Water-Tank Experiment Study for a Fluid-Sloshing Type Wave-Energy Conversion System (FSWECS)

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ABSTRACT

In this study, a new type of wave-energy converting system is developed and installed in an offshore platform structure to take the advantage of strong motion of the platform subjected to waves. In this device, the sloshing power of the fluid filled a U-shape tube may drive the turbine of the electric power generator and then produce electricity. By following previous experimental results in basic vibration behavior for the FSWECS device that under various periods and amplitudes of the stroke in the experimental tests, can effectively convert vibration motion into electricity power, a further test for the effectiveness of energy conversion from the FSWECS device was performed in a water-tank. Parameters identified in previous studies including the natural periods of the FSWECS device, the strokes of the vibration and the relationship between the amount of the liquid filled in the tube and the dynamic character of the device are further studied when subjected to a simulated wave.

Key words: Offshore platform system; wave power conversion; water tank experiment; fluid-sloshing wave energy conversion system (FSWECS)
1. Introduction

Recently, due to the dramatic requirement of petroleum from new developed countries, the price of crude oil has reached skyrocketing height. The exhaustion of crude petroleum in the near future becomes a more realized fact now. Therefore, the development of new energy, particularly reproducible energy such as solar energy, wind energy and ocean energy et al. gets higher and higher attention and in many countries, the green energies have been adapted to a regular power grid system. For the time being, the exploitation of wind energy and solar energy have been more and more matured in terms of the efficiency and safety but however, for the exploitation of ocean energy, there is still a long way to go. Twenty years ago when we look back the development history of wind-energy, the efficiency of electricity generation was very low and the cost for the wind-turbine system was very high, which were almost compatible to the situation the wave-energy conversion system encountered now.

The development of wave-energy conversion system has been lasted for decades and all kinds of model were developed in terms of various power-converting mechanisms [1, 2 7, 8]. The air-power converting system by utilizing the air confined in a wave oscillation chamber moored under the sea is one of the most popular systems. Some other wave-power converting systems use the motion of the water wave to drive mechanical members directly to generate electricity such as the snake system and the vibrating stick system. The one by using heave motion of buoyant members to drive a power-generating machine was also developed [3]. All of these wave-power converting systems have their advantages and drawbacks as well.

In this study, a new type of wave-energy converting system is developed and installed in an offshore platform structure to take the advantage of strong motion of the platform subjected to waves. The floating platform system has been extensively applied to ocean exploitation, particularly, a tension-leg platform (TLP) system in deep water.

By utilizing the sloshing power of the fluid stored in a U-shape tube, the turbine of the electric power generator is driven and electricity can be generated. Some advantages are found from this system. Firstly, because the vibration in surge, heave and other motions of the platform induce the sloshing motion of fluid that further transforms into a mechanical motion of the turbine, the motion of the platform can be eased that makes the platform more stable for the operation. In the end, the platform system can have longer service time. Secondly, the power generated is like a by-product of the platform operation, which aims to a self-content system for the power-supply in the platform. Thirdly, due to the simple structure and common material applied to the wave-converting system, the maintenance of the system is much easier compared to the others. From the testing results of previous study [5, 6], it shows that with respect to various periods and amplitudes of the stroke in the experimental tests, the wave-power converting system can effectively generate electricity. Therefore, by following previous experimental results in basic vibration behavior for the FSWECS device that under various periods and amplitudes of the stroke in the experimental tests, can effectively convert vibration motion into electricity power, a further test for the effectiveness of energy conversion from the FSWECS device was performed in a water-tank. Parameters identified in previous studies including the natural periods of the FSWECS device, the strokes of the vibration and the relationship between the amount of the liquid filled in the tube and the dynamic character of the device are further studied when subjected to a series of simulated waves.


A typical electricity power generating system by using sloshing fluid contained in a U-tube is shown in
Fig. 1, of which the cross section of the tube can be either circular or square. Basic parameters of the U-tube will include the area of the cross-section of the tube, the ratio between the height and the length of the tube and the water level filled in the tube. All of these parameters have influence on the performance of the U-tube system. It is assumed that the U-tube system is fixed on the main structure without any relative motions between them. When the main structure subjected to vibrations, the U-tube system will also shake along the structure in same phase so that the water filled in the tube sloshes alternately along the U-tube while the water level is up and down in the vertical columns of the U-tube. It is noticed that the potential of the water varies alternately between two vertical columns when the water elevation of one column is over the other, respectively.

![Fig. 1 Schematic view of turbine system installed in a U-tube (Lee and Wu 2011)](image)

2.1 Basic Theorems and Equation of Motion for Fluid in U-tube

As shown in Fig.1, the horizontal part of the tube between the center-line of vertical columns is B; the elevation of still liquid in the vertical column of the tube is H; the velocity and acceleration of fluid in the tube are \( \dot{y} \) and \( \ddot{y} \) respectively. The cross section area for the vertical column and the horizontal part of the U-tube are \( A_y \) and \( A_h \) respectively and a ratio between the vertical and horizontal cross section area is also defined as \( R \). The horizontal velocity of the U-tube system induced by the motion of main structure is \( \dot{x} \).

By applying Lagrange equation to the motion of the fluid in the U-tube when the fluid is driven by a horizontal velocity of the tube, the derivation to the fluid motion of kinetic energy and potential is written as

\[
\frac{d}{dt} \left[ \frac{\partial (P - U)}{\partial \dot{y}} \right] - \frac{\partial (P - U)}{\partial y} = Q
\]

(1)

where the kinetic energy \( P \) from the fluid motion is defined as

\[
P = 2 \left[ \frac{1}{2} \rho A_h H (\dot{y}^2 + \dot{x}^2) \right] + \rho A_y B \frac{(R\dot{y} + \dot{x})^2}{2}
\]

(2)

and the potential energy \( U \) of the fluid is written as

\[
U = \rho g A_y \dot{y}^2
\]

(3)

It is also noticed that a non-conservative force \( Q \) the damping force exists when the fluid flows in the tube and it may be defined as

\[
Q = -\frac{1}{2} \rho A_h h_d R^2 |\dot{y}|
\]

(4)

where \( h_d \) is the head loss coefficient of the fluid. Now the equation of motion of fluid in the tube is obtained from Lagrange equation [4] through equation (2) and (3) as

\[
\rho A_y [2H + B; R] \ddot{y} + \frac{1}{2} \rho A_h h_d R^2 |\dot{y}| + 2\rho A_y g \ddot{y} = -\rho A_h B \ddot{x}
\]

(5)

2.2 Design of the U-tube with Required Natural Frequency

Due to the fact that the best performance of a U-tube power generator is from a highest efficiency of energy capture from the rotation of the turbine, therefore to suit for various environments of the system, the very basic parameter of the system is the natural frequency and its relationship to the dimensional parameters. The frequency of the fluid \( f_w \) sloshing in a U-tube is obtained as

\[
f_w = \sqrt{\frac{2\pi}{2H + B; R}}
\]

(6)

Based on the aspect of testing facilities such as the stroke and power of actuator system, the size of
tank and stroke power of eventual testing for the practical application and some other limitations, the frequency of the U-tube with filled fluid of certain density is $f_w = 0.6\text{Hz} \sim 0.66\text{Hz}$ and the testing period designed around the range of resonance is $T = 1.51\text{sec} \sim 1.66\text{sec}$.

3. Water Tank Testing Set-up

According to pre-test analysis, several sets of turbine system were installed in a U-tube system, where the solidity ratio $\sigma$ of the turbine area, number of turbines “n” and width of the turbine $C$ are determined. A schematic view of the turbine and the electricity generator after its installation in a U-tube is shown in Fig.1. The main parameter of testing model applied to the water tank test is the amount of liquid filled in the tube.

The test was performed in the water tank experimental lab, where testing set-ups consist of the water tanks, data acquisition system and hydraulic-power controlling systems. A schematic view of the testing set-up is presented in Fig.2. The testing water tank is 30 m long, 1 m wide and 1.2 m high. At one end of the tank a piston-type hydraulic wave maker is installed while the other end of the tank the energy dissipation device is installed to reduce the reflecting waves. The testing water tank is capable of making a wave of 2.8 seconds long of period and 0.12 m high of amplitude, which is located in the hydraulic laboratory of Dept. of Marine Environment and Engineering, NSYSU. The data acquisition facilities include the wave meters of capacitance type to measure the wave height of water, signal amplifiers of multi-channel, load-cell measuring for the tension force of the mooring cables, angular velocity measuring tool TM-5010, power suppliers and computers. For the motion of the platform system, a high-resolution video camera of CCD high-speed recording system was set-up in front of the water tank to catch the motion of the floating platform under test.

Parameters other than the testing model itself are variaions of testing conditions such as the period and height of the wave applied to the testing model FSWECS. In order to examine the applicability of the electricity power generated from the FSWECS system and relationships to the testing environmental conditions, results including motions of the floating platform, fluid velocity and rotational speed of turbine blade were all studied.

![Fig.2 Schematic view of the testing set-up](image)

4. Testing Results and Discussion

4.1 Motion of the Floating Platform

The platform applied to FSECS system is strained by a single pre-stressed tether designed to allow a universal rotational motion for the platform subjected to incident waves from multi-directions. Typical motions observed in two dimensional water tank experimental lab such as surge, heave and pitch are presented in Fig.3 (a). An orbit of platform circulating in waves is also presented in Fig.3 (b) that is obtained from the simultaneous combination of surge and heave.

![Fig.3 (a) Platform surge, heave and pitch motions](image)
Fig.3 (b) Orbit of platform motions

It shows that the motions of heave and pitch of the platform are pretty much in accordance to the incident waves, while the motion of surge has larger displacement that is in a longer period.

4.2 Flow Speed for Fluid in U-tube

Flow velocity of liquid in the tube is important since the turbine is driven by the sloshing fluid when the tube-container is vibrating. According to the study of Lee and Wu (2011), without installation of electricity power generator in the platform system, fluid sloshing in higher speed may result larger electricity power.

Shown in Fig.4 are time histories of the fluid velocity in the tube, where four curves are related to four various periods applied to the wave maker. It is noticed that the direction of the velocity alternates in accordance to the vibration of the platform. The highest velocity occurs at the testing case of 12-cm high liquid in the column, where the period of applied wave is 1.37 seconds.

4.3 Rotational Speed for Turbine Blade of Electricity Generator Installed in FSECS

The rotational speeds of the turbine blade corresponding to various periods and heights of waves were also examined, while the amount of liquid was varied in terms of the length filled in the tube. Presented in Fig.5 is the rotational speed of the turbine blade when the platform system subjected to waves of 12-cm height in the water tank experiment. It shows that corresponding to decrease of amount of liquid filled in the tube, the rotational speed of the turbine blade will be increased. Waves of shorter period may drive a higher speed for the turbine blade when the other conditions remain unchanged. However, when
the amount of liquid filled in the tube is more, \( L_d \) is larger, the influence from wave-period is less significant.

5. Conclusions
In this study, a U-tube sloshing fluid power converting system was designed into a scaled down model and tested in a water tank of hydraulic laboratory with artificial waves. The testing parameters include the period and wave-height of incident waves, and the dimensional related parameter for the testing model mainly the amount of liquid filled in the tube. Other parameters such as the natural frequency of the designed model system, the solidity ratio of the turbine area were examined in the vibration test in the structural testing laboratory. According to the experimental results, some conclusions are drawn as follows.

1. Under the same testing conditions such as same wave height and period of the wave, the motion of platform shows a larger displacement in surge compared to the heave motions. The orbit of the motion for the platform stretches farther in horizontal direction, which is usually a regular oval shape for multi-strained platform system.

2. The influence of the period of the wave applied is less than the wave height to the testing model as shown in the acquired data from the speed of the turbine blade.

3. The best performance in terms of the speed of the turbine blade seems to occur on the cases, where the period of the wave is lower mostly. It is probably due to the fact that the resonant period of the system partially dominated by the content of liquid is close to the lower period of applied waves. Because when the amount of liquid filled in the tube is more, \( L_d \) is larger, the influence from wave-period seems to be less significant.

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