

MODEL STUDY ON “PENDULOR” TYPE WAVE ENERGY DEVICE TO UTILIZE OCEAN WAVE ENERGY IN SRI LANKA

Gunawardane S.D.G.S.P¹, Abeysekera M.P², Uyanwaththa, D.M.A.R³, Tennakoon, S.B³, Wijekoon³, W.M.J.S, Ranasinghe R.A.P.C³

¹ Senior Lecturer, Department of Mechanical Engineering, University of Peradeniya
¹E-mail: sdgspg@pdn.ac.lk, ; sdgspg@gmail.com,
¹Telephone: +94-81-2393610 ; Fax: + 94-81-2393610

² Postgraduate Student, Department of Energy Technology, KTH University, Sweden
²E-mail: muditha.abeysekera@gmail.com

³ Department of Mechanical Engineering, University of Peradeniya, Sri Lanka
³E-mail: darkera87@gmail.com, Telephone : +94779147180

Abstract

Sri Lanka being an island it is inevitable to utilize the ocean wave energy as a sustainable energy source. The device called “Pendolor”, which is invented in Japan and has proven 40-50% of wave energy conversion efficiency at the sea of Muroran, Japan. The low wave energy density oceanic climate of Sri Lanka makes this device more preferred, because of its high energy conversion capability. The device consist a pendulum flap hinged inside a caisson and the caisson is faced to the ocean waves. The economical feasibility of this device depends on the construction cost. The conventional caisson is a straight chamber and this type of a device is infeasible because of the length that causes increase in construction cost. A modified caisson is proposed to shorten the caisson length towards the sea and to increase the frequency bandwidth of operation.

Model testing of this modified caisson with a solid friction damper is addressed in this endeavor. Laboratory experiments were conducted with a 1/16 scale model of the proposed caisson. A solid friction damper was used for the model testing and a mathematical model for the device was developed and the parametric modeling was done by using MATLAB. The power conversion efficiency with a modified caisson was discussed in this endeavor.

Key words: “Pendolor”, Wave energy, caisson, excitation moment

1. Introduction

The “pendolor” device is invented in Japan. The device consists of a flap hanged inside a caisson which faces towards the ocean waves (Fig 1). The flap is driven by the horizontal water particle motion of the waves. The device operates on standing waves which are created by superposition of the incident waves and reflected waves from the back wall. This excitation moment (M_0) of the pendulum depends on the caisson configuration as well as the wave frequency (f) and wave height (H). A rotary vane pump is driven by this pendulum and it drives an oil motor which drives a generator.

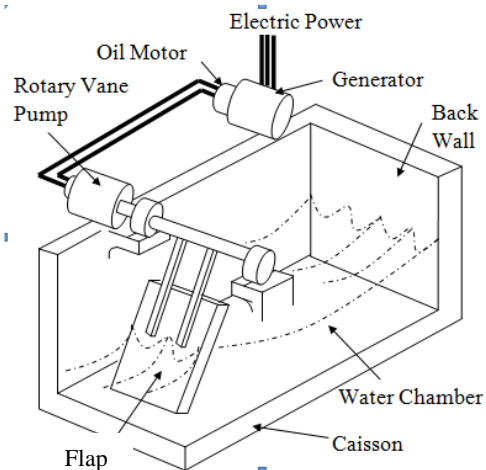


Fig 1 Basic pendulum device

The flap is placed at the node point of the standing waves (Fig 2), where the water particle motion is completely horizontal. The node point is at a distance d from the caisson back wall. Where $d = \lambda/4$ for a wave inside a straight caisson, ($\lambda =$ wave length). Therefore the chamber length depends on the wave length.

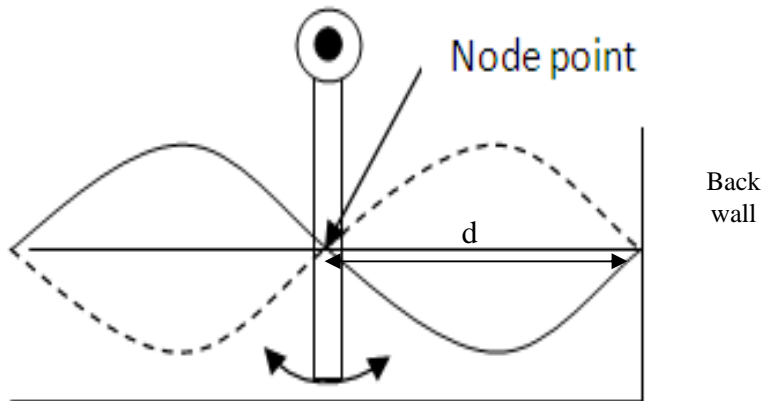


Fig 2 Node point and pendulum placement

Any sustainable system needs to be ecologically viable and economically feasible and socially accepted.

In Sri Lankan ocean climate, the swell wave length is around 100m causing the operating point of flap to be placed at a 25m distance away from the back wall and increases the associated construction cost. A new modified caisson is proposed to shorten the caisson length [3], where a converging section is introduced at the mouth of the chamber and a diverging section is introduced at the back of the caisson (Fig 3). This converging section is expected to create a horizontal particle motion inside the caisson which can drive the flap. Another expected behavior of the modified caisson is to have a broader frequency bandwidth of operation than the straight caisson.

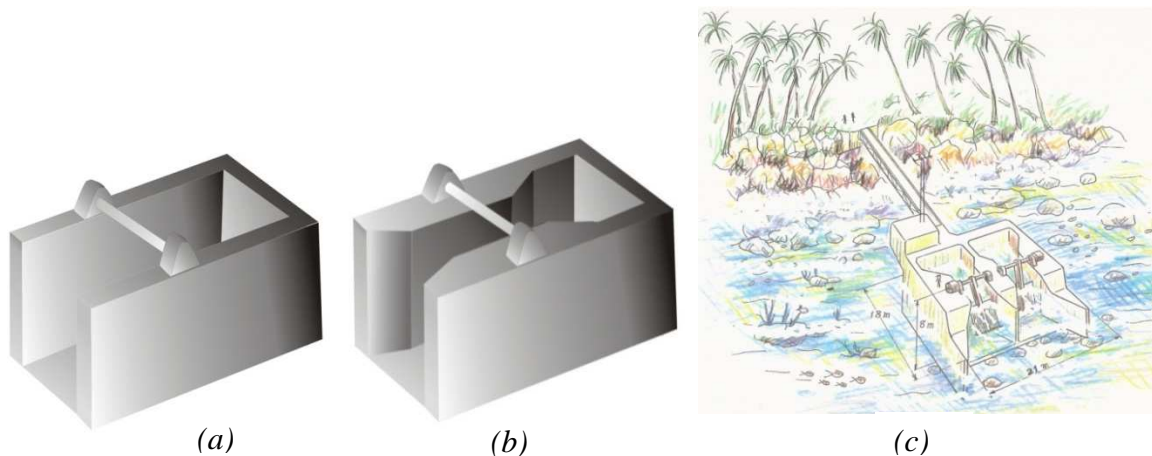
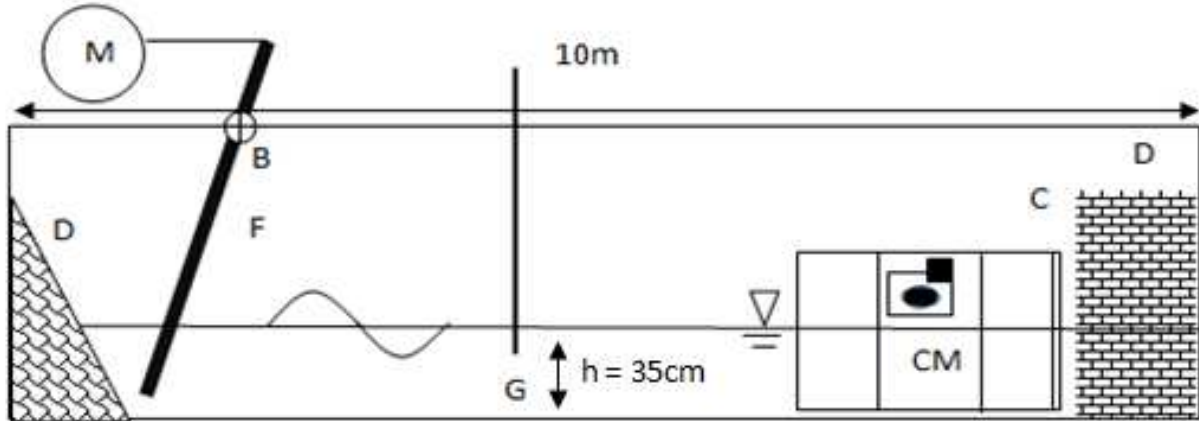


Fig 3 Two caisson types (a) straight caisson, (b) modified caisson, (c) An artistic view of proposed power plant (Watabe)

1.1 Node point variation inside the caisson with the wave frequency

The incoming wave length changes with the time due to the randomness of the ocean , therefore the node point varies and the flap placement point deviate from the node point hence affect the device efficiency. To investigate the node point variation inside the modified caisson laboratory experiments were conducted with a 1/16 scale model of the proposed modified caisson. A visual method was used to identify the node point of the standing waves created inside the caisson



*B: Bearing, C: Caisson, D: Dampers, F: Wave Generating Flap, G Wave Gauge
M: Motor, CM: Camera
Fig 4 Experimental set up*

Wave patterns inside the caisson were observed and snapshots were taken to identify the node points. The node point was identified and the distance from the back wall was measured.

A partial standing wave was created inside the modified caisson due to its geometric construction. The incident and the reflected waves are different due to the effects of reflections and diffractions at the converging and diverging sections

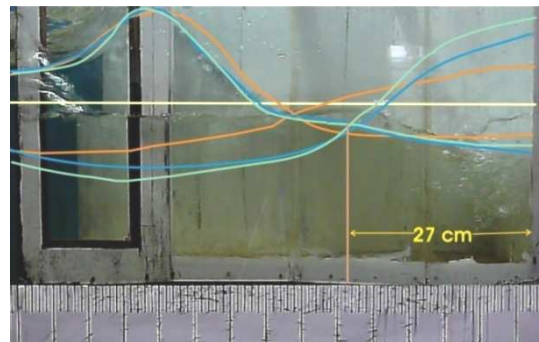


Fig 5 Node point variation inside the modified caisson for $T = 0.9s$

1.2 Node point variation inside straight caisson

As shown in Fig05 it was evident that the modified caisson has a lesser nodal point distance from back wall to the nodal point. This implies the effect of the modification is beneficial on the device construction because the caisson length can be reduced. Since the pendulum has to be placed at the node point, it is implied that, lesser the node point deviation broader the operating frequency bandwidth. From the fig 5 it is visible that the gradient of the modified caisson is lesser than the straight caisson implying that the operating frequency bandwidth is broader in the modified caisson.

The length reduction compared to straight caisson is about 30-40% in the considered frequency range.

The predicted device efficiency behavior for the pendulum model is shown in (Fig 6)[2]

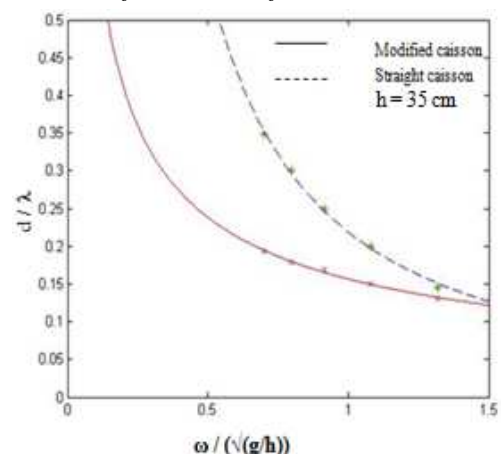


Fig 6 Node point variation for the modified and straight caisson.

2. Mathematical modeling of the pendulor device with modified caisson

The mathematical model for the device with a straight caisson under regular type waves were used in the analysis of the modified caisson [1]. The actual working model of a pendulor device consist a viscous damper (hydraulic pump), but the experiments were conducted under a constant friction damper.

Disc brakes were used as the mechanical damper of the system and the mechanical damping torques were changed by changing the applied pressure on the friction plate. It was assumed that the disc brake plate gives a constant torque at a constant applied pressure on it.

Model for the constant damping brake torque device

$$\sum I \ddot{\theta} + (N_h) \dot{\theta} + N_m + \sum K \theta = M_o \sin \omega t$$

$$\text{Where } \sum I = I_h + I_m, \sum K = K_h + K_m$$

I_m : Moment of inertia of the flap, I_h : Moment of inertia of the added water mass,

N_m : Mechanical Damping factor, N_h : Hydrodynamic damping Factor, K_m : Coefficient of restoring moment by the flap gravitation, K_h : Coefficient of restoring moment by the water mass elevation, M_o : wave excitation moment.

For a straight caisson, the relationship between the above parameters and the wave parameters were discussed in literature [1]. The change of the water chamber cross section changes the velocity potential of the wave inside the caisson. The added moment of inertia and the hydrodynamic damping and the restoring moment from the added water mass elevation depend on the caisson configuration and frequency. Therefore the dynamic system parameters vary from the straight caisson parameters and the complex shape of the modified caisson makes the theoretical investigation complex. Therefore an experimental method was used to investigate the effect of straight caisson.

The input was varied by changing the M_o (changing the input wave), and the output θ was measured while the N_m (Mechanical damping) was at a constant brake torque value for regular waves. Then the parameters were found by minimizing the error between the measured values and the model values.

a. Parametric modeling of the Pendulor device with constant brake torque (Non linear damping torque)

The output of the system was the flap rotation (θ) and the input of the system was the moment of excitation by the waves inside the caisson (M_o). Least square method was used to minimize the square of error between the model values and the measured system values, then optimization techniques were used to optimize the parameters of the model equation to fit the experimentally measured output data. MATLAB programs were used to optimize and find the system parameters (Fig 9).

The MATLAB model was used to obtain Numerical Values for the following parameters

$$\frac{N_h}{\sum I}, \frac{N_m}{\sum I}, \frac{\sum K}{\sum I}, \frac{M}{\sum I}$$

Following parameters of the system were measured.

Mass of the flap (m): 2.12kg, distance to the center of gravity of the flap (lg) - 0.95m

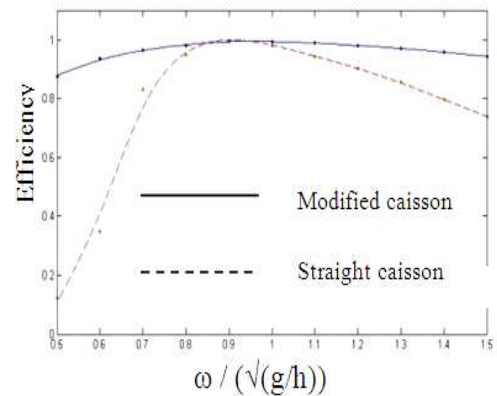
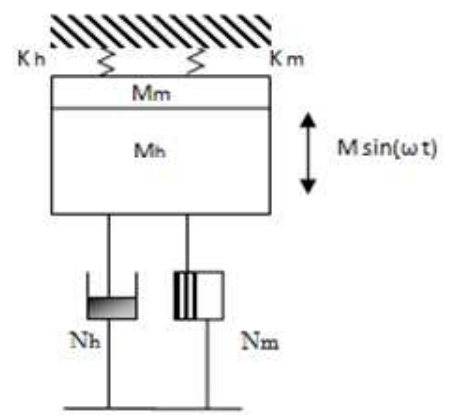


Fig 7 Predicted device performance



h- Hydrodynamic, m - mechanical

Fig 8 Experimental set up with a mechanical brake (constant damping torque)

Therefore

Inertia of the flap $I_m = 1.91 \text{ kgm}^2$

Restoring moment by gravity of the flap $K_m = l_g mg = 19.75 \text{ Nm}$

These calculated values were used with the numerical values of the parameters to find the Parametric Model

$$9.9\ddot{\theta} + 0.33\dot{\theta} + N_m + 23.3\theta = 15.17 \sin(3.60t)$$

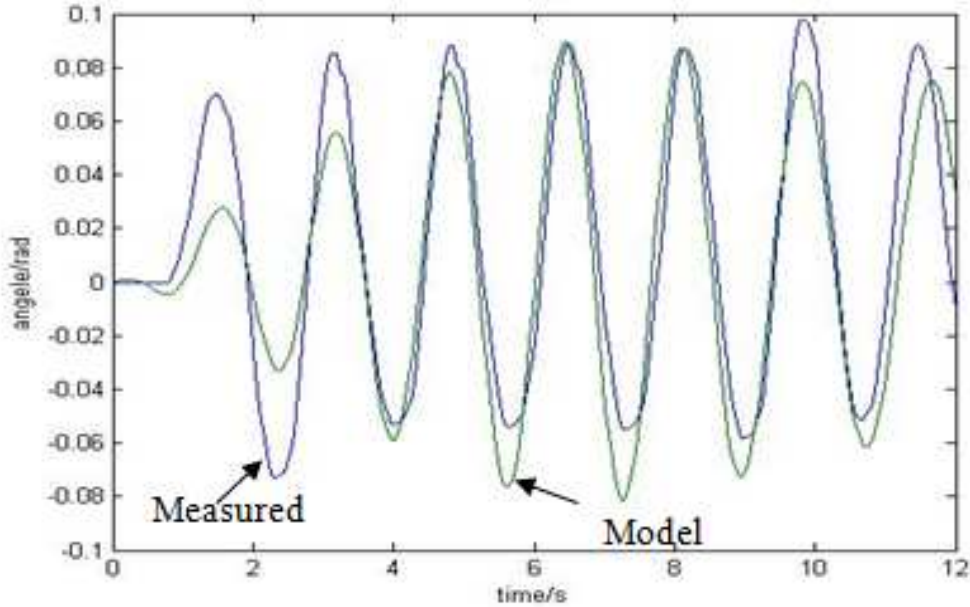


Fig 9 - model and the measured values for $T = 1.75\text{s}$

b. Variation of excitation moment with the frequency

The excitation moment is influenced by the incoming wave frequency. The excitation moment M_o was found from the Mathematical Model and the excitation moment variation for the modified caisson was investigated (Fig 10).

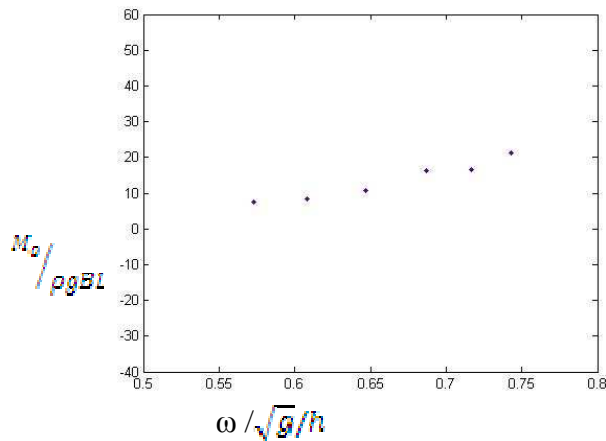


Fig 10 – The variation of excitation moment with the wave frequency

Where, ρ : density of sea water, B : width of the mouth of the caisson, L : wave length, H : wave height and h : water depth.

2.1 Power conversion efficiency of the Pendulor device, with a modified caisson.

The applied brake torque (N) was varied for different wave frequencies. (Fig11)

The work done per cycle

$$W = N \cdot \theta$$

θ , the flap swing angle per cycle.

From Linear Wave Theory, the energy content of an incoming wave for a unit width

$$E = \frac{1}{8} \rho g H^2 L$$

Power conversion ratio for a cycle $\eta = \frac{W}{E}$

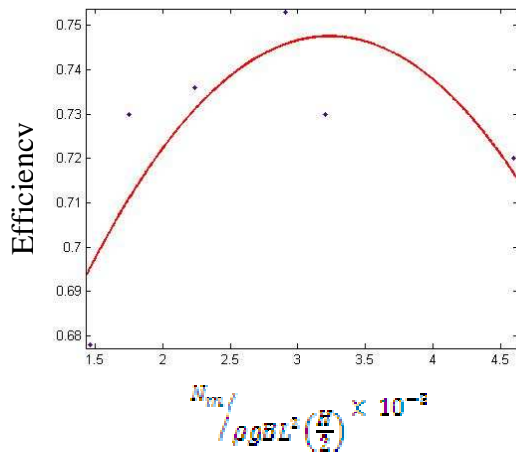


Fig 11 Efficiency Vs damping resistance for wave period 1.35s

The applied mechanical damping torque (N_m) was varied for different wave frequencies to obtain the resonance (damping matching and frequency matching conditions) for the device to perform with maximum power conversion. The device efficiency changes with the Mechanical damping torque and the incoming wave frequency.

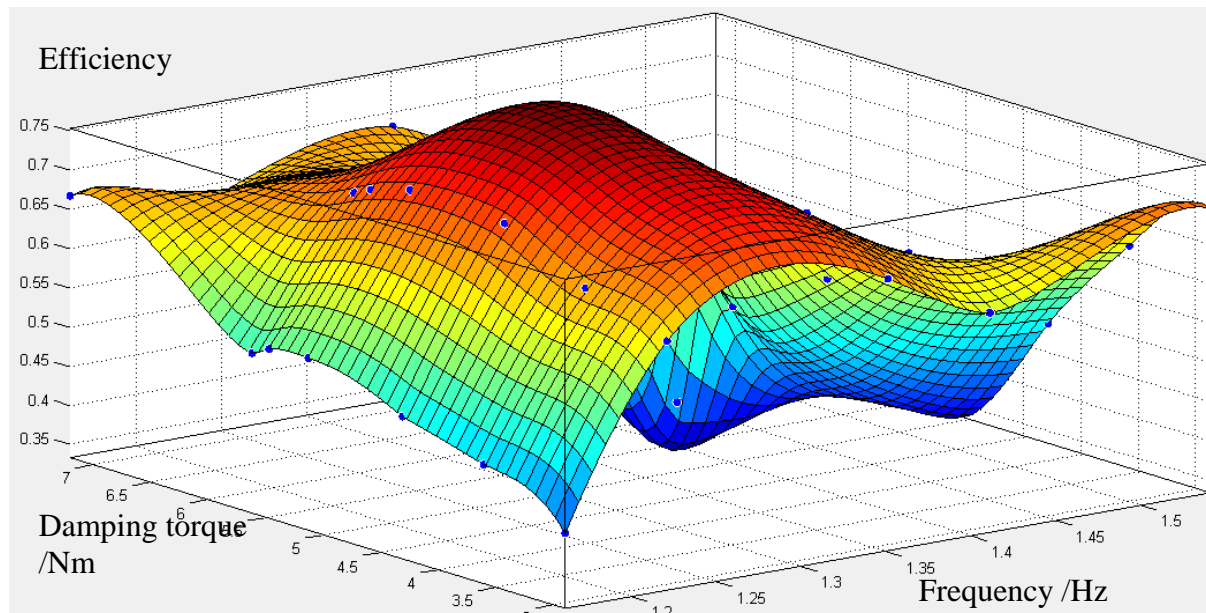


Fig 12 Device performance and operating frequency bandwidth

3. Conclusion

The Pendulor device with the modified caisson has proven caisson length shortening capability of about 40-30%. The device has proven 70% wave power conversion efficiency at the experimental model with the solid friction damper. The economical feasibility of the pendulor system depends upon the construction cost as well as the device performance. The operating frequency bandwidth of this device is expected to be broadened by the introduction of this modified caisson. The modified caisson has to be compared with the straight caisson for this frequency range and investigate the device performance with the modified caisson. The further studies on the performance with the modified caisson are currently being conducted.

References

1. *Utilization of the Ocean wave energy*, 2007. Tomiji WATABE
2. Ando A., Ohtani S., Takagi M., Kuroi M., Kondo H., Yano K., Watabe T., On a Flap Type Wave Energy Converter, Proceedings of the Engineering Committee on Oceanic Resources (ECOR) International conference, 1984 Oct.
3. Tomiji Watabe, Hirotaka Yokouchi, S.D.G.S.P. Gunawardane, "Heave and Pitch Buoy (HPB), A miniature Wave Energy Converter", Proceeding of the Twelfth (2002) international offshore and Polar Engineering Conference, Kitakyushu, Japan, May 26-31, 2002, pp. 649-654.

About the Authors

- Dr S.P Gunawardane, **PhD** : Muroran Institute of Technology, Japan, **MEng** : Muroran Institute of Technology, Japan, **BScEng**: University of Peradeniya, Research interests : renewable energy studies mainly on small wind power and ocean wave energy systems, sound and vibration problems and machine dynamics.
- Abeseykara M.P , currently reading for MSc at the department of Energy Technology , KTH , Sweden.
- Uyanwaththe. D.M.A.R, Tennakoon S.B, Wijekoon W.M.J.S, Ranasinghe R.A.P.C, graduates of Mechanical Engineering from the University of Peradeniya.