Ocean Wave Energy Harvest Using Multi-Piezoelectric Cantilever Beams

Chuttipong Tuma and Danai Phaoharuhansa
Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangkok, Thailand
Email: chuttipong.tuma@gmail.com, danai.pha@mail.kmutt.ac.th

***Abstract*—This study introduces finite element analysis to design multiple cantilever beams for ocean wave energy harvest. The ocean wave energy is transformed to vibration, and it will be converted to electricity by piezoelectric. The natural frequencies of the beams should be tuned as low frequency relative to ocean wave energy in Thailand. The natural frequencies of the beams are designed by finite element analysis such as 4.461, 8.479, 13.802, and 25.105 Hz, which are the frequencies of swaying and bending motions. The experiment result presents that power harvest from piezoelectric is related to the desired frequency. The suitable range of energy harvest is from 11 to 24 Hz. The error occurs about 3.4-5.8%, cause of which depends on stiffness of piezoelectric plate Then, the stiffness and the natural frequency of the beams may be slightly increased.**

***Index Terms*—ocean wave energy, natural frequency, multi-cantilever beams, piezoelectric, FEA**

I. Introduction

The energy is the most importance, it is from Thailand Alternative Energy Situation 2016 report, oil consumption increased from previous year 9.7 percent Ref. [1]. Wave energy is one of the most interest renewable energy. Ocean wave in Thailand is approximately between 0.186-0.198 Hz and wave height estimate 0.5 m Ref. [2].

Wave energy converter (WEC) is a device to convert ocean energy to electricity and it can be classified by working principle and location as shows in Fig. 1. The working principle consists OWC, pressure, floating structure, overtopping and oscillating wave surge/impact. The location consists onshore, nearshore and offshore Ref. [3]. Thailand ocean contains low depth and the floating structure of WEC is suitable than other types.

Point absorber is one of the most popular WEC, which is floated on sea surface. It is oscillated by transverse wave, and it converts energy from vibration energy to electricity. Point absorber has advantage that it is small size and it can absorb energy in several directions. Aqua Energy Group Ltd has developed AquabuOY. It has diameter 6 m and it was installed in deep ocean more than 50 m, the device can harvest electric power much more 250 kW.

To design point absorber device, the frequency of point absorber and natural frequency of mechanism should be designed to similar frequencies. The frequency of point absorber usually equals with ocean wave. Piezoelectric is one of devices to convert energy from vibration. Piezoelectric is attached on some mechanisms, which receives electric energy from stress and strain of material.

To harvest highest energy using piezoelectric, natural frequency of point absorber WEC should be configured on average frequency of ocean wave. Multiple cantilever beams are stacked to increase the bandwidth of natural frequency. It is well known as piezoelectric cantilever beam arrays. It is usually expressed as double mass spring system. The frequency bandwidth of piezoelectric cantilever beam arrays are tuning mass or dimension beams. Several papers Ref. [4-7] presents the multiple cantilever beams arrayed 2-4 beams to increase bandwidth and electric power for scavenge vibration energy ambient. The most multi-cantilever beam systems they are natural frequency between 22 to 245 Hz and tuned natural frequency by changing tip mass.

Therefore, this paper deals finite element method (FEM) for tuning natural frequency of the multiple cantilever beams arrays to nearly Andaman sea frequency. The multiple cantilever beams arrays will have experimented with various frequencies.

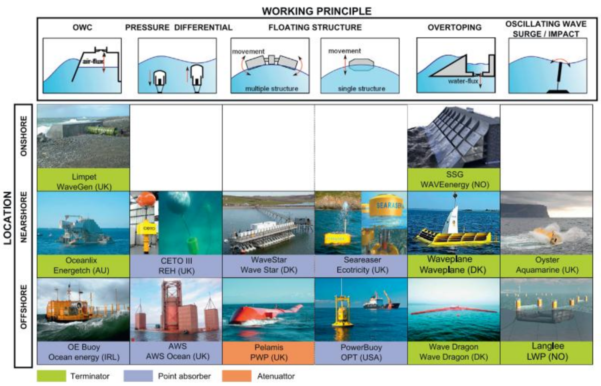


Figure 1. Type of wave energy converter. Ref. [3]

Manuscript received July 1, 2019; revised August 1, 2020.

doi: 10.18178/ijmerr.9.6.911-916

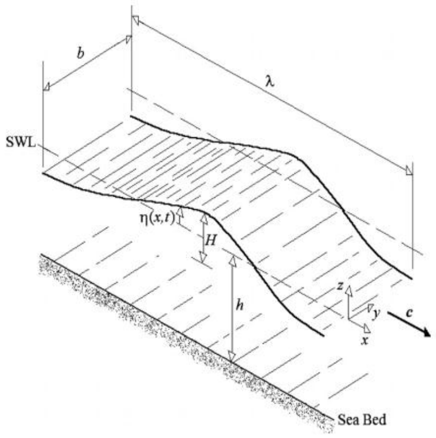


Figure 2. Component of wave. Ref. [8]

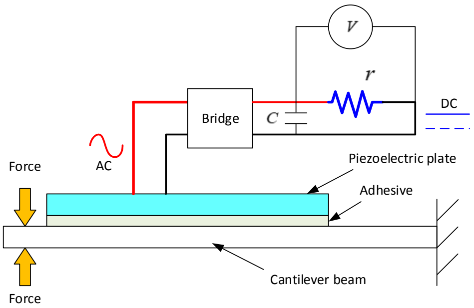


Figure 3. Principle of piezoelectric schematic for energy harvest.

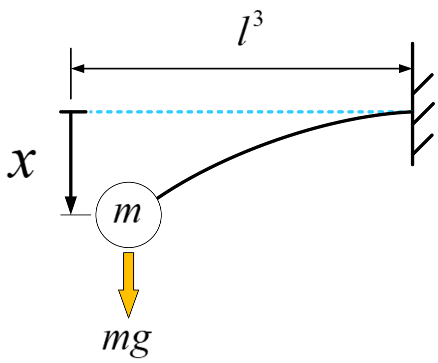


Figure 4. Cantilever beam with mass in single degree of freedom

II. WAVE ENERGY

Wave energy produce by transmitted another energy into ocean surface such as earth rotation, earthquakes and winds. Andaman sea is deep ocean, and the wave steepness equals or greater than 0.2. Power of deep ocean wave (P_w) is expressed that

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

where, ρ is the density of ocean water, g is the gravity force, H is wave high is the deep of ocean, T is the time period of wave and b is the width of wave. Andaman sea has average power 5.12 kW/m.

III. PIEZOELECTRIC ENERGY HARVEST

Piezoelectric is usually used as actuator or sensor devices, which can generate electric power by electric polarization. When the piezoelectric material received stress from force, it is called the phenomenal direct piezoelectric effect is shows in the Fig. 3. The relationship of stress, strain and electric field of piezoelectric is present (2)

$$T_p = E_p S_p - e_p E \tag{2}$$

where, T_p and S_p is stress and strain in piezoelectric plate. E_p is young's modulus of piezoelectric, e_p is piezoelectric coefficient and E is electric field of piezoelectric. The power harvest of piezoelectric depends on electronic resistance. It can as

$$P_V = \frac{V^2}{r} \tag{3}$$

where, V is the voltage across the load resistance and r is the load resistance.

IV. CANTILEVER BEAM

Cantilever beam can convert to spring stiffness. For system a cantilever beam with tip mass m, is shows in Fig. 4. From mechanical of materials, stiffness of cantilever beam is given as

$$k = \frac{3EI}{l^3} \tag{4}$$

Equation of elastic curve is given as,

$$\delta_{max} = \frac{mgl^3}{3EI} \tag{5}$$

where, m is the mass of tip mass, E is the young's modulus of material, l is length of beam and I is the moment of inertia of cantilever beam. The spring stiffness of cantilever beam is given as,

$$k \quad \frac{F}{x} \quad \frac{mg}{\delta_{max}} \quad \frac{3EI}{l^3} \tag{6}$$

A cantilever beam obtained natural frequency narrow bandwidth. To expand the bandwidth.

V. FINITE ELEMENT ANALYSIS FOR MULTIPLE PIEZOELECTRIC CANTILEVER BEAMS ARRAYS

Finite element analysis (FEA) is usually used to solve mathematical model relative to engineering problems. The double cantilever beam arrays in Fig. 5 is simplified as double mass spring system as shown in Fig. 6. The sinusoidal wave will be added as ocean wave.

To certain the strength of the beams, Fig. 7 shows single beam element that boundary condition is defined element in beam by assuming the transverse displacement in term of the nodal degree of freedom in matrix form. Then, moment of the beam can be expressed as

$$v(x) = Nu \tag{7}$$

Where, N denotes shape function and $N = [N_1(x) \quad N_2(x) \quad N_3(x) \quad N_4(x)]$. u denotes nodal displacement and $u = [v_1 \quad \phi_1 \quad v_2 \quad \phi_2]^T$.

Then, nodes are given that

$$N_1 \quad \frac{1}{L^3}\left(2x^3 \quad 3x^2L \quad L^3\right) \tag{8}$$

$$N_2 \quad \frac{1}{L^3}\left(x^3L \quad 2x^2L^2 \quad xL^3\right) \tag{9}$$

$$N_3 \quad \frac{1}{L^3}\left(\quad 2x^3 \quad 3x^2L\right) \tag{10}$$

$$N_4 = \frac{1}{L^3}\left(x^3L - x^2L^2\right) \tag{11}$$

N_1, N_2, N_3 and N_4 are called the shape function of beam element.

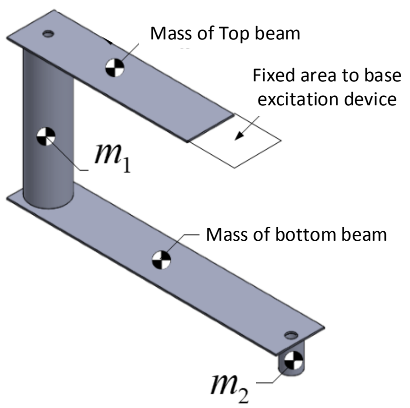


Figure 5. Geometric of module energy harvest structure.

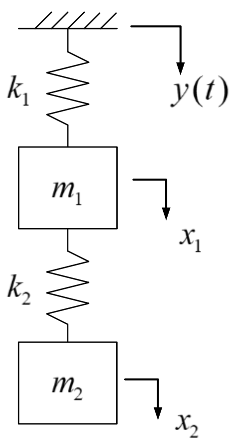


Figure 6. Double mass spring system.

Beam element stiffness matrix can be derived from Galerkin's method in (12).

$$K = \int_0^L [B]^T EI[B]dx \tag{12}$$

where,

$$B = [N_1''(x) \quad N_2''(x) \quad N_3''(x) \quad N_4''(x)] \tag{13}$$

Lumped-mass element matrix in FEA is defined as

$$M = \int_0^L \iint_A \rho[N]^T[N]dAdx \tag{14}$$

VI. DOUBLE SPRING MASS SYSTEM

The double cantilever beam arrays system in Fig.5 can be simplified as double spring mass system is show in Fig.6 consists of two springs and two tip masses. The clamped area attached with moving base. The base excitation has been moving sinusoidal. The mathematic model of this system under base excitation is give as

$$y(t) = y_0 \sin(\omega t) \tag{15}$$

$$m\ddot{x} + kx = U \tag{16}$$

where, $m = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}$, $x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$, $\ddot{x} = \begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{bmatrix}$, $U = \begin{bmatrix} k_1 y(t) \\ 0 \end{bmatrix}$ and $k = \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix}$, m_1 is first tip mass and m_2 is second tip mass, k_1 is first spring stiffness constant and the k_2 is second spring stiffness constant, y_0 and ω are the amplitude of base excitation and frequency of base excitation respectively. $\ddot{x}_1$ and $\ddot{x}_2$ are the acceleration of m_1 and m_2 respectively. x_1 and x_2 are the displacement of m_1 and m_2 respectively.

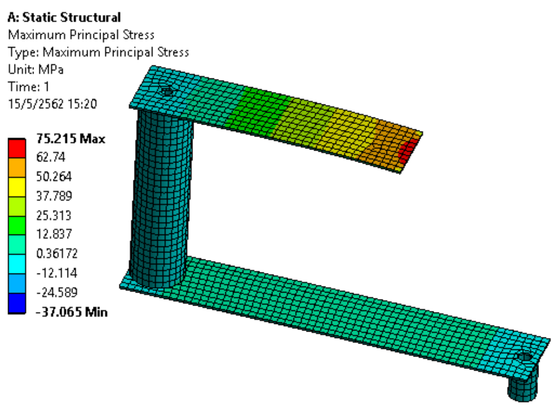
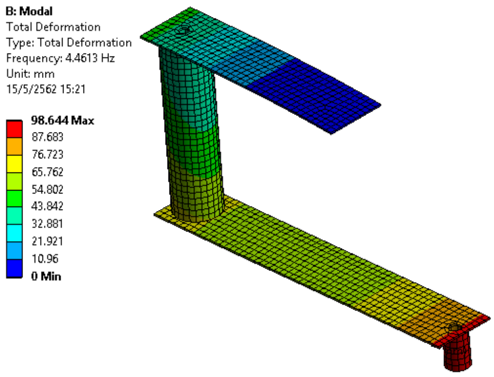
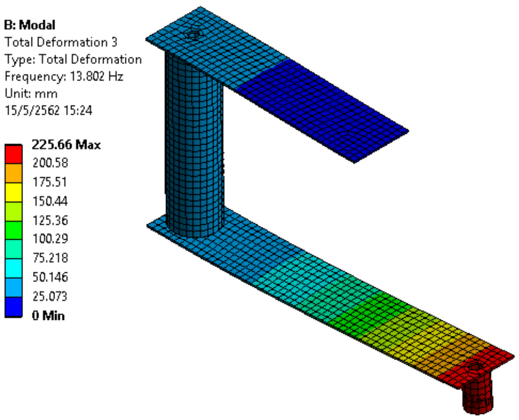


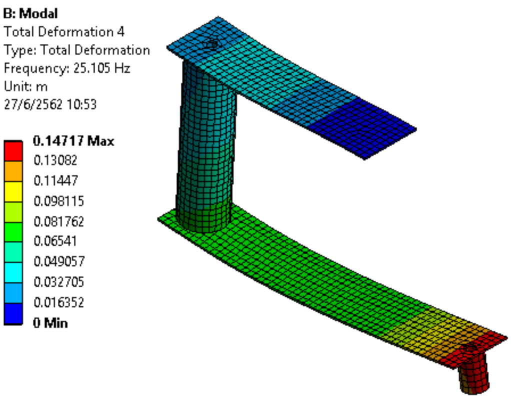
Figure 7. Static structural analysis result



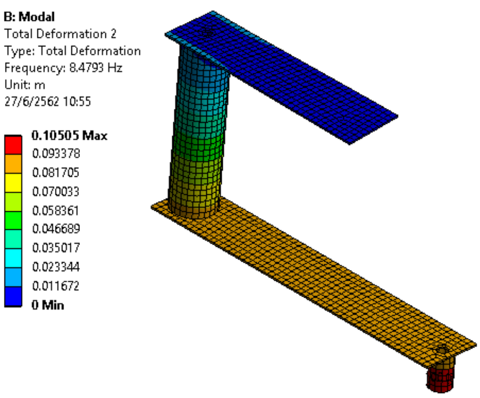
(a) First mode bending



(b) Second mode bending



(c) Third mode bending



(d) Fourth mode swaying

Figure 8. Natural frequencies and mode shape of double cantilever beam arrays (a) bending mode of top plate cantilever beam (b) bending mode of bottom plate cantilever beam (c) bending mode of both plate cantilever beam (d) swaying mode of bottom plate cantilever beam

TABLE I. PROPERTIES OF CANTILEVER BEAM AND TIP MASS

	Top cantilever beam	Bottom cantilever beam
L*W (mm)	120x30	180x31.5
Thickness (mm)	1	1
Mass density (kg/m^3)	2,770	2,770
Young's modulus (GPa)	70	70
Tip mass(kg)	0.3	0.012

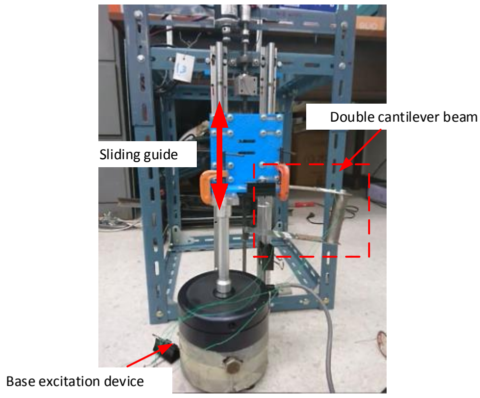


Figure 9. Installation of base excitation test.

VII. RESULTS

This section deals simulation results and experiment result. The structure is analyzed using finite element method in order to consider static structural analysis and modal analysis.

A. *Static Structural Analysis*

To tune the tip mass, the stress should occur to archive maximum energy harvest but it should not greater than yield strength. The upper beam is concerned because it has to carrier the weight of the system. Thus, the static structural analysis will consider stress, strain and displacement, when structure applied any force. Geometric of cantilever beams and mass are exhibited in Table I. The material is aluminum and the boundary condition has shown in Fig. 5 that the upper beam is mounted to oscillator, which will be shake the beams with heaving motion so that the stress is considered as shown in Fig. 7.

Fig. 7 shows the stress in double cantilever beam arrays that the maximum stress of the beams equals 75.22 MPa or 79.17 percent of the yield strength. The strain most occurred on near fix support, that area should be attach piezoelectric.

B. *Modal Analysis*

Generally, double spring mass system obtains 2 natural frequencies of vertical oscillation but modal analysis considers with the complex dynamics model. It can derive natural frequencies and mode shape of structure. It consists of 4 mode shapes such as bending and swaying motion. The initial condition is also similar with previous simulation.

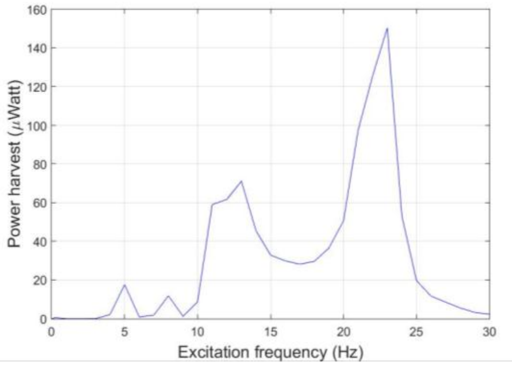


Figure 10. Total power output versus frequency at 0.15-30 Hz.

Fig. 8 presents the modal analysis results of 4 mode shapes. The first mode result is bending mode of top beam as shown in Fig.8(a) and the natural frequency of top beam equals 4.46 Hz. The second mode result is bending mode of bottom beam as shown in Fig. 8(b). The natural frequency of bottom beam equals 13.80 Hz. The third mode result is bending mode of both beams as shown in Fig. 8(c). The natural frequency of overall system equals 25.11 Hz. The fourth mode shape is that swaying mode of bottom beam as shown in Fig. 8(d). The natural frequency equals 8.48 Hz.

C. Experiment Results

To validate the simulation results, the piezoelectric plates are mounted with the double cantilever beams and electronic load is defined as 70 kΩ, which is electronic resistance. The beams are demonstrated using base excitation. The beams are mounted at sliding guide and they are oscillated by base excitation with constant amplitude. The experiment results present energy harvest of piezoelectric plates as shown in Fig. 10. The double cantilever beams are oscillated using base excitation, amplitude of which are constant and the frequency of oscillation is varied between 0.15-30 Hz.

Fig. 10 exhibits the comparison between total power of the beams in range of 0.15-0.2 Hz and maximum power has 0.5472 μWatt at 0.2 Hz. Fig.10 presents the compare between total power of the beams in range 1-30 Hz, the peak power occurs at 5 Hz, 13 Hz, and 23 Hz. The power at 5 , 8, 13, and 23 Hz are 17.62, 11.84, 71.13, and 150.42 μWatt, respectively.

VIII. Conclusion

Piezoelectric cantilever beam arrays are designed to harvest energy at low frequencies, and then the natural frequencies of the cantilever beam system obtain 4.46, 8.48, 13.8, and 25.11 Hz. The experiment result presents that the suitable range of excitation frequency is between 12 – 24 Hz. The range relatives to natural frequencies of bottom beam and overall system. The power harvest is increasing at 10 Hz and it obtains the peak power at 13 and 23 Hz.

As summary, the double cantilever beams are designed the natural frequencies using finite element analysis, and the beams are validated by base excitation device. The error occurs about 3.4-5.8%, cause of which depends on stiffness of piezoelectric plate. Therefore, the stiffness and the natural frequency of double cantilever beams may be slightly increased than design value. The energy harvest has most effect by bending mode of bottom beams and overall system.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

This paper is a part of master thesis. C. Tuma has conducted the paper under the vision of D. Phaoharuhansa. He researched about cantilever beams using finite element analysis and the specimen is demonstrated by commercial base excitation.

References

[1] Ministry of Energy, "Thailand Alternative Energy Situation 2016", vol.15, pp. 1-3, Dec 2016

[2] N. Kemden, C. Ekkawatpanit, W. Wannawong, and D. Kositgittiwong, "Wave energy potential for power generation in the Gulf of Thailand," presented at the Sustainable Energy and Environment, Bangkok, Thailand, November 19-21, 2014

[3] I. López, J. Andreu, S. Ceballos, I. Martínez de Alegría and I. Kortabarria. (July 2013). Review of wave energy technologies and the necessary power-equipment. *Renewable and Sustainable Energy Reviews*. [Online]. 27. pp. 413-434. Available: https://www.sciencedirect.com/science/article/pii/S1364032113004541?via%3Dihub

[4] In-Ho Kim, Hyung-Jo Jung, Bo Mi Lee and Seon-Jun Jang. (May 2011). Broadband energy-harvesting using a two degree-of-freedom vibration body, *Applied Physics Letter*. 214102(98). pp.1-3. [Online]. Available: https://aip.scitation.org/doi/10.1063/1.3595278

[5] Yu-Yin Chen and Dejan Vasic. (Mar 2015). Energy harvesting of two cantilever beams structure: Interfacing circuit discussion. *SPIE Smart Structures and Nondestructive Evaluation.* [Online]. Available: https://doi.org/10.1117/12.2084211

[6] Eduard Dechant, Feodor Fedulov, Leonid Y. Fetisov and Mikhail Shamonin. Bandwidth widening of piezoelectric cantilever beam arrays by mass-tip tuning for low-frequency vibration energy harvesting. *Appl. Sci.* [Online]. 7(12) pp.755-758. Available: https://www.mdpi.com/2076-3417/7/12/1324

[7] S. C. Lin, B. S. Lee, W. J. Wu and C. K. Lee, "Multi-cantilever piezoelectric MEMS generator in energy harvesting," presented at the IEEE International Ultrasonics Symposium, Rome, Italy 20-23 Sept, 2009.

[8] M. E. McCormick, *Ocean Engineering Mechanics with Applications*, 1 st ed, Cambridge.: Cambridge University Press, 2009, pp. 64-67.

[9] D. L. Logan, *A First Course in the Finite Element Method*, 4 th ed, Toronto, Ont.: Thomson, 2007, Chapter 4.

[10] X. L. Chen and Y. J. Liu, *Modeling and Simulation with ANSYS Workbench*, 1 st ed, Boca Raton.: CRC Press, 2015, Chapter 8.

Chuttipong Tuma is graduate student in the Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangkok, Thailand. His interests include wave energy converter and computer-aided engineer.

Danai Phaoharuhansa received D.Eng. in Functional Control System from Shibaura Institute of Technology and he is lecturer at Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's University of Technology Thonburi, Bangkok, Thailand. His interests include wave energy converter and motion control system.