Experimental Studies on a Pendulor Wave Energy Extractor in a Wave Channel

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Abstract—A Pendulor wave energy convertor was tested in a two-dimensional Wave Channel, which produced sinusoidal waves, to study its performance at different wave frequencies (varied from 0.5Hz to 1.0Hz) and four different mean water depths of 240mm, 260mm, 280mm and 290mm. The wave parameters such as wave height and the wave frequencies were measured for the available wave channel. It was found that the wave height increases while the wavelength decreases with increasing wave frequency and water depth. The relationship of pendulor paddle swing angle, rotational speed, torque and output power against wave frequency were obtained and discussed in this paper. It is found that the output power is more when the paddle moves in the direction of wave propagation, compared to the direction backstroke when the paddle is moving against the direction of wave propagation.

Index Terms—wave energy, pendulor, wave frequency, water depth

I. INTRODUCTION

Excessive use of fossil fuels and its effects on the environment have driven the global interest in renewable energy. To prevent the effects of climate change and dependence on fossil fuels, there have been many studies on renewable energy resources such as wind, solar, hydro and ocean waves, and energy conversion technologies for electricity generation. Climate change issues, increased demand of electricity, increased cost of fuel transportation and dependence on fossil fuels by the South Pacific Island Countries are the main reasons for the fundamental quest towards harnessing energy from renewable energy sources. Government policies in Fiji are strengthening and plans are put in place to increase renewable energy in energy mix by 90% by 2020 [1], [2]. Ocean wave energy is a renewable energy source that could make a substantial input to the world's energy demand. The ocean waves are always present as long as wind is blowing over it and have a high energy density, which is highest among renewable energy sources [3], [4]. Wave energy devices are an upcoming and promising technology and the extent of wave energy existing depends upon the wind speed, the wind duration, and the fetch (the extent of water over which the wind blows).

Water waves can be categorized into two types: oscillatory waves and translatory waves. In oscillatory waves, the average mass transport of water is zero. Translatory waves involve the mass transport of water in the direction of wave travel [5], [6]. In oscillatory waves, the water particles undergo free orbital motion, moving forwards with the crest, and upwards on the front, backwards in the trough and downwards on the back. Orbital motion of particles is present in both deep water waves (depth, $D>L/2$) and in shallow water waves ($D<L/20$). Mathematical analysis is available for both shallow and deep water waves [7]. Oscillatory waves are taken for this study as there is nearly insignificant forward mass transfer of the water particles.
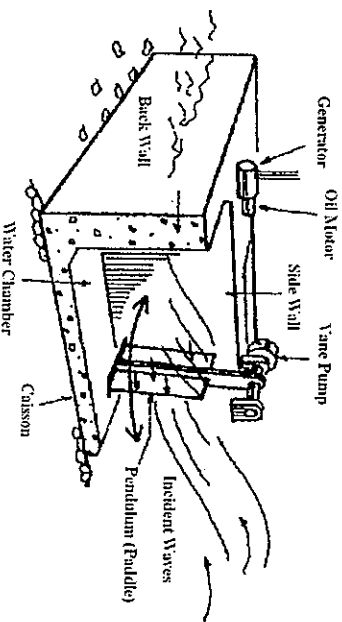

Figure 1. Schematic diagram of a pendulor wave energy converter [6].

A pendulor wave energy convertor was developed and studied by the Muroran Institute of Technology, Japan. Wave action causes pendulum oscillations of a pendulor paddle at the entrance of the device. This movement was used in combination with a hydraulic power take-off to produce electricity [8]. The front of the device is open, which allowed the incident waves to enter the device and impact on the paddle. The waves change to standing waves in the chamber as the incoming waves and the reflected waves collide. At the nodal point of the collision, the waves oscillate horizontally with the maximum energy [9]. The paddle hanging inside the chamber undertakes pendulum motion energized by the waves. This excitement moment of the pendulor paddle depends on the caisson configuration, wave frequency and wave height. The key mechanisms of the pendulor are situated above the water and hence it is easy to maintain. A pendulum device can be a floating type or have a caisson fixed to the earth [8]. Several small schemes (≥5kW) have been built in Japan and there are plans to develop a larger plant [9]. Fig. 1 shows a working principle and schematic diagram of a pendulor wave energy device.

The present work is intended at studying the wave energy extraction by the pendulor device. The experiments were conducted at different wave frequencies and four mean water depths.

II. EXPERIMENTAL PROCEDURE

The experiments were conducted in a Cussons Wave Channel, model P6325. The wave height and the wavelength were measured using Seiki pressure transducers model PSHF002KAAG and GL500A midi-LOGGER dual data logger. The wave period was measured by recording the time it took for two successive crests to pass a given point. Wave frequency was obtained by taking the reciprocal of the wave period. Experiments were conducted for mean water depths of 240mm, 260mm, 280mm and 290mm and varying wave frequencies. The pendulor model tested is is manufactured primary from Perspex. The chamber of the device has a width of 300mm, a length of 600mm and a height of 665mm. The pendulor device was placed at a distance of 2200mm for the wave maker to ensure fully developed waves impinged on the paddle. The pendulor is placed 45mm from the bottom of the wave channel to allow for water flow. The paddle has a clearance of 5mm from the sides of the pendulor chamber and 10mm from the bottom of the pendulor chamber. The torque of the pendulor in motion was recorded using a rotary torque meter. The time for 10 oscillations of the paddle and the swing angle were also recorded. Fig. 2 shows geometric details of a pendulor wave energy device tested (dimensions in mm).
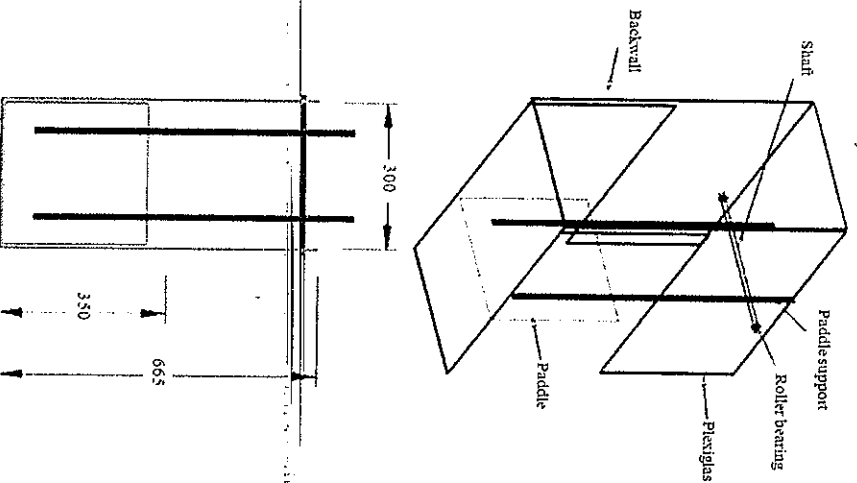

Figure 2. Geometric details of the pendulor

III. RESULTS AND DISCUSSION

The variation of the wave height to water depth ratio (H/D), wavelength to water depth ratio (L/D) with the wave frequency is given in Fig. 3. The wave height increases with increasing wave frequency, while the wavelength decreases. A linear relationship exists between the wave height to water depth (H/D) ratio against wave frequency and the slope is almost similar for the four water depths plotted. Same is true for wavelength to water depth (L/D) ratio against wave frequency. These results are experimental wave characteristics for waves generated in a wave channel and not for fully developed sea conditions. The trend for fully developed sea conditions is different.
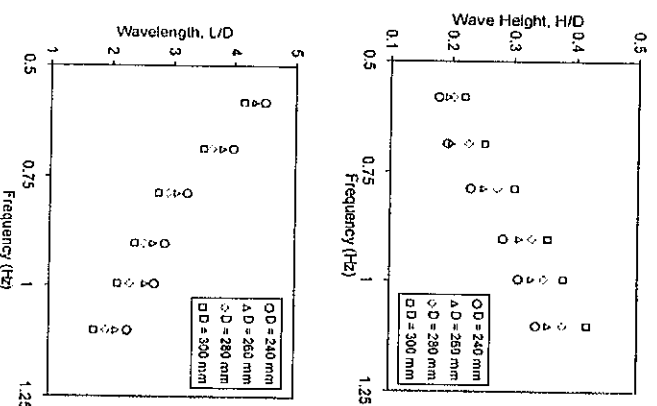

Figure 3. Variations of the wave height and wavelength with wave frequency.

In oscillatory waves, the water particles undergo free orbital motion. Most of the energy is present at the upper surface of the water; hence, it is important to analyze the paddle submergence depth. When the pendulor is in operation the paddle submergence depth changes because of the wave action over the paddle, therefore, the paddle submergence depth refers to the paddle submergence in water at standing wave for this study. At a standing wave, the submergence depth of the pendulor paddle at 260mm water depth is less compared to that of water depth of 290mm. Further, with varying frequencies this submergence depth with also fluctuate. Fig. 4 shows the output torque of the pendulor device tested at different wave frequencies for water depths of 260mm and 290mm and paddle submergence depths of 60%, 70% and 80%. The backwall is placed at a distance of 400mm from the paddle of the pendulor. The paddle submergence depth in water was optimized in terms of output torque. It was found that a submergence depth of 70% at most of the frequencies showed better results for all water depths. The same is true for other water depths of 240mm and 280mm.
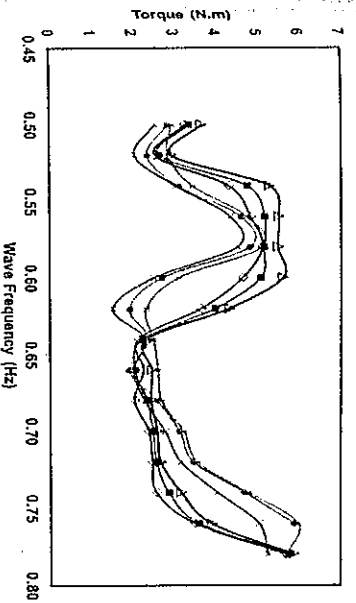
0.78Hz for all the water depths except 240mm and this could be the natural frequency of the device in the wave channel for which the maximum performance could be obtained. The swing angle rises rapidly and then drops sharply with increasing wave frequency, irrespective of the water depth. Then it is almost constant for wave frequencies of 0.64Hz to 0.70Hz, after which it increases sharply again. Faizal et al. [5] also discussed the similar behaviour of the swing angle, however, their work involved a bottom-hinged pendulor wave energy converter in a wave channel.

The backward flow of the waves inside the Pendulor device and its interference with the oncoming waves are important in its performance. The backwall of the pendulor plays some very important role during the pendulor operation. The paddle and the backwall essentially forms a water column that helps in the tuning of the device. Hence, the placement of the backwall from the paddle was studied as this had a great effect of the final output power. Fig. 5 shows the test results to determine the best backwall placement distance. The optimum distance found of backwall placement is 400mm from the paddle of the pendulor device. The torque obtained is generally lower for the case of pendulor device with no backwall. This is because the momentum of the wave on the paddle is only in one direction, in the direction of wave propagation. Hence, the rest of the results presented here is for the pendulor device with a backwall placed at a distance of 400mm from the pendulor paddle.

Furthermore, relationship of Pendulor paddle swing angle, angular velocity, torque and the output power against wave frequency was established as shown in Fig. 6-Fig. 8. From Fig. 6, it is seen that to achieve the same swing angle by the pendulor paddle the wave frequency needs to be increased as the water depth increases. The maximum total swing angle occurs at a frequency of

Figure 4. Variation of output torque of the pendulor device against wave frequency at the tested water depths (WD) for three different paddle submergence depth (PSD).
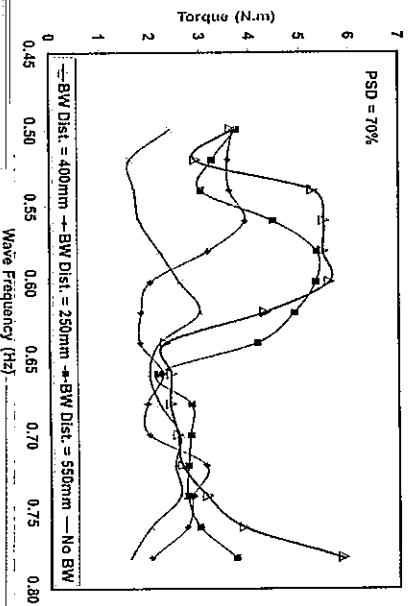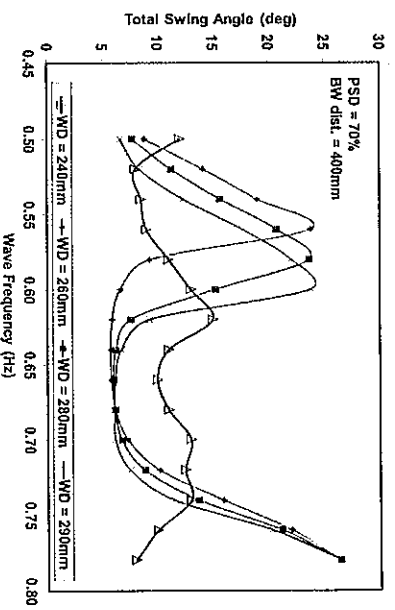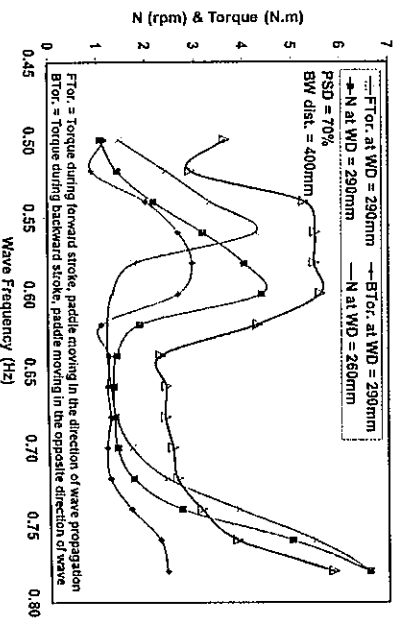

Figure 5. Variation of output torque of the pendulor device against wave frequency at a water depth of 290mm for three different backwall placement distance (BW Dist.).

Figure 6. Total swing angle at varying wave frequencies at all water depths.

As seen in Fig. 7 the angular velocity (N) behavior is similar to the swing angle behavior and it peaked at the same frequencies. The maximum N was obtained at a frequency of 0.78Hz. This may be due to the decreasing wavelength with increasing frequency which in turn shifts the location of the nodal point. Further, this shift in nodal point is also observed by Gunawaradane et al. [10] which affects the performance of the pendulor wave energy extractor at changing frequencies. An important point to note is that the output torque is lower when the paddle's motion is against the direction of wave propagation. The water particles lose some energy in the pendulor water chamber by impinging on the paddle and backwall, hence, less energy is available during the return stroke. The available wave power is calculated using the following equation,

Figure 7. Angular velocity (N) and torque at varying wave frequencies.

$$P = \frac{\rho g^2 H^2 T}{32\pi} \tag{1}$$

It can be seen in Fig. 8 that when the paddle is moving in the direction of the wave propagation the output power is more than the backward stroke of the pendular paddle. In the backward direction, some wave energy is lost inside the chamber due to reflection from the backwall of the device and the momentary upsurge of the water to the surface when the paddle approaches the backwall. This is the reason for low torque and power output during the backward stroke. The maximum output power occurs at a frequency of 0.78Hz and the efficiency of 40% is achieved at this frequency. Similar results were found by Gunawaradane et al. [10].
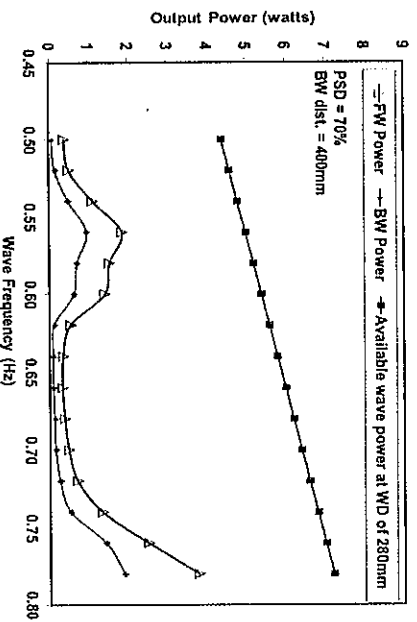

Figure 8. Output power at varying wave frequencies at water depth of 280mm.

IV. CONCLUSION

The water channel wave characteristics were studied and it is found that the wave height increases with increasing frequency, while the wavelength decreases. It is found that when the paddle is moving in the direction against the wave generated, the total swing angle and output power is low compared to when the paddle is moving in the direction of wave generated. This is because the reflected waves from the backwall of the chamber are not as strong as the incident waves. In the frequency range of 0.5Hz to 0.78Hz, the swing angle and the output power of the pendular device first rise, then drop sharply and then rise to their maximum values.

Further, improvements can be made to the performance by modifying the wave entry chamber and backwall shape. This will be considered for future work.

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