Poseidon: A Novel Wave Energy Converter

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TAMUG 2016 Student Research Symposium, Galveston, TX, USA, 19-20 April 2016

Abstract

Design and analysis of a novel concept for a completely submerged wave energy converter (WEC) is presented. The device is comprised of a horizontally submerged plate that is free to oscillate vertically as a result of forces induced by passing surface waves. A detailed hydrodynamic analysis on plate motion is performed using the Level I Green-Naghdi (GN) wave equations, and computational fluid dynamics (CFD) to solve the Navier-Stokes equations. A linear direct drive power take-off system (PTO) is designed and utilized to convert mechanical plate energy into electrical energy. The motion of the plate and characteristics of the PTO can be optimized for particular environmental conditions based on the geographical location of the device. In this project, the electrical power output is optimized for the wave climate near the North Shore of Oahu, Hawaii.

Introduction

The ocean is one of the world's largest sources of renewable and sustainable energy, existing in the form of waves, currents, and tides. The most conspicuous and observable form of ocean energy is contained in surface waves, which has remained largely untapped worldwide. The majority of present-day WECs are located on the surface, which introduces several hindrances and disadvantages. Imminent damage from impacts of large breaking waves, unsightliness, and difficulties in the hydrodynamic analyses of surface devices are some key contributors to the relatively slow progress in this field. In order to alleviate these problems, a completely submerged WEC is developed in this work, called 'Poseidon'.

The WEC is comprised of a horizontally submerged plate that is free to oscillate due to the forces caused by nonlinear waves passing over the device. The plate is connected to a linear direct drive PTO to extract mechanical energy from the oscillating plate and convert it to electricity. The motion of the plate is determined by use of the GN equations and CFD, which is required to determine power output. The physical dimensions and damping properties of the PTO are optimized based on the oscillation amplitudes and velocities.

In this study, the device is designed and optimized for the wave climate found just off the coast of the North Shore of Oahu, Hawaii. The design water depth is 12 meters, and the significant wave height and period is 2 meters and 12 seconds, respectively. The plate and PTO are supported in place by a frame, which is shown in Fig. 1.

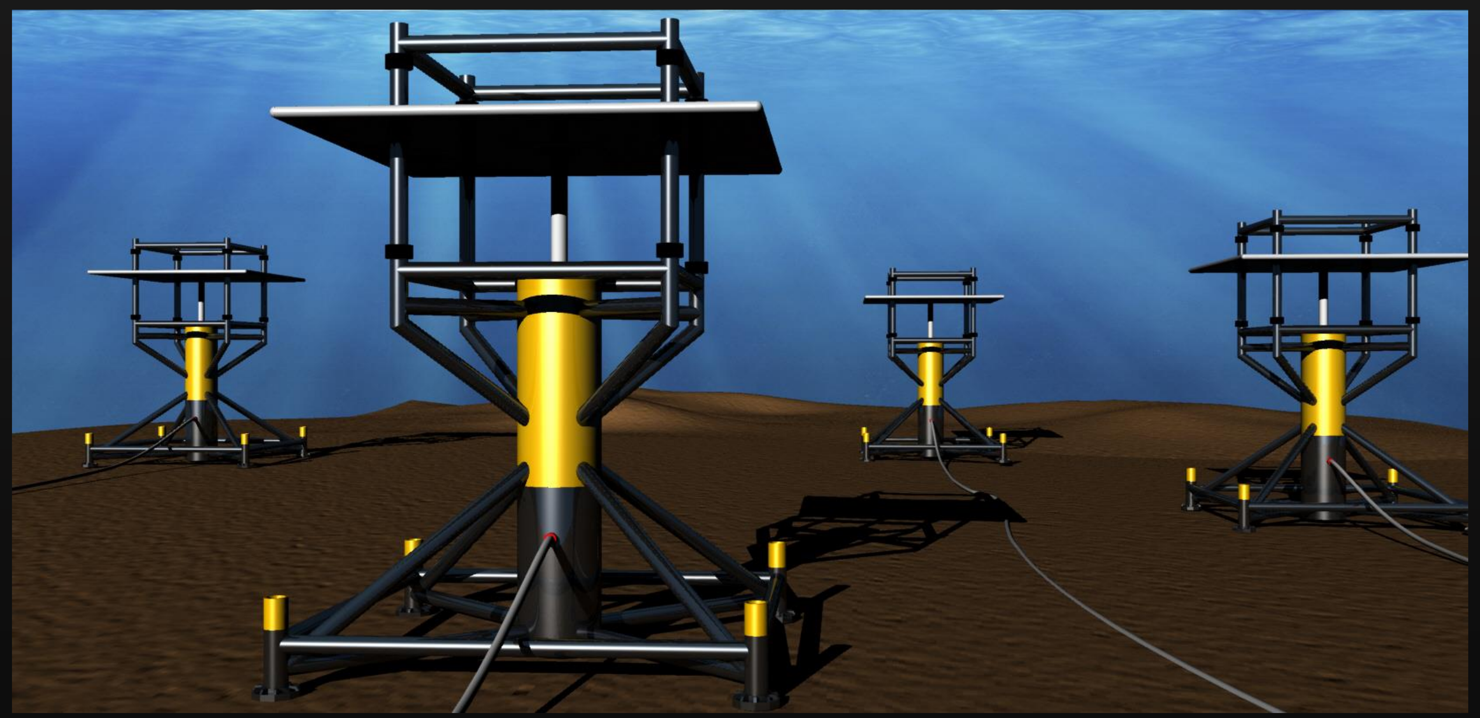

Figure 1 - Three-dimensional concept rendering of an array of Poseidon devices.

General Design and Layout

The plate is restricted to vertical motion by four guide-rails built into the frame. The range of plate motion is limited by stops to conform to the requirements of the PTO. For optimization, a linear spring is incorporated into the generator housing. The structure is attached to the seafloor by driven piles through the base. The layout and dimensions are shown in Fig. 2.

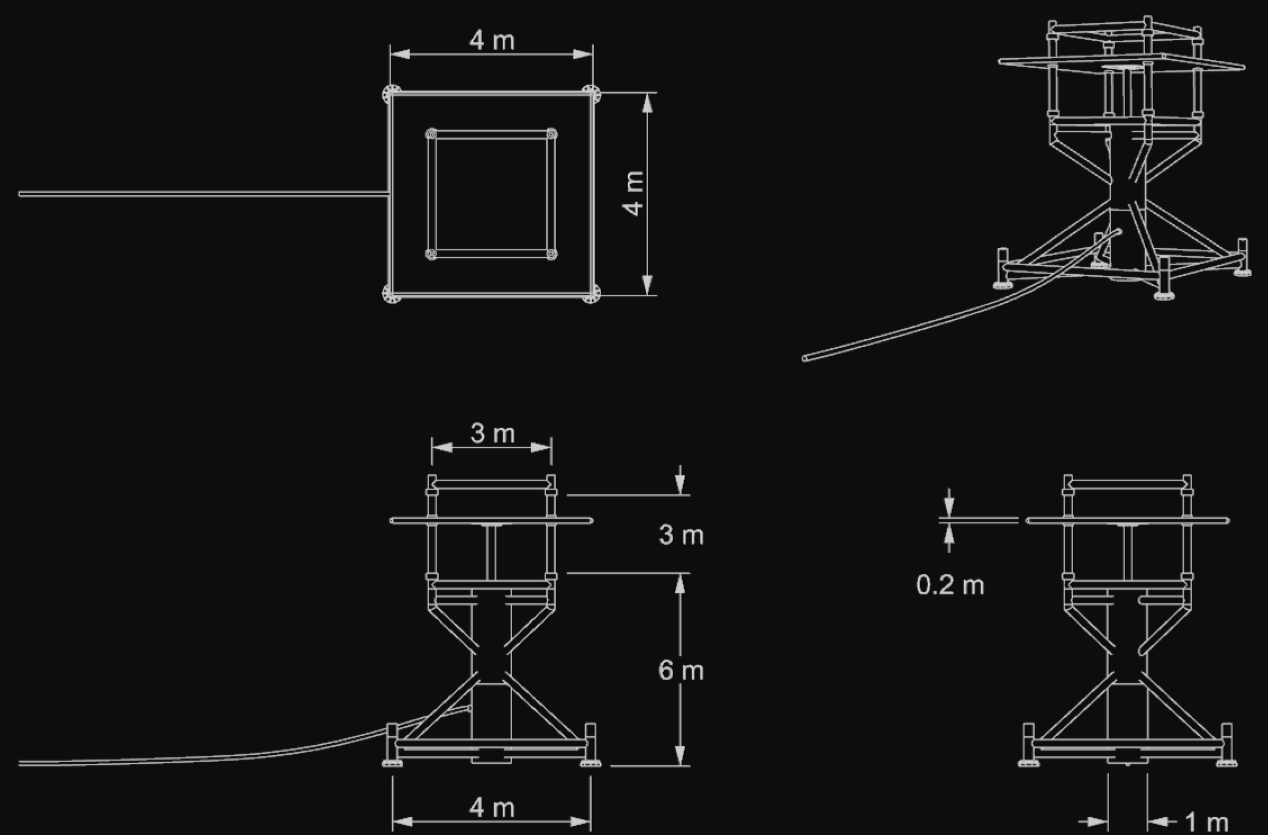

Figure 2 – Orthographic projection of the device including primary dimensions.

Hydrodynamic Analysis

In order to determine the power output of the WEC, the oscillation of the submerged plate due to propagating surface waves must be determined. The hydrodynamic response of the plate and the interaction of the oscillating plate with the free surface is studied by use of the GN equations and by use of CFD. A simplified schematic of the domain and structure is shown in Fig. 3, where η is the surface elevation, h is the water depth, H is the wave height, $s(t)$ is the instantaneous plate submergence depth, SWL is the still water level, k is the spring stiffness, and c is the damping coefficient provided by the PTO. The effect of the PTO on the plate oscillation is simply attributed to linear damping.

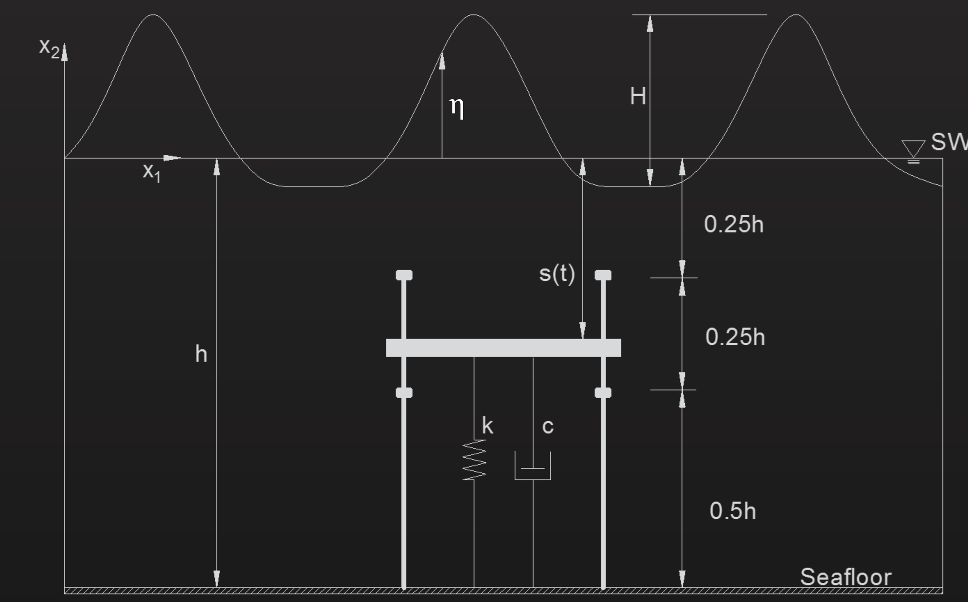

Figure 3 – Schematic of the fluid domain and simplified device structure.

The Green-Naghdi Equations

The Green-Naghdi (GN) equations were originally based on the theory of directed fluid sheets, given by Green & Naghdi (1974). The final form of the equations is given by Ertekin (1984) in the form of nonlinear, partial differential equations.

Hayatdavoodi & Ertekin (2015*a* & *b*) utilized the GN equations to find the forces on a fixed, submerged plate. To calculate the motion, we have coupled the GN equations with the equation of vertical plate motion and solved numerically using a 4th Order Runge-Kutta scheme. The equation of plate motion is defined as:

$$\sum F = F_{x_2} + F_f + F_s + F_{EM} + F_{st} = m\ddot{s},$$

where m is the plate mass, $\ddot{s}$ is the vertical plate acceleration, F_{x_2} is the vertical wave force calculated by the GN equations, F_f is the frictional force, F_s is the spring force, F_{EM} is the electromagnetic force produced by the generator, and F_{st} is the constant hydrostatic force due to the difference between plate weight and buoyancy.

Computational Fluid Dynamics

Additionally, plate motion is analyzed by solving the Navier-Stokes equations via computational fluid dynamics. The open-source CFD program OpenFOAM is used to study the wave-plate interaction with the water-air interface tracked by a volume of fluid (VOF) method.

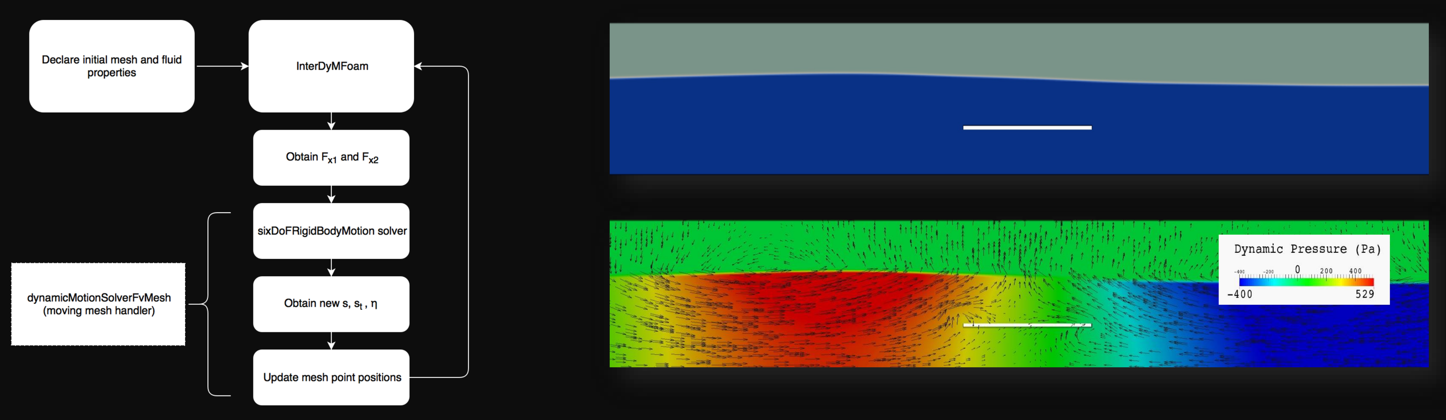

Figure 4 – A flowchart representing the major steps taken in OpenFOAM (left) and a CFD snapshot (right) of a propagating cnoidal wave over a submerged plate that oscillates as a result of the wave-induced forces acting on it.

GN-CFD Comparison

The results given by both solutions are compared using the following dimensionless parameters: $\overline{H} = 0.1$, $\overline{\lambda} = 8.5$, $\overline{B} = 1.0$, $\overline{c} = 0.025$, $\overline{k} = 0.0153$, and $\overline{m} = 0.00475$. Here, $\overline{\lambda}$ is the wavelength, $\overline{B}$ is the plate width, and $\overline{m}$ is the plate mass. All values, including time, are nondimensionalized with respect to ρ, g, and h, where ρ is water density, g is the acceleration due to gravity, and h is the water depth.

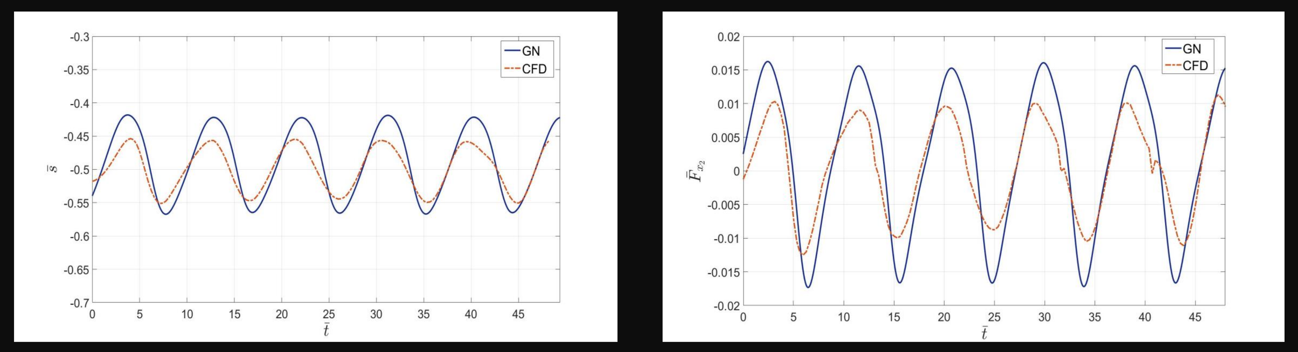

Figure 5 – A comparison of plate oscillation, $\bar{s}$, (left) and the vertical wave-induced force of the plate, $\bar{F}_{x_2}$, (right).

Generator Analysis and Design

The WEC utilizes a direct drive PTO system that directly links the motion of the plate to the translator of a permanent magnet linear synchronous generator (PMLSG) in order to convert the mechanical motion of the plate into electrical energy. Within the generator, a stator experiences varying magnetic flux linkage due to the translator's relative motion, which induces an electromotive force (EMF) in the stator coils according to Faraday's law of electromagnetic induction. A schematic of the basic design of the Poseidon's PMLSG is shown in Fig. 6, including an enlarged cross-sectional view of the stator section that features internal machine parameters key to efficient power absorption.

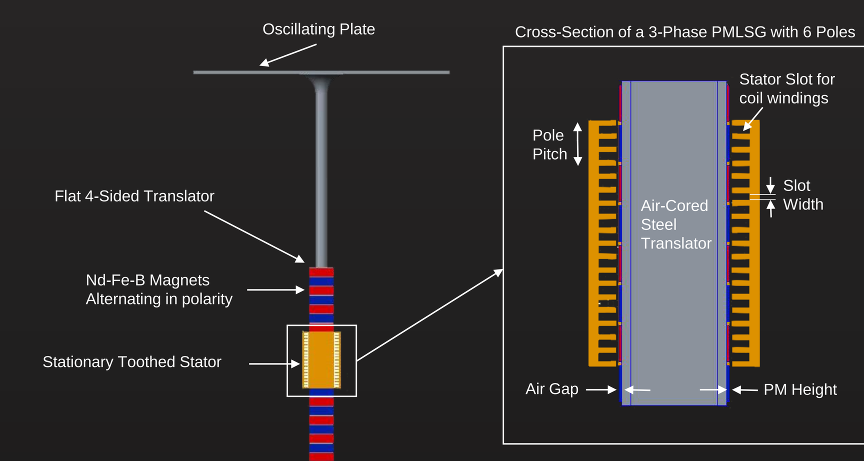

Figure 6 – Schematic of the Poseidon's PMSLG

Material properties and dimensions of the electrical machine influence the magnitude and frequency of the induced EMF. Therefore the efficiency of the PTO system is calculated by:

$$e = \frac{P_{OUT}}{P_{IN}} \cdot 100,$$

where e is the efficiency, P_{OUT} is the power outputted by the generator, and P_{IN} is the power provided to the generator from the oscillating plate. The electromagnetic force induced by the generator, F_{EM}, is proportional to the velocity of the translator, and hence is the same as the force provided by a viscous damper.

$$F_{EM} = c_{gen} \cdot \dot{s}$$

where c_{gen} is the damping coefficient of the generator and $\dot{s}$ is the translator velocity , which is directly connected to the plate by a rigid linkage. The power available for absorption by the generator is given as $P_{IN} = F_{EM} \cdot \dot{s}$.

If the damping effect of the PTO is too light, then little power will be absorbed, on the other hand, if the damping is too high the motion of the plate will be limited and little power will be converted. Therefore, the PTO system must be designed for optimal damping, which necessitates an integrated design approach. This approach includes an iterative process between hydrodynamic and generator analyses to determine a damping that yields the optimum power output.

Case Study - Hawaii

A single device, located just off the northern most point of Oahu, Hawaii (Fig. 7), is considered. The hydrodynamic and generator analysis are performed in order to determine the average power output a single device can generate during the winter months where this location experiences large north swells. The wave, plate, and generator parameters, selected specifically for this site, are given in Table 1. The plate oscillation, given by the GN solution, for this case is shown in Fig. 8. The power output of the generator, in the form of electric power, is shown in Fig. 9. The average power output from the generator for these parameters is 19.8 kW. The generator is able to achieve 90.5% efficiency.

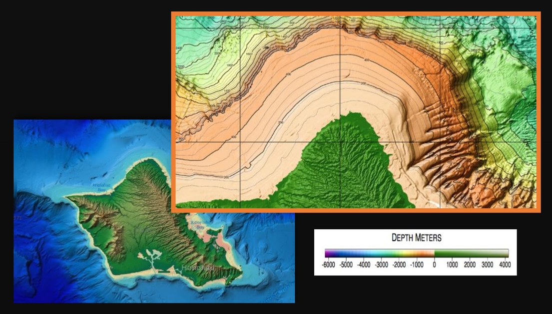

Figure 7 – Map of the site location.

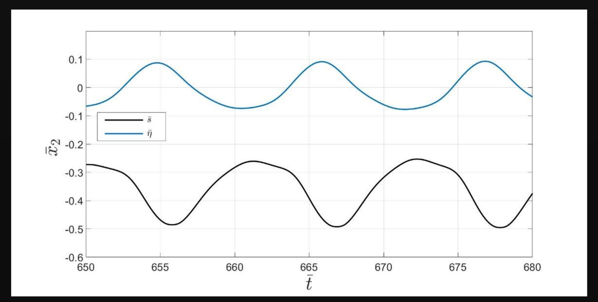

Figure 8 – Time history of plate oscillation and surface elevation.

Table 1 – A list of wave, plate, and generator parameters.

Parameter	Value
Water Depth (h)	12 m
Period (T)	12 s
Wave Height (H)	2 m
Plate Mass (m)	2246 kg
Spring Stiffness (k)	9.6 kN/m
Damping Coefficient (c)	49.47 kN s/m

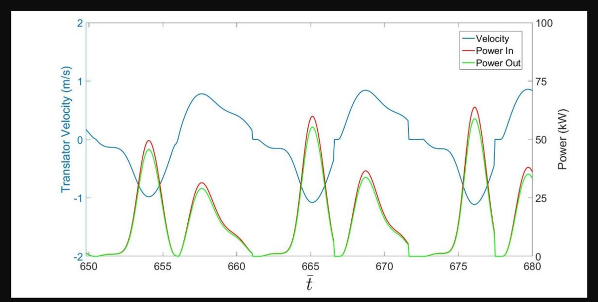

Figure 9 – Time history of electrical power the generator outputs.

Conclusion

It is shown that a completely submerged WEC can extract a significant amount of energy from ocean waves. A single Poseidon device is able to achieve an average power output of nearly 20 kW in 2 meter waves. This is a promising result since the 2 meter wave height that is considered is a rather conservative value for this location, therefore power output is likely to be much higher, depending upon the swell. Also, a device array can be implemented, with each device having little influence on the other.

References

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2. Ertekin, R. C. (1984). Soliton generation by moving disturbances in shallow water: theory, computation and experiment. PhD dissertation. University of California, Berkeley.
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4. Hayatdavoodi, Masoud, and Ertekin, R. Cengiz. (2015*b*) "Wave Forces on a Submerged Horizontal Plate – Part II: Solitary and Cnoidal Waves." J. of Fluids and Structures, 54(April), pp. 580-596.