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Study of Vibration of Dual-Buoy on the Linear Electrical Generator for Wave Energy Converter

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Abstract: ***Today, Ocean wave energy is a renewable energy source with a large potential to contribute to the world's electricity production. This report presents the results on the modeling and optimization the systems of two buoys for wave energy converter. The first is a floater. The second is a semi-submerged body. The energy is converted from the relative motion between the two buoys by the linear generator. For simulation in three dimensions, the system of equations (6 modes of motions) has been obtained. The governing equations are solved by ANSYS AQWA software and Matlab tools. In this report, Response Amplitude Operators (RAOs) are analysed. Based on the RAOs results, we will determine the wave frequency domain for the maximum energy. The obtained results can be used for the simulation, calculation and geometry optimization of the more realistic system in wave energy convertion.***

Keywords: Wave-energy converter; heaving-buoy; dual-buoy; linear generator

1. Introduction

Today, the focus on generating electricity from marine renewable sources is an important area of research. There are many wave energy devices investigated, tested and deployed in the oceans. There is a large number of concepts for wave energy conversion [1, 2, 3], WECs are generally categorized by location (Shoreline devices, Nearshore devices, Offshore devices), by types (Attenuator device, Terminator device, Point absorber) and by modes of operation (The submerged pressure differential device, An oscillating wave surge converter, An Oscillating water column (OWC), An overtopping device).

In Vietnam, according to the latest studies, the total wave power in the coast zone is about 58677.02 MW while the total electric power generation capacity of Vietnam in 2010 was 12200.00 MW [4, 5, 6, 7]. The region has great potential for wave energy in Vietnam is South-Central offshore. The annual average wave energy flux for this region is over 30kW/m and reaches the maximum value of about 100 kW/m in December. This is a good energy resource to meet the energy demand of the development.

One of the major challenges of WECs is concerned with how to drive generators. During early wave power research, the possibility of using electrical linear generators was investigated [8, 9, 10]. A linear generator offers the possibility of directly converting mechanical energy into electrical energy.

The basic concept of a linear generator is to have a translator on which magnets (or windings) are mounted with alternating polarity directly coupled to a heaving buoy, with the stator containing windings (or magnets), mounted in a relatively stationary structure [11, 12, 13]. As the heaving buoy oscillates, an electric current will be induced in the coils.

In this article, we will present a simple modeling of the linear permanent magnet generator and the structure of the direct driven wave-energy converter. The results of numerical simulation in 1D and experimental analysis of the two point-absorbed system will be presented. The rest of the topic presents the numerical simulation results in 3D for the behavior of the buoy in waves with different frequencies, the RAOs (Response Amplitude Operators) will be calculated and analyzed.

2. Governing Equations

The concept of the device isdescribed in **Figure 1**. The piston is covered with rows of permanent magnets of alternating polarity.The stator is made of laminated electrical non-oriented steel sheets and isolated copper conductors. The conductors are wound in slots (holes) in the stator steel and forms closed loops or coils. When the buoy oscillates under wave forces, it makes piston move relative to the stator. Reciprocate movements of the piston induce currents in stator winding. The current in turn affects the piston with Lorentz force opposite to the direction of motion.

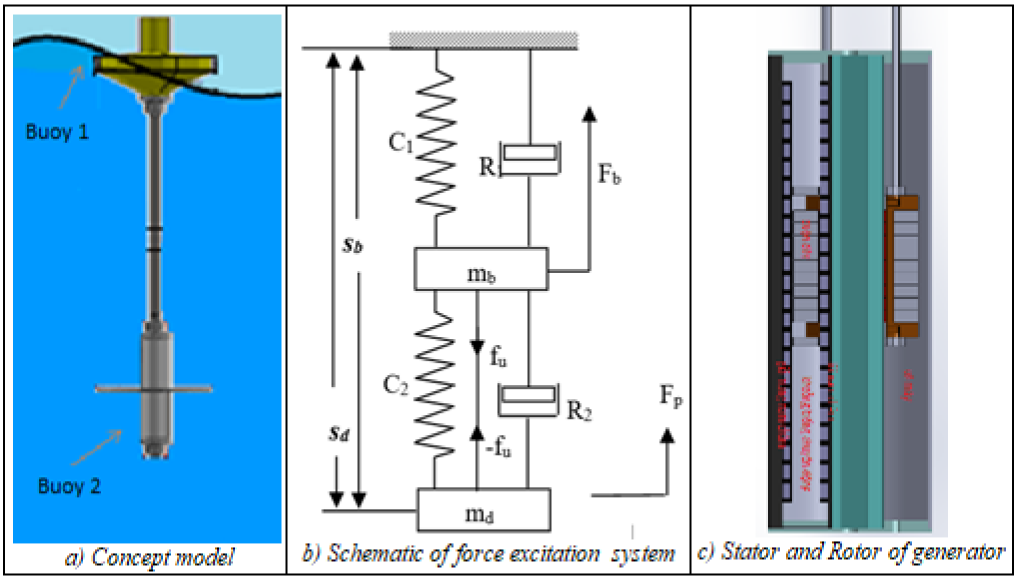

Figure 1: Device's model

For analyzing, the mathematic model of the device which includes the governing equations of bodies' motion is obtained. Based on this model the relative between wave parameters, physical dimensions, electric and magnetic behavior can be set and studied. In this study, the analysis is carried out for the linear wave theory only. Then the wave equation has the form:

$$\eta(t) = \eta_a \cos(\omega t - kx) \quad (1)$$

In which, $\eta(t)$ is the surface water displacement related to still water level, η_a is the wave amplitude, ω is angular frequency, k is wave number.

In the case of 1D simulation, the equations of motion for the two bodies can be expressed as follows:

$$m_b \ddot{s}_b(t) + S_b s_b(t) = F_{w,b}(t) + F_{f,b}(t) + F_u(t) + F_c(t) + F_m(t) + F_{drag,b}(t) \quad (2)$$

$$m_d \ddot{s}_d(t) = F_{w,d}(t) + F_{f,d}(t) - F_u(t) - F_c(t) - F_m(t) + F_{drag,b}(t) \quad (3)$$

Where subscripts $_b$ and $_d$ are used to indicate for buoy and disk respectively; s_b and s_d are the vertical displacement from equilibrium for the buoy and the disk. m_b is the mass of the buoy and the translator (body 1) and m_d is the mass of the disk and the magnet (body 2). $S_b = \rho g A_{w,b}$ is the hydrostatic stiffness, $A_{w,b}$ being the water plane area of the buoy, $F_{w,b}(t)$ is the wave force. $F_{f,b}(t)$ is the friction force, $F_m(t)$ is the net buoyancy of the buoy, $F_c(t)$ is the force from the end-stop device, $F_{drag}(t)$ is drag force. The electromagnetic force $F_u(t)$, is a consequence of the damping from the electrical system and has an influence on the WEC's ability to absorb energy. The expressions of the forces are given by:

$$F_{w,b}(t) = F_{e,b}(t) + F_{r,b}(t) \quad (4)$$

$$F_{e,b}(t) = \eta(t) * f_b(t) \quad (5)$$

$$F_{r,b}(t) = m_{r,b}\dot{u}_b(t) + k_{11}(t) * u_b(t) \quad (6)$$

$$F_{f,b}(t) = -R_{f,b}(t)\big(u_b(t) - u_d(t)\big) \quad (7)$$

$$F_m = g(\rho V_b - m_b) \quad (8)$$

$$F_{drag,b} = -0.5 C_T \rho A_{w,b} |\dot{s}_b(t)| \dot{s}_b(t) \quad (9)$$

In which $\eta(t)$ is the elevation of wave surface, $f_b(t)$ is the excitation force kernel of the buoy, $k_{11}(t)$ is the integration kernel for the radiation force on the buoy due to the motion of the buoy, $m_{r,b}$ is the added mass of the buoy, $R_{f,b}$ (=$R_{f,d}$) is friction coefficient. The expressions of forces acting on the disk are the same manner which sub-index $_d$.

In the previous study, by assuming the function of harmonic wave$x(t) = \cos(2\pi ft + \varphi)$, with $f = 1/7$, $\varphi = \pi$, based on the above equations of motion for two bodies, we can simulate the relative movement between the floating body and semi-submerged body in **Figure 2**. The results from experiences are measured and compared to the simulation ones and a good agreement is observed (**Figure 3**).

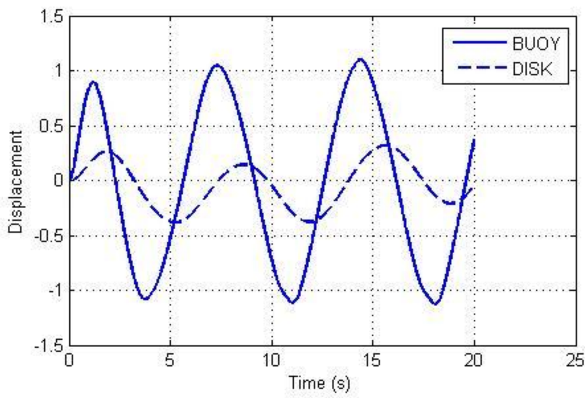

Figure 2: Displacement of BUOY and DISK with the function of harmonic wave: $\mathbf{x(t) = \cos(2\pi ft + \varphi)}$, with $\mathbf{f = 1/7, \varphi = \pi}$.

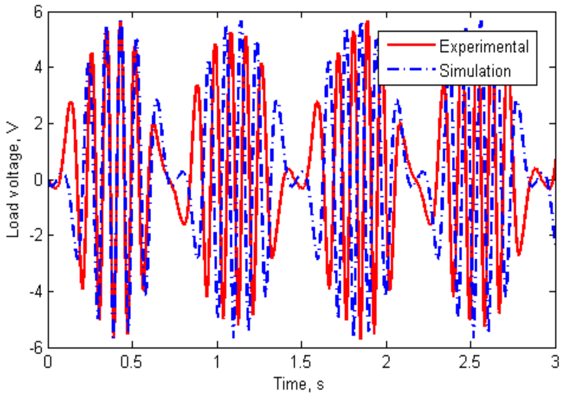

Figure 3: Load voltage from experience and simulation.

In the case of 3D simulation, the equations of motion for the two bodies can be expressed as follows:

$$M_b\ddot{X}_b + M_a\ddot{X}_b + C\dot{X}_b + KX_b = F \quad (10)$$

Where M_b is the mass matrix of buoy, M_a is added mass matrix, C is radiation damping matrix, K is linear stiffness matrix, F is the total forces which act on each body, X_b is response motion(**Figure 4**).

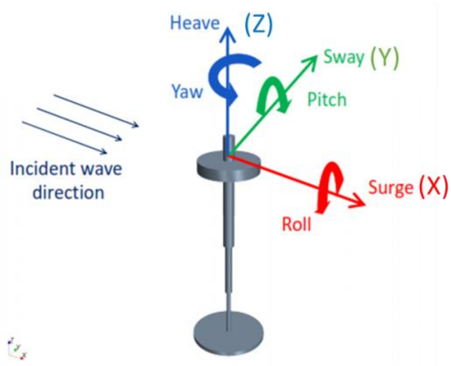

Figure 4: The translation and rotation of the body

In order to determine the behavior of the buoy in waves with different frequencies, the RAOs (Response Amplitude Operators) will be calculated in the following. The RAOs depends of the size (draft and area of waterline) and the mass properties of the body, wave direction and period. RAOs are not physical parameters but they can be useful in determining the frequencies at which maximum amount of power can theoretically be extracted. RAOs are transfer functions which are defined:

$$RAO(\omega) = \frac{F_e(\omega)}{K-\omega^2(M+M_a(\omega))+j\omega C(\omega)} \quad (11)$$

Where ω is the wave frequency

3. Simulation Results Analysis

In this section, the governing equations are solved by ANSYS AQWA software and Matlab tools. Response Amplitude Operators (RAOs) are analysed.The parameters of buoy are given in the **Table 1**. The schematic discretization of a typical buoy geometry considered in this work is presented in **figure 5**. Two meshes have been considered: mesh of body 1 with 1101 panels and other one with 2210 panels.

To defining the environment of a wave energy converter, a simple model of the waves is used. Linear wave theory (Airy wave theory) provides such a simple model, which assumes that the fluid flow is irrotational, incompressible and inviscid. **Figure 4** presents the wave direction, the translation and rotation of the body.In this study, a monochromaticwave with amplitude of 1 m and a frequency of 0.5 Hz is considered. Based on the simple model in the previous section, we obtained following results.

Table 1: The parameters of heave body

Parameters	Value
Density of water [kg/m^3]	1030
Mass of buoy 1 (*HB1*) [kg]	4432
Mass of buoy 2 (*HB2*) [kg]	12300
Number of Elements for Buoy 1	1101
Number of Elements for Buoy 2	2210
Centre of Gravity for buoy 1[m]	0,1
Centre of Buoyancy for buoy 1 [m]	-0,1
Centre of Gravity for buoy 2 [m]	-9,35
Centre of Buoyancy for buoy 2[m]	-9,36

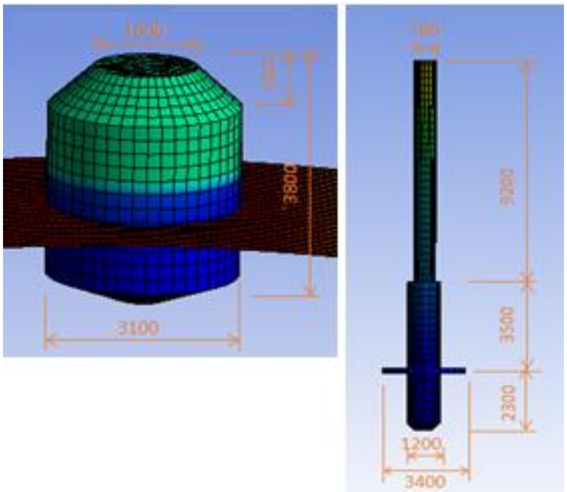

Figure 5: Geometry dimensions of heave body

Figure 6shows the displacement amplitude of each bodyin the vertical direction from 3D simulation. It indicates that displacement shapes are homologous in 1D and 3D cases.In oders to design proper buoy for WECs in a specific coast, characteristic parameters RAOs of buoys with inrteraction waves need to be calculated.

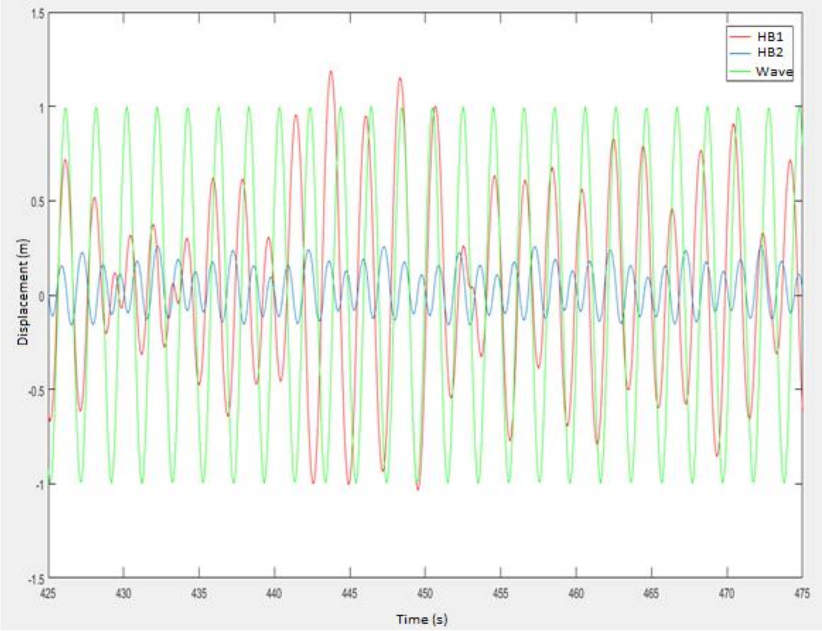

Figure 6: Displacement of buoys from 3D simulation

By using the hydrodynamic package of Ansys Aqwa Software, we will obtain the RAOs for each body. A translation - RAOs magnitude plot is shown in **Figure 7-9**. As the plot shows the response drops off for waves with a high frequency. If a monochromatic wave with amplitude of 1 m and a frequency of 0.2 Hz is considered, the heave motion of the float (OZ) will have a magnitude of approximately 1.5 m for body 1 and 0.1 m for body 2.**Figure 8-10** plots the pitch, roll, yaw responses of two bodies versus the wave frequency. It shows that the roll responses (RX) and yaw responses (RZ) of two bodies are very small.

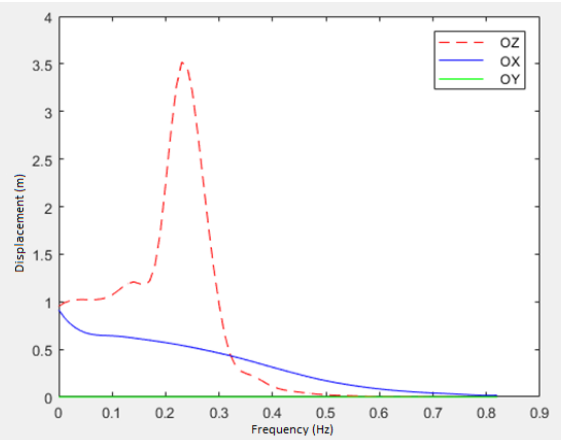

Figure 7: Amplitude of translation – RAOs for buoy 1

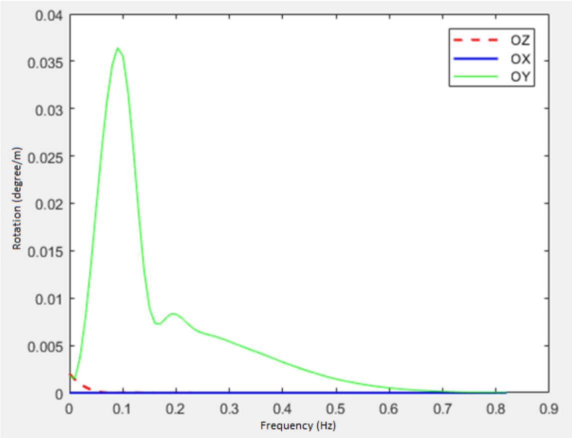

Figure 8: Amplitude of rotation – RAOs for buoy 1

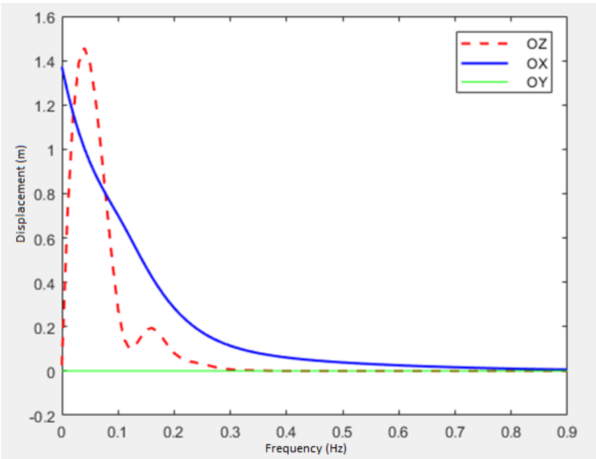

Figure 9: Amplitude of translation – RAOs for buoy 2

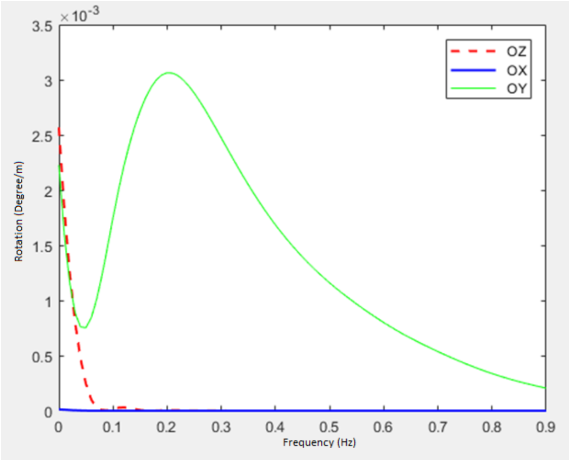

Figure 10: Amplitude of rotation - RAOs for buoy 2

From the results of RAOs obtained, we noticed that only one frequency band will give the buoy the largest energy. For buoy 1, the frequency range of 0.15 - 0.35 Hz (wave periodfrom 3s to 6.5s) will make buoy 1 oscillate in the largest vertical direction (OZ). However, for buoy 2 to move small vertically, the frequency of the wave must be greater than 0.1Hz.

Due to the calculated RAOs above, and assumption that the harvested energy from sea wave – linear proportional to the displacesment changed rate between two buoys, the calculated energys absorbed from sea wavescorresponding to loads of different generators, according to frequency domain as shown in **Figure 11**. From this results, there is a range of frequency of sea waves provided high absorbed energy with designed bouy systems.

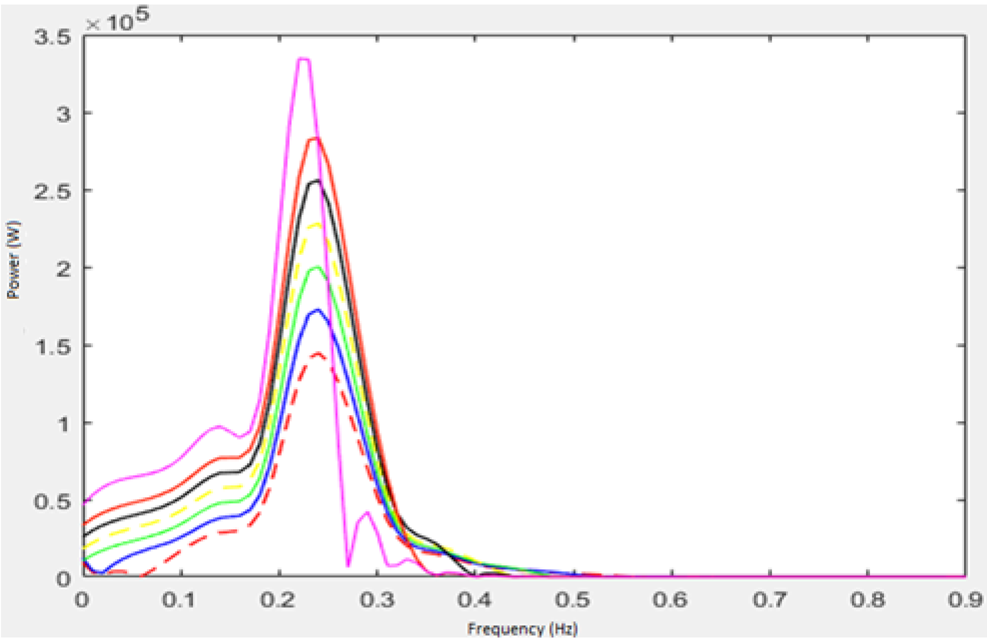

Figure 11: Mean power adsorbed for each wave frequency

4. Conclusions

In this study, the concept of wave energy and the WEC technology has been presented. A schema of two-body point absorber for wave-energy converter using linear permanent magnet is described. The relative movement between the floating body and semi-submerged body in 1D, 3D is simulated and compared with testing results. In order to determine the behavior of the buoy in ocean waves with different frequencies, the RAOs of two types of buoy is calculated and analyzed by using Ansys Aqwa software.This study's results have also been used for analyzing different design options in order to improve the quality of buoy-type direct-driven wave energy conversion at VNU.

5. Acknowledgment

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