A Study of Oscillating Water Column Wave Energy Converters Array Configurations Based on Simulation

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ABSTRACT

Wave energy is a potentially important renewable clean source of energy that can help solve the energy demand throughout the world. A great deal of research has been conducted in the last few decades and it is now reaching the point of full implementation. In order to compete with other energy sources, we must first demonstrate that it is commercially viable. So far, researchers and developers have been able to demonstrate proof of concept utilizing a small number of wave energy converters (WECs) deployed in the open ocean or on shore. However, to make this source of energy commercially viable, the deployment of a large number of WECs is necessary. Regardless of the type of WEC used, the deployment of these devices has to be carefully thought out, since the direction of the wave fronts varies throughout the year and once the WECs are installed, they will remain fixed in those locations and they will experience only relatively small displacements on the ocean surface. When a group of WECs is deployed on the ocean surface, their motion resulting from the excitation force due to the arrival of a wave front will affect other WECs in the vicinity. Furthermore, depending on the angle of arrival of the wave front, the interaction between WECs will vary and the energy conversion capability will be affected. This interaction has been coined as the q factor by researchers in the field. In this thesis, we consider the deployment of an oscillating water column (OWC) WECs developed by researchers from the Polytechnic of Lisbon in Portugal and their Spanish collaborators, namely, the MarmokA5. Our deployment strategy has as its main objective the maximization of average power of the array of WECs. When we consider an array configuration, namely, its geometric configuration, distance between WECs, angle of arrival of the wave front, and sea state, we implement a mathematical model of the array produced by ANSYS AQWA in Simulink to compute the average power generated by the array. We evaluate array power generation performance by varying the form of its configuration and the number of WECs in it. The results of our strategy suggest that they can be incorporated into more formal mathematical objective function to optimize WEC array generated power.

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1 Introduction

1.1 Ocean Energy

Oceans are the most extensive water bodies in the world, compared with lakes, rivers and icebergs, with a total area of approximately 360 million square kilometers, covering over 70% of the Earth's surface. Current climate change, global warming, ice sheets melting, sea-level rising at an accelerated rate are not a positive trend (Nerem et al., 2018).

Research activity power generation using the renewal energy of waves and tides of the ocean has increased significantly in order to reduce the use of fossil fuel and improve the environment (Pelc & Fujita, 2002). Additionally, Ocean Energy System (OES, 2019) introduces another energy source from ocean, namely, salinity power, which makes use of the salinity gradient between fresh water with saltwater and pressure-retarded reverse osmosis. Seawater temperature, ocean wave, ocean current, sea breeze and even seawater salinity are all sources of renewable energy which affect each other. For instance, the ocean current movement may result from wind or non-uniformity density distribution of seawater thermal or salinity.

Based on the report of global ocean energy vision in 2017 from OES (Melo & Villate, 2017) their research on assessment of global wave energy, the worldwide theoretical potential ocean thermal power, has been estimated at 44,000 TWh/year, tidal energy about 1,200 TWh/year, wave power around 29,500 TWh/year, as well as salinity gradient power which is approximate at 1,650 TWh/year. The OES also predicts that the potential of ocean energy can develop over 300 GW installed capacity and save 500 million tonness of greenhouse gas CO2 emissions by 2050 (Melo & Villate, 2017).

Worldwide, ocean energy is distributed unevenly among different ocean regions and differently between various types of energy. The world distribution map of wave energy is shown in Figure1.1.

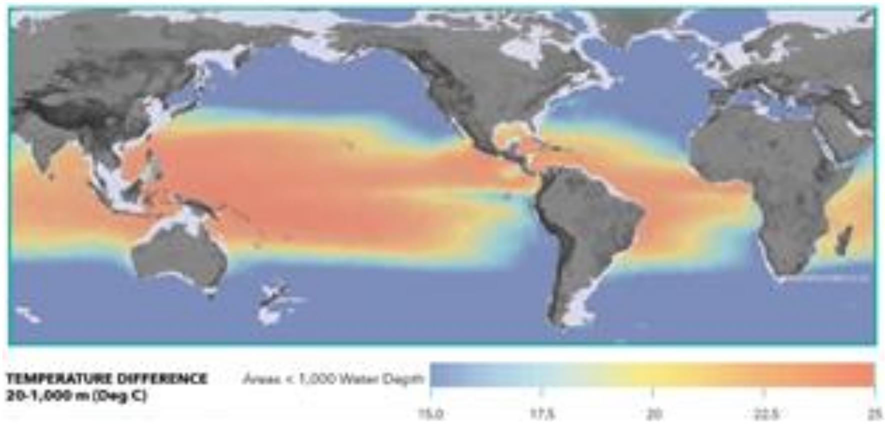


Figure 1.1 World Distribution Map of Ocean Energy. Reprinted from An International Vision for Ocean Energy 2017 by Melo & Villate, 2017, Ocean Energy Systems.

1.2 Wave Energy

Wave energy, in essence, is a form of solar energy which leads to different temperatures across the planet's atmosphere and generates wind blowing on the surface that causes waves in ocean. Furthermore, the thermal, ocean current and salinity also influence wave energy as mentioned before due to the complex and interweaved ocean system. Wave energy is a combination product of kinetic and gravitational potential energy, and the stored energy could be represented as

$$E = E_k + E_p \tag{1.1}$$

where E_k is the kinetic energy and E_p is the potential energy. The mean wave power density is roughly proportional to two wave parameters, one is significant wave height H_s and the other is peak period T_p (Cruz, 2008). The mean wave power is described by

$$P = \frac{\rho g^2}{64\pi} H_s^2 T_p \tag{1.2}$$

where ρ is the water density and g is the earth acceleration (Poullikkas, 2014).

Researchers simplified wave simulation to fluent, harmonic, and regular waves as shown in Figure 1.2 (a). In reality, an ocean is likely more irregular and complex, for different ocean regions like shallow water or deep water which is totally different, therefore needs different research methods and simplification approaches.

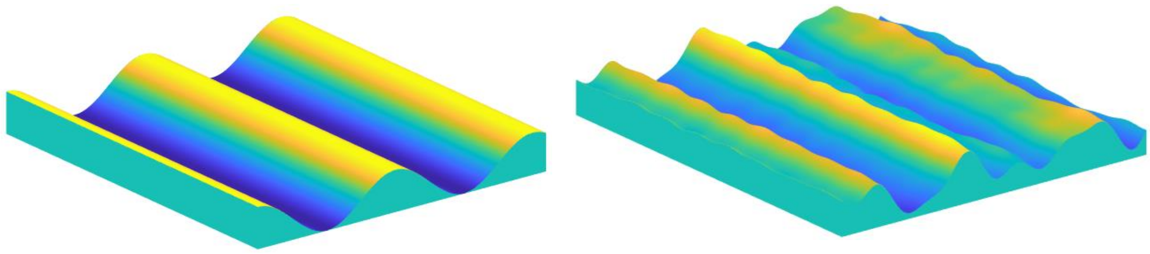


Figure 1.2 Waves Model (a) Regular Wave Model, (b) Irregular Wave Model.

Based on the introduction in (Cruz, 2008), the history of the application of wave energy could be traced back to the first recorded patent about wave energy conversion in 1799. However, wave energy research renewed development can be contributed to Prof. Stephen Salter's influential article in Nature in the 1970s (Cruz, 2008). Since the middle of the 1990s, significant improvement has been achieved in the offshore wave power systems and the UK government has made an enormous contribution to the development (Cruz, 2008).

Research on wave energy has achieved tremendous technological advances which are characterized by a variety of wave energy converters (WECs). There are different ways to classify WECs into several groups, such as by device location, work principles, etc.

According to the research of (Pecher & Kofoed, 2017), all the devices can be classified into three basic types based on the designs, attenuator, terminator as well as point absorber or categorized into wave active body (WAB), overtopping and oscillating water column (OWC) by the method introduced by IEA-OES. Attenuators and terminators can be distinguished by the direction of extensions that attenuators are perpendicular to the wave direction while terminators have a parallel large extension, and point absorbers are identified by the small dimensions of devices compared with the wavelength of incident waves (Pecher & Kofoed, 2017).

From the descriptions in (Czech & Bauer, 2012), we can know how WECs work that WABs consist of units around a reference point and extract energy from the movement of device bodies as well as a reference point which can be excited by incident waves. Overtopping devices capture water over the edge of devices with wave propagation and the higher sea-level in reservoir leads to return water to the ocean through low-head turbine in order to convert energy (Czech & Bauer, 2012). OWCs generate power with a turbine which is activated by the airflow in the chamber as the sea-level changes with wave movements (Czech & Bauer, 2012). In Figure 1.3, OWCs, WABs and overtopping are subdivided into various groups and shown with typical example devices for each group.

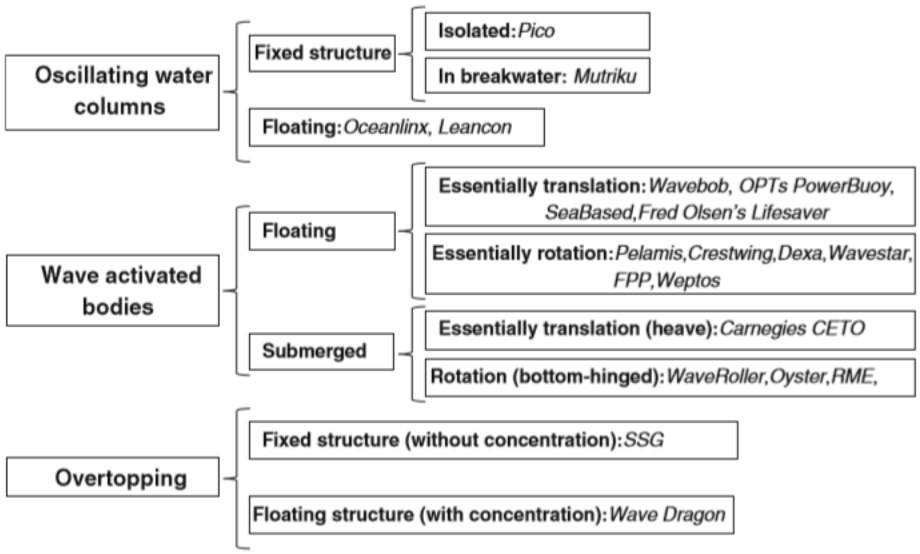


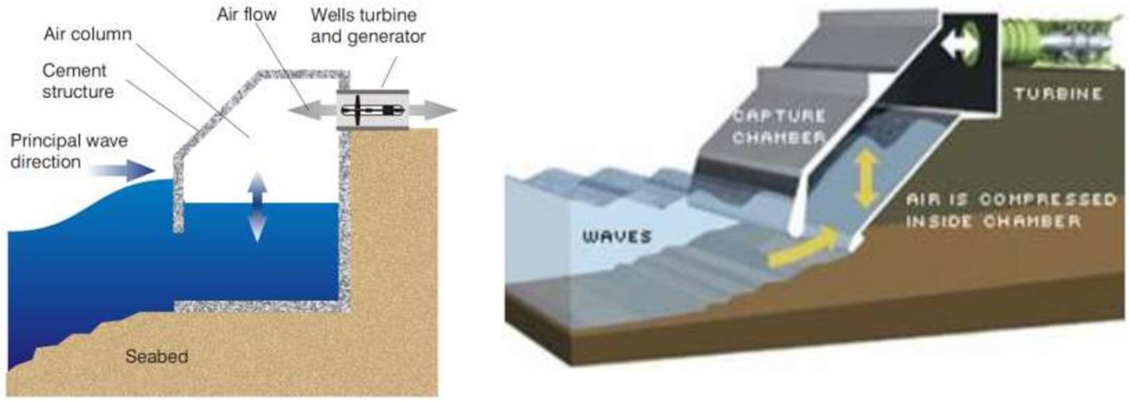
Figure 1.3 Categorization of wave energy technologies. Reprinted from Handbook of ocean wave energy, by Pecher, A., & Kofoed, Jens Peter, 2017, Springer Open

1.3 Oscillating Water Column

The work in this project is based on one kind of OWC device, the basic structure or design, working principles and several typical device examples will be introduced in detail in what follows.

For fixed OWCs, the basic structures are described by a capture chamber with a fixed structure, a turbine and a generator, as shown in Figure 1.4. Figure 1.4 (b) shows a commercial fixed OWC LIMPET from Wavegen installed in the UK with 500 kW unit power (Poullikkas, 2014).

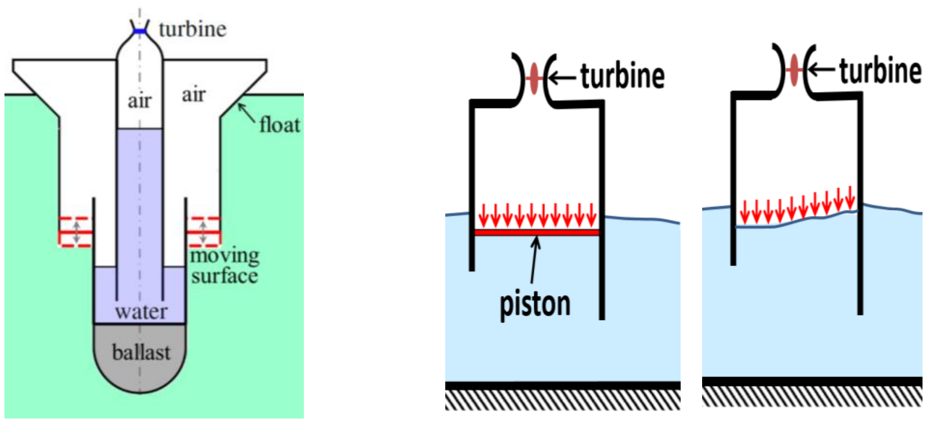
The wave motions make the water column in the chamber move up and down like a piston and changes of sea-level in the chamber pressurize and depressurize the air inside in order to drive a turbine connected with a generator to generate electric power (Poullikkas, 2014).



(a) (b)

Figure 1.4 (a) Operation Principle of fixed structure OWC, (b) Operation Principle of LIMPET OWC. Reprinted from Technology prospects of wave power systems, by Poullikkas, 2014, Electronic Journal of Energy & Environment

For floating OWCs, structures become more diverse and complex with more choices. For instance, to make the floating devices stable in a controlled range, added ballast or mooring is necessary and floating component as well as surface can also change, like three examples shown in Figure 1.5.



(a) (b)

Figure 1.5 (a) Floating Device with Compressible Air Volumes and Water Columns, (b) Piston model and Free-surface Uniform Pressure model of OWC. Adapted from Oscillating-water-column wave energy converters and air turbines: A review, by Falcão & Henriques, 2016, Renewable Energy.

1.4 Power Take-off System

The power take-off systems for WECs need to consider the whole process, and some example parts, namely, turbines, hydraulic circuits and generators are shown in Figure 1.6.

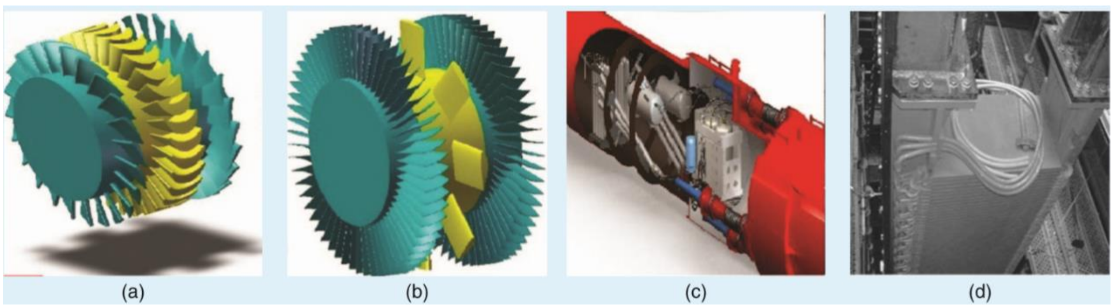


Figure 1.6 PTOs for WECs. (a) Wells turbine, (b) impulse turbine, (c) hydraulic system, (d) linear generator. Adapted from Wave Energy Converter Concepts: Design Challenges and Classification, by Czech & Bauer, 2012, IEEE Industrial Electronics Magazine.

For various WECs, their corresponding PTOs are identified to meet the different requirements. For example, a prototype PTO for attenuator Pelamis has two separate parts. The primary transmission is made of hydraulic devices as well as corresponding controls, and the secondary transmission consists of hydraulic motors as well as generators to convert the stored energy in the hydraulic accumulators into electricity (Czech & Bauer, 2012). However, for the Wave Dragon PTOs, low-head turbines play a vital role in extracting energy, while for Limpet PTOs, two bidirectional turbines are necessary (Czech & Bauer, 2012).

1.5 Contribution

This project aims to find out about the influence of WECs configurations on generated power to improve system efficiency which focuses on interaction between devices rather than device design.

In chapter 2, we describe the basics of wave energy, hydrodynamic theories and dynamic model needed in the research. Waves and bodies interaction is important to the research.

In chapter 3, the simulation processes of the implementation of OWC from (Gaebele, 2018) research is briefly described.

In chapter 4, simple basic arrays, such as linear, triangle and square arrays will be considered and evaluated using computer simulation.

Specially, Matlab and Simulink will be used in the simulation to characterize the interaction between bodies and the effect of configurations. We will consider factors such as geometric configuration of devices array, the number of WECs, distance between WECs, angle of arrival of the wave front, as well as the incident wave height and period.

2 Wave Theory

Wave theory is complex and is used to describe the dynamic behavior of the ocean. This chapter presents a brief description of the principles of wave theory applied in this research.

2.1 Fundamentals

The fundamental principles here in described come from (Falnes, 2002). A gravity wave on water is dispersive, which means that the phase velocity depends on the frequency and for waves on deep water ($kh \gg 1$), the relationship is given by

$$v_p \equiv \frac{w}{k} = \frac{\lambda}{T} = \frac{g}{w} \tanh{(kh)} \approx \frac{g}{w} \tag{2.1}$$

where g is the acceleration of gravity, k is wave number, w is the angular wave frequency, λ is wavelength and T is wave period (Falnes, 2002).

Based on the Equation 2.1, the wavelength on deep water is

$$\lambda = \frac{2\pi}{k} = \frac{2\pi g}{\omega^2} = \frac{g}{2\pi} T^2 \tag{2.2}$$

Equation 2.3 and 2.4 are two fundamental equations which together with the continuity equation and the Laplace equation are used to analyze a boundary element.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \tag{2.3}$$

$$\nabla^2 \phi = 0 \tag{2.4}$$

where ρ is the mass density, $\vec{v}$ is the velocity element and ϕ is the velocity potential.

Wave energy consists of potential energy and kinetic energy and the average energy can be simplified as equation 2.5 for harmonic wave and equation 2.6 for progressive, plane, harmonic wave (Falnes, 2002).

$$E_p(x, y) = \left(\frac{\rho g}{4}\right) |\hat{\eta}(x, y)|^2 \tag{2.5}$$

$$\langle E_p \rangle = \left(\frac{\rho g}{4}\right) |A|^2 \tag{2.6}$$

where η is wave elevation and A is the complex elevation amplitude at $x = 0$.

Similarly, we can obtain the kinetic energy for a progressive, plane, harmonic wave as

$$\langle E_k \rangle = \left(\frac{\rho g}{4}\right) |A|^2 \tag{2.7}$$

and the total stored energy is

$$E = E_p + E_k = 2E_p = \left(\frac{\rho g}{2}\right) |A|^2 \tag{2.8}$$

2.2 Body Motion

A body in water will actively interact with the surrounding waves if it is not fixed. The motions of body depend on the type of force acting on it.

2.2.1 Types of Body Motion

In (Falnes, 2002), the motions are described by six components which represent six degrees of freedom, as shown in Figure 2.1.

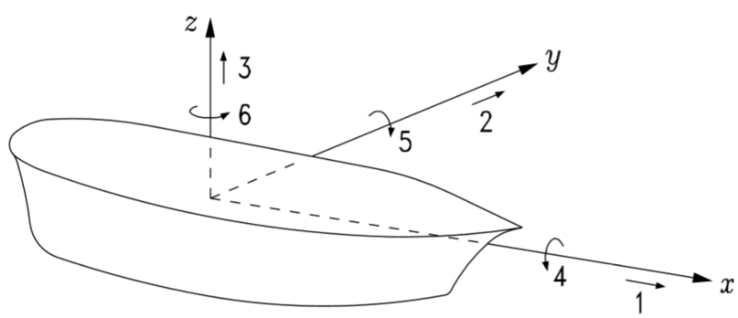


Figure 2.1 Six Modes of Motion. Adapted from Ocean waves and oscillating systems linear interactions including wave-energy extraction. Cambridge, by Falnes, J., 2002.

Mode numbers 1, 2, 3 represent surge, sway, heave and the three modes are translation modes, while mode numbers 4, 5, 6 represent rotation modes roll, pitch and yaw.

Considering the case of the OWC, if the water column movements create a variation in the z direction, only three modes namely heave, roll and pitch may influence its behavior.

2.2.2 Force Acting on a Body

From Newton's law,

$$m\ddot{x} = F_{total} \qquad (2.9)$$

For a body in water, besides gravity and buoyance, we need take the hydrodynamic forces acting on the body into consideration.

In (Falnes, 2002), for a given potential $\hat{\phi}$, force j is given by

$$\hat{F}_j = i\omega\rho \iint_S \hat{\phi} n_j dS \quad (j = 1,2,\cdots,6) \qquad (2.10)$$

For excitation force, equation 2.10 can be rewritten as

$$F_{e,j} = i\omega\rho \iint_S (\hat{\phi}_0 + \hat{\phi}_d) n_j dS \quad (j = 1,2,\cdots,6) \qquad (2.11)$$

where $\hat{\phi}_0$ and $\hat{\phi}_d$ represent the potential for incident wave and diffracted wave (Falnes, 2002).

Given a potential for radiated wave $\hat{\phi}_r = \varphi_j \hat{u}_j$, the equation for radiation force given by

$$F_{r,j'} = i\omega\rho \iint_S \varphi_j \hat{u}_j n_{j'} dS = -Z_{j'j} \hat{u}_j \qquad (2.12)$$

where Z is the radiation impedance matrix and $\hat{u}_j$ is a constant (Falnes, 2002).

2.3 Energy Absorption in Wave

Bodies in water absorbed energy from incident wave will produce waves at the same time. The produced waves will become incident waves for other bodies and influence them.

An example of absorbed and generated waves is shown in Figure 2.2 that the incident wave is curve a, the wave produced by the body with the motion of heave is curve b and it generated antisymmetric wave, curve c, with another motion. Combining the incident wave and two generated waves, the body almost absorbed the whole incident wave energy and gave a result in curve d.

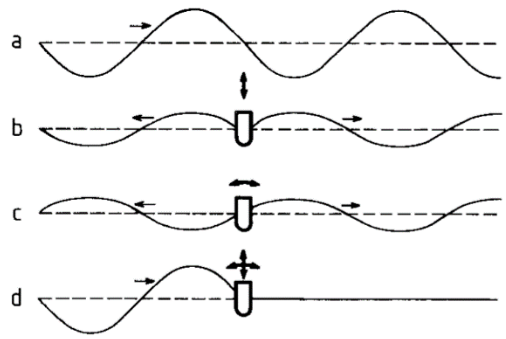


Figure 2.2 Wave Absorption by Floating Bodies. Adapted from Ocean waves and oscillating systems linear interactions including wave-energy extraction. Cambridge, by Falnes, J., 2002, Cambridge University Press.

From (Falnes, 2002), for a body in one mode of motion, the maximum absorbed power is

$$P_{max} = (P_r)_{opt} = \frac{1}{2}(P_e)_{opt} \quad (2.13)$$

2.4 Bodies interaction

Let us introduce the interaction faction q as

$$q = \frac{P_{array}}{N \cdot P_{Single}} = \frac{\sum_{i=1}^{N} P_i}{N \cdot P_1} \quad (2.14)$$

where N is the number of devices in an array, P_{array} is the sum of all devices generated power in the array, P_{Single} and P_1 represent the generated power when there is only one device (Babarit, 2013).

When q>1, the configuration is constructive and the situation is what we expected, while for q<1, the interference is destructive (Andres et al., 2014).

3 OWC Array Modeling Approach

In order to evaluate WEC array power generation performance, we use the MarmokA5 OWC. We use AQWA to calculate the boundary conditions for various incident waves. When we get the boundary conditions and postprocessing with Matlab, we use Simulink to evaluate the generated power for different incident waves and angles of arrival.

3.1 MarmokA5

MarmokA5 is a full scale prototype OWC built by researchers from the Polytechnic of Lisbon in Portugal and Spanish collaborators. The deployed device on the ocean is shown in Figure 3.1.

Figure 3.1 Full Scale of MarmokA5 device. Adapted from http://opera-h2020.eu/.

The MarmokA5 is described in Figure 3.2 (Gaebele, 2018), and it consists of a floater and a piston.

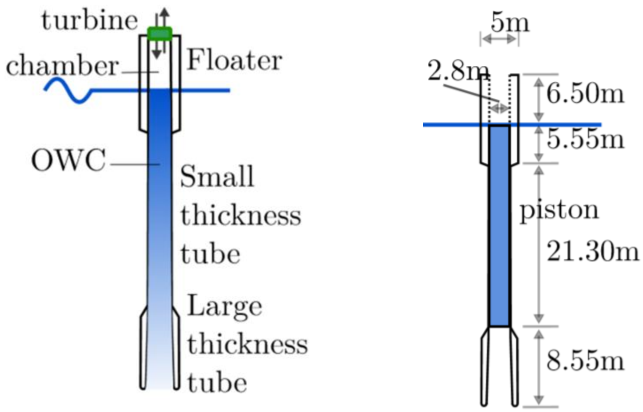


Figure 3.2 Sketch of MarmokA5. Adapted from Gaebele, D., Dissertation, University of Stuttgart, 2018.

3.2 AQWA

AQWA is a hydrodynamic modeling software from ANSYS to solve boundary element. Based on the sketch of MarmokA5, generated the structure of a single device.

3.2.1 Geometry

Figure 3.3 shows the construction of a 3-OWC WEC array, which is then processed by AQWA to generate a hydrodynamic model.

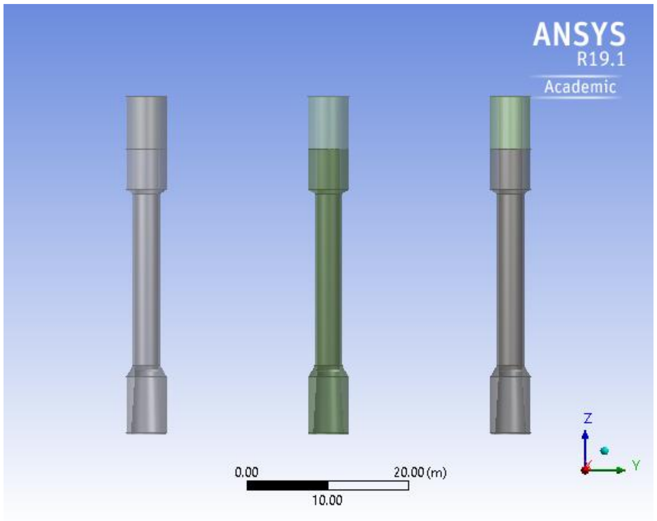


Figure 3.3 Geometry of Array

3.2.2 Meshing

After deploying the devices, it needs to be meshed. The meshed model is shown in Figure 3.4. Different mesh sizes, yield different model numerical accuracies

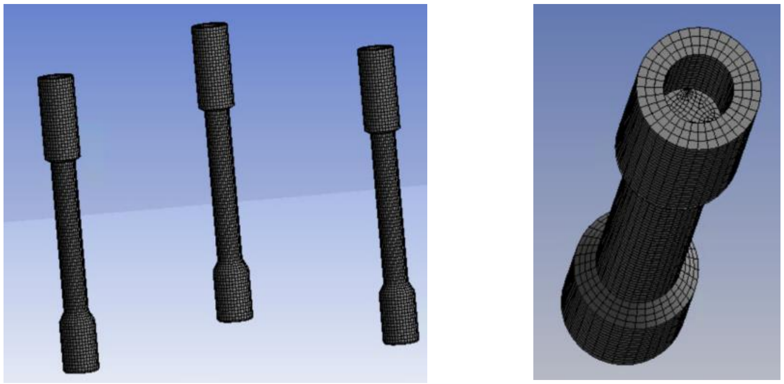


Figure 3.4 Mesh of OWC

3.2.3 Hydrodynamic Diffraction

Adding incident waves from different directions with several frequencies, we calculate the hydrodynamic diffraction and solve the boundary element. The corresponding results would be generated, such as added mass and radiation damping.

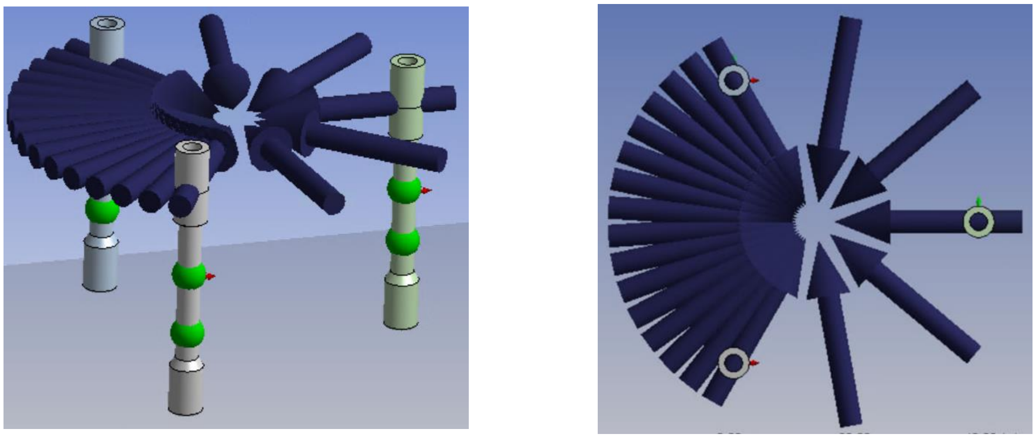


Figure 3.5 Hydrodynamic Diffraction of OWC

3.3 Simulink Model

After we obtain the results from AQWA, we use the Matlab code to process the data and calculate the generated power using the Simulink model for OWCs as shown in Figure 3.6.

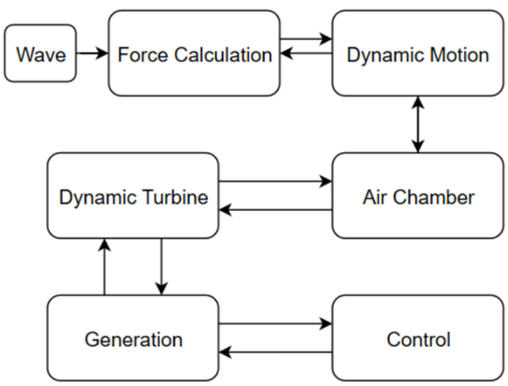


Figure 3.6 Diagram of OWC Simulink Model

Once we calculate the forces, we obtain the dynamic motion and their effect on the air chamber. Based on the recorded air flow history, we get the turbine torque control and calculate the generated power.

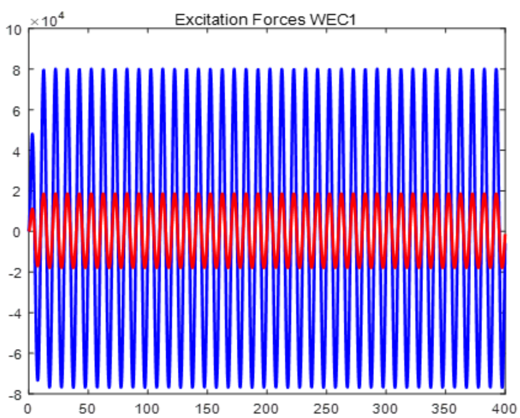
4 Power Generation Performance Evaluation

For large scale WECs arrays, wave scattered and radiated from other devices would influence the generated power of each device. Using the simulation setup described in chapter 3, we can analyze the influence of wave parameters on the generated power as well as the interaction factor of WECs array.

In the simulations, arrays are tested with regular and irregular incident waves separately and vary influence factors like simulation time, wave height, wave period and wave angle of arrival.

4.1 Simulation Environment

For regular waves and irregular waves, the corresponding excitation forces of a single device are shown in Figures 4.1 and 4.2. For an irregular wave, it is a summation of several regular waves with random phases and amplitudes, but in terms of the control variable, the forces are the same for each simulation.



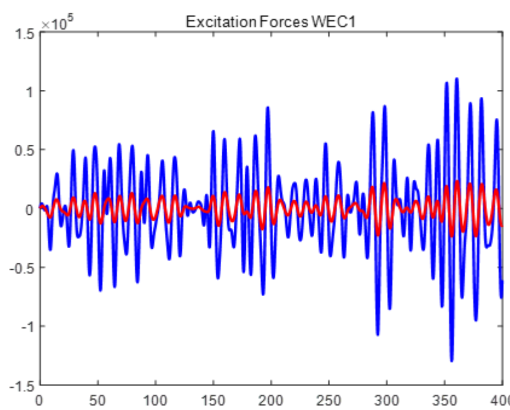


Figure 4.1. Regular Wave Excitation Forces. Figure 4.2. Irregular Wave Excitation Forces.

For the influence of simulation time and wave height, the simulation results are based on a single device, while the influence of wave period and incident direction is analyzed for several arrays. All results of generated power and q factor are based on average power in an effective interval among simulation time and instantaneous data are not listed because average power is more practical and systematic in these conditions.

4.2 Wave Parameters

A single device deployed in the ocean and simulated with corresponding incident waves are shown in Figure 4.3. This figure shows that the simulation of the wave front direction and its relationship between the position of the device and the wave incident the angle of zero.

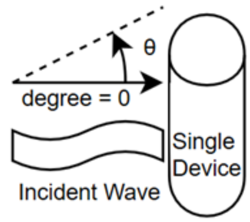


Figure 4.3. Single Device with Incident Wave.

4.2.1 Wave Height

In order to analyze the influence of simulation time and wave height on generated powers, simulation results from regular and irregular waves are shown in Figure 4.4.

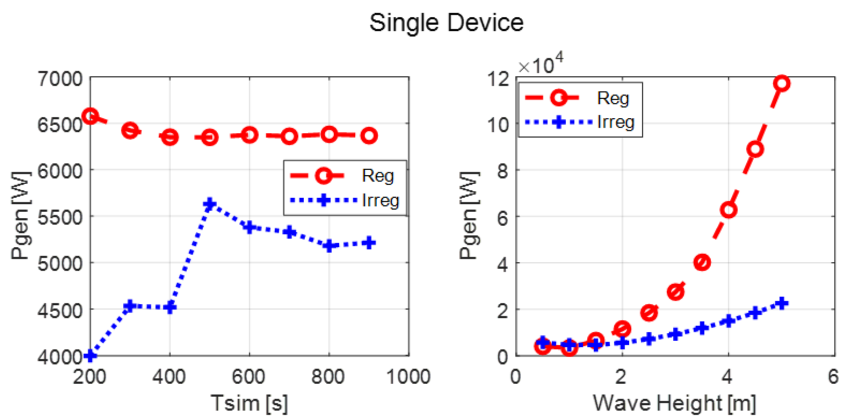


Figure 4.4. Incident Wave and Single Device.

For regular waves, the excitation forces have a period which is much smaller than simulation time. As seen in Figure 4.4, simulation time increasing, the average generated power tends to be more stable and the absolute value of the difference between them is small.

For irregular waves, the excitation forces do not have any periodicity. Therefore when simulation time changes, the generated powers have obvious differences as excitation forces changed with added time intervals. However, the generated power also tends to be stable with simulation time increasing.

Furthermore, it is a significant factor when deploying devices in the ocean as we need to take irregular or long period time factors into consideration such as the cyclical changes of ocean currents. However, the following results are from the same simulation time to analyze other variables described in this chapter.

For Figure 4.4, the simulation parameters of wave height, the trend of the curves for regular and irregular waves are similar, because the corresponding generated power performs like the results of quadratic functions of wave height. Therefore, the simulated influence of wave height is coincident between regular wave and irregular wave, so that the following simulations used are fixed wave height and focus for the other two wave parameters, wave periods and wave incident directions.

4.2.2 Wave Period

The influence of wave period to the generated power are similar between several devices in array in regular waves or irregular waves by comparing the plots in Figure 4.5. But the differences between regular wave and irregular wave curves are distinguishable.

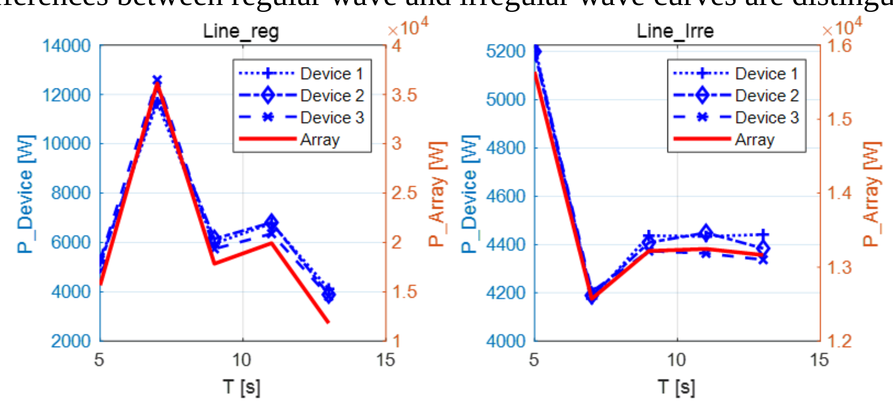


Figure 4.5. Line Array Generated Power vs. Wave Period.

For other arrays, the curves in one kind of wave are also similar, that more arrays are simulated and the results for a single device can be found in Figure 4.6.

The influence of wave period on generated power will not be mentioned in following simulations but the influence on q factor will still be discussed.

4.2.3 Wave Direction

The generated powers among regular waves and irregular waves for single device with different wave periods and wave incident directions are shown in Figure 4.6. According to the cross section of Figure 4.5, it supports the conclusion in 4.2.2.

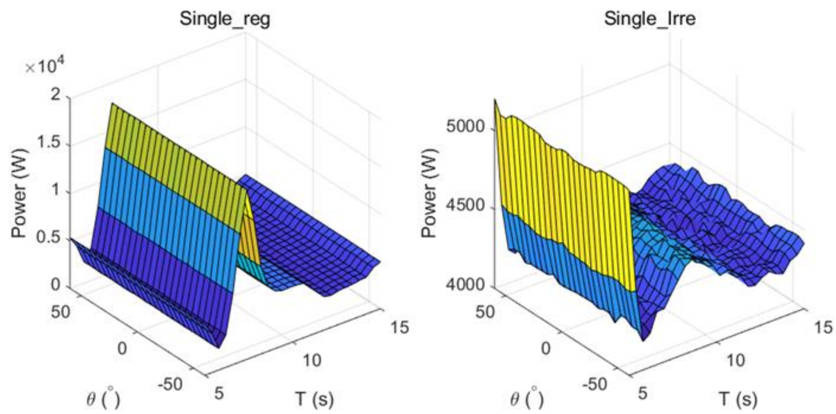


Figure 4.6. Single Device Generated Power.

For incident wave directions, the difference in regular wave is minimal because the configuration is symmetrical with countless axes of symmetry. However, the performance is totally different in irregular wave. Due to the different performance between regular and irregular waves, the following analysis will focus on the influence of wave incident directions, for array configuration parameters.

4.3 Array Configuration Parameters

One of the influence factors for generated power is array configuration. For array configuration, there are several parameters such as geometry of array, the number of devices and distance between devices. As mentioned before, in chapter two we defined interaction factor q to assess the configuration influence that if q>1, the configuration is constructive and for q<1, destructive. In this section, the simulation results analyzed, responds to the variables, wave period and wave incident direction. The performance of whole array would be assessed by the q factor while the separate devices generated power would be shown to discuss the interaction between devices in the array. For generated power, the fixed wave height is 2m, wave period is 10s and simulation time is 400s.

4.3.1 Geometry

- Line Array

While WECs deployed in line shown in Figure 4.7, the array with two devices or three devices are simulated, with the results shown in Figure 4.8-4.11.

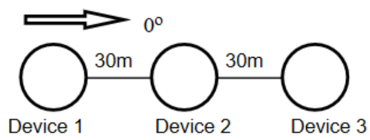


Figure 4.7. Line Array Distribution.

- Two Devices

For two devices in line, the array consists of Device 1 and Device 2 with 30m distance between them. The generated powers with different incident directions for each device are shown in Figure 4.8 and the corresponding q factors for various period and angles are shown in Figure 4.9.

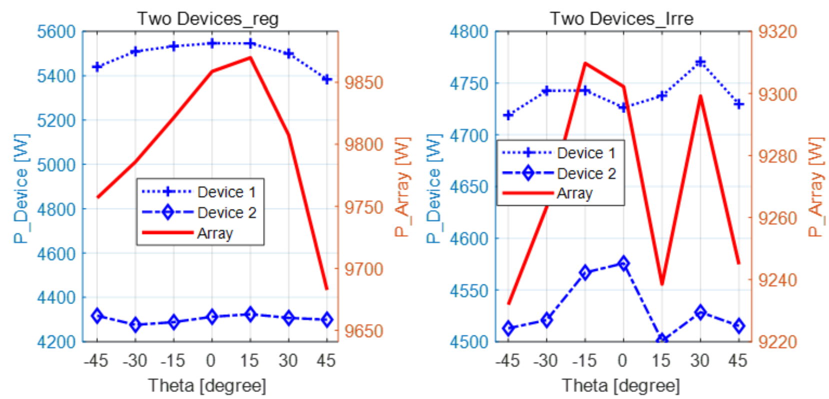


Figure 4.8. Two Devices Generated Power vs. Incident Wave Angle.

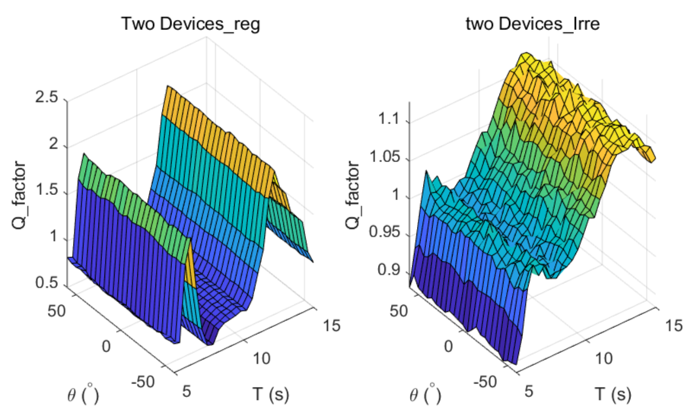


Figure 4.9. Q factor for Two Devices with Regular Waves and Irregular Waves.

As Device 2 is on the shadow of Device 1, the generated power is smaller than Device 1's. With direction changes, the total power among array becomes smaller with the deviation from zero degrees.

When comparing the q factor in Figure 4.9 with the results of single devices in Figure 4.6, the changes of q factor is totally different with the change of the single device generated power. Therefore with regular waves, the difference caused by the change of direction is small compared with the influence of periods.

For irregular waves, the influence of incident directions is obvious but chaotic and the results show an increasing trend with the period increase among the simulated periods range.

- Three Devices

For three devices in line shown in Figure 4.7, generated power for each device with various incident directions are shown in Figure 4.10 and corresponding q factor is shown in Figure 4.11.

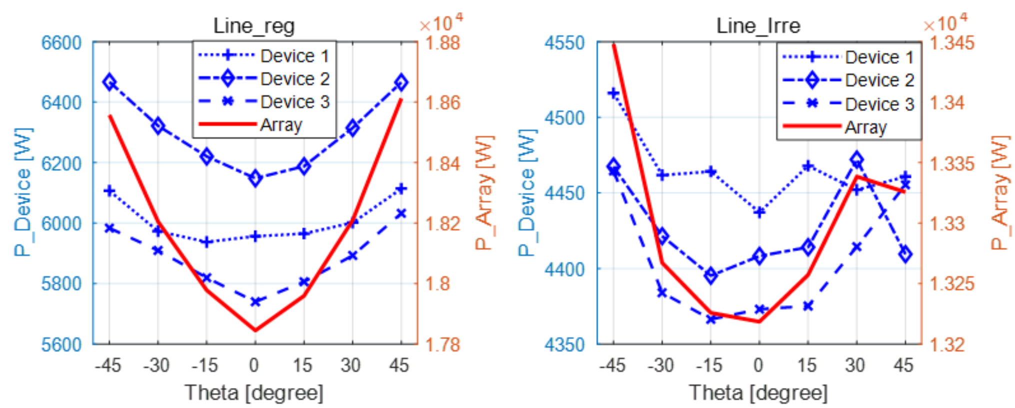


Figure 4.10. Three Devices Generated Power vs. Incident Wave Angle.

The device which generated the largest power among three devices is Device 2 instead of Device 1 because of the combined effect of Device 1 and Device 3, which is different with the situation of two devices. But Device 1 can capture more power than Device 3 which is similar with the situation of two devices. However, the results for irregular waves are totally different with no obvious regularity.

For irregular wave, Device 1 can generate the most power while Device 3 generates the least which shows similarity with the results in two devices.

But the interaction situations become more complex, therefore, we cannot simply estimate the performance considering it in one way. The generated power with irregular waves have more influence factors which cannot reflect the interaction between the devices clearly and directly, compared with regular waves.

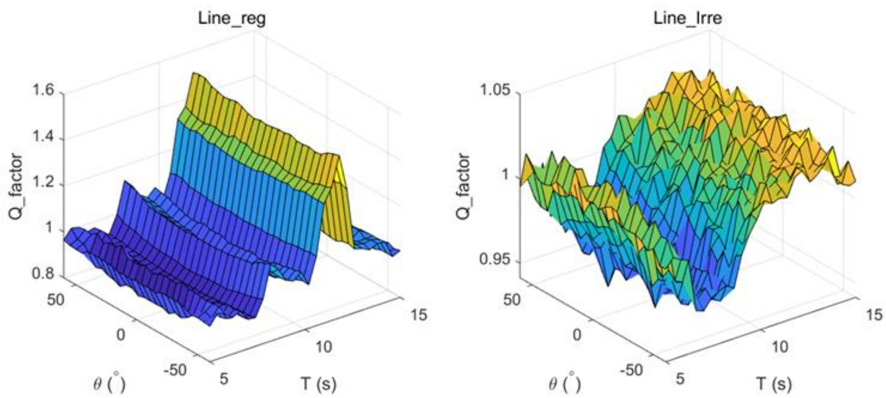


Figure 4.11. Q factor for Three Devices with Regular Waves and Irregular Waves.

The performance of regular and irregular waves is still distinguished for q factors, furthermore, the trend is also changed comparing the results with two devices.

- Regular Geometry

For regular configurations, like regular triangle and square, they are symmetric geometry with several axes of symmetry. The interaction between devices may have clearer regularities which can present in the simulation results analysis. The deployed position and corresponding waves are shown in Figure 4.12 and 4.13.

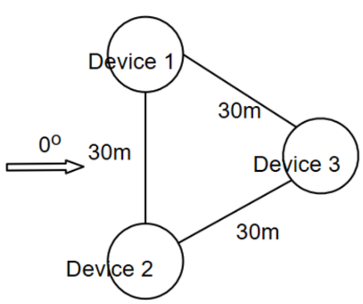


Figure 4.12. Regular Triangle Array Distribution.

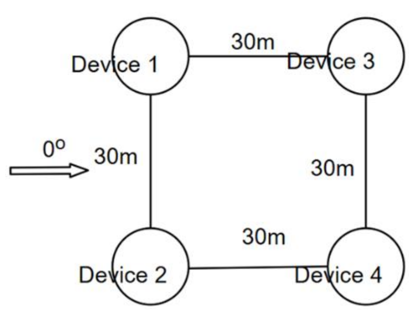


Figure 4.13. Square Array Distribution.

- Triangle Array

Based on the simulation results in Figure 4.14, for regular wave, the values of generated power for Device 1 and Device 2 are closed but with contrary change trends as they locate in the opposite positions symmetric about the zero degree. Device 3 can generate least power under the shadow of Device 1 and Device 2. While incident wave is on the zero-degree, Device 3 obtains the least power with the absolute value of angle degree increasing, the generated power also increases.

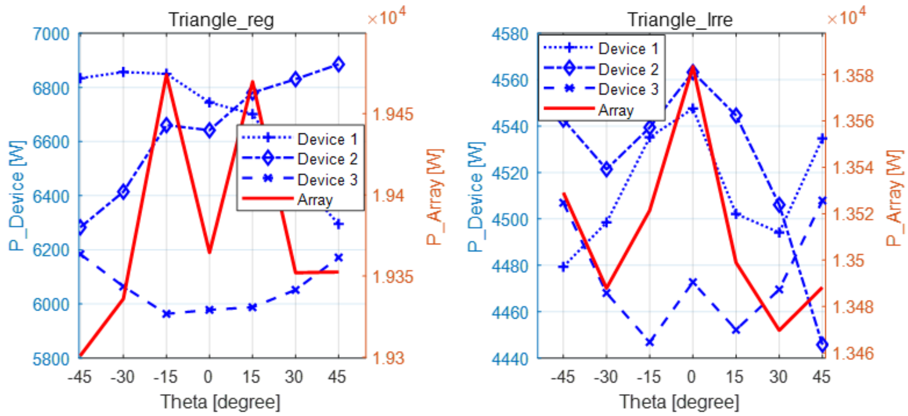


Figure 4.14. Triangle Array Generated Power vs. Incident Wave Angle.

For irregular wave, Device 3 can capture more power than Device 1 and Device 2 while the incident direction is away from the central axis. But the array obtains most power when the incident direction is on zero degrees.

- Square Array

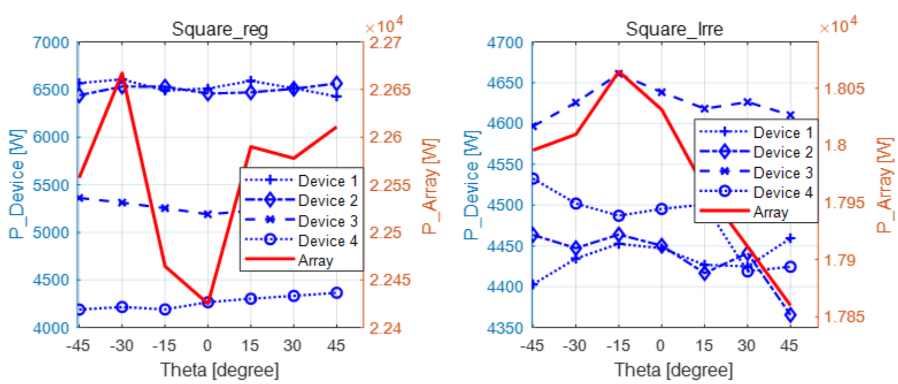


Figure 4.15. Square Array Generated Power vs. Incident Wave Angle.

For the regular wave, two symmetric devices Device 1 and Device 2 have a closed value of power while the other two devices in symmetric position have contrary changes with the direction change.

4.3.2 The Number of Devices

- Three Devices

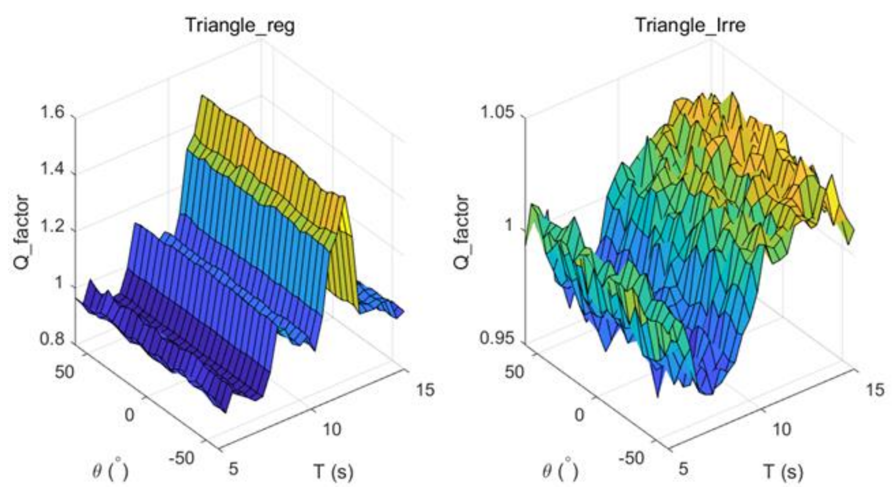


Figure 4.16. Q factor for Triangle Array.

For line array and triangle array, both have three devices and the q factors are shown in Figure 4.11 and 4.16. As we compare these graphs, both show a peak value with period 11.8s for the regular wave. The values are closed as well as the trends are similar for the irregular wave.

When this study compares with the research of (Andres et al., 2014), the wavelength L for the period T=11.8s is about 230m which is approximate 8 times of distance D=30m. However, Andres et al. noticed that the highest q factors always correspond to the distance D equal to L/2 which can make a 180^{o} separation in phase to get higher power (Andres et al., 2014).

- Four Devices

Besides square array, rhombus array is a typical geometry which can also be compared with triangle array as it can be split into two triangles. Square and rhombus arrays have four devices with the q factors shown in Figure 4.17 and 4.18.

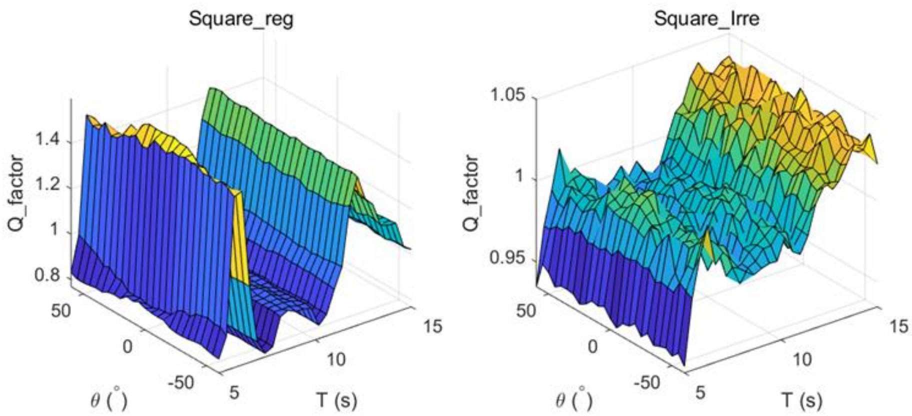


Figure 4.17. Q factor for Square Array.

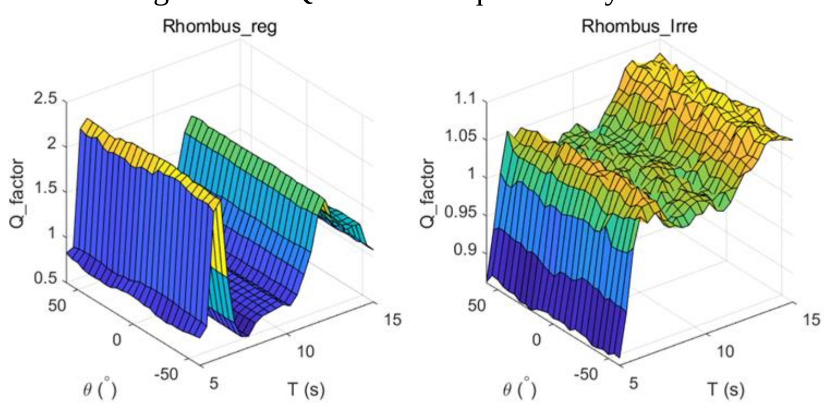


Figure 4.18. Q factor for Rhombus Array.

Both get two extrema with period 6.2s and 12.2s for regular wave and the trends are similar for irregular wave. Furthermore, the extremum values with 6.2s are also the maximum values. The wavelength for the period 6.2s is about 60m which is exactly 2 times distance. According to the paper of Andres et al., the results match the conclusion that highest q factors always correspond to the L/2 distance.

Besides four devices, two devices array also get the extremum value at 6.2s but not the maximum.

4.4 Conclusion

For various changeable parameters, the influence is different and the performances for regular and irregular wave can be observed.

For simulation times, the average generated power with regular wave tends to be stable and the absolute value of difference is small. But the results of irregular wave are unpredictable as aperiodic variation of excitation forces.

For wave height, the influence is coincident between regular wave and irregular wave that the corresponding power is similar with the results of quadratic functions of wave height.

For wave period and wave incident direction, the changes of generated power and q factor have regularities for regular wave while it hard to find one for irregular wave. The analysis methods for regular and irregular wave should be different for further research.

Q factors have extremum value around 12s and 6s which present the eight- and two-times distance wavelength. When the distance between devices is half of wavelength, there is a 180^{o} difference in phase to get more power. But only square array and rhombus array support the theory among all those simulated arrays.

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