]}{\cosh(Kh)} - \frac{\cosh\left[K\left(h+\frac{H}{2}\right)\right]}{\sinh(Kh)} - \frac{\sinh[K(h-d)]}{\cosh(Kh)} + \frac{\cosh[K(h-d)]}{\sinh(Kh)}\right]\cos(Kx-\omega t) + \rho g l\frac{\left(d-\frac{H}{2}\right)^2}{2} \quad (5)$$

Cartesian coordinate system is on the still water level (SWL), which is the calm-water position. h, water depth, is from the seabed to the SWL. Wave height, H, is from trough to crest. The wavelength, λ is from crest to crest and travels in the x-direction and wave number and K equals to $\frac{2\pi}{\lambda}$. ω and g are wave period and gravitational acceleration, respectively [6]. The wave transmission coefficient is defined as the ratio of the transmitted wave height (H_t) and the incident wave height (H_i) as [7]:

$$C_t = \frac{H_t}{H_i} \quad (6)$$

C. Experimental Study

A small physical model (dimensions of each plate is 20×15 cm.) is simulated in the Hydraulic Laboratory at Ferdowsi University of Mashhad. In the case of large incident wave heights reflected wave heights become large, incident coming wave and reflected wave effect on each other and they become nonlinear and break [7]. So, small wave heights are considered.

D. Results

According to Eqs. (1), (4), (5) and (6), wave and model parameters, the following results are obtained via Matlab Simulink and experiment. The elongation of the spring, x_2, is shown in Fig. 2. Five experimental data obtained in order to analyze energy transmission from this breakwater as shown in Fig. 3.

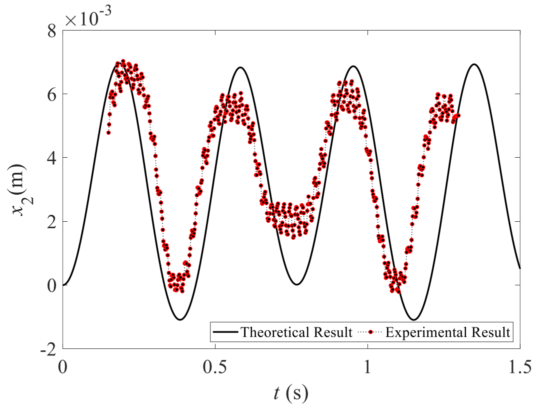

Fig. 2. Time history of translational motion of the guided roller of the second plate.

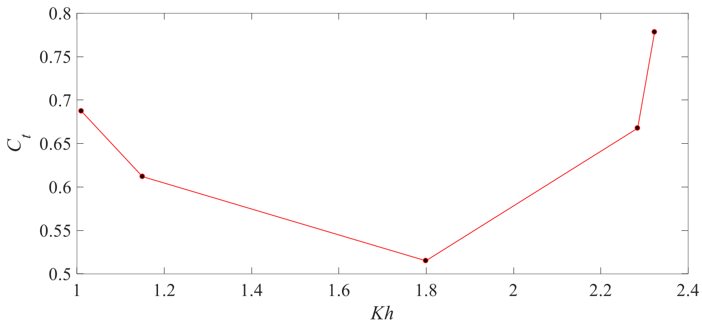

Fig. 3. Wave transmission coefficient (C_t) according to the dimensionless incident wave frequency number (Kh).

E. Conclusion

A new mechanism was introduced as a breakwater and energy harvester. This mechanism was theoretically modeled and validated by the experiment. Difference between theoretical and experimental results was related to the damping, friction, viscous and eddy losses. The wave transmission coefficient was experimentally obtained according to the dimensionless incident wave frequency number.

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