A Novel Wave Energy Converter Using the Stewart Platform

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Abstract

Ocean wave is one of the biggest sources of renewable energy that is economically attractive. However, technology of harvesting wave power is relatively undeveloped compared to other renewable energy technologies. Finding optimal structures of wave energy converter (WEC) is still an open research problem. The idea of using Stewart platform as a WEC is for the first time proposed in this paper. Its key module is a Stewart platform, which is a parallel mechanism with six degrees of freedom, used to convert the motion induced by waves to the prismatic motions of multiple hydraulic/ pneumatic cylinders. The proposed new type WEC can be used in the offshore wave power generation systems and put in any place where there exist roaring waves. The mathematical model has been set up and the numerical simulation has been performed to verify the effectiveness of the proposed converter. The simulation results show that more energy can be generated by this new type of converter than other existing WECs.

Keywords: Wave Energy, Converter, Parallel Mechanism.

1 Introduction

In recent years there has been a growing attention to the development of renewable energy technology. Ocean wave energy is one of the biggest

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untapped sources of renewable energy that is economically attractive (Scruggs and Jacob 2009). Using this source of energy causes no emissions that impact the climate or the environment and reduces cost of energy generation to a reasonable size. Although study in this area began three decades ago (Salter 1974), the speed of research has been just accelerated by growing interest in renewable energy recently (Clément, McCullen et al. 2002).

Marine and Hydrokinetic Technology Database developed by U.S. Department of Energy contains the information of various types of ocean energy harvesting devices which have been registered. Many of them are related to wave energy. It depicts the remarkable capabilities of wave energy which stands out as a noticeable form of ocean energy (Falcão 2010). However, in spite of all advantages and functionalities, technology of harvesting wave power is relatively undeveloped compared to other renewable energy technologies like wind power or solar energy.

In spite of variety of Wave Energy Converters (WECs) which have been invented and studied, finding optimal structure of wave energy converter is still the centre of attention for research and technology.

WEC systems can be categorized into a few types based on their methods of energy conversion. The popular WEC systems include oscillating water column, overtopping, pitching, membrane, and point absorber. However, the focus of this paper is on floating-point absorbers.

The existing WEC with a floating part can convert the energy from the heave motion (Figure 1) or from the pitching motion of the float (Figure 2). The principal axis for floating-pitching devices is either perpendicular or parallel to the wave direction. One of the famous types of floating-pitching devices, called *Duck*, is located perpendicular to the wave direction (Figure 2). *Pelamis* is another type of floating-pitching convertor which is located parallel to the wave direction (Figure 3). The world's first commercial wave farm was installed off the coast of northern Portugal in 2008. This farm employed three WECs and could generate 2.25 MW using three *Pelamis* machines. However, the massive equipments used in this kind of WEC limit its performance. Thus, finding a compact and lighter WEC is desirable.

The main problem of existing wave energy converters is that they are just able to convert limited amount of wave energy due to the constraints on their motions. Vasquez et al. (Vasquez, Crane et al. 2012) addressed the possibility of using a tensegrity mechanism for wave energy harvesting. They analysed the kinematics of their proposed device by using the theory of screws. Vasquez have also compared the performance of tensegrity mechanism with the purely heaving system and shown the advantages of using parallel mechanism for

Figure 1 A classic wave energy converter with a floating part which can convert the energy from the heave motion of the float (Web-1)

Figure 2 A WEC with floating-pitching devices is located perpendicular to the wave direction called *Duck* (Thorpe 1999)

Figure 3 A WEC with floating-pitching devices is located parallel to the wave direction. It is well-known as *Pelamis* (Web-2)

wave energy harvesting. The energy converter that they proposed is a planar 3-dof tensegrity mechanism which though still cannot convert the whole energy induced by wave motions due to the limitation on the effective number of degrees of freedom. Thus, this work aims to study the feasibility and advantages of using a Stewart platform, which is a spatial 6-dof mechanism, as a WEC for increasing the capability of converter for energy harvesting.

Stewart platform is a typical spatial 6-dof parallel mechanism which has been used in applications in flight and vehicle simulators, high-precision machining centres, mining machines, and so on. However, the possibility of using Stewart platform in ocean wave energy harvesting was not referred in literature. Accordingly, this work aims at realizing the advantages of using a Stewart platform as a new wave energy converter for the first time.

In this new converter, the motion induced by waves is converted to the prismatic motion of six hydraulic or pneumatic cylinders in the Stewart platform. The float platform on the top plate of the parallel mechanism can follow the wave motion in the six degrees of freedom. Thus, much more energy can be converted in comparison with existing forms of converters with limited degrees of. The cylinders can pump high-pressure fluid through hydraulic/pneumatic motors via accumulators that smooth out variations in flow and pressure. The pressurized fluid can be used in hydraulic/ pneumatic motors that drive electric generators to produce electricity. The proposed converter can be used in the offshore equipment like platforms and everywhere there exist roaring waves.

The paper is organized as follows. In Section 2, the theory of wave motion is presented. In Section 3, the inverse kinematics of the Stewart platform related to energy conversion is discussed. Simulation results on the wave energy conversion with the Stewart platform is presented in Section 4. The conclusion is given in Section 5.

2 Wave Theory

The simulation of floating-point absorbers is a wave-body interaction topic. It requires knowledge of the wave theory. Before reviewing the modeling methods for Stewart Platforms, we review the fundamentals of wave theory.

2.1 Governing Equations for Waves on the Sea Surface

Obviously, waves can be appeared in verity of sizes and forms, depending on environmental conditions, such as bottom topography, temperature and fluid density. In general, waves can be categorized as linear or nonlinear, regular or irregular, unidirectional or omni-directional. The governing equation of free surface waves is derived based on using potential flow method, where the flow is assumed to be incompressible and irrotational. Flow can be assumed irrotational ($\nabla \times \mathbf{V} = 0$), where, $\mathbf{V}$ is the fluid velocity. This means that there is a velocity potential φ that the velocity $\mathbf{V}$ is its gradient.

$$\nabla \varphi = \mathbf{V} \quad (1)$$

By assuming the incompressibility of fluid, ($\nabla \cdot \mathbf{V} = 0$), the Laplace's equation is formed.

$$\nabla \cdot \nabla \varphi = \nabla \cdot \mathbf{V} = 0 \quad (2)$$

$$\nabla^2 \varphi = 0 \quad (3)$$

where the boundary conditions are:

a) Kinematic boundary condition:

$$\frac{\partial \varphi}{\partial \eta} = 0 \quad (4)$$

where η is the elevation of the water surface. It means the fluid particles on the free surface of fluid won't leave the free surface.

b) Dynamic boundary condition:

$$\frac{D\eta}{Dt} = w \text{ at } z = \eta \quad (5)$$

where w is the elevation velocity, z is the elevation of the water and $\frac{D\eta}{Dt} := \frac{\partial\eta}{\partial t} + (\nabla\varphi \cdot \nabla)\eta$. It means the pressure remains continuous at atmospheric pressure over the free surface.

The above boundary conditions are reduced to following equation (Thakur and Gupta 2011).

$$g \frac{\partial\varphi}{\partial z} + \frac{\partial^2\varphi}{\partial t^2} + 2\nabla\varphi \cdot \nabla\left(\frac{\partial\varphi}{\partial t}\right) - \frac{1}{g} \frac{\partial\varphi}{\partial t} \frac{\partial}{\partial z} \left(\frac{\partial^2\varphi}{\partial t^2} + g \frac{\partial\varphi}{\partial z}\right) = 0 \quad (6)$$

The solution of Equation (5) satisfying the boundary condition (Equation (6)) yields the expression for the velocity field φ and an ocean wave free surface η .

$$\varphi = \frac{gA}{\omega} e^{kz} \sin(kx \cos\theta_w + ky \sin\theta_w - \omega t) \quad (7)$$

where,

- g : acceleration due to gravity in $\frac{m}{s^2}$,
- θ_w : wave direction in *radian*,
- ω : wave frequency in *radian/s*, and
- A : wave amplitude in *m*.

$$\begin{aligned} \eta(x, y, t) = & A \cos(kx \cos\theta_w + ky \sin\theta_w - \omega t) \\ & + 0.5A^2 k \cos(2kx \cos\theta_w + 2ky \sin\theta_w - 2\omega t) \end{aligned} \quad (8)$$

The wave number k is related to the wave frequency ω for the infinite depth by the dispersion relationship given in

$$k = \frac{\omega^2}{g} \quad (9)$$

The wave elevation η thus obtained is the starting point for determining the position and orientation of the float due to the wave float interaction.

2.2 Position and Orientation of Float

The position and orientation of the moving platform mainly depends on the interaction between floating-platform and ocean wave. The orientation of platform can be calculated based on normal vector of the free surface of the wave. In Figure 4, it was assumed that u is the normal vector of wave

Figure 4 Ocean wave modeled by Equation (8), the normal vector of wave and rotation axis are shown by u and q respectively.

at point P . For determining of the moving platform orientation, the attached coordinate system of platform should be rotated till the Z axis (along vector) situates on the u vector. The rotation matrix can be found as follows. First, the rotating axis, q , should be determined by using Equation (10). then, the rotating matrix can be formed (Equation (11)).

$$q = k \times u \quad (10)$$

$$R = \begin{bmatrix} \cos\varphi + q_x^2(1 - \cos\varphi) & q_x q_y(1 - \cos\varphi) & q_y \sin\varphi \\ q_x q_y(1 - \cos\varphi) & \cos\varphi + q_y^2(1 - \cos\varphi) & -q_x \sin\varphi \\ -q_y \sin\varphi & q_x \sin\varphi & \cos\varphi \end{bmatrix} \quad (11)$$

$$u = Rk \quad (12)$$

After reviewing the fundamentals of wave theory and determining the position and orientation of the float due to the wave float interaction, we review a modeling method for a Stewart platform using for our new WEC in following section.

3 Inverse Kinematics of the Stewart Platform

The calculation of the degrees of freedom for the Stewart platform is based on the configuration shown in Figure 5. There are universal, prismatic and

spherical joints. The number of degrees of freedom in the Stewart platform can be calculated by using the Grübler equation as follow:

$$m = \lambda(n - j - 1) + \sum_{i=1}^j f_i - I_f \quad (13)$$

Where:

m = Number of degrees of freedom of the system.

λ = Degrees of freedom of the work space where the mechanism is located.

n = Number of fixed links of the mechanism including the base and the top part.

j = Number of joints in the mechanism.

f_i = Degrees of the relative movements of joint.

I_f = Number of passive degrees of freedom of the mechanism.

By using the Equation (13), it is yields that the Stewart platform is a spatial 6-dof. For calculation the amount of pressured fluid pumps to the accumulator, it requires the knowledge of inverse kinematic of the Stewart platform. The Inverse kinematics is the calculation of the legs length, in order to satisfy a desired position and orientation. It is assumed that the platform is tangent to the wave surface. The formulation of inverse kinematic of the Stewart platform can be found in some research by (Merlet 2004), (Liu, Fitzgerald et al. 1993), (Perng and Hsiao 1999) and (Salcudean, Drexel et al. 1994). To find the inverse kinematics of the mobile plate based on the geometry platform in Figure 5, the coordinates XYZ of points $A_1, A_2, A_3, A_4, A_5, A_6$ must be known, as shown in Figure 5.

These coordinates are computed when the system is in the initial rest position. Equation (14) applies to find out the coordinates of all vertices of the upper plate, through the transformation matrix T_A^B with reference to the base and the initial coordinates $x_{A_i}, y_{A_i}, z_{A_i}$ it is found the value of the coordinates of the vertices for $i = 1, \dots, 6$ (Gonzalez, Dutra et al. 19–25 June, 2011).

$$\begin{bmatrix} X_{A_i} \\ Y_{A_i} \\ Z_{A_i} \\ 1 \end{bmatrix} = T_A^B \begin{bmatrix} x_{A_i} \\ y_{A_i} \\ z_{A_i} \\ 1 \end{bmatrix} \quad (14)$$

Figure 5 Geometry of Stewart platform

Where the value of the transformation matrix is:

$$T_A^B = \begin{bmatrix} C\varphi_A C\theta_A + S\varphi_A S\psi_A S\theta_A & -C\varphi_A S\theta_A + S\varphi_A S\psi_A C\theta_A & S\varphi_A C\psi_A & P_x \\ C\psi_A S\theta_A & C\psi_A C\theta_A & -S\psi_A & P_y \\ -S\varphi_A C\theta_A + C\varphi_A S\psi_A S\theta_A & S\varphi_A S\theta_A + C\varphi_A S\psi_A C\theta_A & C\varphi_A C\psi_A & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (15)$$

Where, S and C stand for sine and cosine respectively.

By having the coordinates of mobile plate and base points the values of length of the legs (L_i) can be calculated by following equation.

$$L_i = \sqrt{(X_{A_i} - X_{B_i})^2 + (Y_{A_i} - Y_{B_i})^2 + (Z_{A_i} - Z_{B_i})^2} \quad (16)$$

Now, by having the govern equations of the wave and Stewart platform, we can illustrate the ability of using a Stewart platform for harvesting wave energy in the next section.

4 Simulations

In this section, the solution of inverse kinematic for the Stewart platform mechanism under the influence of ocean waves is performed and its relation to the wave energy generation is simulated.

The solution for the position of point P and the orientation of the top platform are determined from Equation (8) and (12) represent the inputs for the inverse kinematic analysis. The parameters used for the Stewart platform are given as:

$$\begin{aligned}
 A_1 &= \begin{bmatrix} -0.1 \\ 1 \\ 1 \end{bmatrix} & A_2 &= \begin{bmatrix} 0.1 \\ 1 \\ 1 \end{bmatrix} & A_3 &= \begin{bmatrix} -0.816 \\ -0.586 \\ 1 \end{bmatrix} \\
 A_4 &= \begin{bmatrix} -0.916 \\ -0.413 \\ 1 \end{bmatrix} & A_5 &= \begin{bmatrix} 0.916 \\ -0.413 \\ 1 \end{bmatrix} & A_6 &= \begin{bmatrix} 0.816 \\ -0.586 \\ 1 \end{bmatrix} \\
 B_1 &= \begin{bmatrix} 0.75 \\ 1.3 \\ 0 \end{bmatrix} & B_2 &= \begin{bmatrix} -0.75 \\ 1.3 \\ 0 \end{bmatrix} & B_3 &= \begin{bmatrix} -1.5 \\ 0 \\ 0 \end{bmatrix} \\
 B_4 &= \begin{bmatrix} -0.75 \\ -1.3 \\ 0 \end{bmatrix} & B_5 &= \begin{bmatrix} 0.75 \\ -1.3 \\ 0 \end{bmatrix} & B_6 &= \begin{bmatrix} 1.5 \\ 0 \\ 0 \end{bmatrix}
 \end{aligned}$$

$$L_{Max} = 1.9, \quad L_{min} = 0.7$$

And, the parameters used for wave equation (Equation (8)) are given as:

$$\begin{aligned}
 g &= 9.81 \frac{m}{s^2} \\
 \theta_w &= \frac{\pi}{6} \text{radian}, \\
 \omega &= 1 \text{radian/s} \\
 A &= 0.1 \text{ m} \\
 t &= 6.28 \text{ second}
 \end{aligned}$$

Figure 6 shows that the moving plat of Stewart platform moves with the wave. Equations derived in Sections 2.1 are used to calculate the lengths of legs of Stewart perform. Figure 7 shows the motion of each leg. Hence, the total volume of transferred pressured fluid can be calculated.

The modeling result has been presented in Table 1. For comparison, the amount of pumped pressured fluid using the Stewart platform was compared with 6 cylinders with the same size which located vertically. These cylinders can convert the energy from the heave motion of the float (Figure 1).

Figure 6 The moving plat of Stewart platform moves with the wave

For calculating the generated pressure of fluid, the following equation has been used:

$$P = \frac{\beta}{V_0} A_c x + P_o \quad (17)$$

where,

- $\beta = 1.01 \times 10^5$ Pa, Bulk modulus
- $V_0 = 1 \text{ m}^3$, Value of accumulator
- $A_c = 0.00785 \text{ m}^2$, cylinder cross sectional area
- x = Forward displacement of piston
- $P_0 = 100 \text{ kPa}$

Table 1 depicts the amount of pressured fluid pumped by proposed converter is approximately 39.6% more than using 6 Floating-Point point absorbers. Thus, the simulation results show that more energy can be observed by proposed WEC than other existing WECs which can convert the energy from the heave motion of the float.

Table 1 Comparison between proposed WEC and one Floating-Point absorber

Converter	Generated Gauge-Pressure
Proposed WEC	15.8 (kPa)
Six Floating-point absorbers	11.3 (kPa)
One Floating-point absorber	1.88 (kPa)

Figure 7 Legs' length of the Stewart platform

5 Conclusions

The idea of using Stewart platform as a WEC was for the first time proposed in this paper. This work addressed the kinematic analysis of a Stewart platform for ocean wave energy harvesting. The interaction between ocean waves, a multi-degree-of-freedom linkage poses challenging problems in terms of mathematical modeling and simulation. Nonetheless, the ideas of using parallel mechanisms such as Stewart platform will be useful for the analysis and testing of more advanced and complex energy harvesting devices. The mathematical model and numerical simulation have been performed in order to verify the effectiveness of the proposed converter. The simulation results show that more energy can be generated by this new type of converter than other existing WECs.

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