Experimental Study on the Performance of a Fluid-Sloshing Type Energy Conversion System (FSECS)

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ABSTRACT

Recently, due to the dramatic requirement of petroleum from new developed countries, the price of crude oil reached skyrocketing height. Therefore, 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 stronger motion of the platform subjected to waves. By utilizing the sloshing power of the fluid stored in an 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, the motion of the platform can be eased and the platform becomes more stable for the operation. Secondly, the power generated is 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, 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.

Key words: U-tube fluid-sloshing generator(UTPG), wave power conversion, actuator experiment, fluid-sloshing power generator (FSPG), fluid-sloshing power conversion system (FSPCS)

1. INTRODUCTION

As many developing countries rapidly emerged in the last two decades, the requirement for the supply of energy is more dramatic than ever. On the other hand, rapid increasing usage of the petroleum causes the green house effect and then the global warming as well so that natural caused disasters such as flooding, storming and deserting infertility induced from the rapid and large scale weather changes happened more often and caused larger casualties in last two decades. The storage of the petroleum is rapidly used up and yet, the requirement is continually increased more than ever. Searching for the substitution of petroleum is more intensive than ever now. Particularly, a recyclable, re-producible and more environmentally friendly energy or so-called green energy is under development in large scale [3].

An innovative idea by utilizing the sloshing power of liquid filled in a U-shape container to produce electric power is provided in this paper. Sloshing behavior of liquid in a pipe is similar to a flow that may quickly reverse its direction during alternate sloshing induced from tube vibration. Therefore, in this study a turbine system is selected due to its specialty that no matter which direction flow flows the turbine may maintain rotating in the same direction. This turbine system was developed by Gorlov and Darrieus [1, 2] for the power generator of sea flows or any flows that may change its direction. It was found that the efficiency of energy capture from the newly-developed turbine system is higher than traditional ones [5, 6].

After analysis, models of a U-tube sloshing-flow power converter were innovatively manufactured. A series of experimental tests were also designed and performed to obtain the influence of both dimensional parameters of the U-tube sloshing power converter and the environmental conditions. It is found from the experimental results that the newly developed system can successfully generate electricity. It is also found that parameters such as the amplitude and the period of the excitation of the U-tube that driving the flow-sloshing are closely related to the efficiency of the power converting system. The dimensional parameters of the U-tube flow-sloshing power converter must be carefully designed based on the application and environmental conditions.

2. THEORETICAL BASIS AND SYSTEM DESIGN

A typical U-tube is shown in Fig.1, of which the cross section of the tube can be any shape such as 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 the 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.

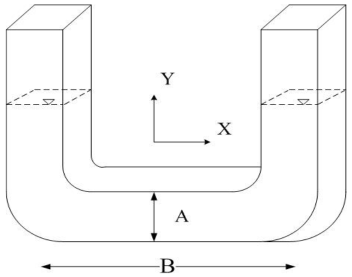


Fig. 1 A typical U-tube filled with liquid

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

$$\frac{d}{dt}\left[\frac{\partial(P-U)}{\partial\dot{y}}\right]-\frac{\partial(P-U)}{\partial y}=Q \tag{1}$$

where the kinetic energy P from the fluid motion is defined as

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

and the potential energy U of the fluid is written as

$$U=\rho g A_v y^2 \tag{3}$$

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

$$Q=-\frac{1}{2}\rho A_v h_d R^2\left|\dot{y}\right|\dot{y} \tag{4}$$

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, 7] through equation (2) and (3) as

$$\rho A_v\left[2H+B\cdot R\right]\ddot{y}+\frac{1}{2}\rho A_v h_d R^2\left|\dot{y}\right|\dot{y}+2\rho A_v g y=-\rho A_v B\ddot{x} \tag{5}$$

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

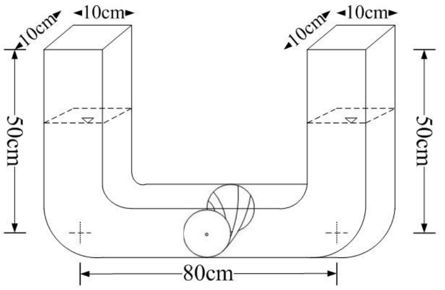
$$f_w=\sqrt{\frac{2g}{2H+B\cdot R}} \tag{6}$$

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 =0.6Hz□0.66Hz and the testing period designed around the range of resonance is T=1.51sec□1.66sec.

3. EXPERIMENTAL MODEL AND TESTTING SET-UP

Turbine System Installed in A U-tube

According to pre-test analysis, several sets of turbine system were installed in a U-tube system, where the solidity ratio □ of the turbine area, number of turbines n and width of the turbine C are determined. A schematic view of the turbine and the generator device after its installation in a U-tube is shown in Fig.2.



U-tube with turbine

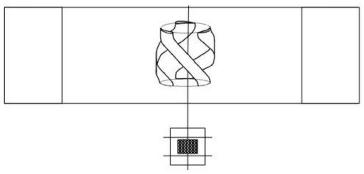


Fig. 2 Schematic view of turbine system installed in a U-tube (Lee and Wu 2009□

Experimental testing set-up

The test was performed in the structural testing lab, department of MEE, NSYSU, where a strong wall and strong floor system was in-built and additionally, an MTS hydraulic actuator of capability of 12 cm stroke and 30 Hz frequency along with signal amplifiers and data aquisition system were applied to the test.

Testing Parameters and Procedure

Parameters selected for the experimental test are basically the excitation amplitude induced from the stroke of actuator, period of the excitation and the natural frequency of the fluid that is determined from the relationship of fluid contained in the tube and the dimensional parameters of the tube as introduced in section 3. According to the parameters to be examined and their interrelations to be observed, totally 128 sets of tests were carried out in this part of experiment. Before performing the proposed sequence of the tests, a pre-testing run is necessary to re-correct the accuracy of measurement system.

3. EXPERIMENTAL RESULTS AND DISCUSSION

During the experimental test, the phenomenon to be investigated is analyzed through raw datum from data aquisition system. The phenomenon observed includes the velocity of flow, rotational speed of the turbine with and without the loading of power generator, the voltage, current and power rate generated by the generator. The parameters that may influence the results are set into various values, which include the solidity of turbine area, sloshing frequency of the fluid filled in the tube, the period and amplitude of excitation force.

Velocity of Fluid in the Tube without Generator Loading

Typical variation of the fluid flow in the U-tube during excitation is obtained and shown in Fig.3 and Fig.4, where due to sloshing motion, alternate velocity is observed. The maximum velocity of the flow can reach 2m/s. The sloshing flow is mostly in a stable vibrating pattern when the applied force to the U-tube system is a stable excitation. The influence of solidity of turbine area on the flow velocity is not positively related, but however, under same solidity of turbine area the rotational speed is positively related to the velocity of fluid flow.

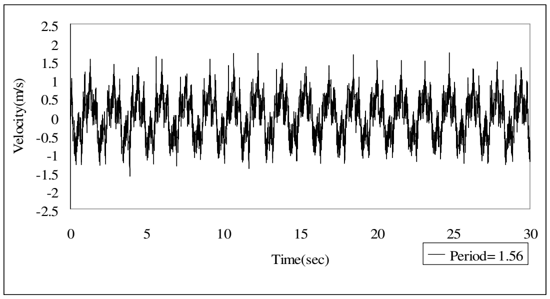


Fig. 3 Velocity of flow (T=1.56, solidity=0.3, amp.=90mm, f=0.66Hz)

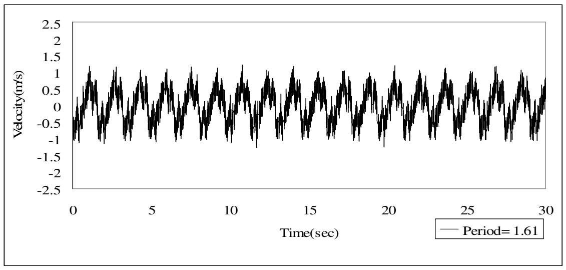


Fig. 4 Velocity of flow (T=1.61, solidity=0.3, amp.=90mm, f=0.66Hz)

Turbine Speed with Loading of Generator

Turbine of 0.3 solidity of turbine area: As shown in Fig.5 to Fig.8, where rotational speed of the turbine with loading of power generation is shown, when the solidity ratio of turbine area is 0.3, sloshing frequency of fluid is 0.64 and excitation period is 1.56 the maximum rotational speed of the turbine is 110 rpm. For the same solidity ratio of turbine area, when the sloshing frequency of fluid is 0.66 and excitation period is 1.66 the maximum rotational speed of the turbine is 89 rpm.

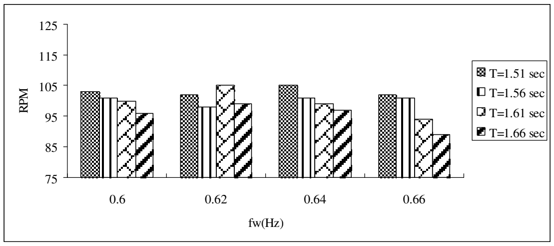


Fig. 5 Rotational speed of turbine under various fluid-frequency and excitation period (solidity=0.3, amp.=50mm)

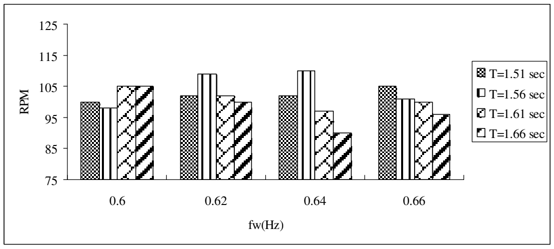


Fig. 6 Rotational speed of turbine under various fluid-frequency and excitation period (solidity=0.3, amp.=70mm)

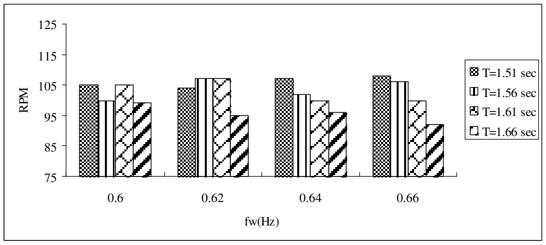


Fig. 7 Rotational speed of turbine under various fluid-frequency and excitation period (solidity=0.3, amp.=90mm)

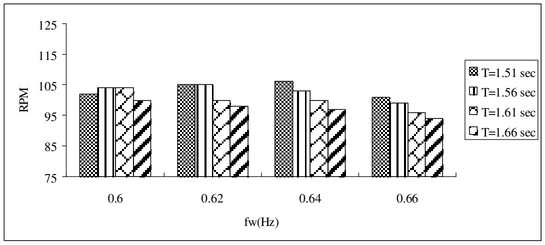


Fig. 8 Rotational speed of turbine under various fluid-frequency and excitation period (solidity=0.3, amp.=110mm)

Turbine of 0.3 solidity of turbine area: As shown in Fig.9 to Fig.12, where rotational speed of the turbine with loading of power generation is shown, when the solidity ratio of turbine area is 0.4, sloshing frequency of fluid is 0.66 and excitation period is 1.51 the maximum rotational speed of the turbine is 165 rpm. For the same solidity ratio of turbine area, when the sloshing frequency of fluid is 0.66 and excitation period is 1.66 the maximum rotational speed of the turbine is 98 rpm.

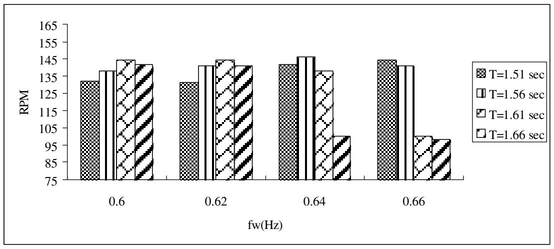


Fig. 9 Rotational speed of turbine under various fluid-frequency and excitation period (solidity=0.4□amplitude=50mm)

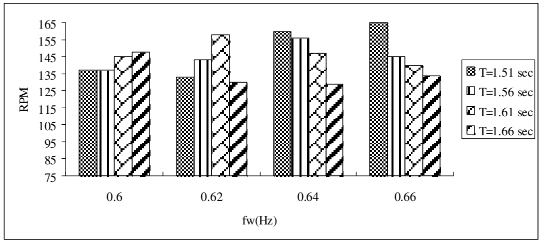


Fig. 10 Rotational speed of turbine under various fluid-frequency and excitation period (solidity=0.4□ amplitude=70mm)

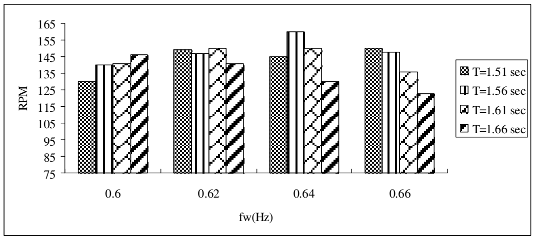


Fig. 11 Rotational speed of turbine under various fluid-frequency and excitation period (solidity=0.4□ amplitude=90mm)

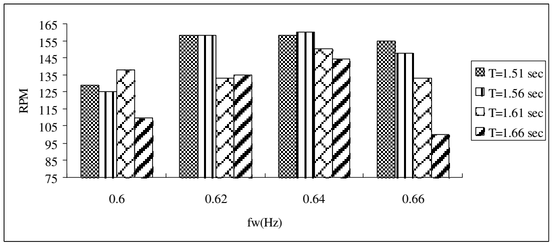


Fig. 12 Rotational speed of turbine under various fluid-frequency and excitation period (solidity=0.4□ amplitude=110mm)

Discussion and Analysis of the Results

It is noticed from the experimental results as were shown in the figures that the minimum speed of the turbine occurs when the amplitude of the excitation is 50mm, the fluid-frequency is 0.66Hz and the excitation period is 1.66 seconds. The maximum speed of the turbine occurs when the amplitude of the excitation is 70mm, the fluid-frequency is 0.64Hz and the excitation period is 1.56 seconds.

It is not necessary that the maximum speed occurs in the test having the largest amplitude, but most testing cases have better performance for larger excitations for same testing model under same testing conditions. For larger solidity turbine system, the energy capture ability in terms of the rotational speed of the turbine is better. The performance of the system is strongly related to the relationship between the fluid-frequency and the period of applied excitation and the solidity ratio of the turbine.

4. CONCLUSIONS

In this study, a U-tube sloshing fluid power converting system was designed and tested in a structural laboratory with actuator excitation system. The testing parameters including the period and amplitude of excitation force, and the dimensional related parameters of the testing model such as the natural frequency of the designed model system, the solidity ratio of the turbine area. According to the experimental results, some conclusions are drawn as follows.

1. Under the same testing conditions such as same stroke amplitude and excitation period, the model of 0.4 solidity ratio of turbine has better performance than the one of 0.3 solidity ratio for the same design of natural frequency system.
2. The best performance of the system evaluated from the testing results is when the amplitude is level 2, the fluid frequency is level 4, excitation period is level 4 and solidity ratio is level 3.
3. Under the same testing conditions, model system of 0.4 solidity ratio of turbine area has a better performance that may be further improved if a more stable rotation for the turbine is obtained.

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