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A Novel Design to Harness Water-Wave Energy

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A NOVEL DESIGN TO HARNESS WATER-WAVE ENERGY

By

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Dedication

I dedicate this thesis to my parents for their everlasting support every step of the way. Without them I would not have been able to be here. I am very thankful for a great family that always has my back whenever needed and helps me strive to be better. I want to greatly thank my friends that have pushed me forward and never stopped believing in me, I am here today because of every single one of you. I LOVE YOU ALL!!

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Abstract

Renewable energy sources are essential to our future, not only because they generally minimize harm to our environment but are also a relatively free source of energy that are available for generations to come. Wind and solar energy are proven sources of renewable energy, but both are highly variable. On the other hand, water wave energy is relatively persistent in locations around the world. Many researchers have tried to capture the energy of ocean waves, some were successful, but most were not. Harnessing wave energy is not a simple matter. One must design systems that can withstand the extreme forces of waves, the corrosive nature of salt water, and biofouling effects that can impact the system, while safely extracting energy from waves. This thesis presents the process followed in developing a new system to capture wave energy that has the potential to overcome many of the problems faced by other wave energy convertors (WEC). The concept of the design consists of a floating compliant structure that utilizes a mechanical system to harness water wave energy. The floating system can house several mechanical systems within the same structure, improving its power production and utilizing a greater area on the sea surface. The methodology uses linear wave theory to simulate different wave conditions to calculate the available energy to the system. This model provides estimates of the orbital motion of water particles which can be used to quantify the motions that such a system will undergo. The model can also be used to calculate the forces acting on the structure assuming rigid conditions. As with wind and solar power the wave energy greatly varies depending on the wave conditions, making the design of the structure much more difficult. The designed system must be capable of generating energy at low and high wave conditions and surviving extreme wave events.

Chapter 1 Introduction

The needs for energy continue to increase to meet the demands of the growing population. Renewable energy sources have been introduced lately for integration into existing power production systems to help relieve the environment from the pollution produced by relying entirely on fossil fuels. Renewable energy sources are critical to our future, not only because they do not harm our environment, but also, they can be available for generations to come. Wind and solar energy have been used and researched extensively in the past decades. The problem they face is consistency. Solar energy can only be utilized during relatively non-cloudy days by photovoltaic panels or heat concentration plants, leaving a gap that needs to be filled to continue the power production needed. Wind energy is a highly variable renewable energy source. Winds are not always constant, and they are not always blowing at sufficient speeds to be captured effectively by wind turbines. Both wind and solar energy are great ways to harness energy, but they are not the only way. Water-wave energy is an untapped source of energy that has not been researched and investigated to the same extent as wind and solar. By using ocean wave energy, it not only increases the options of renewable energy, but also adds a source of energy that has heretofore not been utilized effectively.

Wave energy is potentially a very powerful source of electricity. Water is 800 times denser than air so even at lower speeds it can generate significantly higher amounts of energy compared to wind. The need for wave energy harnessing systems could play an essential role in energy production in many areas of the globe in the future. Looking at the demographics of where people are living, it is well known that people tend to live near shorelines more than in inland areas. A study done by the National Oceanic and Atmospheric administration (NOAA) states that more than 39% of the US population lives directly on coast lines, and this number is to increase

to 47% by 2020 (NOAA, n.d.). From this study we can understand the need to invest in research and deploying systems that can harness energy from waves and tides. Instead of investing and trying to produce electricity using fossil fuels, it makes sense to utilize the surrounding environment to produce the energy needed to power our cities. Oceans supply us with two sources of energy that are available around the clock, depending on location: waves and tide energy.

In this thesis, a novel design to capture water wave energy is introduced. This design aims to overcome many of the problems that have been facing other wave energy harnessing systems, such as extreme wave forcing, corrosion, and biofouling. A provisional patent was submitted for this idea and its different configurations. This thesis will be divided into several chapters. A literature review will discuss previous work done in the field of harnessing wave energy in chapter 2, followed by chapter 3, the concept of the design and how the design reached its current shape. Chapter 4 will discuss the methodology used to calculate the available energy and prove the concept, and chapter 5 will include the theoretical, physical test results and the discussion. Finally, the conclusion will be discussed in chapter 6.

Chapter 2 Literature Review

Before researching new ways of harnessing wave energy from the ocean, gaining an understanding of how other systems work, their advantages and disadvantages, and the economics of wave energy harnessing is beneficial. The initial step is to classify previously developed systems in terms of operations and designs. Many have tried to capture the energy of waves, some were successful, but most were not. Capturing wave energy is not a simple matter, wave forces in nature can be huge. Consequently, to capture their energy a system should be designed to withstand the slamming forces of waves, the corrosive nature of salt water, and the biofouling affects that systems undergo.

2.1 Different Design Concepts

There are several different types of systems developed to extract the energy from waves. According to an article published in 2015 under the title, "A Review on Front End Conversion in Ocean Wave Energy Converters". In this review WEC concepts are discussed with their general working mechanism (Drew et al., 2009). Mainly these systems are divided as follows:

I. Attenuator (line absorber)

This system consists of linked arms that are free to move with the propagating waves, creating a relative motion that is used to capture the energy. The energy is captured by different pneumatic, mechanical, or hydraulic systems that are linked to a generator to produce electricity. One of the most well-known designs is the Pelamis, shown in Figure 1.

Figure 1. Pelamis deployed off the cost of Portugal (The European Marine Energy Centre LTD n.d.)

Figure 2. One segment of the Pelamis WEC system

The energy is taken from the waves at the joints using several hydraulic pistons that are connected to high pressure accumulators that then turn a generator to produce electricity (Henderson, 2006). The system is well known because it was the first to produce energy connected to the grid. The prototype was deployed in 2004 after 6 years of development. Further testing was needed so a second prototype was developed and tested and deployed in 2009. The system was subsequently dismantled due to component failures and administrative issues.

The main issue that faces these systems is the sheer size needed to generate commercial grade energy and the huge expenses needed to reach that scale. From Figure 2 you can see the scale of the system and the amount of material (steel) needed to build the system, taken into consideration that the Pelamis system consist of 5 segments.

II. Point Absorber

A point absorber is one of the most popular designs for researchers in the coastal engineering field due to its use of power data collection instruments. The point absorber is based on buoy systems that oscillate on a shaft, either with the energy captured mechanically or by using magnets and coils (generator), see Figure 3. The mechanical system is not used extensively for large scale power generation because it is not reliable and vulnerable to failure. The magnetic system has fewer moving parts and uses a permanent magnet that coils around the shaft of the buoy. With the oscillation due to the wave's electricity is generated. The issue that this system faces is mainly that the buoy system only covers a narrow segment of waves propagating by the system, so less power is generated. Another problem is that such systems must be deployed in deep water, making it very expensive to transport the electricity back to shore.

Figure 3. A deployed buoy system that is part of a project off the cost of Australia (Levitan, 2014)

III. Oscillating Wave Surge/ Water Column Converter

The wave surge energy convertor, like the one seen in Figure 4, uses the slamming forces of the wave to move a lever action system to pump water into a generator to produce electricity (Whittaker & Folley, 2012).

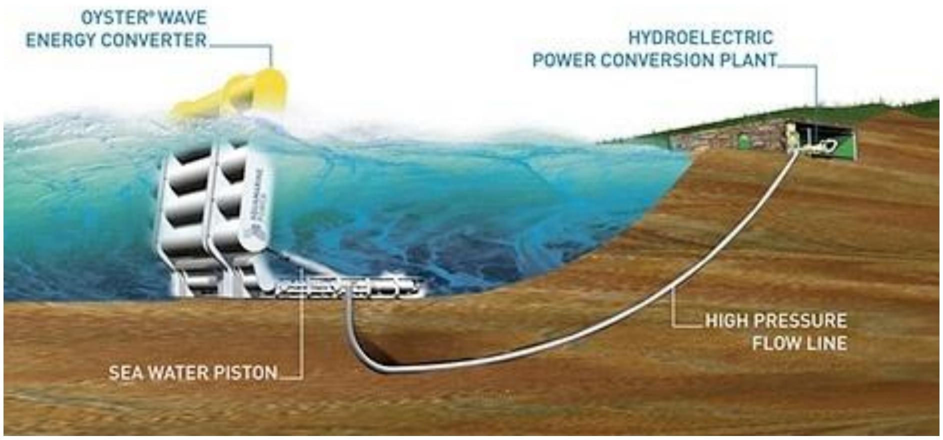

Figure 4. The Oyster WEC schematic of the process of electricity production (Mitchell, 2009)

The system was developed to be deployed in the near shore area. The problem that this system faces is the extreme forces (moments) that it must withstand to be able to produce electricity and not surpass thresholds for moments or fatigue of parts.

The water column wave converter, instead of using the slamming (horizontal) forces of the waves, captures the difference in height created by the propagating waves to compress air into turbines to produce electricity. In Figure 5, a cross section view of the system can be seen that explains the mechanism used to produce electricity.

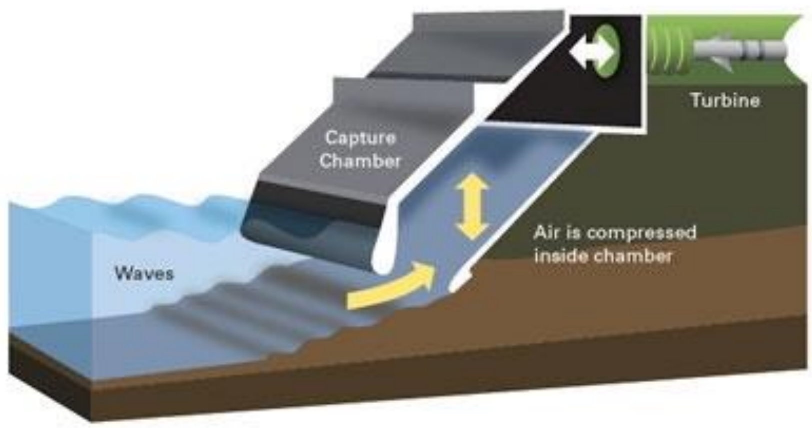

Figure 5. Oscillating water column WEC system. (Stauffer, 2008)

I. Submerged Pressure Differential

This system converts the difference of pressure created due to the propagating waves into a mechanical motion to produce electricity, as shown in Figure 6. The WEC is fixed to the sea bed and a mechanical system translates the motion developed from the difference in pressure into electricity.

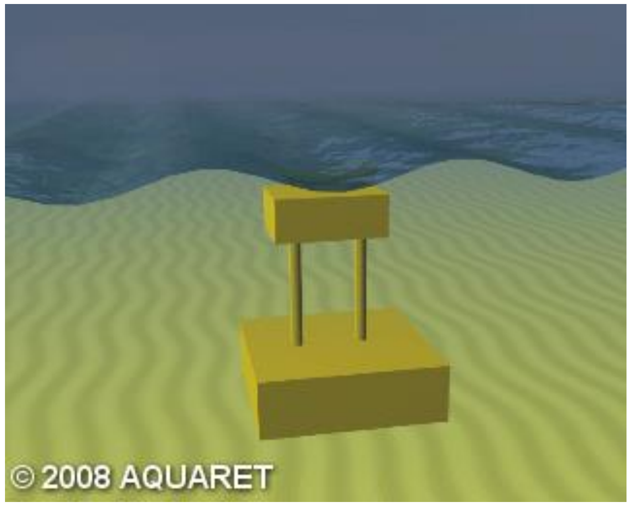

Figure 6. Submerged pressure differential WEC (AQUARET, 2008)

These are the main types of systems developed thus far for extracting wave energy, each in its unique way. Not only is the design itself of the system very important but also the economics of the system must be a factor.

In this thesis a levelized cost analysis was used, “Evaluation and Comparison of the Levelized Cost Analysis of Tidal, Wave, and Offshore Wind Energy” (Astariz et al., 2015) to further understand the economics of WEC systems. This levelized cost analysis was performed for three renewable energy systems: tide, wave, and offshore wind energy systems. The analysis was based on the cost of the system, installation, mooring and connection to the grid (underwater cables, cable installation and electric substation). The levelized cost analysis is based on the lifetime cost of a system over its energy production. It calculates a present value of the total cost of building and operating a system over its lifespan. This allows for a comparison of different systems using unequal life span, project size, different capital cost, risk, returns, and capacities.

2.2 Cost Analysis

A levelized cost of energy analysis of different renewable energy systems allows for a comparison based on weighted average costs of criteria that are set to all systems. The discounting method of Levelized Cost of Energy (LCOE) is used (Astariz et al., 2015). From the findings wave energy is the most expensive compared to the other 2 systems, as seen in Table 1. This could be explained by the fact that offshore wind energy systems are already in the commercial stage, unlike tide and wave that are still in the development stage.

Table 1. LCOE of different renewable energy sources per MWh based on European systems and estimates (Astariz et al., 2015)

Technology	LCOE (€/MWh), ($/MWh)
Offshore Wind	165, 193
Tidal	190, 222
Wave	325, 380

Another factor that must be considered is the complexity of design in the systems to harness the energy, which is very dependent on the different environments in which the systems will be operating. Wave energy convertors (WEC) must mainly be able to withstand huge forces from waves and sudden changes in direction of motions. The systems previously designed to overcome many of these problems took the traditional route of building extremely strong and large structures to withstand the immense forces acting on the system. By doing this the systems tend to be extremely expensive to manufacture, transport, and maintain. The design approach of most concepts forces the cost to increase leading to a more expensive design and therefore a more expensive energy production compared to other renewable energy sources.

Chapter 3 Conceptual Approaches

This thesis proposes a novel design to harness water-wave energy, using a compliant system that minimizes effects caused by both the massive destructive forces of the waves and the corrosive nature of salt water combined with biofouling. The design is based on a new concept of a compliant (flexible) fabric kite system that captures the energy carried by the propagating waves and converts it into a simple rotational motion that can be used to turn a generator to produce electricity. A compliant structure is a structure that can be flexible enough to be able to absorb wave forces and the generated moments and therefore increase survivability. The design of this system explored several alternatives and went through several iterations to reach the final design.

The first design concept envisioned was a pressure differential system, since most existing systems utilize this concept in their design. Pressure differential is created at the bottom of the water column due to the propagated waves at the sea surface. The most common system utilizes a float system that is anchored to the bottom of the sea bed, and due to the pressure differential, the float oscillates (up and down) engaging a pump system that pumps hydraulic fluid to a reservoir and then into a generator (EMEC, 2008). A research team in the University of California, Berkeley, has suggested a similar method of harnessing wave energy using the pressure differential created by the propagated waves. This system was "inspired by the natural phenomenon of strong attenuation of oceanic surface waves by muddy seafloors" (Lehmann et al., 2014). The design consists of a compliant structure that acts like a carpet connected to a complex series of double action pumps that are then connected to a generator to produce energy.

3.1 First Design Concept Considered

The idea of a compliant system is one step closer to achieving better, more reliable power production. The initial attempt to create a new design for harnessing wave energy utilized a closed fabric tube system that encapsulated fresh water and a series of turbines. A Fortran code was written to calculate the pressure at the sea bed using the pressure equation incorporated with the pressure response factor equation 1 were $\gamma = \rho g$ and $\eta = a \sin(kx - \sigma t)$ (Ippen, 1966), see Figure 7.

$$p = \gamma[\eta \frac{\cosh k(h+z)}{\cosh(kh)} - z] \tag{1}$$

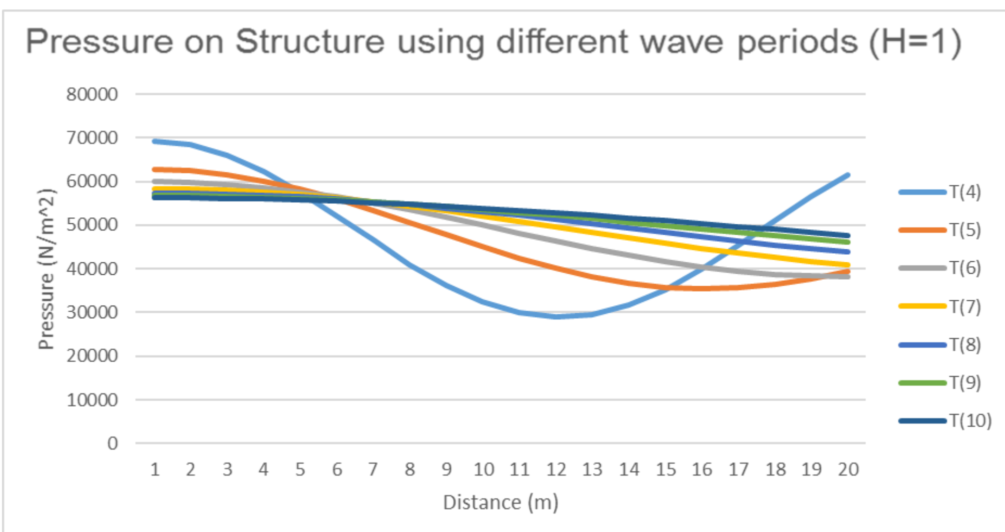

Figure 7. Pressure differential at a depth of 8m from 1-meter propagating wave.

Over a structure that spans a length of 20 m it can be seen that there is a difference in pressure created by the different wave periods. This pressure differential drives the water to

move inside the tube. For example, a 4 second wave denoted with the blue line shown in Figure 7 shows the large pressure change created by the propagating wave. The major problem is that water inside the tube cannot move fast enough to efficiently turn the turbine and generate needed quantities of energy. The problem faced is that the mechanism suggested to harness the generated energy due to the difference in pressure is not adequate. The original concept of the design is a simple enclosed system with no use of open mechanical moving parts to overcome the problems faced by previously designed systems. So, a new approach was taken for the concept using that same enclosed system but located at the sea surface, instead of using the pressure to drive the fresh water inside the tube, the slopes generated by the waves will be used to drive the system.

3.2 Second Design Concept Considered

The suggested alternative used the same enclosed system with fresh water and the turbines but locating it at the sea surface. As shown in Figure 8 the design concept utilized the increase pressure difference in height created by the propagating waves between a peak and a trough at the wave surface and utilized this difference to force the enclosed water along the slope and through the turbine sections.

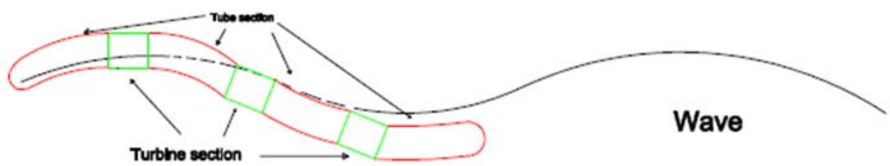

Figure 8. The suggested enclosed system to harness wave energy. The red tube sections are the water compartments and the green sections are the turbine sections.

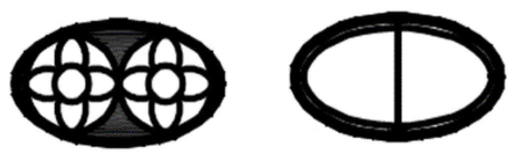

Figure 9. A front view of the sections, on the right is the Turbines section. On the left is the water storage compartment.

To utilize the high energy density of water waves a 2-turbine alternative is suggested and to divide the water compartments into sections, as shown in Figure 9. All the water compartments will be split in the middle but at either end of the system the compartments would be open with one-way flaps, so water can flow from one side to the other in the same direction and does not create back flow in the system. With this closed configuration that would fully contain the water in the system, energy would be extracted as water flowing in either direction. This means that the turbines had to be oriented in opposite directions so one turbine is always turning with the flow. The problem with existing turbines is that blades are designed for unidirectional flow and optimized for a certain direction, thus any spin in the opposite direction reduces system efficiency and slows the water flowing through the system. To test the idea out a circulating system was built and is shown in Figure 10.

Figure 10. The circulating system to simulate the enclosed system.

A model was built to mimic an enclosed circulating system built with one-way flow. To achieve that four-inch pipes were used with two one-way flap valves resulting in a circulating system that operates in one direction. In Figure 4 an empty section between the pipes is seen. This empty section is there to mount the generator system built to see if the concept will generate electricity. The turbine generator system is shown in Figure 11.

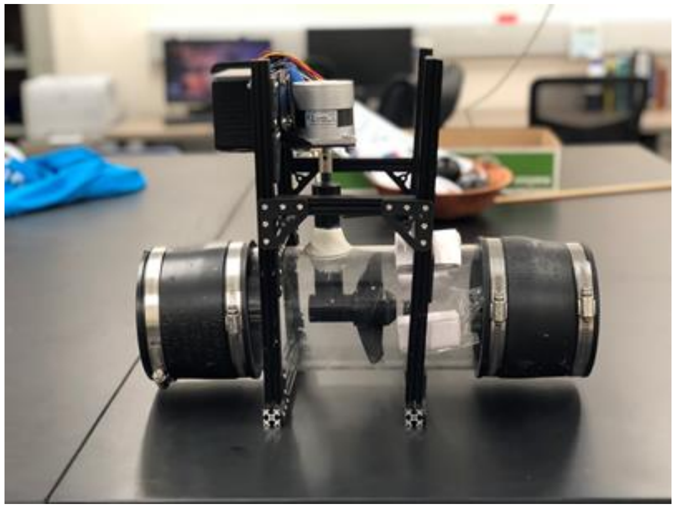

Figure 11. The turbine generator system built to test the concept of the enclosed system

The turbine generator system was a design mainly developed by the research team. The generator consists of a 4.5-inch clear pipe, a right-angle drill attachment, a blower's turbine blades, a shaft coupler, a 10-watt motor, and a rectifier. All these components were procured from different off-the shelf sources in order to build a setup that can be used to prove the concept. With this system attached to the testing apparatus, the concept can be tested. A 'sea-saw' oscillating table was built to mimic wave action to test the system concept. The oscillating table is shown in Figure 12.

Figure 12. The oscillating table used to simulate wave action to be used in proof of concept for the water enclosed system.

After assembling the testing apparatus together by connecting the turbine generator to the piping system and filing it with water, testing was performed. A voltmeter was attached to the leads of the load connected to the rectifier to be able to measure the generated electricity. A rectifier was used to transform the AC current generated into DC current. This process is important to have a constant readable power output. A load was needed to be added to the generator rectifier setup to simulate some of the expected resistance that the generator will face when connected to a grid or to a battery system. After attaching everything and monitoring the turbine movement through the clear pipe and at the same time looking at the volt meter recordings, the system was securely attached to the testing table and the test started. The turbine was rotating at a very slow speed insignificant to the point that the volt meter was not able to read any outputs from the generator. The test was stopped and the whole generator setup was taken apart and reassembled just to double check if all the components were correctly assembled. The generator was tested on a dry run, just manually turning the turbine by hand to check if the voltmeter is picking any readings. The setup was working fine, the test was running once more.

The results were negative, indicating that no power was generated. It was concluded that the scale of this test was too small, and a larger scale was needed, with a more efficient turbine generator setup. Because of lack of funding for the project it was not possible to obtain the needed larger, more efficient turbine generators. Also because of the size issue a larger-scale test was not possible given the confines of the available laboratory facility.

3.3 Third Design Concept Considered

The final alternative is a very simple system that we believe may address many of the previous problems faced by WEC systems. The basic concept of the design was to again pursue a simple compliant system.

For this system, the energy associated with the waves is captured by an inflatable fabric material that acts like a resisting structure ('Kite') but instead it is deformable and free to move, so it can displace from one position to the other with little structural resistance. To convert the wave motion, the fabric structure is anchored to the sea bed, where a power generation unit is located above the fabric structure above the water line to be out of the water. The displacement due to the waves is translated into a rotational motion with the help of a marine grade line that is anchored into the sea bed and connected to a reel on a shaft, with the help of a mechanical system that is then connected to the generator to produce electricity. The mechanical system is enclosed in a dry box located on top of the fabric. A conceptual sketch is represented in Figure 13.

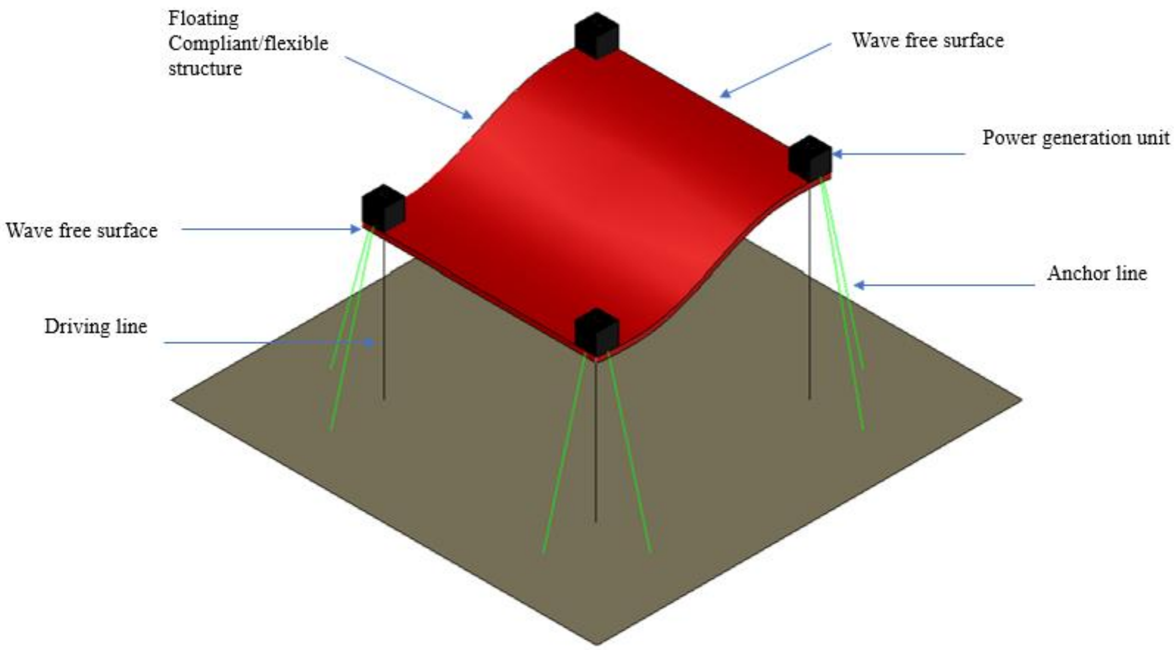

Figure 13. Concept sketch of the suggested design of the compliant WEC system.

The design also adds a potential step to large energy production from wave energy, in that it is scalable in size. The scale chosen would depend on deployment location and the amount of electricity needed. It is scalable in two ways. Firstly, power generation units can be added to a single fabric structure, or the fabric structure can be sized depending on location of deployment of the system and the power needed to be generated. The design proposed should overcome many of the problems faced by designs that are already in use. With this compliant approach wave loading forces are minimized (i.e. reduced), shear forces and moments acting on the structure. Other systems as mentioned in the literature review mainly depend on a strong structural interface between the waves and the mechanism to extract the energy.

The suggested concept of design also has an advantage that no other system developed possesses i.e., this concept can be altered and be setup differently. Water waves have two modes of motion in the vertical and horizontal directions and water particles possess an elliptical trajectory motion in shallow water and becomes circular in deep water. In Figure 14 the concept of a compliant WEC system that exploits the horizontal motion of waves is shown.

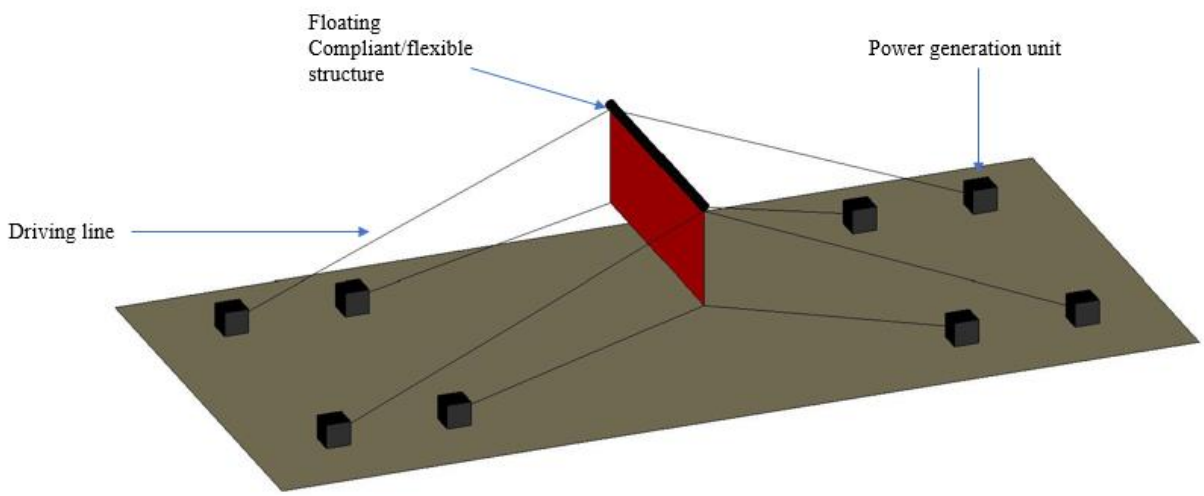

Figure 14. The horizontal-motion compliant WEC concept design.

The design is based on the same concept of compliance. In Figure 14 it shows a Kite System in red which is basically a fabric material with floatation at the top to keep the fabric neutrally buoyant and keep the fabric straight. The fabric is then connected by lines to energy generation boxes in which the energy harnessing mechanism is housed is similar to that used in the vertical system Figure 13. This system can potentially be used in shallow water with high wave activity. The major asset of such a design is its ease of scalability. All the suggested concepts have a potentially great advantage in that they are very compliant and can be oriented to optimize for the predominant wave direction. For the vertical system the suggested concept can

simply easily and swiftly face the propagating wave because of the compliant design and the ability to harness energy from all directions of motion, on other hand the horizontal system Figure 14 will be able to adjust for a range of wave directions only. On each end of the fabric structure there is a generator connected making it easier to harness energy in all directions. Even if the energy production will be reduced on one side due to the wave angle, it will be compensated with the other set of generators that will be facing the waves.

From the same concept a revolutionary idea was suggested by Dr. Don Resio, i.e., the use of the same system scaled down to be able to deploy it from boats in case of emergencies. In Figure 15, a design concept of a small emergency wave energy harnessing system is presented.

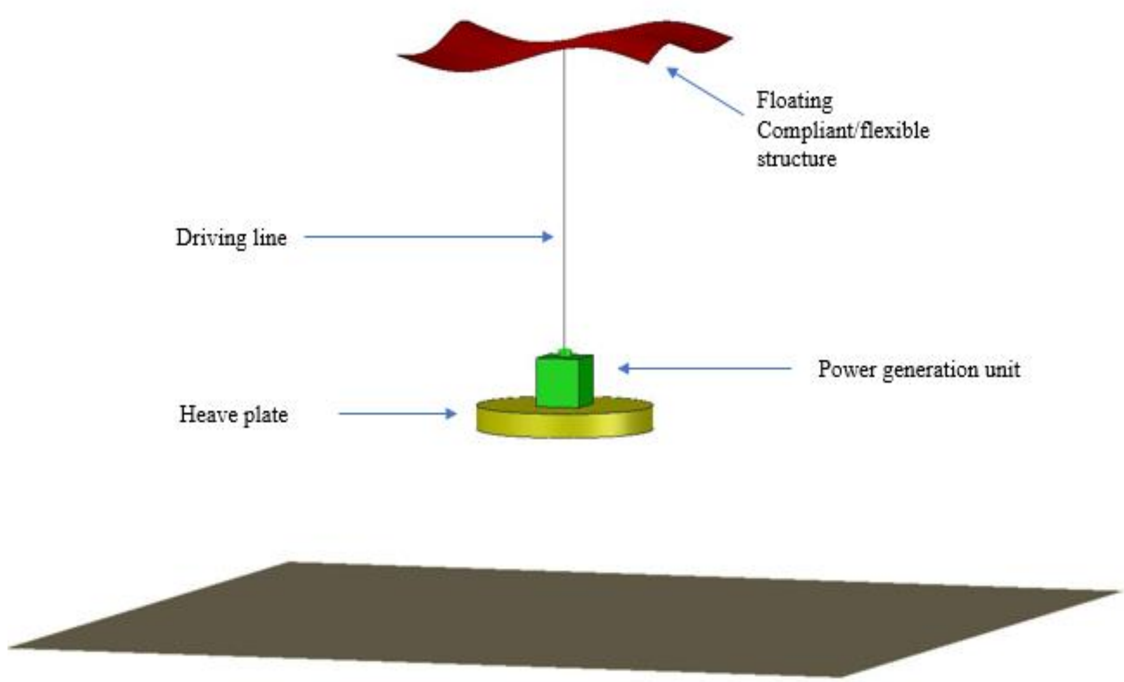

Figure 15. The floating life raft emergency WEC

This system consists of a heave plate weight counteracting wave motion, therefore relatively stable and can be used as support for the system, attached to it a smaller energy harnessing mechanical system that could power up a radio, charge up a device, or can be used to desalinate water for emergency. The system can be small enough to be stowed in a small compartment and deployed when needed or can be modified to be deployed with life rafts. The ability to have power in an emergency "at-sea" may be a key to survival.

In Figure 16 an infographic of the concept can be seen and how the system is expected to be set-up. The design of these systems is aimed to directly power neighborhoods or if deployed on a large scale it may be able to power cities. The main motivation is that wave energy is a very dense source of energy that is available in all oceans and seas. The concept of renewable energy is to have a combination of different systems that are redundant and back one another, to be able to totally depend on it. The main reason the wave energy is a very solid contender for being at the forefront of renewables is that most people live by the coast and it makes sense to utilize the available source of renewable energy that is closest to them and potentially more efficient than other methods.

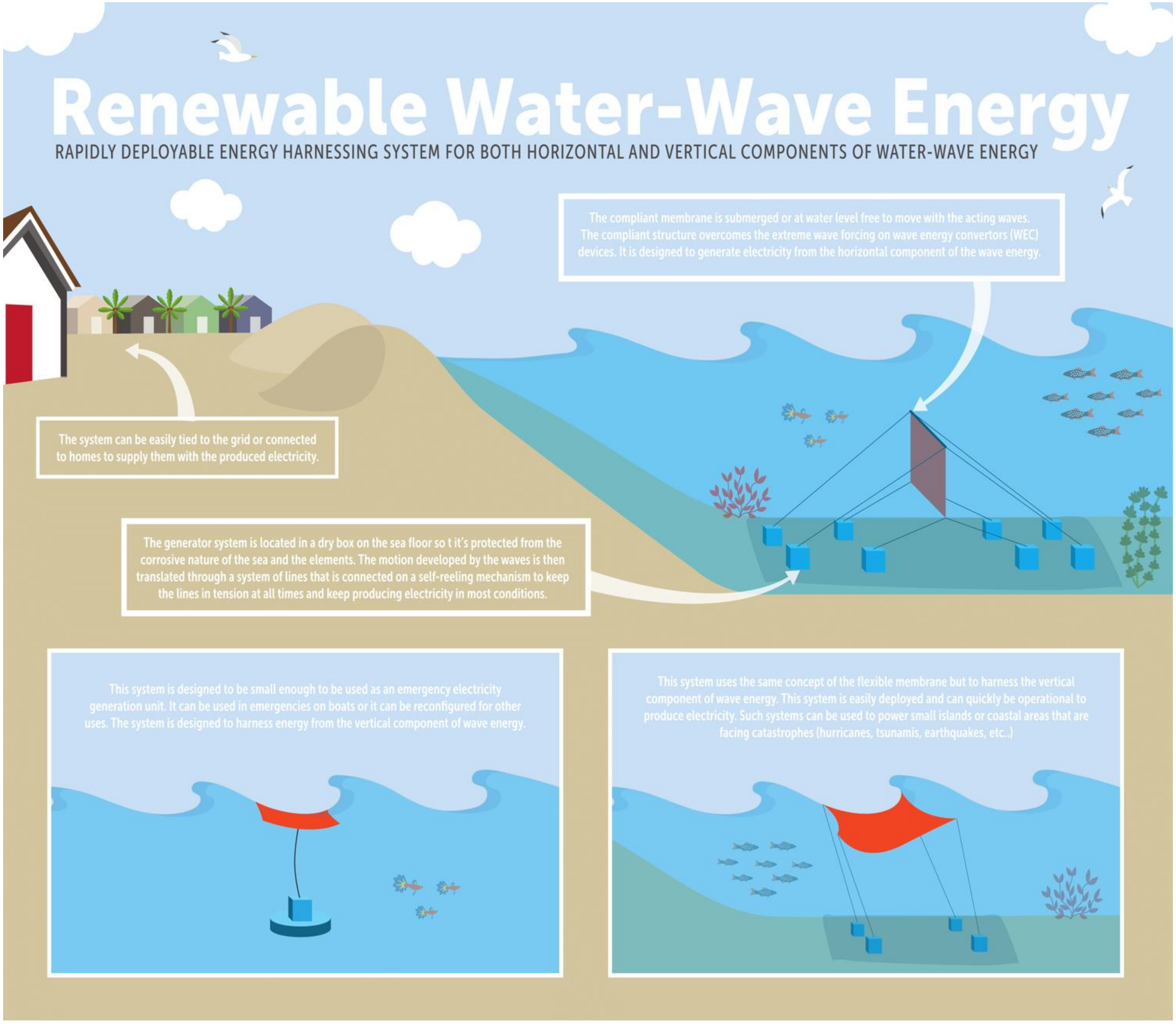

Figure 16. WEC systems infographic.

Chapter 4 Methodology

4.1 Available energy

To investigate the proposed design many different tasks were completed. To start, the available energy transported by the waves was calculated to obtain the design to harness as much energy as possible. This was achieved by calculating the available energy in different scenarios, to be able to choose the best design depending on location and situation. The idea is to have a system that can be easily deployed wherever it is needed. To achieve this goal a system must be able to withstand different wave scenarios and be efficient as possible. A Fortran code was written using linear wave theory to compute the needed information. Using the kinetic energy equation, (Equation 2), the amount of energy available in the system was computed. To calculate the amount of power that is available, the energy flux was calculated. To calculate the energy flux, (Equation 3), the group velocity and the radian frequency is needed, (Equation 5) and (Equation 4) respectively. The wave height, radian frequency, depth at which the analysis is done in the water column, and the wave number, all this is needed to calculate the kinetic energy in the system. Because Equation 5 is transcendental in wave number, k, a computer program was written using Fortran to numerically compute the available power produced by a wave. A combination of wave heights varying from 1 to 3 meters, with different wave periods ranging from 4-12 sec was adopted. By having this range of wave heights and wave periods it puts it into perspective the amount of power possible to harness from such an environment if an efficient system is developed. The different combinations of wave periods and wave heights are very important to compute because in nature waves vary in size and period constantly. By doing this it shows the different variations in power output and at various combinations of the given parameters.

$$KE = \frac{\rho}{2L}(\frac{gHk}{2\sigma}\frac{1}{\cosh(kh)})^2 \int_x^{x+L}\int_{-h}^{0}\frac{1}{2}[\cosh(2k(h+z)) + \cos(2(kx-\sigma t)]\,dz\,dx \quad (2)$$

$$EF = KEC_g \quad (3)$$

$$\sigma = \frac{2\pi}{T} \quad (4)$$

$$C_g = \frac{C}{2}(1+\frac{2kh}{\sinh(2kh)}) \quad (5)$$

$$\sigma^2 = gk\tanh(kh) \quad (6)$$

To calculate all these equations, the dispersion relationship, (Equation 6), was used to obtain the wave number to be able to compute the energy available. The wave number is one of the common properties that are constant as long as the wave period and depth of analysis stay the same through the same run.

The next step was to address the motion of the water particles due to the waves, as this is what drives the motion of the fabric structure. The motion due to the waves are in 2 directions, the vertical and horizontal. Water particle trajectories tend to take an elliptical shape in shallow

water. This elliptical behavior of water particle trajectories is provided by Equations 7 and 8. The particle displacements are important to the anticipated movement of the kite system and therefore account for this motion in terms of energy harnessing.

$$A = \frac{HT}{4\pi}\sqrt{\frac{g}{h}}\ (m) \tag{7}$$

$$B = \frac{H}{2}\left(1 + \frac{Z}{h}\right)\ (m) \tag{8}$$

Wave forces are another major issue in harnessing wave energy that other systems face. To understand the wave forces acting on the structure a calculation of forces acting on the structure were computed. The issue of calculating wave forces on this design are the extreme variations in the status of the system. Generally calculating wave forces on a structure in the water whether it's a bridge deck or a floating vessel, one knows the status of the structure in that it is still in its place or is it floating. In the present situation case it's both and this adds another level of complexity of the problem in analyzing the forces acting on the system theoretically. The system as explained in the concept in the previous chapter, it's floating but anchored to the sea bed with a level of freedom for it to move in the vertical direction (vertical system). Also, the system has the driving lines that turn the shaft. This means that the system is floating with some restriction due to the anchoring and the lines that drives the shaft. So, this restriction can be accounted for if a scale model is built to test it. For the purpose of this research we are trying to prove the concept.

As an initial approach the structure is assumed to be fully rigid and does not move, resulting in the extreme case of loading. The system in this scenario is under the maximum load due to its resistance to wave forces while experiencing no motion. By doing this we can understand the extreme forces acting on the structure and therefore account for it in the design of the system.

To calculate the forces that are acting on the structure in the z direction(vertical) Equation 9 is used to calculate the forces acting on the structure in the z direction (vertical). The acceleration term $\frac{\partial}{\partial t}$ in the Z-direction, Equation 10, is also needed as input into Eq.9

$$Fz = \rho V \frac{\sinh(kl^3/2)}{kl^3/2} \frac{\sin(kl_1/2)}{kl_1/2} \frac{\partial w}{\partial t} \tag{9}$$

$$\frac{\partial \omega}{\partial t} = -\frac{H}{2} \sigma^2 \frac{\sinh(k(h+z)}{\sinh(kh)} \cos(kx - \sigma t) \tag{10}$$

For initial testing we are assuming that the waves are going to be completely perpendicular to the structure, so the angle of the wave won't have a factor in the wave energy. This is just to prove the concept and reduce the degrees of freedom in the system to have a constructive analysis and set a strong base to continue evolving the system and have productive analysis. From the given equations we can understand the impact of the forces generated by the propagating waves in the structure.

In table 2 the different variable inputs were used to calculate the power output and the forces acting on the structure.

Table 2. Different variable ranges used in calculating wave energy and forces.

Variable	Range
Wave height	1-3-meter waves
Wave period	4-12 sec
Length of the structure	4 meters

4.2 Physical model

To further investigate the concepts a physical model should be constructed and tested in a controlled environment (wave tank). The importance of the building of a physical model and testing it is understanding how the different parts of the system interact together and how the system interacts with its environment. The physical model will allow the concept of using a floating deformable structure to harness wave energy to be explored. The system will be scaled down to 1-meter by 1-meter deformable sections. To simulate the deformable structure, segmented plywood strips connected with polymer fabric will be used. In a full-scale model the inflatable fabric structure will be developed. Plywood is cut into rectangular sections connected by fabric section creating a joint made from fabric, this mimics the idea of having a flexible fabric floating on top of the water. By combining all of these small pieces, the final setup of the floating system will consist of 3 plywood section with 2 fabric connections in the middle. To prove the idea of harnessing the energy, the energy harnessing system must be modeled. The energy harnessing system will be modeled by a mechanical system placed on top of the plywood section. The mechanical system will be divided into 3 sections, each contributing to the system

differently with different responsibilities. The first system is the driver of this mechanical system. The driver of the system is a spool of wire that is attached to a shaft. The wire on this spool is anchored to the bottom of the sea bed, but for modeling purposes it will be attached to the bottom of the wave tank. This wire will be the main driver of the system as the waves are propagating towards the system, the wire will be then reeled off the spool connected to the shaft and this is due to the waves lifting the platform and placing it at higher levels. As the line is reeled off the spool (driver line) it turns the shaft, at the same time on the opposite side of the shaft a self-winding mechanism that is connected to the shaft is storing energy to be used to reel back the driver line onto the spool after the upwards motion of the wave has been covered (trough to peak). Figure 17 shows the sequence in which the system is going to operate in.

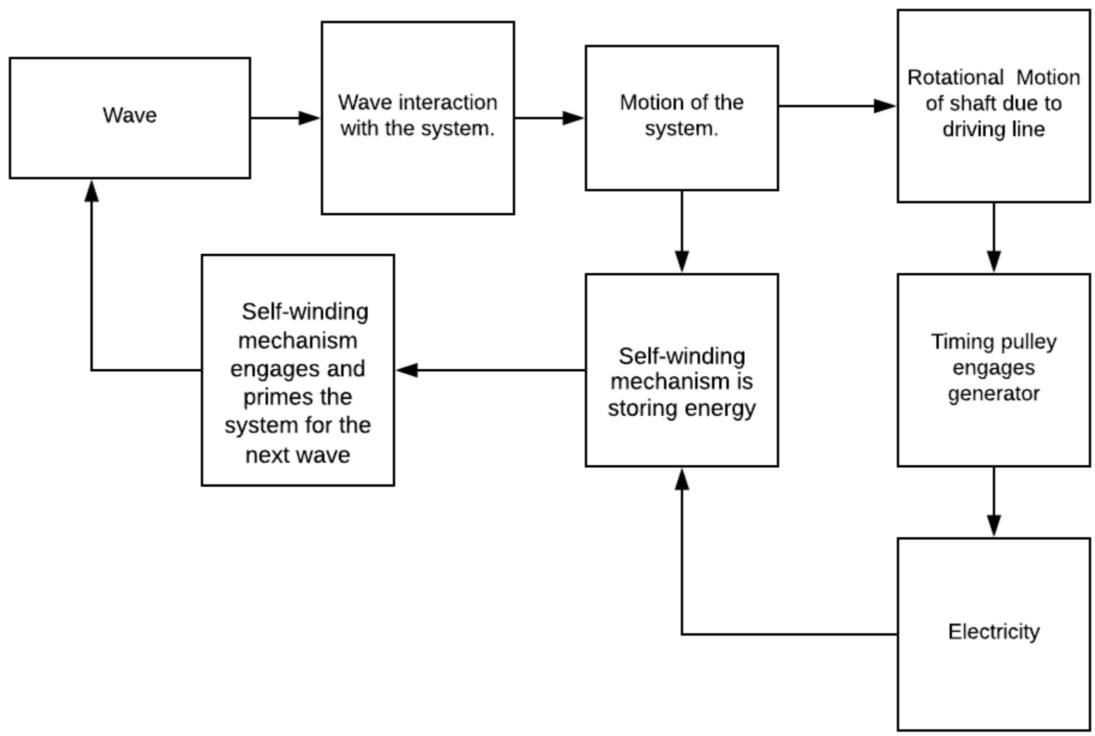

Figure 17. System running sequence flow chart.

The shaft has a timing pulley gear that is connected by a belt to a small gear attached to the generator. The generator will then be connected to a volt meter, so the power output of the system can be determined. The whole idea of the physical model is a proof of concept and an understanding of the components that needs to be redesigned or improve what works and what does not. This whole process of trials and testing is the path of optimizing the system to reach an efficient yet simple system that can be then pushed to a full-scale model. For this thesis and due to the limited time and the complication of construction with the available resources, only a test of the generator could be performed. The scaling properties of the wave tank have a 1:49 in the spatial scale and 1:9 for the temporal scale. One used the expected wave heights and constructed a series of tests simulating different wave heights. In the expected test, gears with 1:4 ratio will

be used to gear up the rotation of the shaft and therefore have higher rate of revolution. On the first test the expected gear diameters are going to be 4 cm gear and 1 cm. From the wave pool scale it is known that if a simulated 9 second wave period will correspond to a 1 second wave in the tank. From this information we can then calculate the circumference of the gears and the expected displacement due to the waves. The revelations per second (RPS) resulted from the propagating wave and the motion of the system is transferred to the shaft, adding the gear ratio factor to the original generated rotation we can know the final RPS of the system. This is then converted into rounds per minute (RPM). Table 3 provides different combinations of wave heights and the expected RPM.

Table 3. Scaling of wave tank waves into expected RPMs.

wave height (cm)	3	4	5	6	7	8	9	10
Large gear diameter (cm)	4	4	4	4	4	4	4	4
Small gear diameter (cm)	1	1	1	1	1	1	1	1
circumference(Large gear) (cm)	12.57	12.57	12.57	12.57	12.57	12.57	12.57	12.57
circumference(small gear) (cm)	3.14	3.14	3.14	3.14	3.14	3.14	3.14	3.14
gear ratio	4	4	4	4	4	4	4	4
revolutions per second (big gear)	0.24	0.32	0.40	0.48	0.56	0.64	0.72	0.80
revolutions per second (small gear)	0.95	1.27	1.59	1.91	2.23	2.55	2.86	3.18
RPM	57.30	76.39	95.49	114.59	133.69	152.79	171.89	190.99

Using the generator shown in Figure 18, we can test for the following RPMs and see what the energy output is and then run optimization problems to set what resistance is optimum for the corresponding RPM. By doing that we run our first test for the generator and values for power outputs can be obtained that can be used as guidelines for the full-scale that will be done in the future.

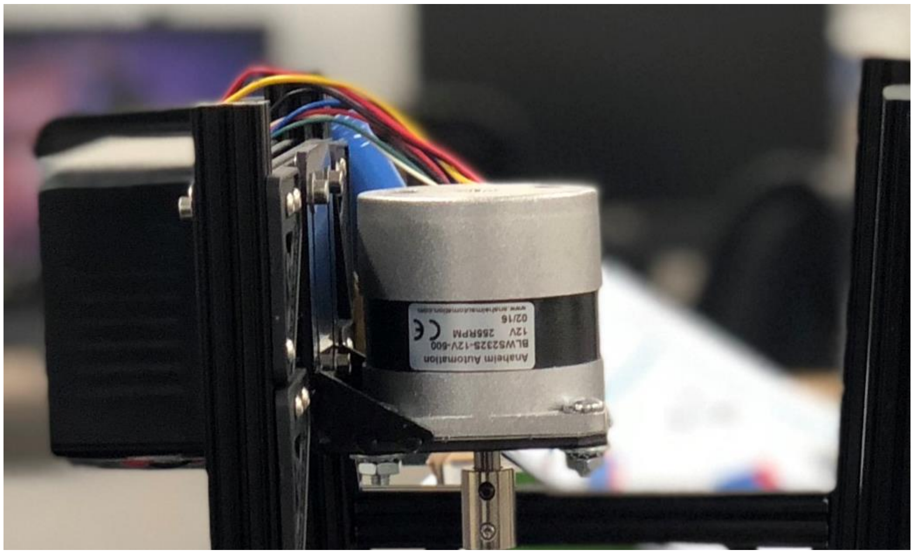

Figure 18. The AC brushless motor with the rectifier (Black box) and the attached resistor (blue tube).

<u>4.3 Wave climate</u>

To design a WEC one must understand the expected wave climate to be able to design an efficient system able to harness the maximum energy. For this thesis, two approaches were taken to calculate available power and wave climate. First approach was to generically calculate the available power for different wave heights (H) and wave periods (T). The problem faced was the depth at which the wave climate is to be computed is unknown. Since the depth of deployment of the system depends on location and can greatly affect the wave conditions at that site, a location must be specified for this estimate to make the results relevant. The Field Research Facility for Coastal and Hydraulic laboratory for the Army Corps of Engineers (FRF) (FRF, 2013) Duck, North Carolina has been chosen as the test location at which we can assume our system would be deployed. This research facility has placed many wave measurement systems that provides wave height, wave period, and direction. They have placed semi-permanent measurement instruments

at depths of 8, 17, and 26 meters. Figure 19 shows one of the waverider systems in the deeper sites and Figure 20 shows an acoustic wave current profiler for the shallower sites.

Figure 19. Wave rider buoy placed at 17-meter, 26-meter depth at FRF Duck, North Carolina.

Figure 20. Acoustic wave and current profiler (AWAC) at 8m depth Duck, North Carolina

All data collected from FRF is available online on their website. For the 3 instruments the most consistent data availability is for the year 2013. Data were extracted for an entire year in these three different depths. This information is used to quantify the wave climate at different depths and potential challenges. Figure 21, 22 and 23 shows the significant wave heights (Ho) of year 2013 for the 8, 17, 26 meters respectively.

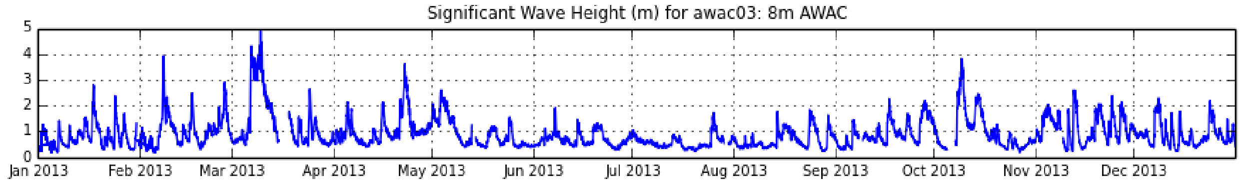

Figure 21. Significant wave height (m) at 8 m depths for the AWAC instrument at FRF Duck, North Carolina for the year 2013.

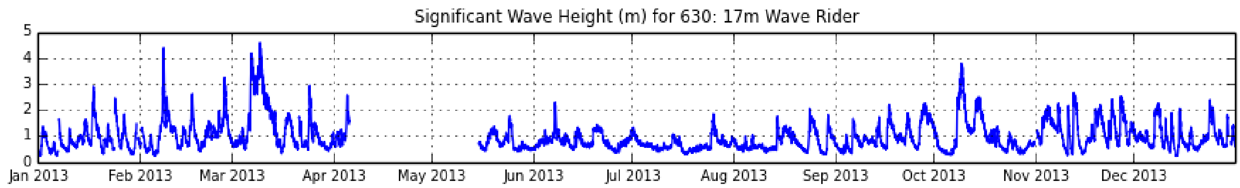

Figure 22. Significant wave height (m) at 17 m depths for the wave rider instrument at FRF Duck, North Carolina for the year 2013.

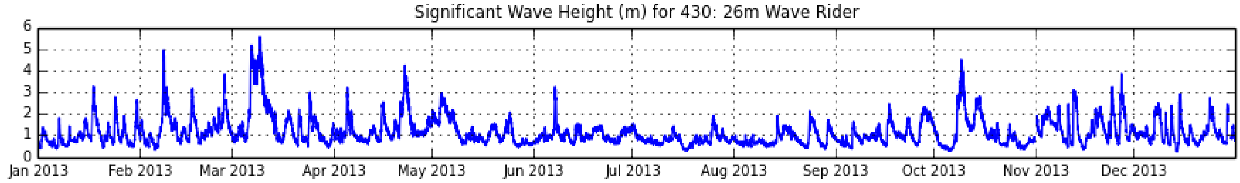

Figure 23. Significant wave height (m) at 17 m depths for the wave rider instrument at FRF Duck, North Carolina for the year 2013.

From Figures 21, 22, and 23 the wide variation in wave height is evident, depending on the time of the year. An effective WEC must be able to efficiently generate electricity in a range of wave climates. To further characterize the wave climate in this area, histograms are used to evaluate the significant wave height distribution over the whole year of 2013, presented in Figures 24, 25, and 26 for the depths of 8, 17, and 26 meters, respectively.

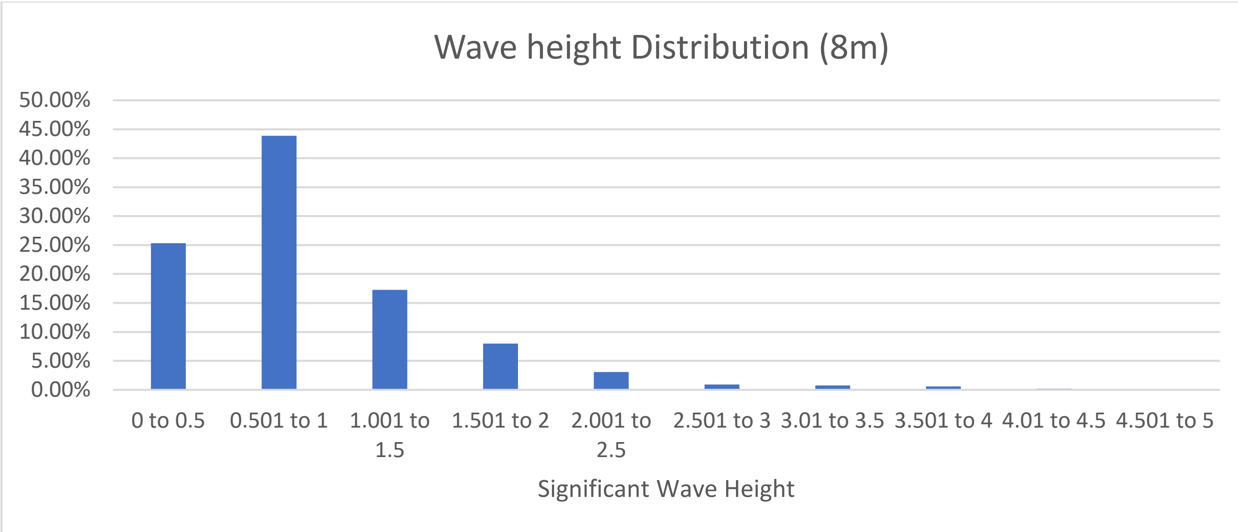

Figure 24. Wave height Distribution for the 8 m depth placed AWAC for the year 2013.

These wave distributions provide an overview of the generally dominant wave heights expected in the area. The power take-off mechanism (PTO) for the WEC must be optimized for the most common waves expected to achieve a wide operating time window, while still being able to handle the extreme wave heights that occur on rare occasions compared to normal conditions. For example, approximately 80% of the waves in the year 2013 at FRF range between 0 to 1.5m. However, the system must still survive 5-meter waves that occur during storms in the area. Therefore, generating electricity from waves and harnessing their energy is very complicated and until now is very expensive and mostly economically risky, and that's why investors are hesitant to invest (Duggan, 2016).

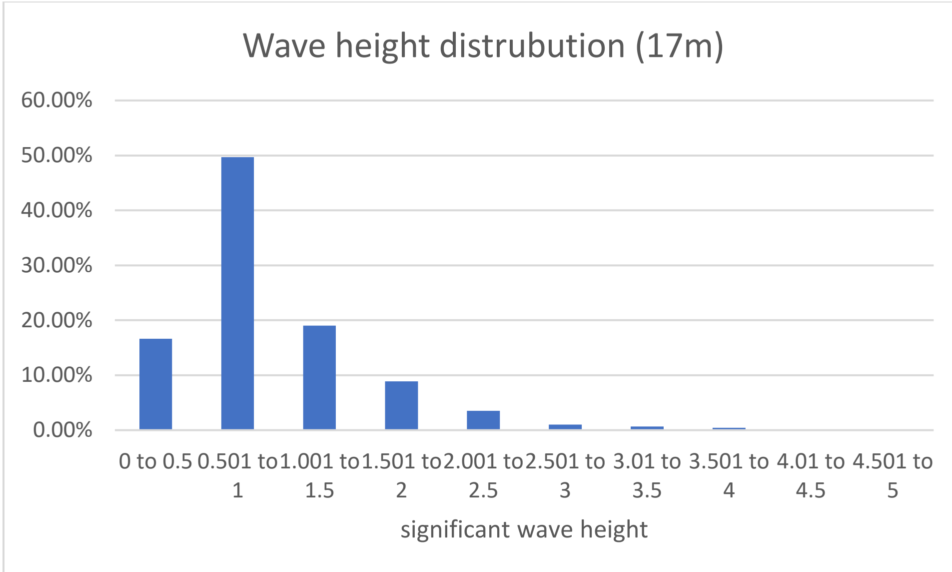

Figure 25. Wave height distribution for the wave rider placed at 17m depth for the year 2013.

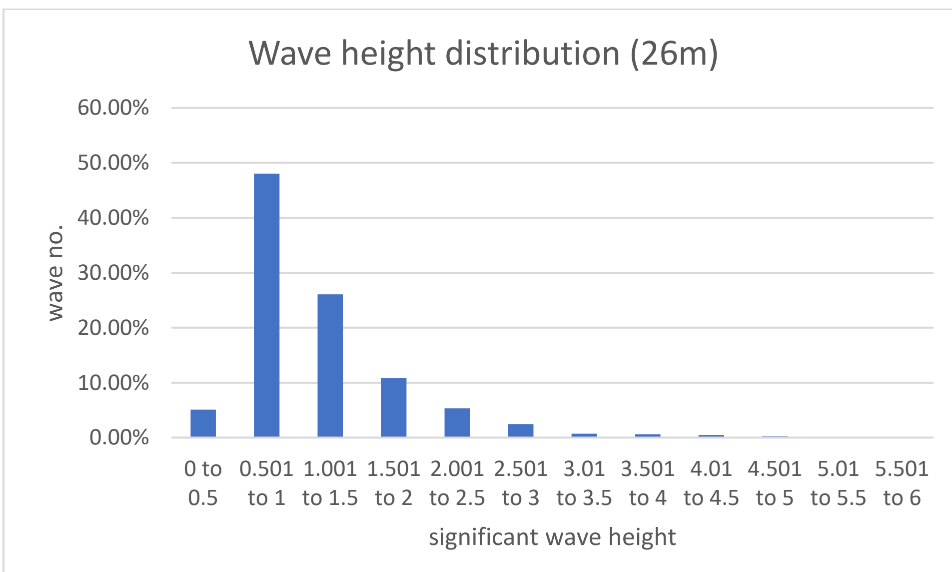

Figure 26. Wave height distribution for the wave rider placed at the 26m depth for the year 2013.

The wave height distribution for the 17 and 26-meter wave riders are similar, with 80% generally within the 0 to 1.5-meter wave height. All 3 instruments recorded that most waves

occur in the 0.5 and 1-meter wave heights range 50% of the time. This highlights the need to optimize the system, so to efficiently generate electricity and still be strong enough to withstand more extreme wave heights.

Using a similar approach to characterize the second critical property of waves, wave period. Figures 27, 28, and 29 show results for the measurement at 8, 17, 26 meters depths respectively.

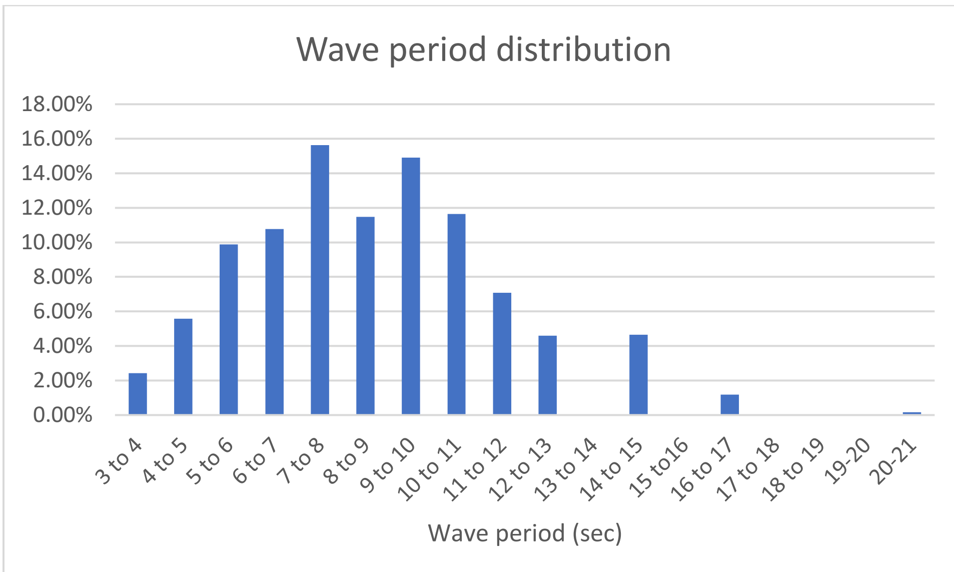

Figure 27. Wave period distribution for the 8 m depth placed AWAC for the year 2013.

Analyzing the wave period distribution for the 8m AWAC, shows the difficulty with designing a system to cover this wide range of changing factors, and be as efficient as possible. The distribution shows that approximately 43% of the recorded waves have wave periods that range between 7-10 sec. leaving about 27% less than 7 second waves and 30% higher than 10 sec waves. This adds to the complications of the system, having to deal with all this variation. Looking at the data emphasizes the importance of having a compliant structure able to survive

forces and moments produced by different wave conditions, while still being able to efficiently harness wave energy.

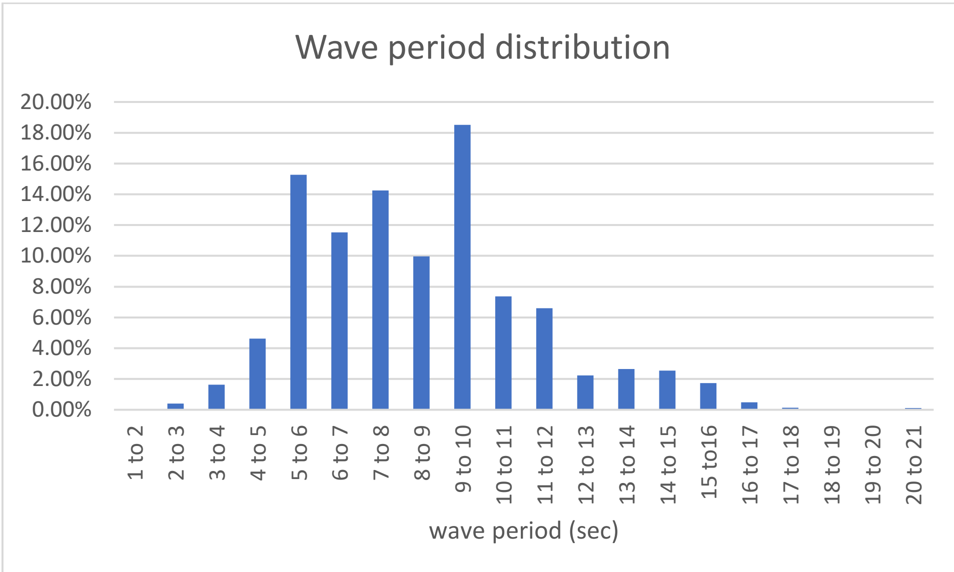

Figure 28. Wave period distribution for the17 m depth placed wave rider for the year 2013.

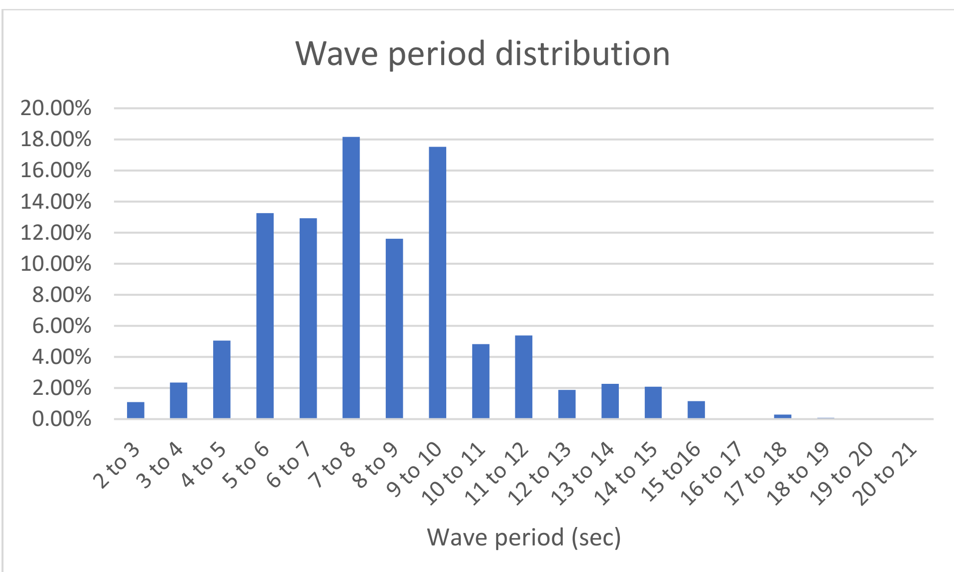

Figure 29. Wave period distribution for the 26 m depth placed wave rider for the year 2013.

Similar distributions of wave periods can still be seen in the 17 and 26-meter wave riders. At the 17 m wave rider, wave periods have a 42% occurrence in the 7-10s period range, 33% to less than 7 seconds and 25% for higher than 10s periods. For the 26-meter wave rider the distribution is very similar with approximately 47% of the wave periods between 7-10s periods, and 29% lower than 7 seconds, and wave periods higher than 10s only 24% of the time. Thus, the change between the 3 depths and wave periods only have 4% to 6% changes in period distributions compared to the shallow gage. This is an important point in that the wave periods for which the system must be designed are relatively invariant with distance and depth.

Chapter 5 Result and Analysis

5.1 Energy availability

Using the wave climate in Duck, North Carolina as an example, a computer code was written to calculate the available energy for a range of wave heights from 1 to 3 meters and periods between 4-12 seconds at the 3 different depths. This provides a sample of 81 different combinations as shown in Appendix A. The only constant in all the combinations was the system size, assumed to be 4 meters by 4 meters floating on the surface. The system dimensions are based on the expected size of the protype to be built. These dimensions were chosen because with this scale we can deploy the system and test it in the ocean and remain stable when deployed. Also, with this size, commercially available structural elements can be utilized which will reduce the cost of the prototype and will make the fabrication of the system faster and easier. In Figure 30, from the combinations of wave properties it was possible to generate an energy flux contour plot enhancing the understanding of the amount of energy that is provided by nature to us.

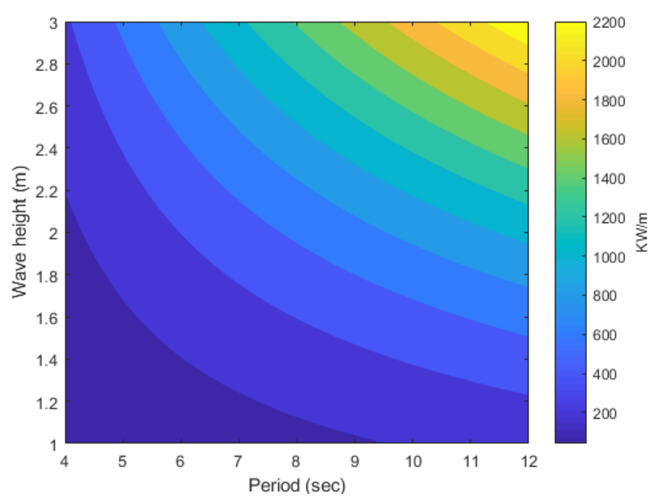

Figure 30. Energy flux contour plot using a range of 1-3 wave heights and 4-12 wave periods based on Equations (3) and (5) .

From Figure 30, one can understand the scale of energy at which the WEC must be able to withstand. Most common waves are around 30-70 KW/m, and these are the wave where energy production generally happens but at the same time the system must be designed to withstand the rarely occurring 2000 KW/m waves (Drew et al., 2009).

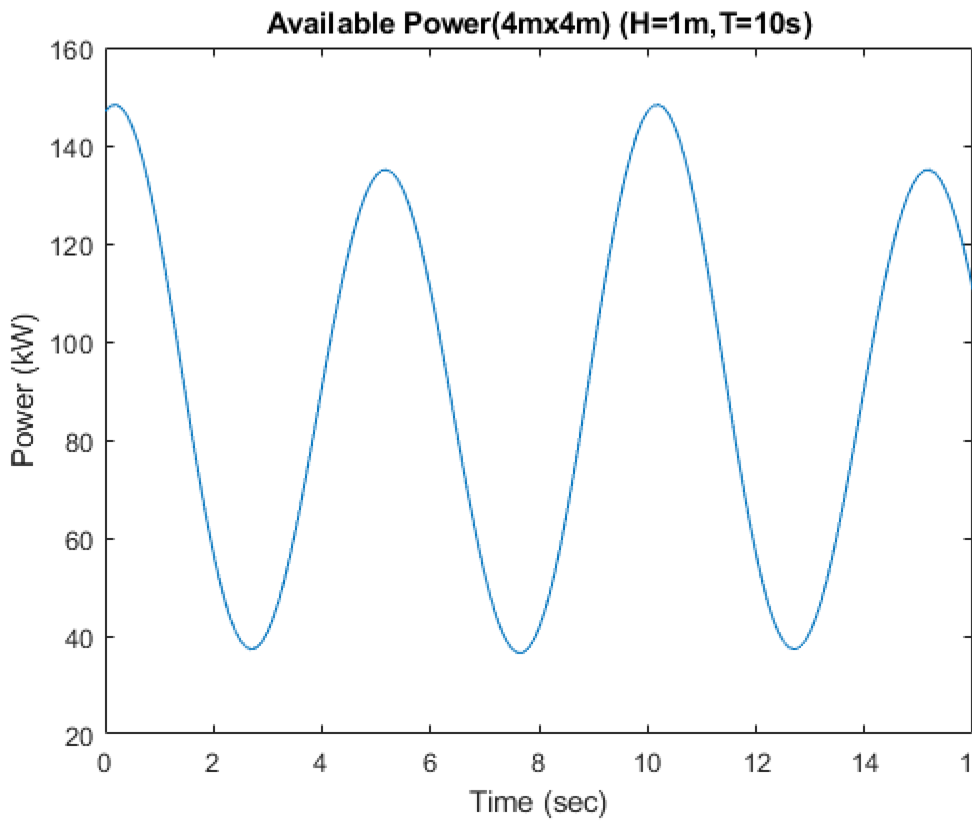

Figure 31. Available power for a 4x4 m system based upon Equations (1), (3), (4) for a wave period of 10s, a wave height of 1 m, at a depth of 17 m.

As shown in Figure 31, a peak energy production, assuming a 100% efficiency of about 150 KW and lower limit of 40 KW is attained. This changes depending on the wave properties and the depth at which the waves are in action. This time-varying system makes it impossible to generate electricity at a uniform rate, however an energy recovery/storage system, such as a flywheel, will smooth the energy production of the system power. A clear advantage to the

system concept here, is the ability to distribute a number of these 4m by 4m units over an extended area. The combination of these two concepts will greatly reduce the overall fluctuations in the power generation. Variability in energy production introduces problems for energy providers in the grid because the production is not always matching the need for the energy (APS, 2011). Methods to partially store the energy produced by this system and release it to the grid at a uniform rate will greatly improve the systems capabilities.

5.2 Forces acting on the structure

The first step in designing a survivable structure is to compute the loads acting on the structure. This dictates several of the design elements and components of the system. The use of a compliant/flexible structure elements greatly reduces many of the design problems faced by other systems discussed earlier. Compliance greatly reduces moments on a structure, potentially increasing the survivability of the system and ensuring that the system will function for longer periods of time. The design process also involves a quantification of demands imposed by the environment surrounding the system. Highly corrosive salt-water environments and extreme wave forces are two of the main obstacles that any system must overcome.

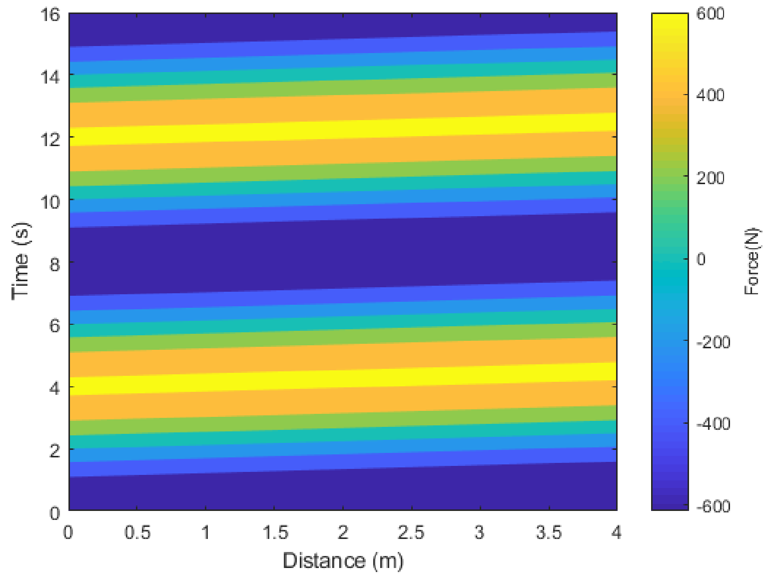

Figure 32. Wave forces acting on a 4mx4m structure. (assuming it's a fixed structure)

Maximum forces acting on the structure occur if the assumption is made that the structure is fixed and not floating. From the computed forces in Figure 32 the maximum force is about 600 newtons acting in either direction (up/down) depending on the phase of the wave. This yields a conservative design parameter that the energy harnessing system and the floating structure must be able to withstand. By doing the testing for the full prototype it can be possible to have comparable data and then redesign the system and improve its efficiency. Since this prototype will act as a test-bed the assumption of maximum load helps establish a safety limit. Calculating this force also provides an idea of how the mooring system must be designed, since maintaining location is a crucial part of its operation. The mooring system will be part of future research to determine the best way to safely secure this system and at the same time produce the maximum electricity.

5.3 Physical testing

The testing of the generator was set by calculating the expected RPM under which it will operate. The calculation was based on the expected wave heights and the expected wave periods and the amount of rotation (RPM) expected by the gears by comparing the wave height(H) to the circumference of the gear over the period(T). This was done to estimate the expected rotation due to the motion of the system with the wave its interacting with. In table 3, it shows the expected RPMs to different wave heights and the expected RPMs from them. The test is performed by coupling a larger AC motor to the brushless AC motor generator already in place. By manipulating the larger AC motor voltage, one can change its RPMs and with a help of a hand-held tachometer it is possible to quantify the RPMs performed by the generator. The test results show that the generator generated 0.8 Watts at 200 RPM. This shows that the generator chosen is not suitable for our application. The setup of the test was an AC brushless motor using a rectifier and connecting it to a fixed resistance. This result of the test dictates that another generator setup is needed for our application and a varying resistance is needed to optimize the power generated by the system in all conditions. As the generator increases speed then the power output increases. This means that the load on the system increases resulting in a higher resistance to simulate the load on the generator. The varying resistance will offer more accurate testing because it will help automatically adjust the resistance compared to the generated electricity. The test results showed that small scale testing is not ideal because of the scaling problem of the motor's physical properties and the mechanical and electrical resistance of the system.

5.4 LCOE (levelized cost of energy) of WEC systems

This section is based on the study performed by (Astariz et al., 2015), a group of researchers in Europe that evaluated and studied the levelized cost of energy for three different renewable energy sources: offshore wind, tidal, and wave energy. The study provides different values for predicted costs and prices of energy production.

Every new technology being developed first faces the question of economic viability. Wave energy is at an early stage of development, and the process of harnessing energy from waves is mostly viewed as difficult and uneconomical (Astariz et al., 2015). To overcome this potential problem a thorough investigation must be done of any WEC system to assess the costs and economic viability.

It is clear from the levelized cost of energy done for the three renewables, Table 1 in the literature review, that offshore wind is the cheapest and wave energy is the most expensive. From the study done by the authors of the report it was explained that the reason for the huge differences between the cost of the different systems is due to their development stage. Wind energy systems, including offshore wind energy systems, are at the commercial level already, unlike wave energy which is far behind in terms of research. Most wave energy systems in operation today are only at the prototype level and none have been successfully commercialized. Another factor that should be understood is that not only is wave energy technology at its starting point, but there is a steep learning curve that effects how fast the development is carried out.

Tables 4 and 5 show the predicted cost of a WEC device and how the cost is broken down into percentages and in terms of expected expenditures. In Table 4 the cost of the WEC device itself costs from 30%-50% of the total cost of the system. That is one of the main reason

WEC devices are very expensive; therefore, when energy prices are calculated this makes the total cost very expensive. Most WEC devices approach the design of the system in very similar fashion. They all tend to build stronger, heavier, and bigger systems to overcome the immense forces by waves and the extreme environment in which they are deployed. The only way for wave energy to compete using the traditional WEC systems is by heavy subsidies from the government. The proposed design in this thesis takes a totally different approach in the design process reducing a lot of the costs of the system. This should help bring down the energy production cost per MWh for the system and not be as dependent on subsidies for the system and be commercialized. It is contended that the new design concept in this thesis can totally change the economics of energy production. This system approaches the design with a compliant structure that is simple in design. This concept of compliance may be the key to achieving a safer, cheaper, and more economic system that will be a leap forward in the development of WEC devices.

Table 4. Approximate breakdown of capital costs (Astariz, Vasquez, & Iglesias, 2015)

Distribution of Capital Cost	**Percentage of total Cost**
WEC device	30%-50%
Installation	16%-30%
Electrical installation	16%-20%

Table 5. Summary of expected initial cost of a WEC system (Astariz, Vasquez, & Iglesias, 2015)

Element	**Cost ($)**
WEC & installation	M €2.5-6/MW (M $2.9-7/MW)
Mooring system	10% WECs cost
Mooring installation	€50,000/day ($58,256/day)
Underwater Cable	10% CAPEX
Cable installation	€2.07/m (2.41/m)
Electrical substation	≈M €1.2 (M $1.4)

5.5 Failure Mode and Effect Criticality Analysis (FMECA) of the Design

Any system in operation is vulnerable to failure. To evaluate the risk of failure of each component on a system it is important to understand what the most critical components are and how to improve design and monitoring. Conducting the FMECA exercise is important before production begins, to either improve the design of components or increase monitoring of the system (AIAG, 1995). This systematic tool is important in identifying the effects of a potential isolated failure on the complete design (Skelton, 1997). The analysis consists of 3 main variables

I. Severity (S)
II. Occurrence (O)
III. Detection (D)

The scale used for these three variables are from 1-10 but each has its own definition. The severity category is the level of the failure, how serious is the failure, and its effect on the system. The severity value of 1 corresponds to no effect; so, in the case of a failure the system is not affected, and 10 means that the failure is most detrimental. Occurrence refers to how frequent the failure is expected to occur. For the occurrence, the value 1 means that the failure is highly unlikely and 10 refers to the high possibility of the failure to happen. Detection means that there are detection methods for identifying the possibility of failure. For detection category a value of 1 means the installed controls will detect the failure and 10 refers to that it is certain the controls won't detect the failure. To understand and rank the risk of the failures of the analyzed components from the system the Risk Priority Number (RPN) is used. RPN is a simple calculation, obtained by multiplying the scores of all three components. Estimating the RPN score for each component helps minimize the likelihood of failure of each component on the system and by doing this one can gain insight as to improving this component in design, develop a more effective maintenance

plan or improve monitoring. This tool is useful to rank the failures which are higher in risk and what components must be adequately designed and monitored. Table 6 shows the estimated scores for the components in all categories

Table 6. Failure mode effect analysis (FMEA) table with the calculated risk priority number (PRN)

Step, Operation,	Potential Failure Mode	Potential Effect(s) of Failure	S	Cause(s) of Failure	O	Controls/ Evaluation	D	S x O	RPN
Floating structure	loose floatation capability	lose the area coverage and loose the ability to generate more energy	7	debris in contact with the structure	5	Physical detection/ lower energy output	6	35	210
Anchored Line (system driver)	snapped line	no power production	8	Fatigue/ excessive loading	3	No power production system is inoperable	10	24	240
Bearings	lose grease/bearing (rougher motion)	inefficient power production	5	wear and tear	3	lower power production than estimated	4	15	60
Shaft	broken	no power production	8	excessive loading	1	No power production system is inoperable	10	8	80
Winding Mechanism	lose tension and minimum rotation	minimum power production	7	lifetime of part	5	Reduced power production (inefficient system)	5	35	175
Driving belt	torn belt	no power production	8	lifetime/fatigue failure	3	No power production	10	24	240
Generator	malfunction/ the wiring	lifetime/excessive power production	10	overloading the generator leads to overheating	3	no power production	7	30	210

From the analysis we can easily identify the most critical parts of our system, which appear to be the anchor line that drives the system and the drive belt that connects all the moving parts, although the generator and the winding mechanism could also be problematic. This is very important to have as a tool to understand the critical components in the system and understand the importance of telemetry equipment that can monitor the system to make it easier to identify failures and generally maintain the whole system.

Chapter 6 Conclusion

As has been shown in this thesis harnessing water-wave energy is not a simple process. The main issue confronted is the need to balance the ability to extract energy efficiently within the constraint that the system is not significantly damaged by the waves from which they are collecting energy. Specific problems faced by WEC systems include surviving extreme storm events, salt water environment, mooring system functionality, energy transfer to shore, and energy generation demands. Therefore, many attempts have failed to design a system that can effectively harness energy from waves, while remaining intact. Previous approaches for the design of WEC are based on the concept of building extremely large and rigid systems to withstand wave forces and related moments. This concept of design forces the system to be very expensive to build, transport, and maintain. Consequently, wave energy harnessing is currently perceived as an expensive green energy alternative compared to other renewable energy.

The concept for the design approach taken here is for the WEC to have compliant/deformable structural elements designed to withstand and dissipate high forces more efficiently than large, inflexible structural components, resulting in a more robust, easier to maintain, and economical system. Having many separate energy harnessing units imbedded within a single compliant larger system gives four critical advantages over previous systems. First, it simplifies maintenance because an individual energy-harnessing unit can be disconnected without disrupting the rest of the module harnessing energy, making it a modular system. Second, it improves the economics of the system when more than one module (a complete system) is connected to each other forming an array of the system, generating more energy efficiently that yields a more consistent power production rate. Third, it allows for better economics related to operations and transportation, by being a modular system it is easier to

transport because of is flexible structure and interchange energy production units within a system without disrupting the operation of the other units. Also, it allows for a much wider range of locations in which the system can be deployed and operated. For example, a system can be placed close to shore, where it can more easily be maintained and can more efficiently transfer the energy to shore, while still withstanding the largest waves experienced at the location of deployment.

The initial testing of the generator showed that a new generator system must be used that can withstand and efficiently transfer the expected motions in the system into power. From this test it appears that the available generator is too small and inefficient to the subjected rates of revolution produced by the expected wave conditions. The scaling down of the system increases complexity of construction testing and physical properties of the system.

The proposed 4-meter x 4-meter prototype should provide a better prototype scale for all system evaluations. The calculations of the energy available from the waves demonstrates that even at very low efficiency this system will still exceed other existing systems. The design will truly show its advantages when a full-scale prototype is built and prove that it's more economic, safer and can handle all the expected wave climates that it is deployed in. This work will continue in the patent development and demonstration phase of this work.

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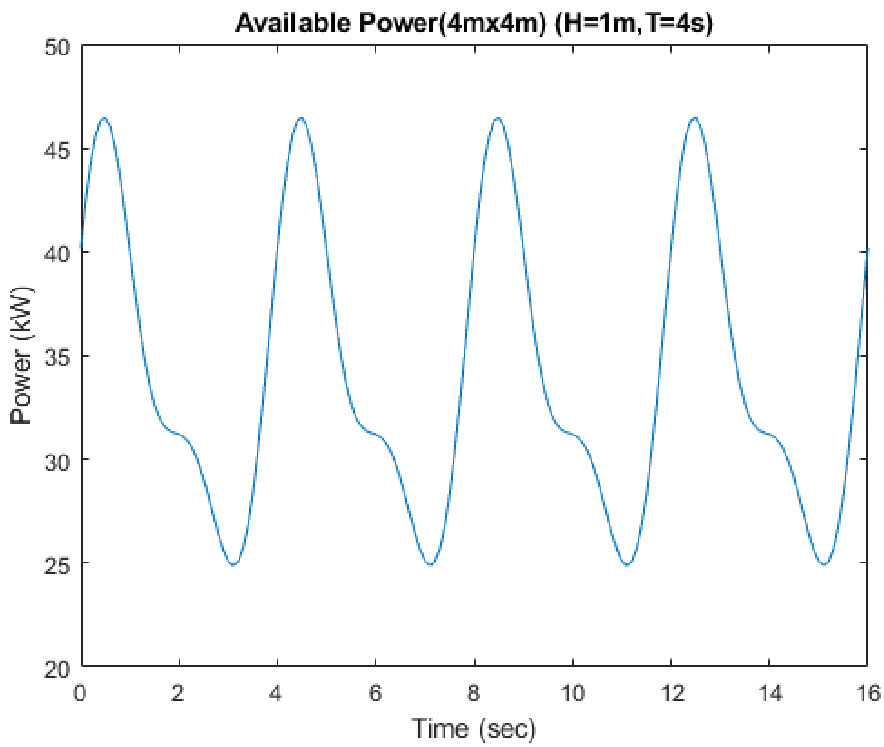
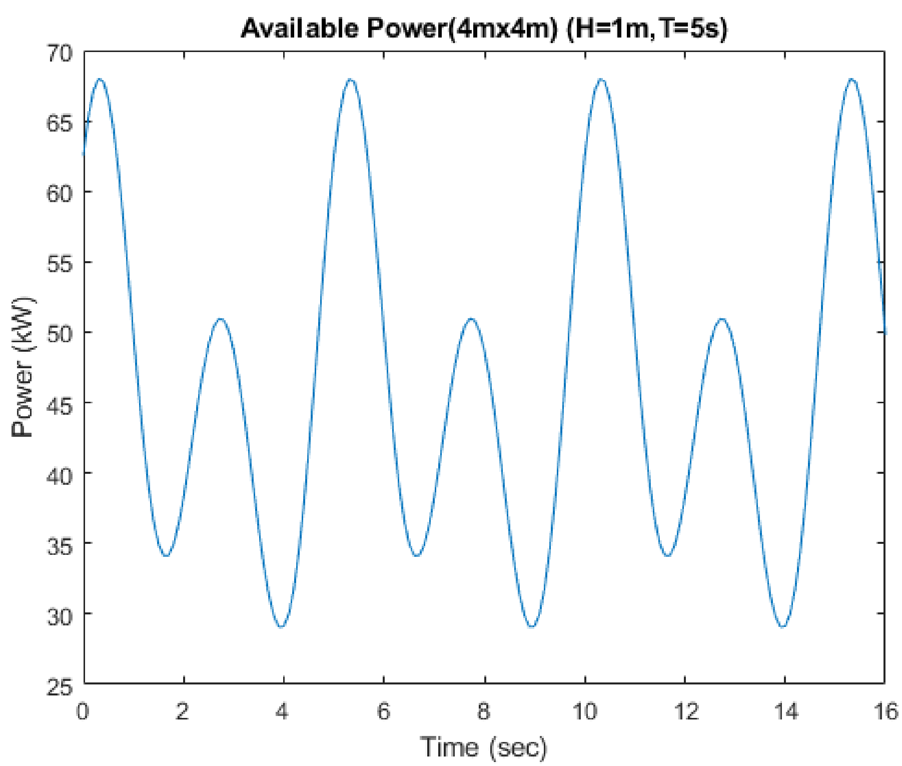
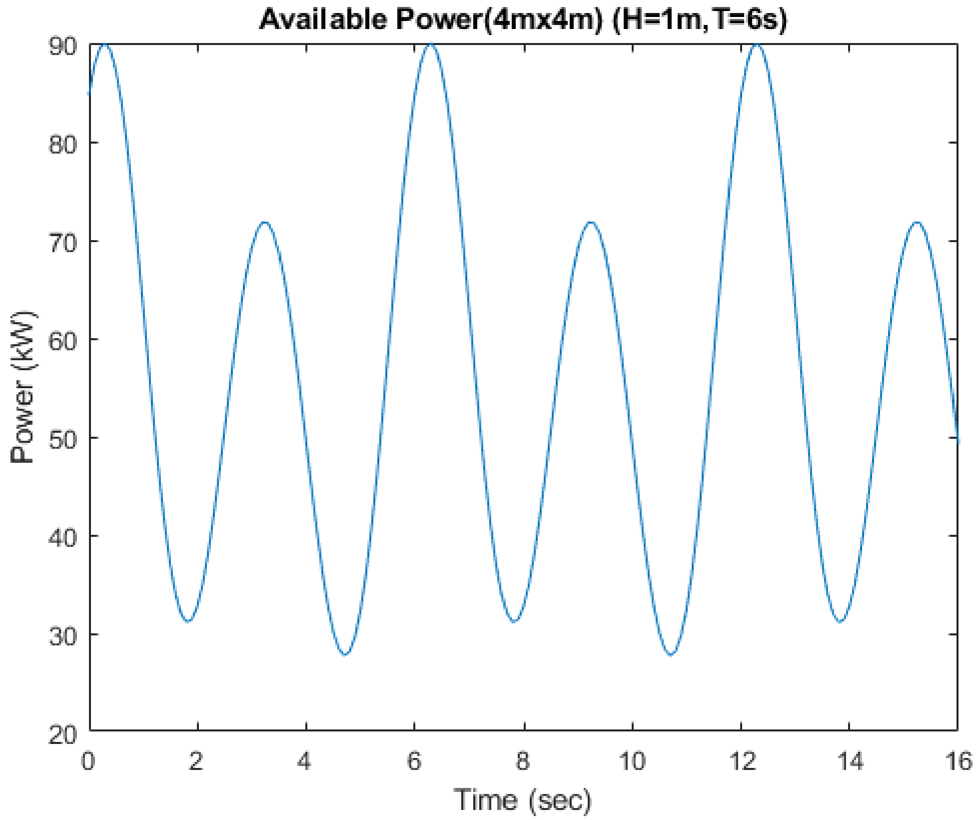
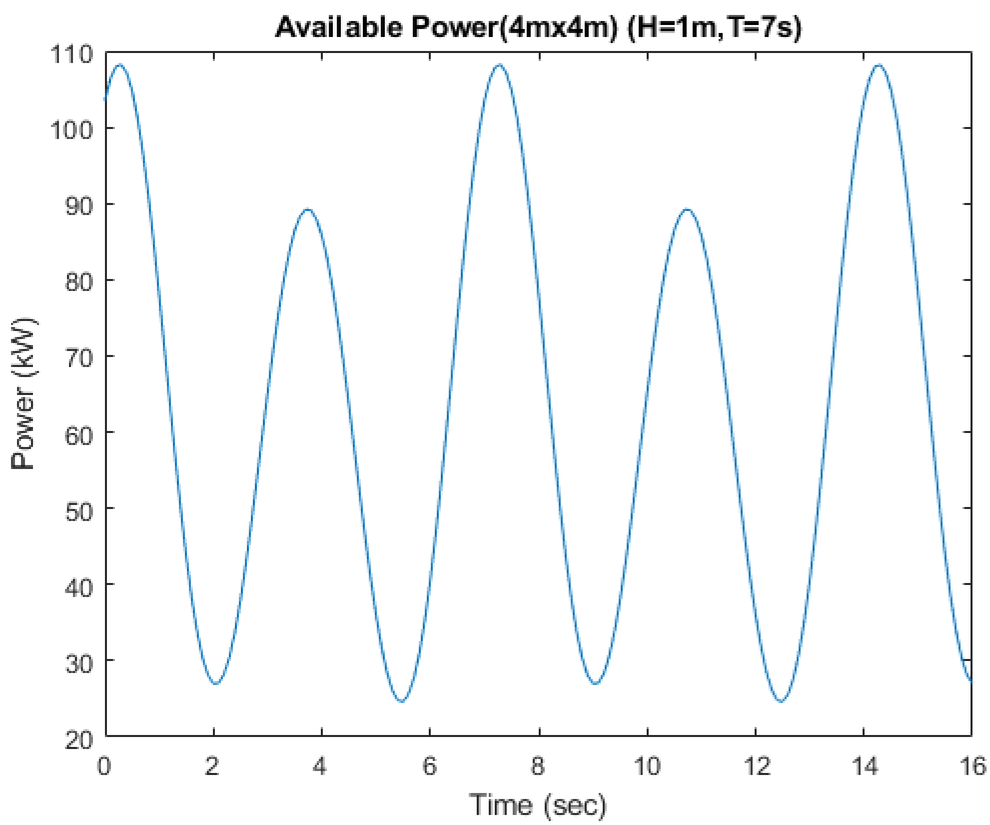
Appendix A

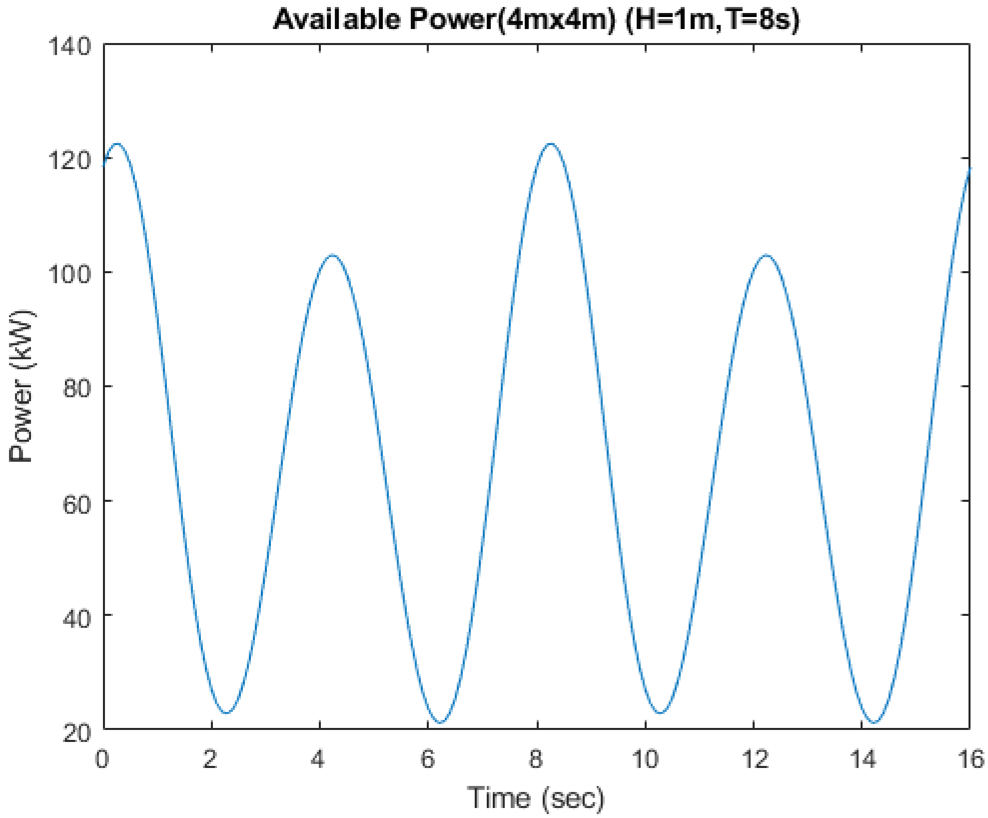
H=1 m, h=8 m






Available Power(4mx4m) (H=1m,T=6s)
Power (kW)
Time (sec)
90
80
70
60
50
40
30
20
0
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=1m,T=7s)
Power (kW)
Time (sec)
110
100
90
80
70
60
50
40
30
20
0
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=1m, T=8s)
Power (kW)
Time (sec)
140
120
100
80
60
40
20
0
2
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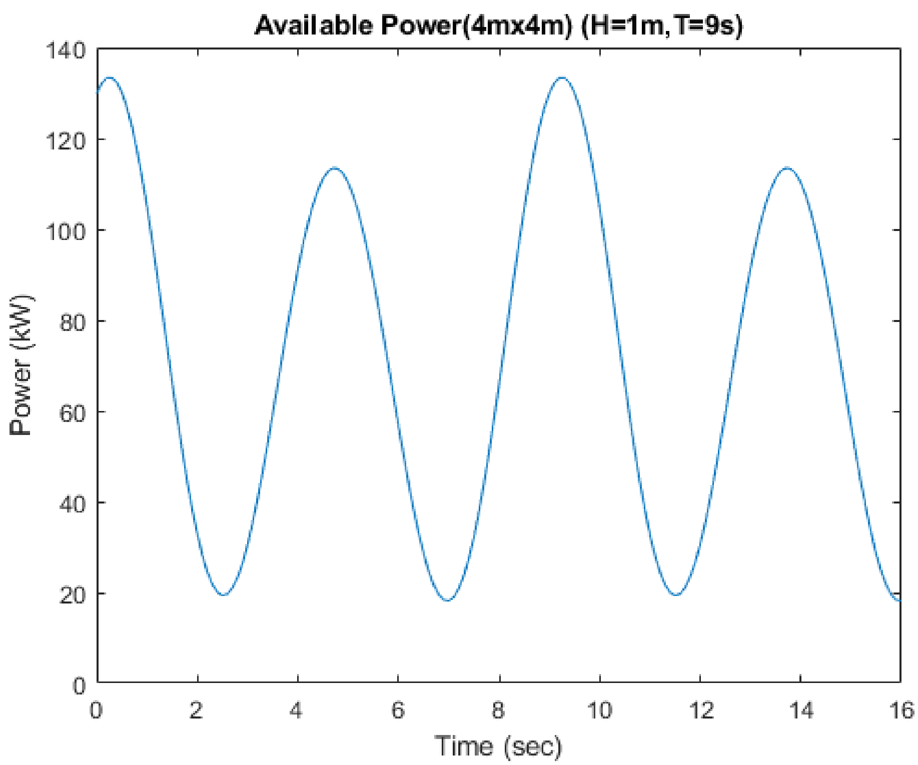
6
8
10
12
14
16


Available Power(4mx4m) (H=1m, T=9s)
Power (kW)
Time (sec)
140
120
100
80
60
40
20
0
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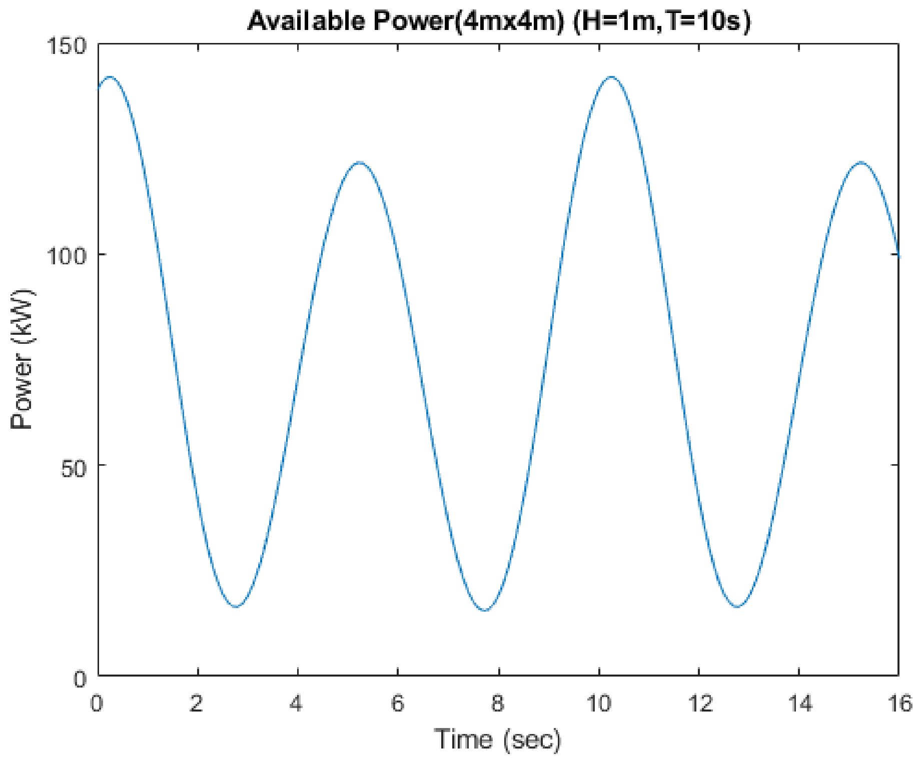
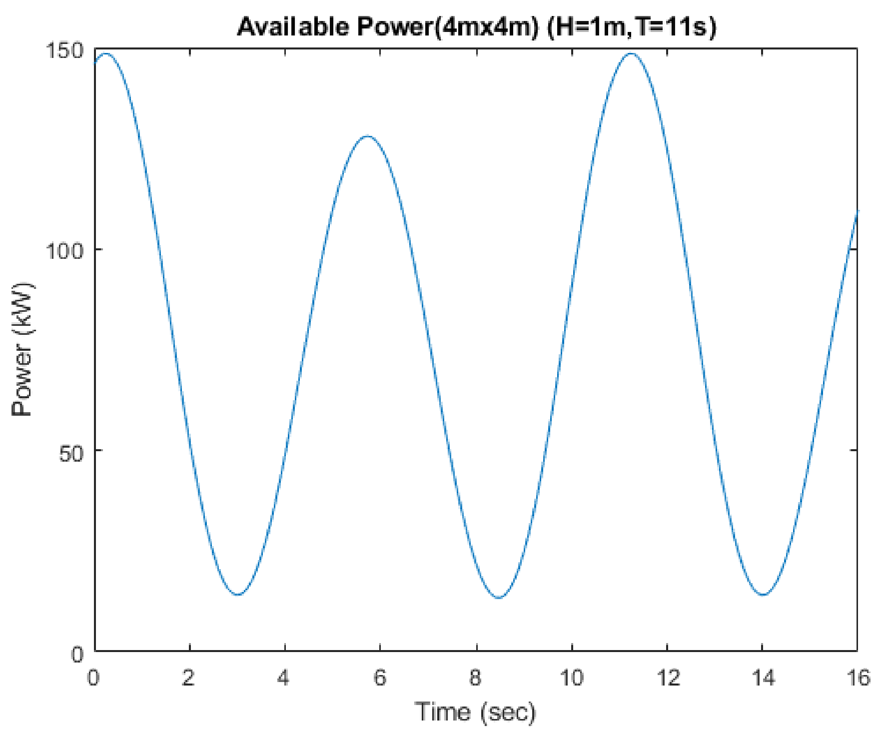
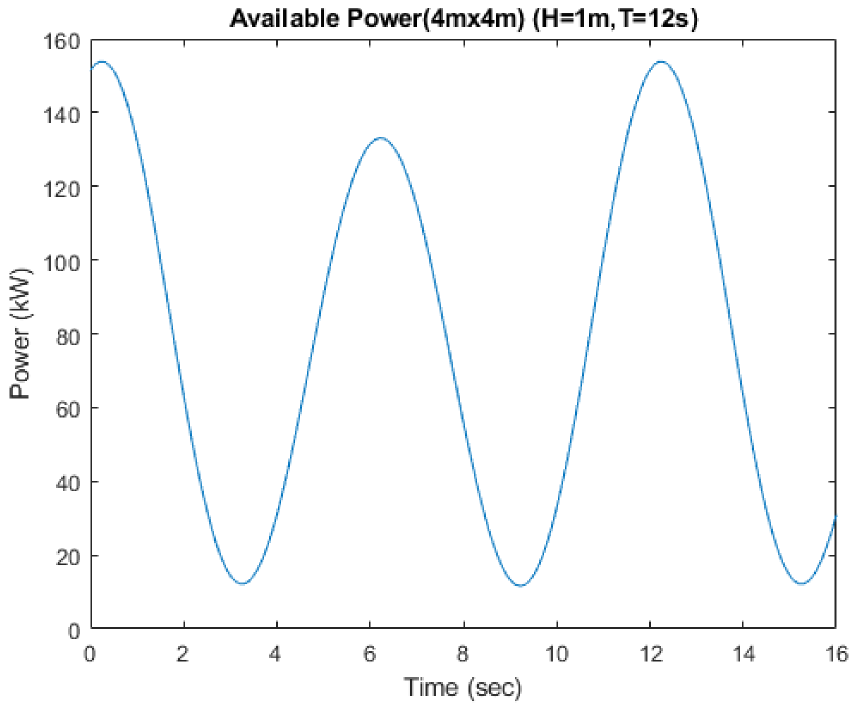
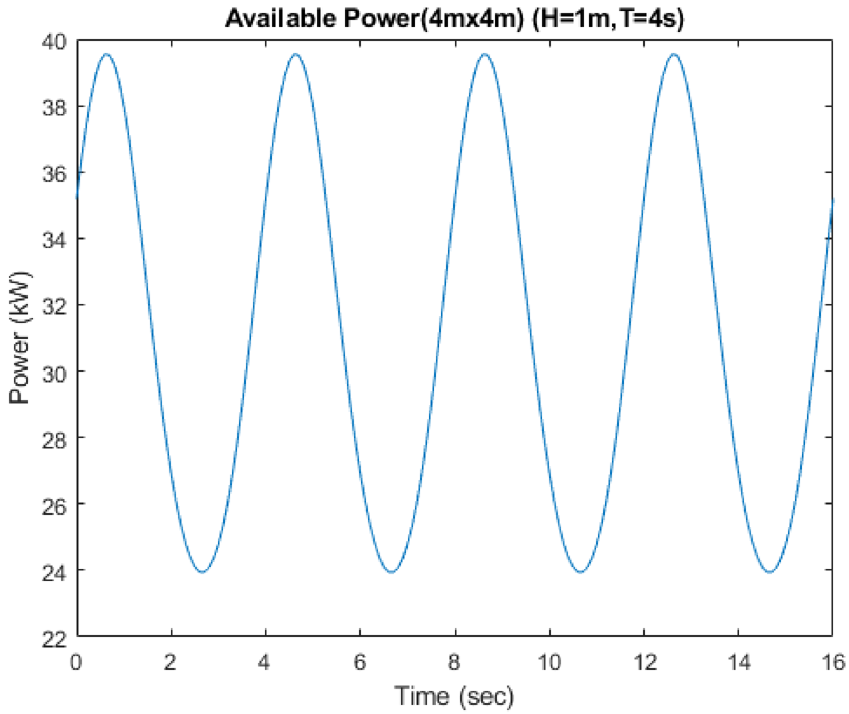
8
10
12
14
16


Available Power(4mx4m) (H=1m,T=10s)
Power (kW)
Time (sec)
150
100
50
0
0
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=1m,T=11s)
Power (kW)
Time (sec)
150
100
50
0
0
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=1m,T=12s)
Power (kW)
Time (sec)
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16

H=1 m, h=17 m


Available Power(4mx4m) (H=1m,T=4s)
Power (kW)
Time (sec)
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38
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34
32
30
28
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24
22
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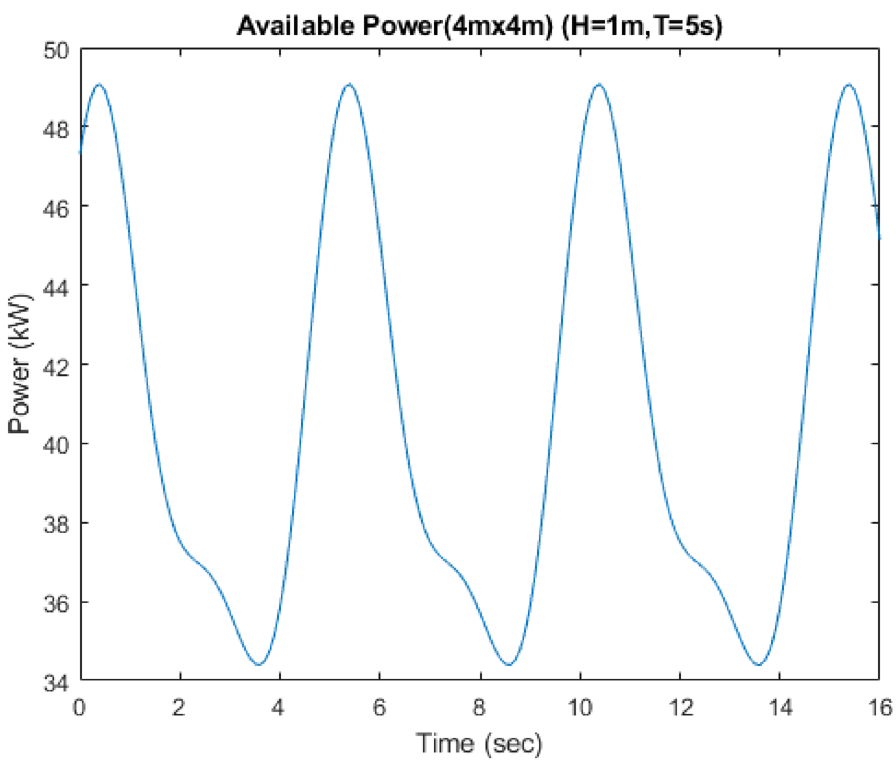
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=1m,T=5s)
Power (kW)
Time (sec)
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44
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40
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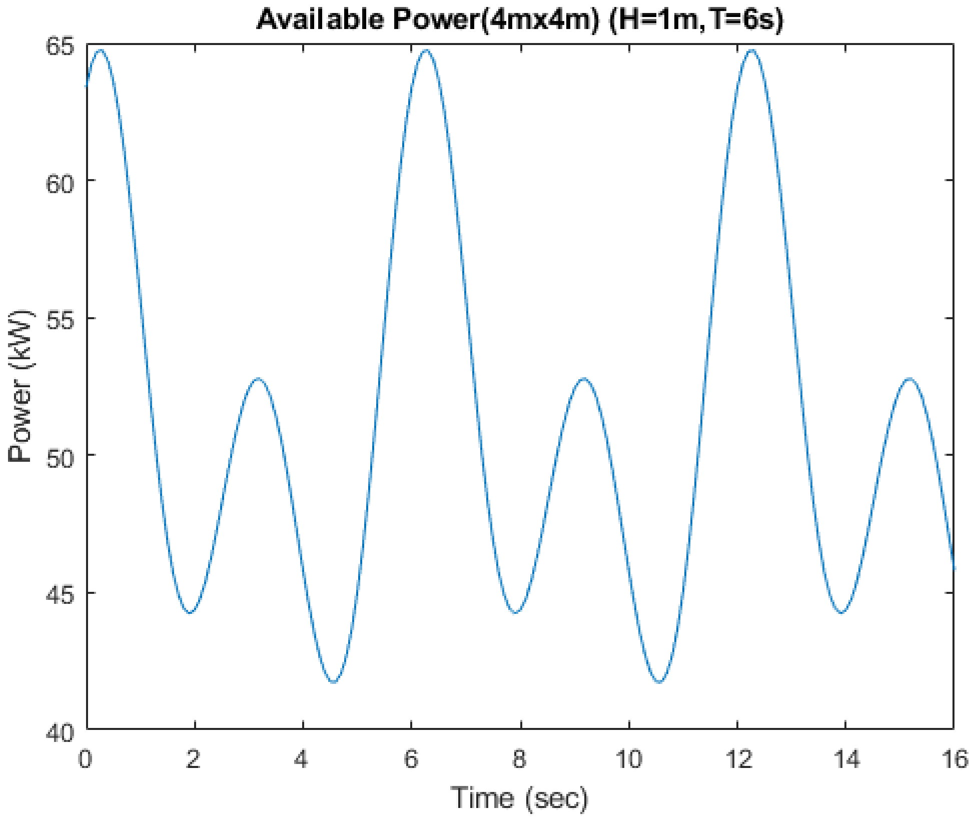
34
0
2
4
6
8
10
12
14
16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Power (kW)
Time (sec)
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55
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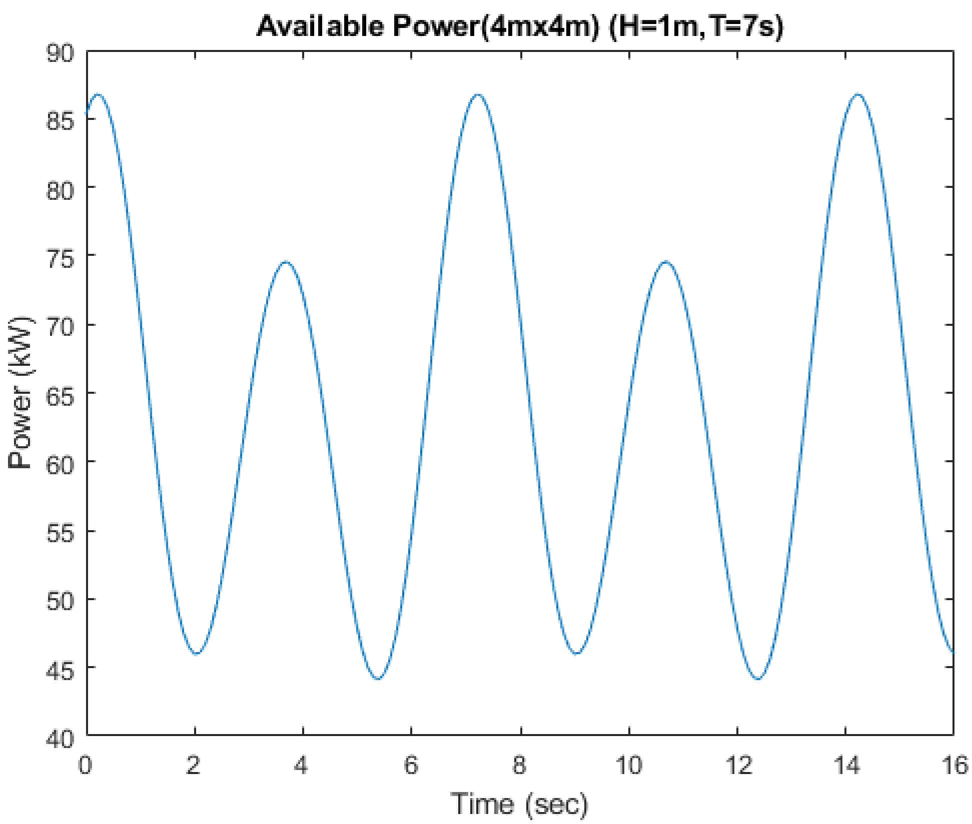
8
10
12
14
16


Available Power(4mx4m) (H=1m,T=7s)
Power (kW)
Time (sec)
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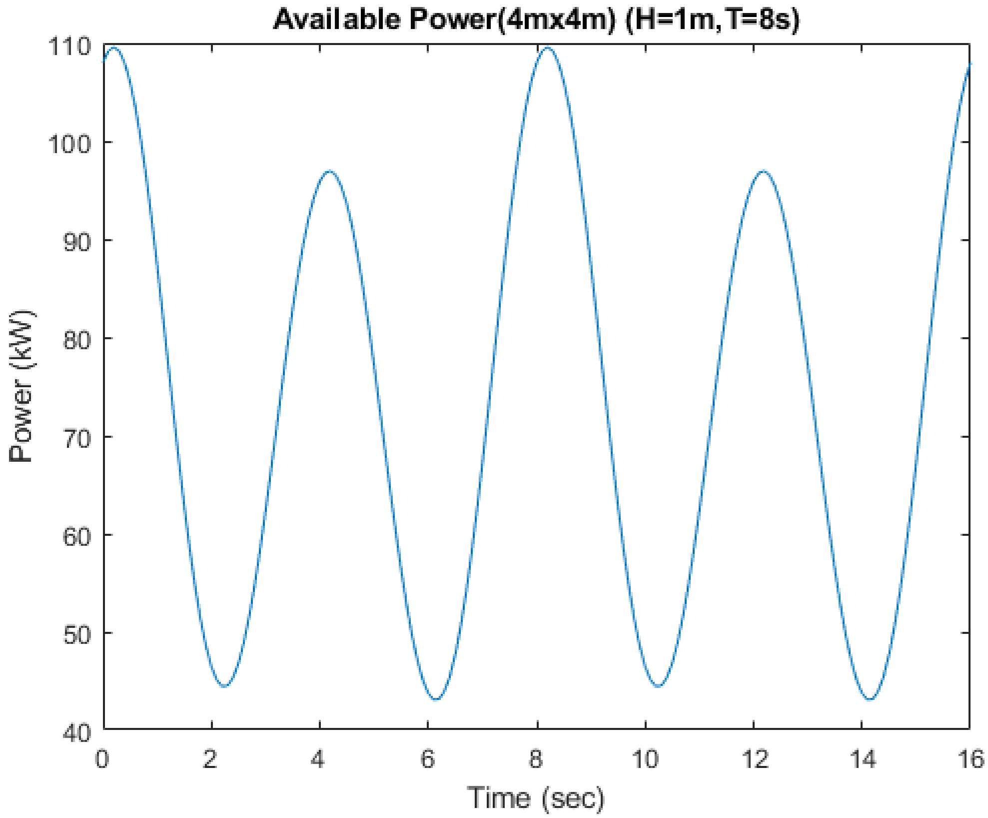
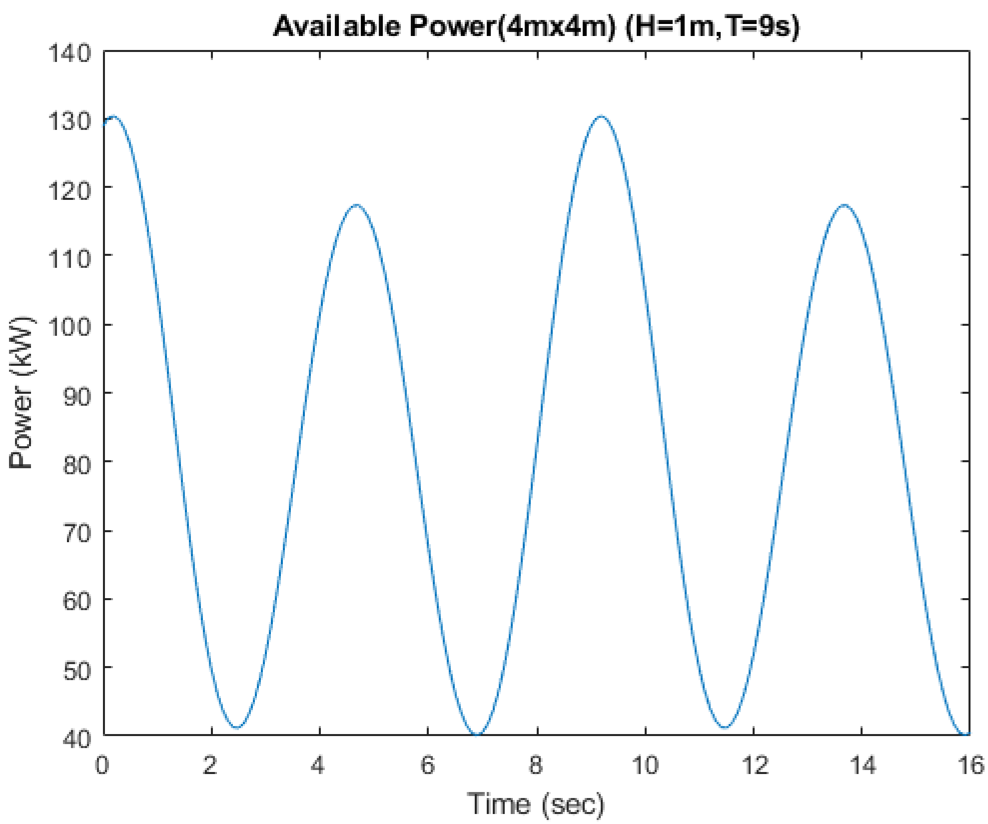
45
50
55
60
65
70
75
80
85
90
0
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=1m,T=8s)
Power (kW)
Time (sec)
110
100
90
80
70
60
50
40
0
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=1m,T=9s)
Power (kW)
Time (sec)
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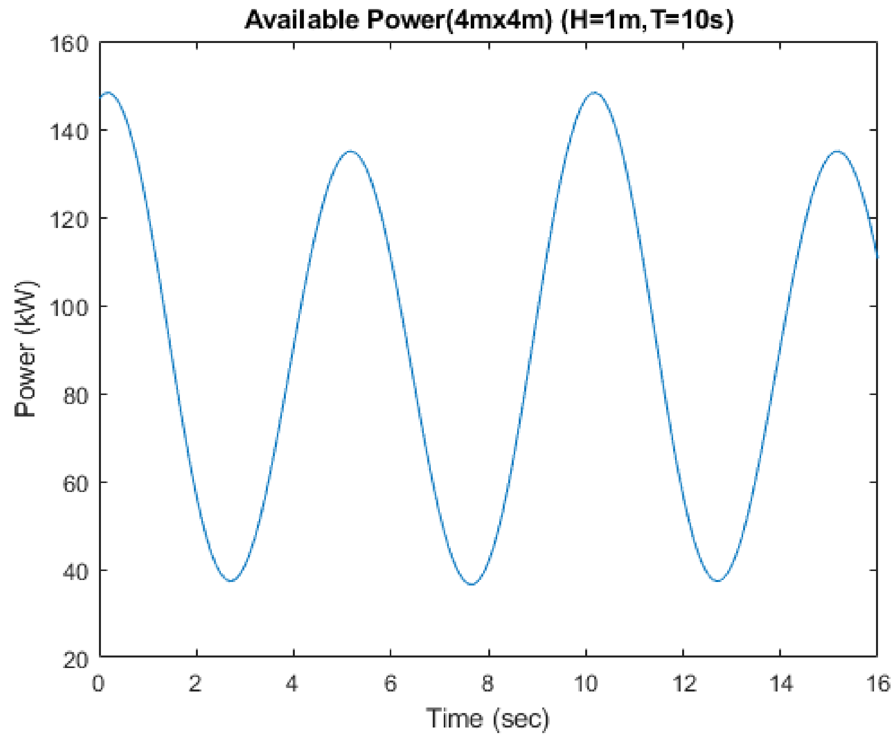
130
120
110
100
90
80
70
60
50
40
0
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=1m,T=10s)
Power (kW)
Time (sec)
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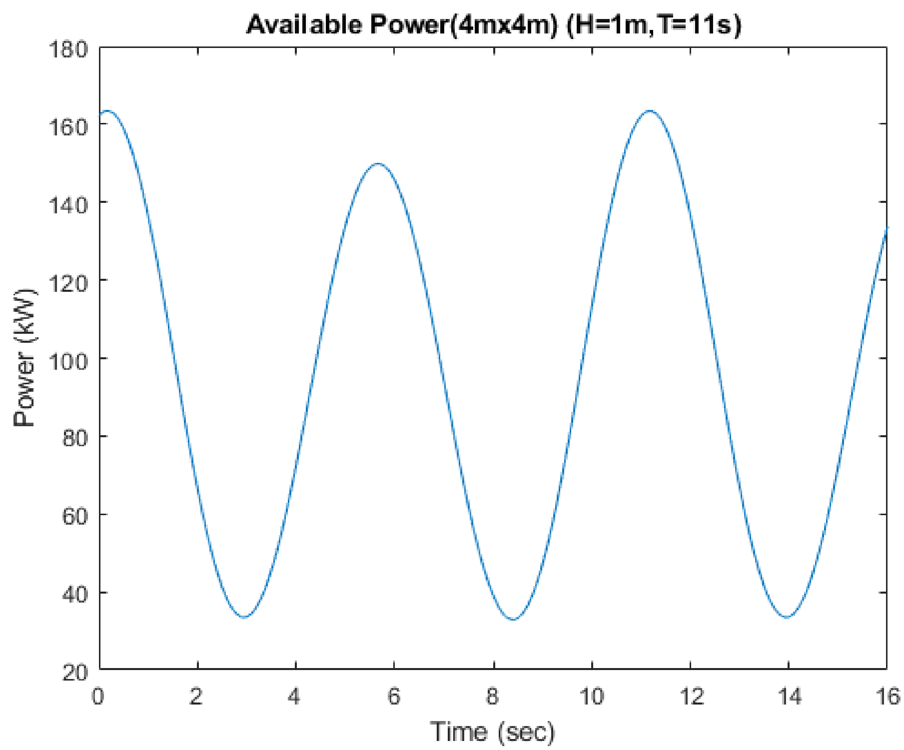
140
120
100
80
60
40
20
0
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=1m,T=11s)
Power (kW)
Time (sec)
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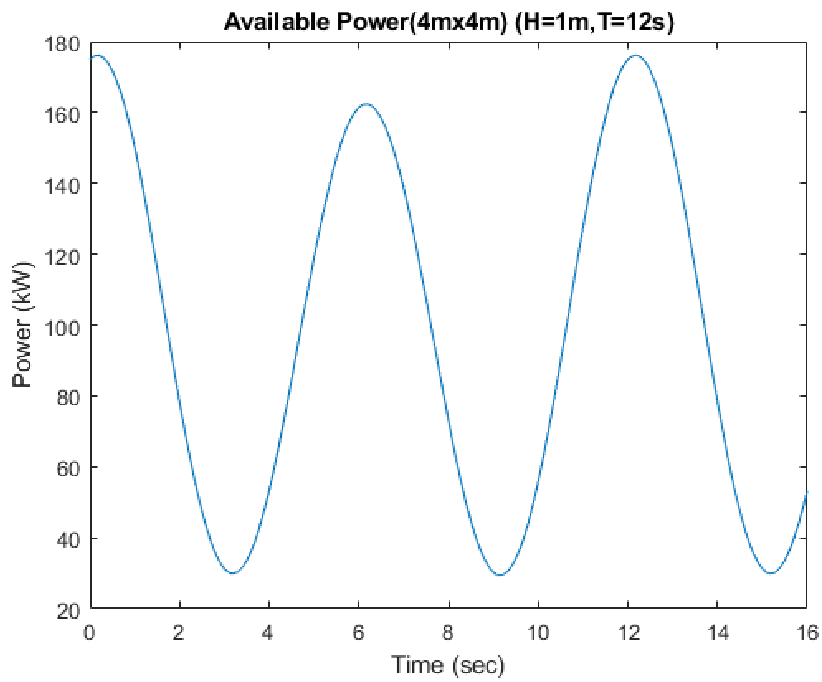
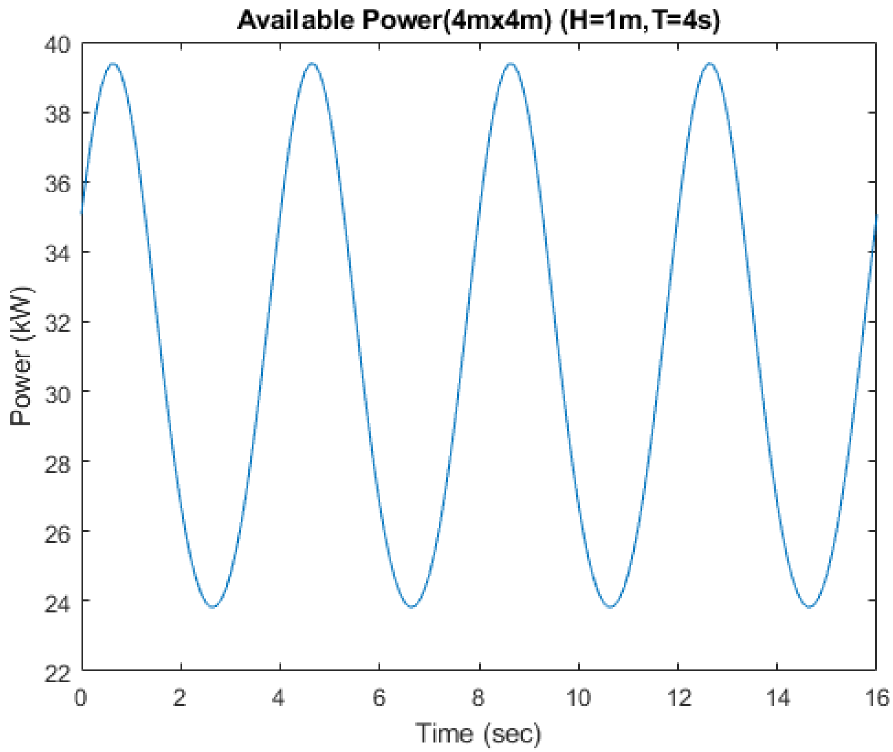
160
140
120
100
80
60
40
20
0
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=1m,T=12s)
Power (kW)
Time (sec)
180
160
140
120
100
80
60
40
20
0
2
4
6
8
10
12
14
16

H=1 m, h=26 m



Available Power(4mx4m) (H=1m,T=4s)
Power (kW)
Time (sec)
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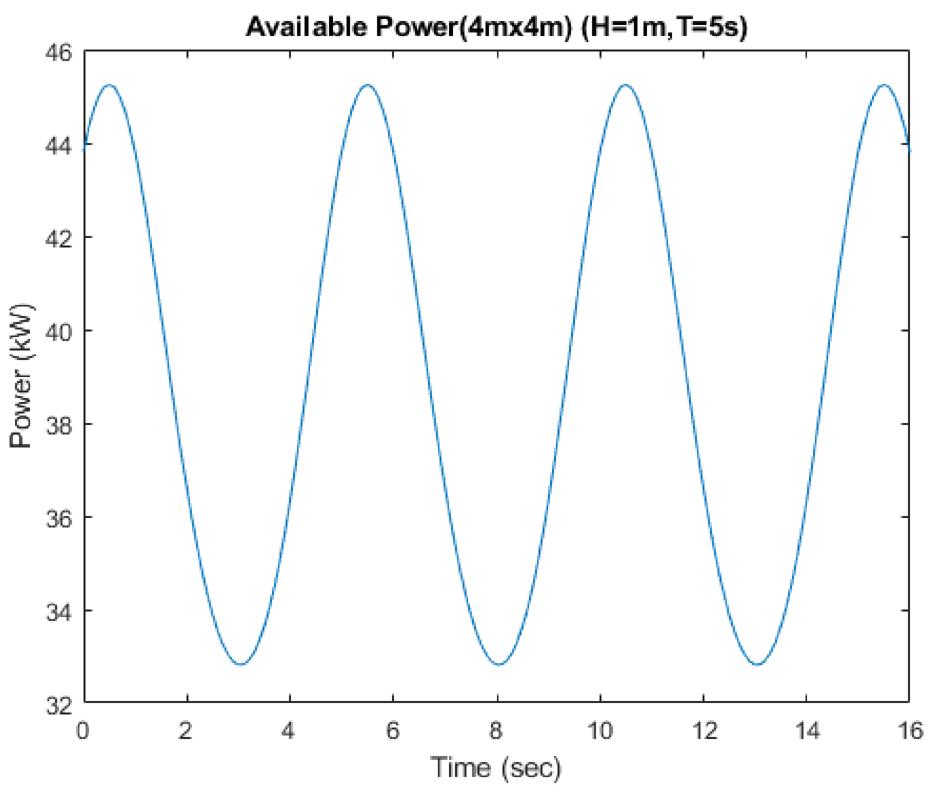
38
36
34
32
30
28
26
24
22
0
2
4
6
8
10
12
14
16



Available Power(4mx4m) (H=1m,T=5s)
Power (kW)
Time (sec)
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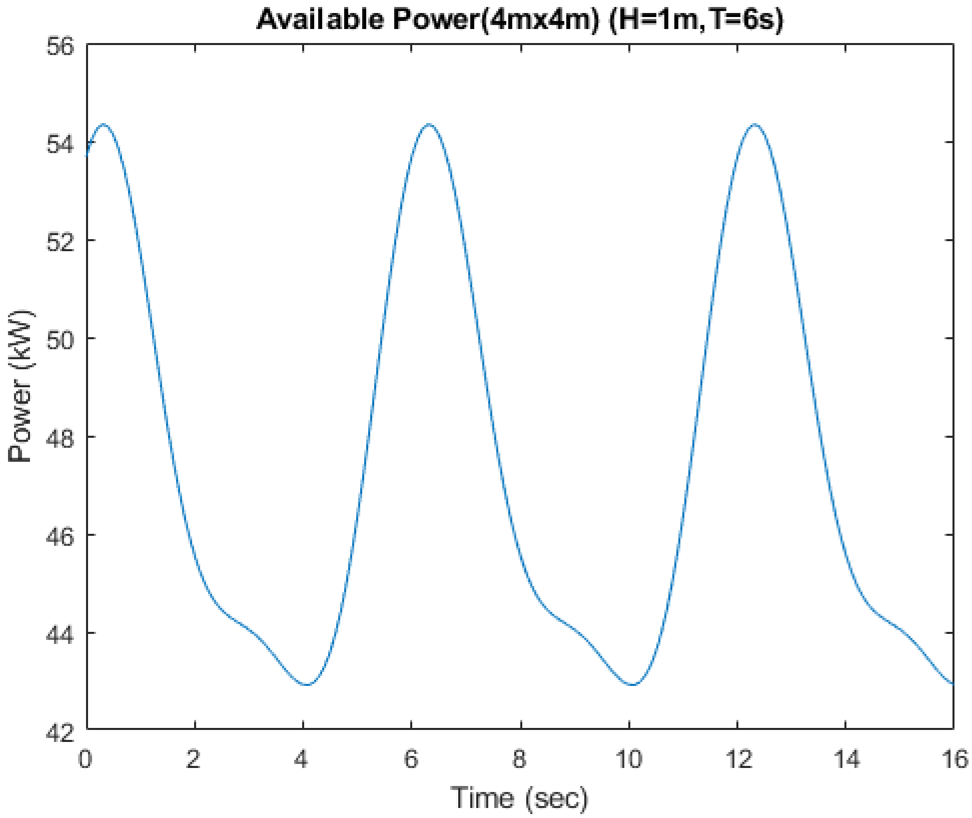
44
42
40
38
36
34
32
0
2
4
6
8
10
12
14
16



Available Power(4mx4m) (H=1m,T=6s)
Power (kW)
Time (sec)
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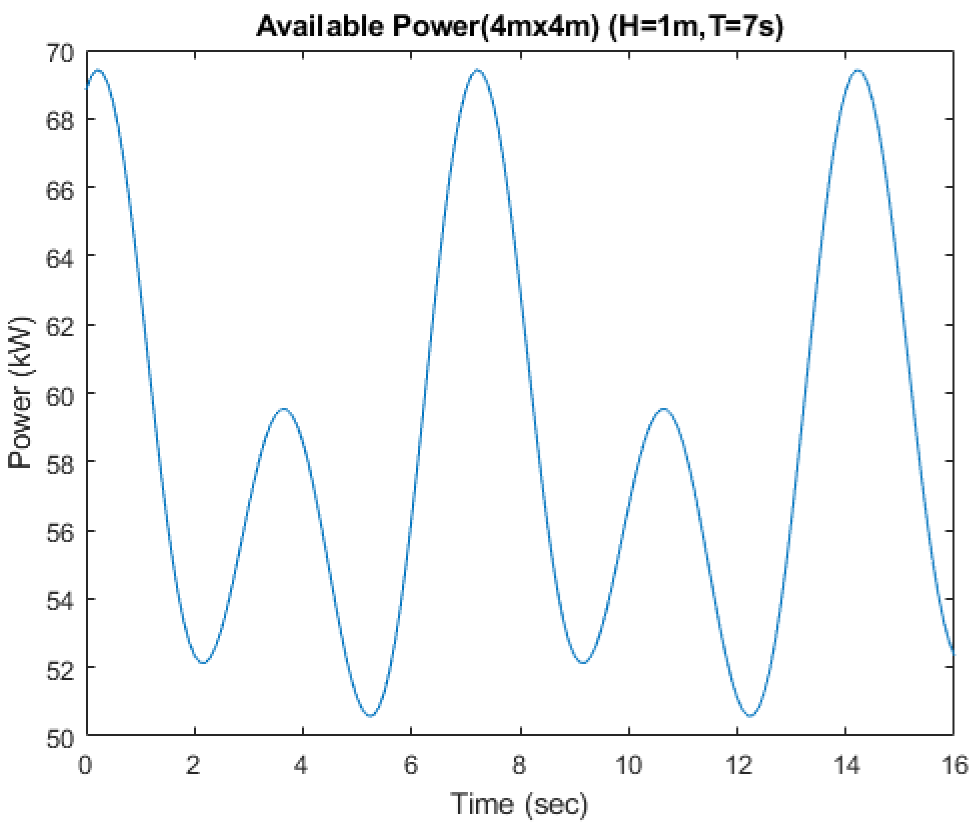
54
52
50
48
46
44
42
0
2
4
6
8
10
12
14
16



Available Power(4mx4m) (H=1m,T=7s)
Power (kW)
Time (sec)
70
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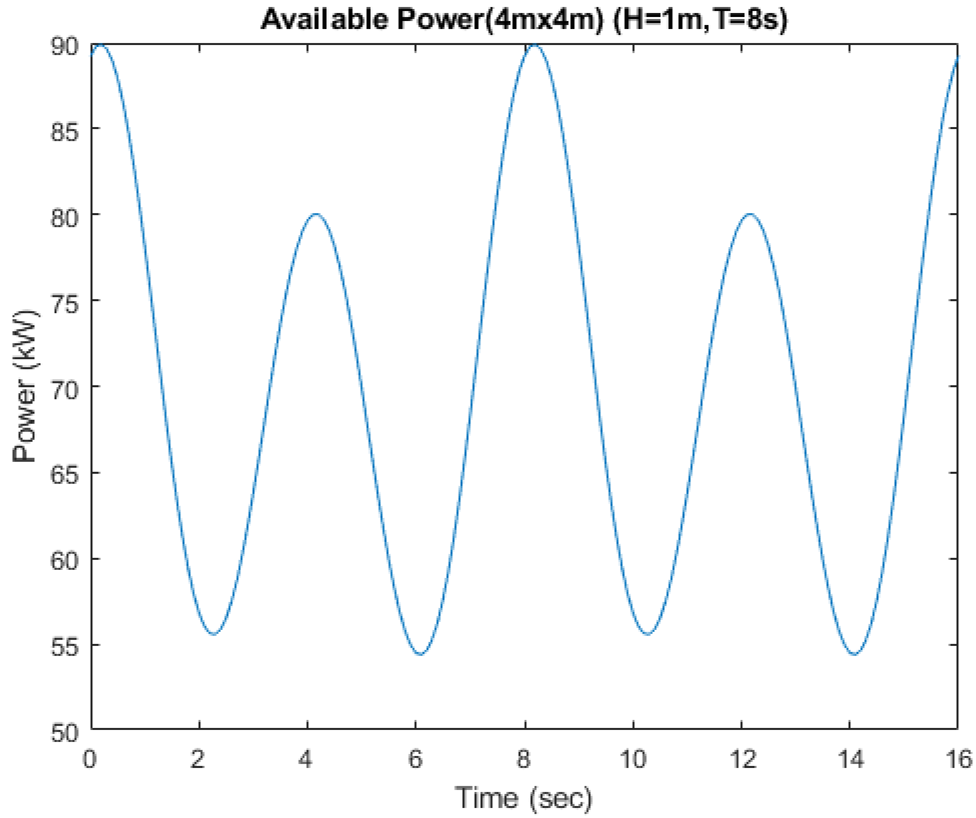
64
62
60
58
56
54
52
50
0
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=1m,T=8s)
Power (kW)
Time (sec)
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75
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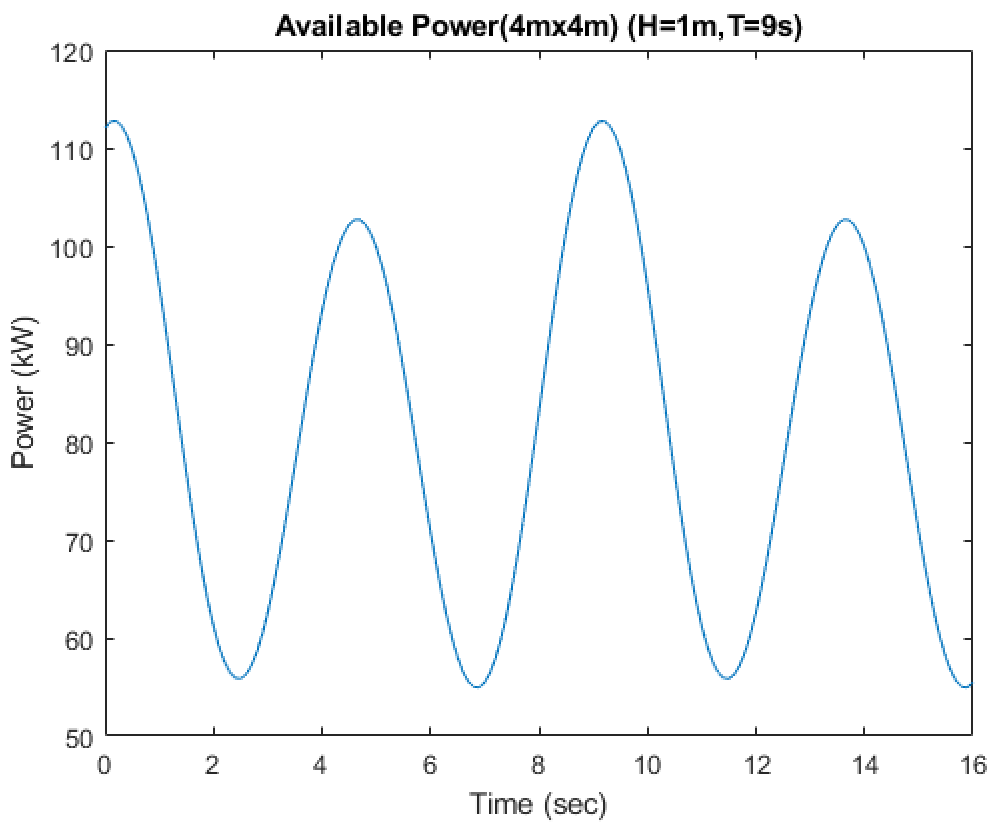
50
0
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=1m,T=9s)
Power (kW)
Time (sec)
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110
100
90
80
70
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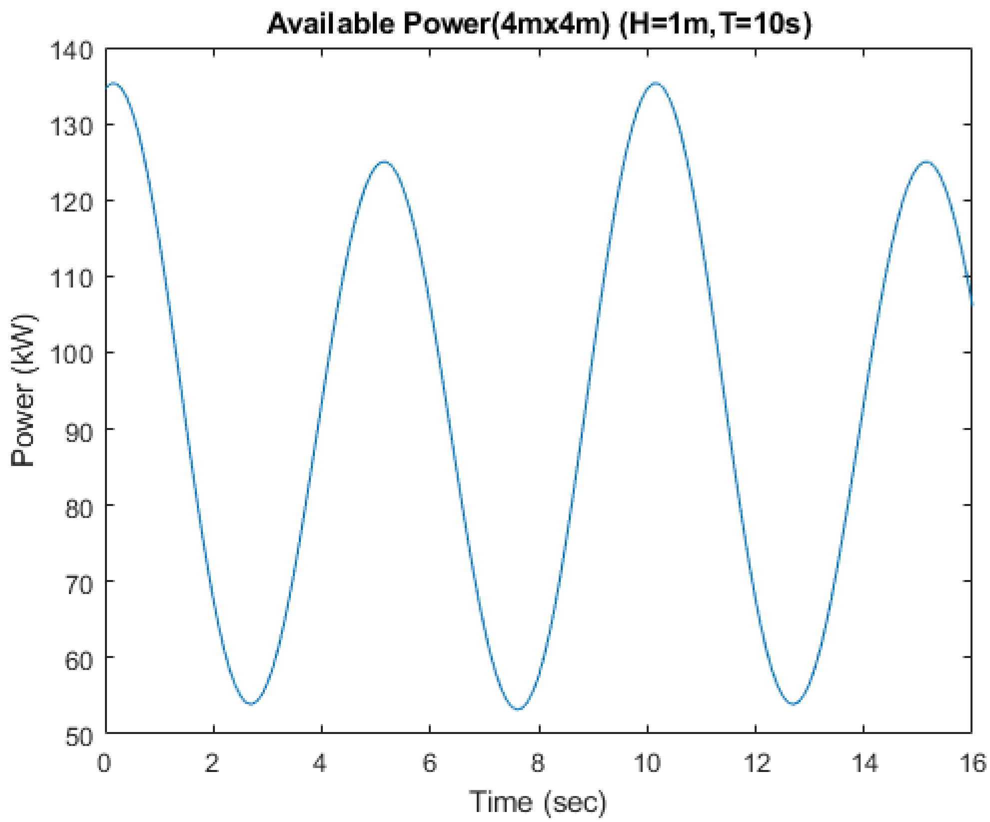
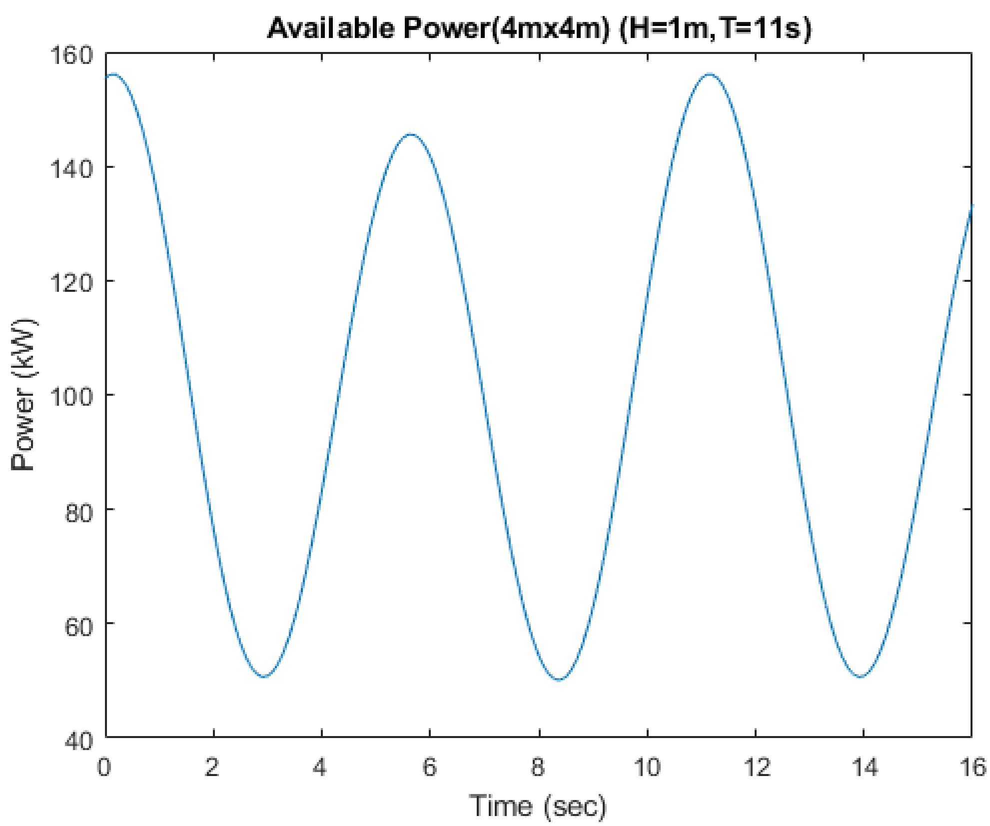
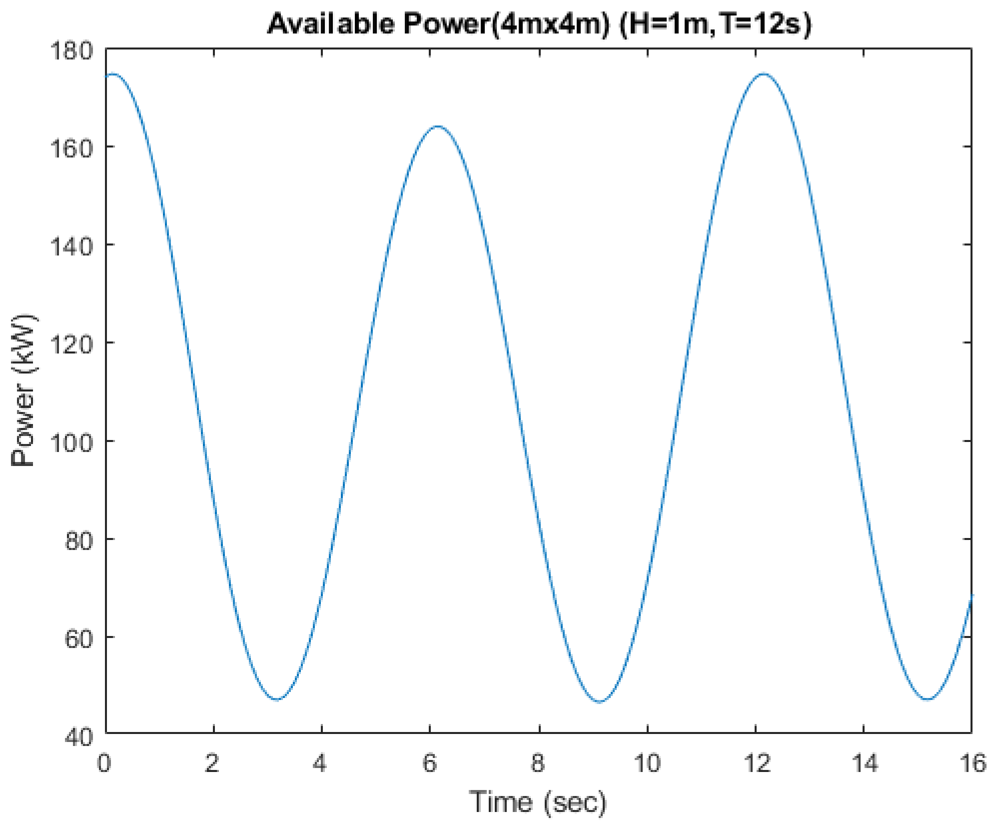
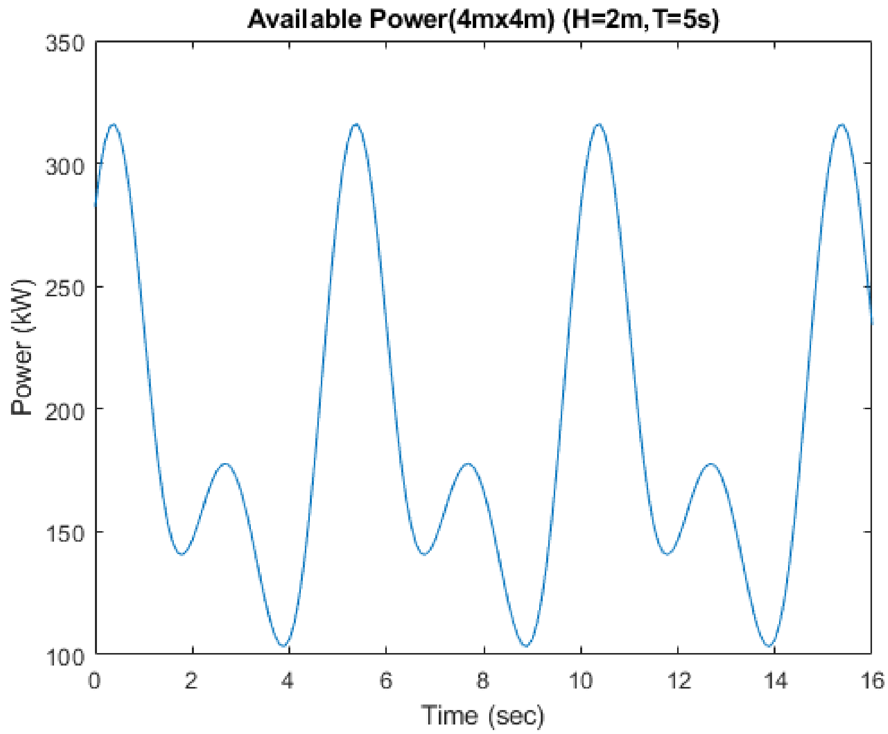
0
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=1m,T=10s)
Power (kW)
Time (sec)
140
130
120
110
100
90
80
70
60
50
0
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=1m,T=11s)
Power (kW)
Time (sec)
160
140
120
100
80
60
40
0
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=1m,T=12s)
Power (kW)
180
160
140
120
100
80
60
40
0
2
4
6
8
10
12
14
16
Time (sec)

H=2 m, h=8 m


Available Power(4mx4m) (H=2m,T=5s)
Power (kW)
Time (sec)
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300
250
200
150
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0
2
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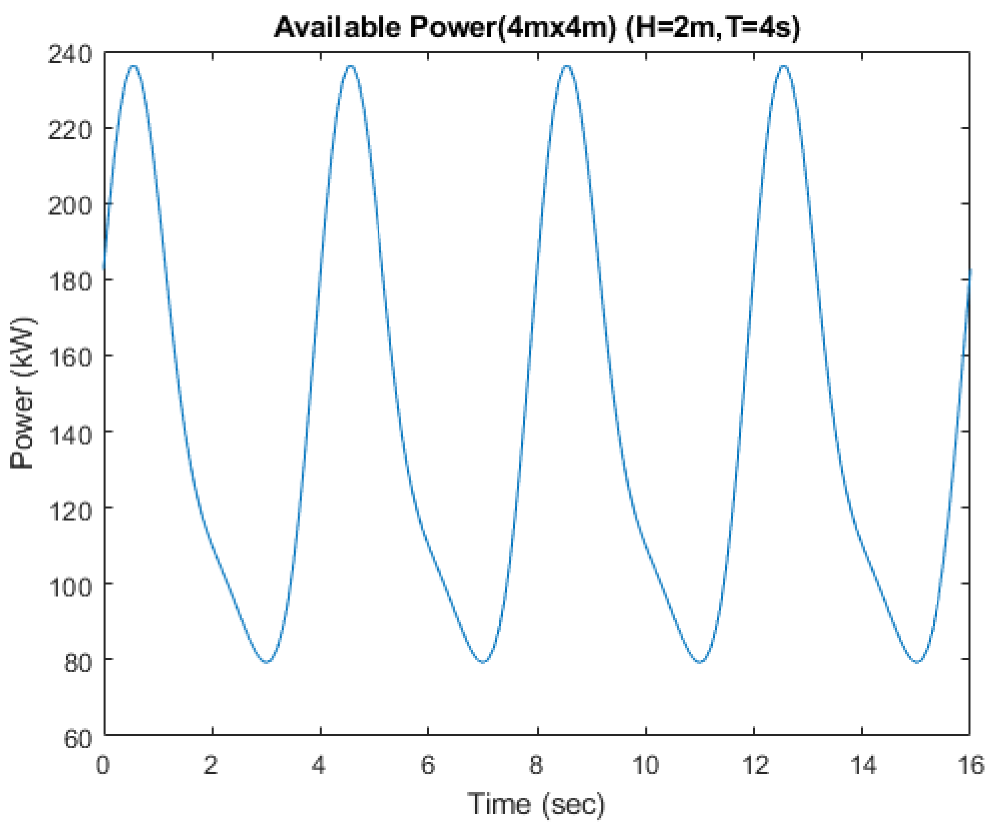
8
10
12
14
16


Available Power(4mx4m) (H=2m,T=4s)
Power (kW)
Time (sec)
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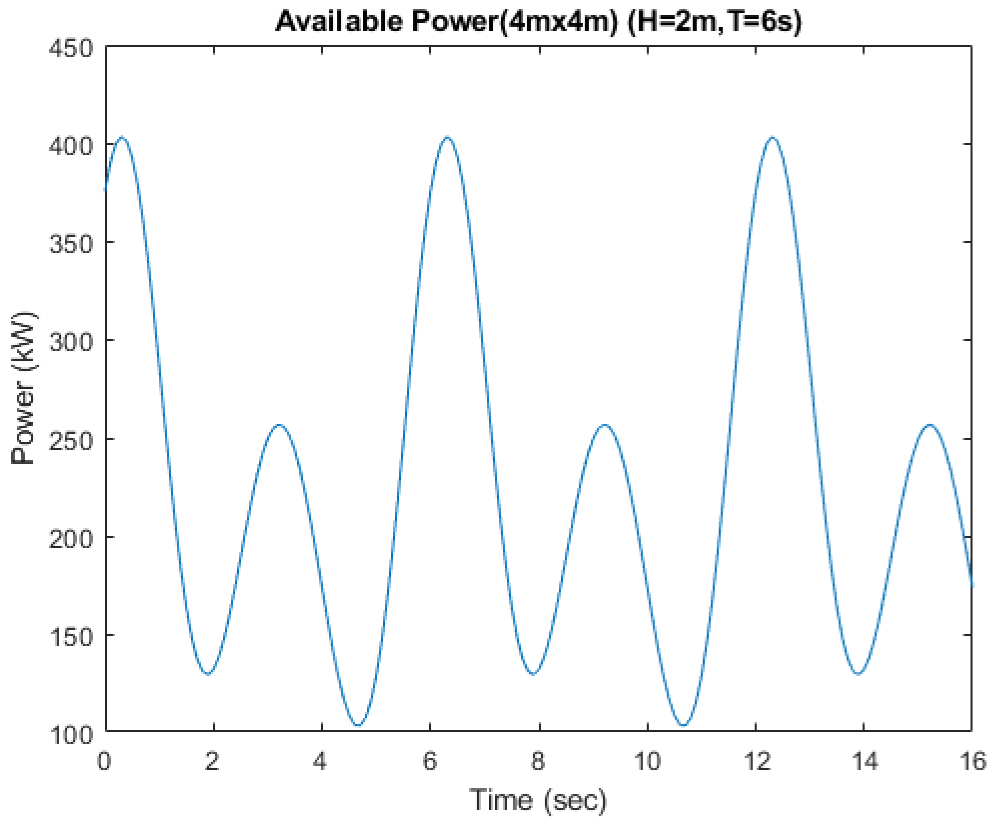
180
160
140
120
100
80
60
0
2
4
6
8
10
12
14
16



Available Power(4mx4m) (H=2m,T=6s)
Power (kW)
Time (sec)
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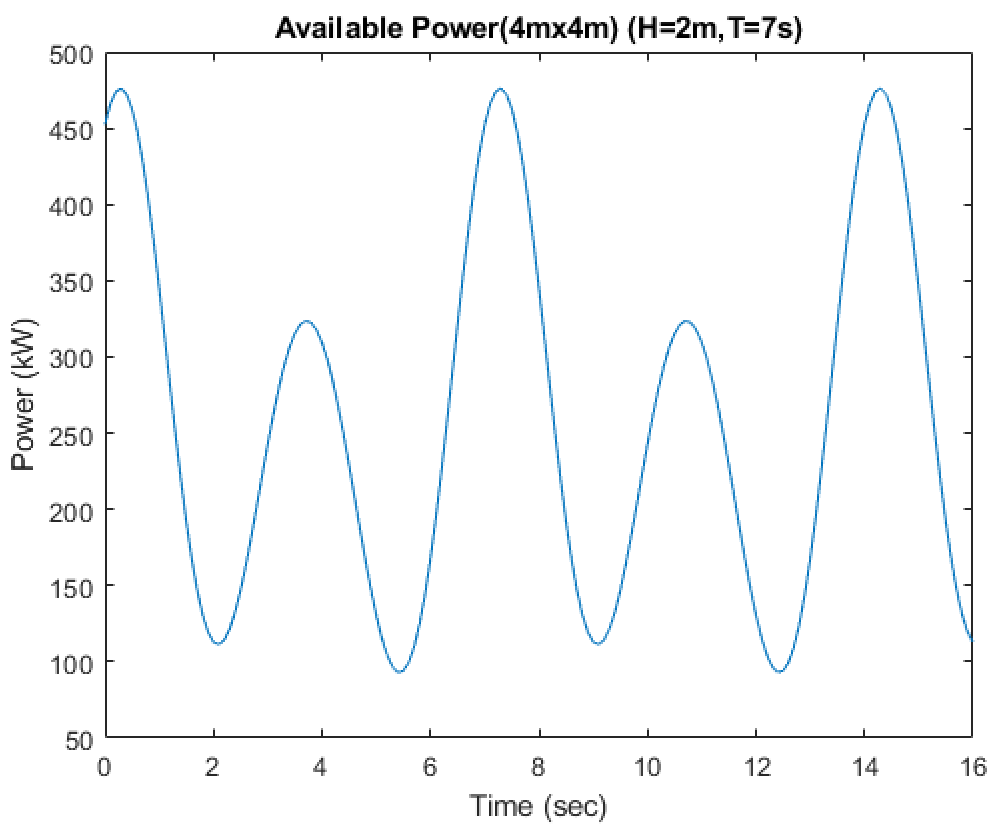
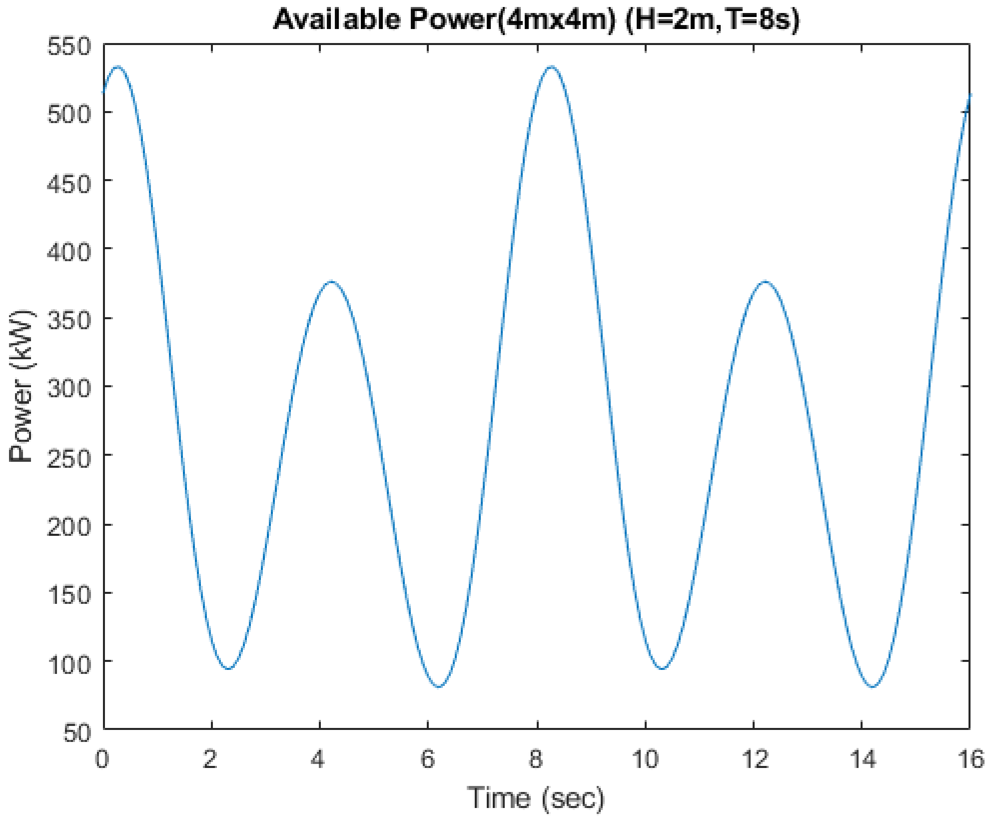
400
350
300
250
200
150
100
0
2
4
6
8
10
12
14
16



Available Power(4mx4m) (H=2m,T=7s)
Power (kW)
Time (sec)
500
450
400
350
300
250
200
150
100
50
0
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=2m,T=8s)
Power (kW)
Time (sec)
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500
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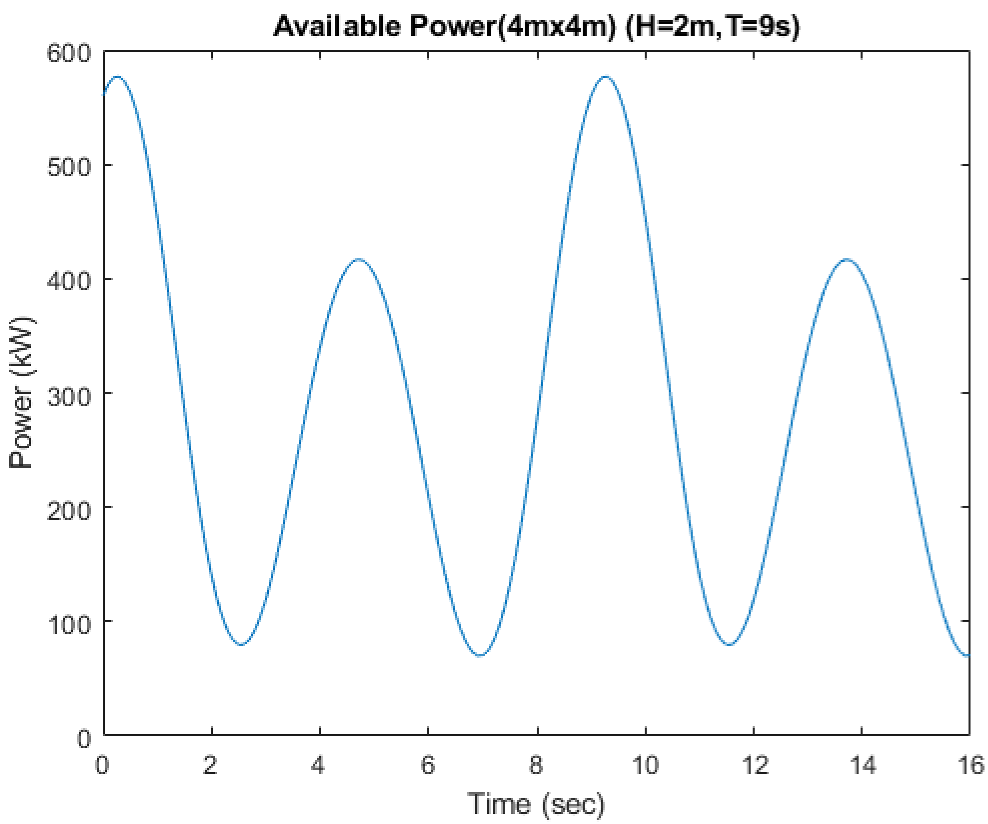
400
350
300
250
200
150
100
50
0
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=2m,T=9s)
Power (kW)
Time (sec)
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500
400
300
200
100
0
0
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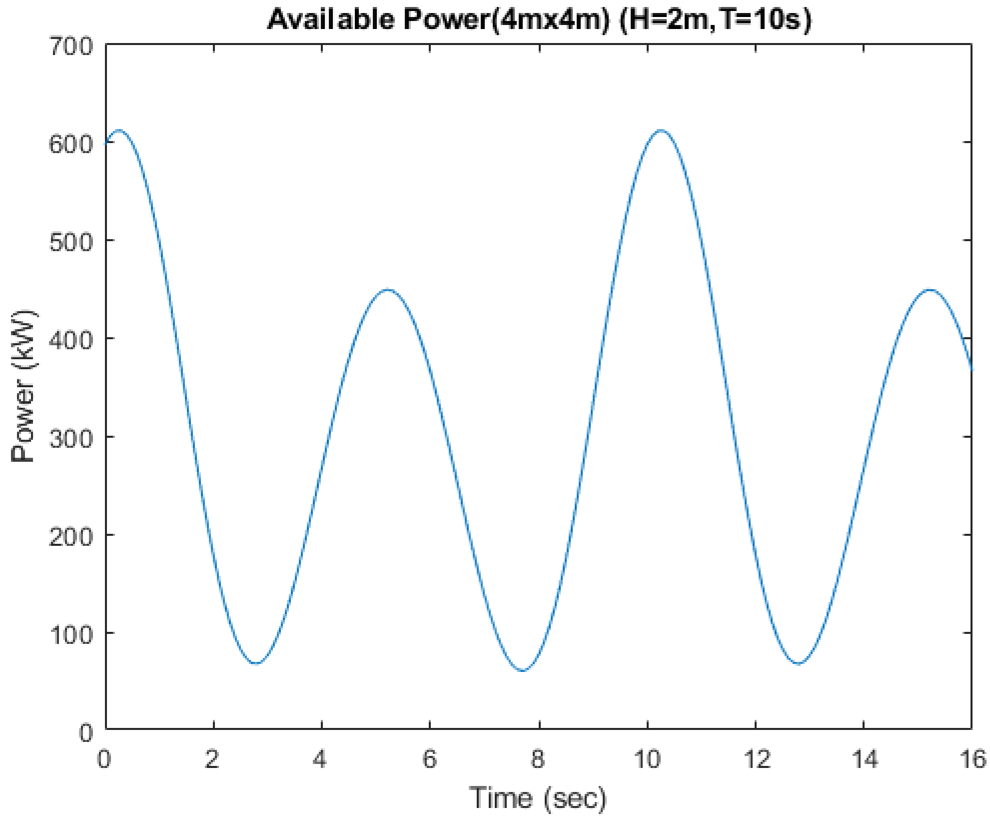
8
10
12
14
16


Available Power(4mx4m) (H=2m,T=10s)
Power (kW)
Time (sec)
0
100
200
300
400
500
600
700
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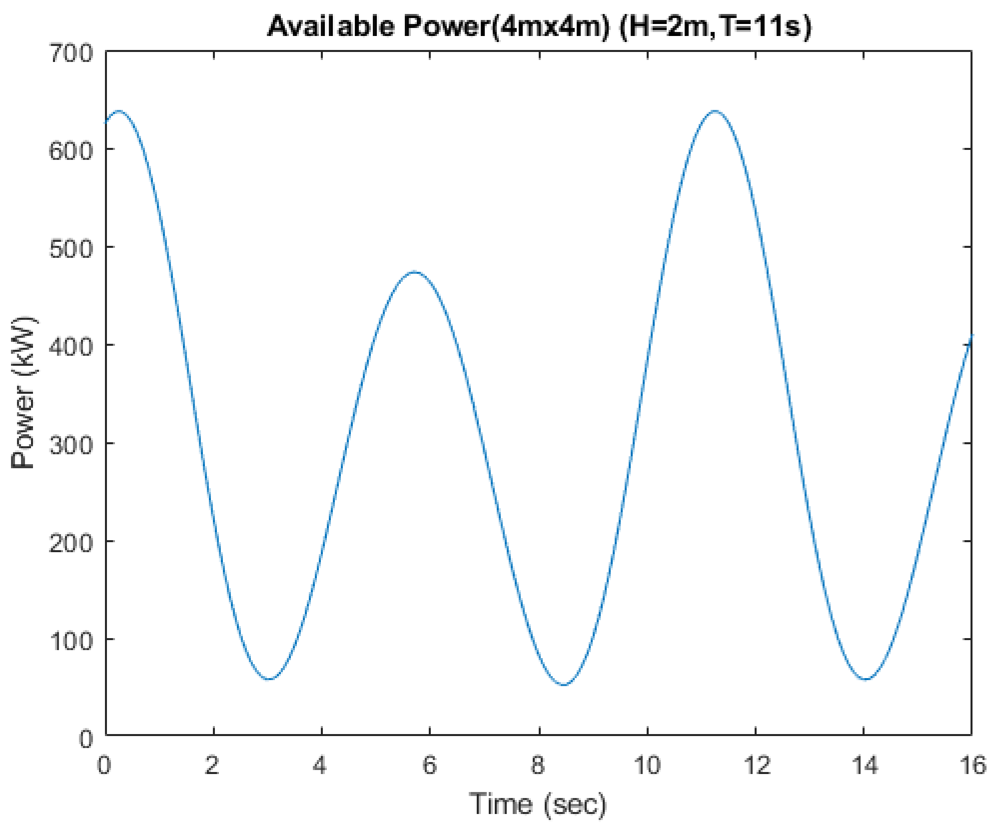
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=2m,T=11s)
Power (kW)
Time (sec)
0
100
200
300
400
500
600
700
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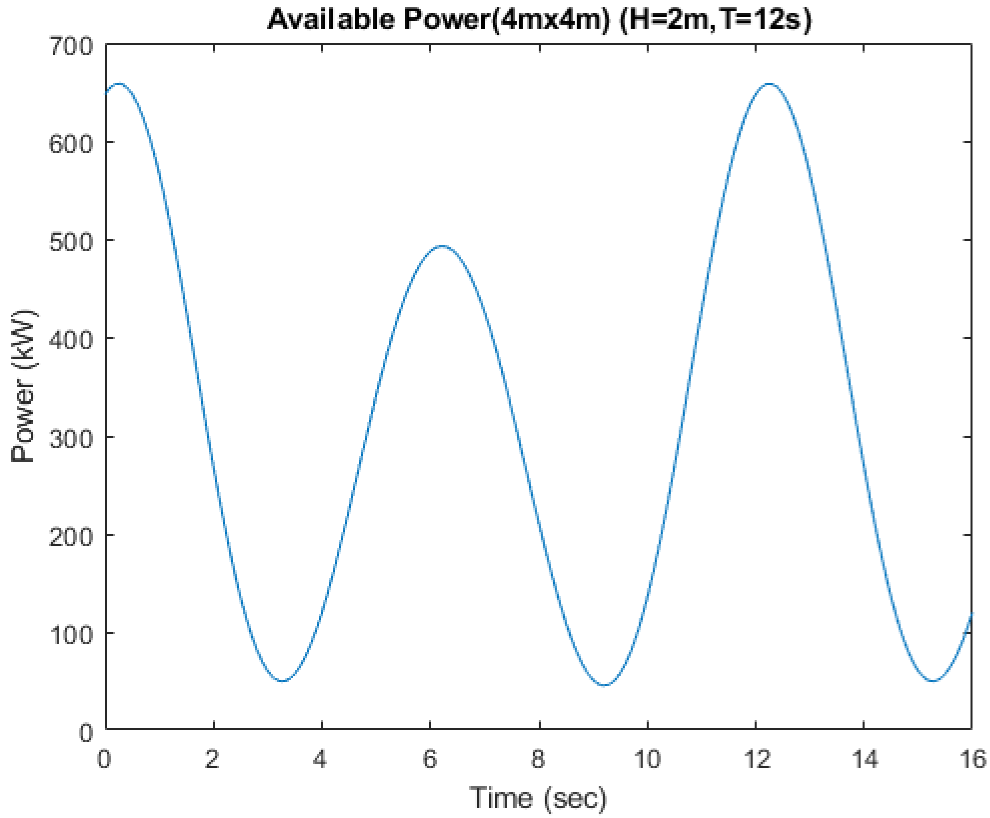
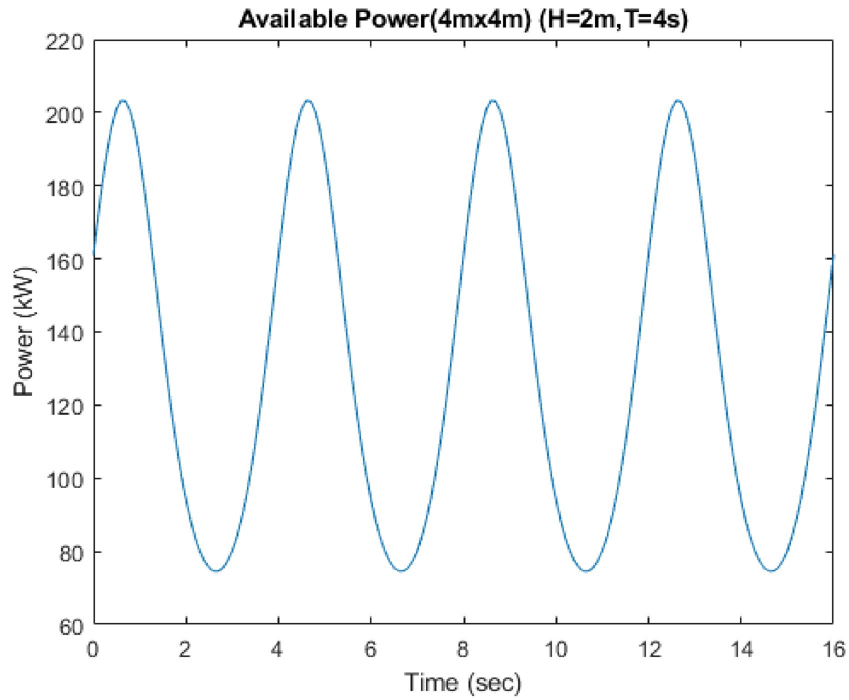
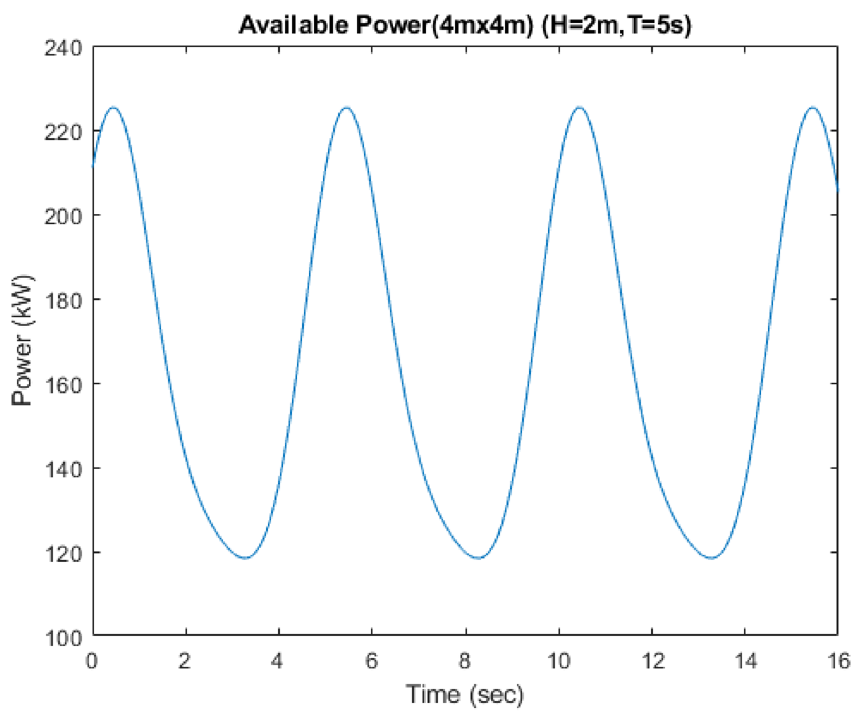
8
10
12
14
16

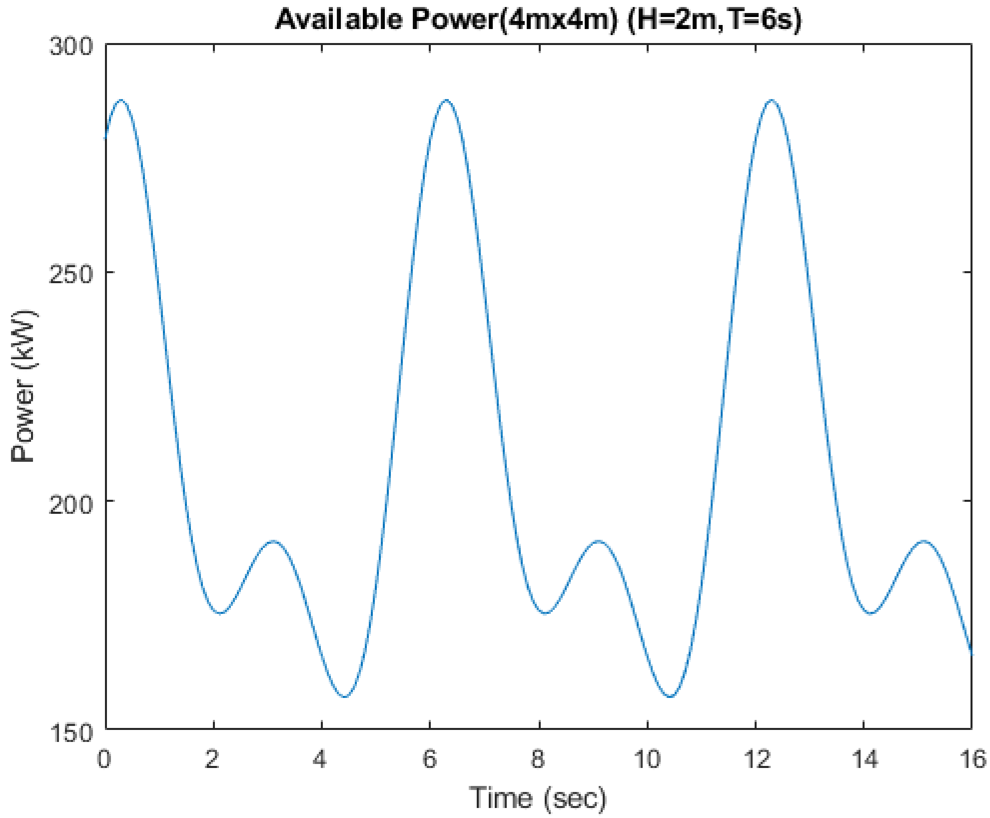


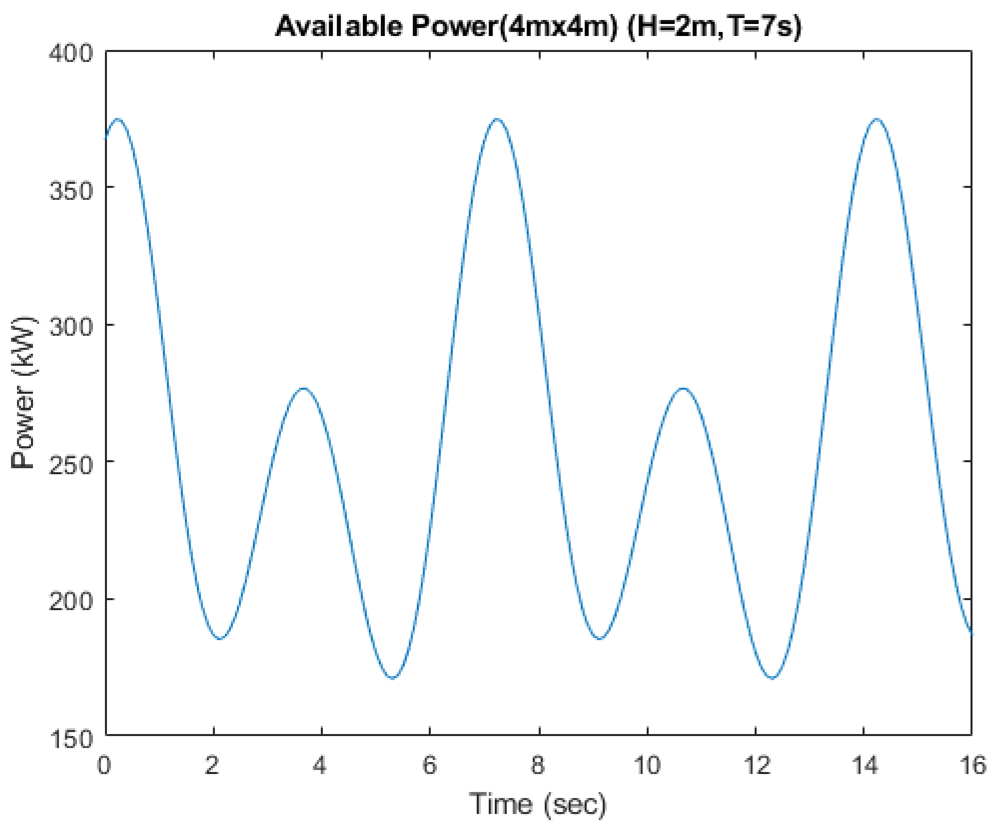
Available Power(4mx4m) (H=2m,T=12s)
Power (kW)
Time (sec)
0
100
200
300
400
500
600
700
0
2
4
6
8
10
12
14
16

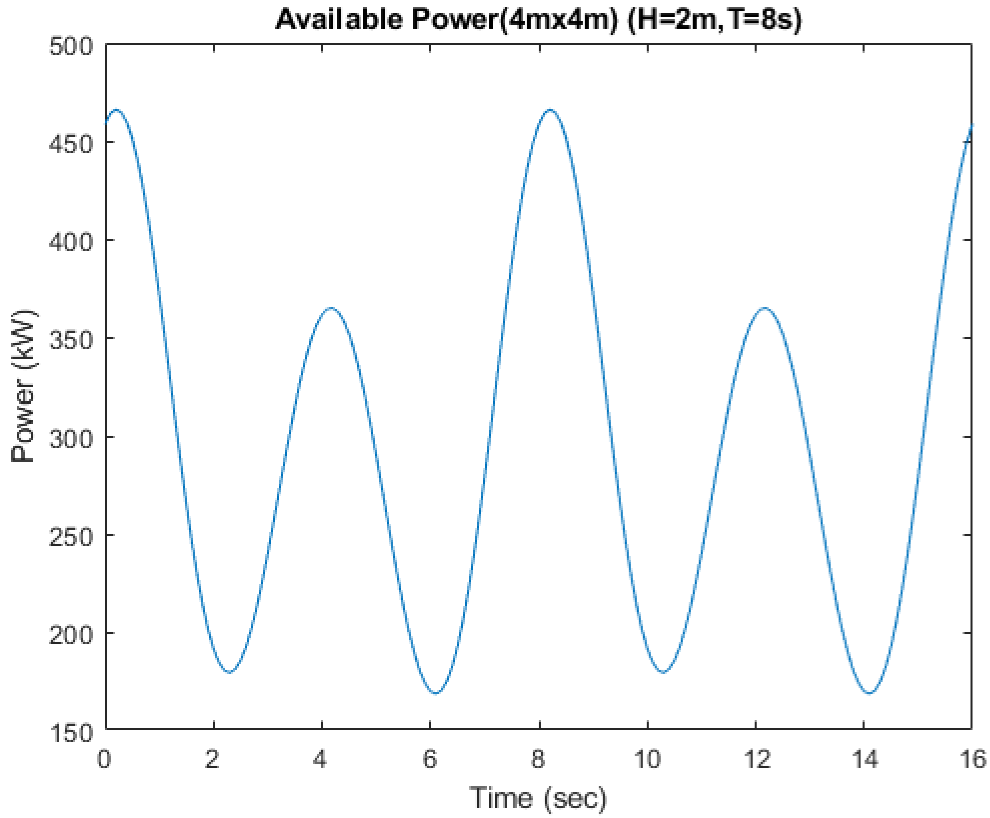
H=2 m, h=17 m

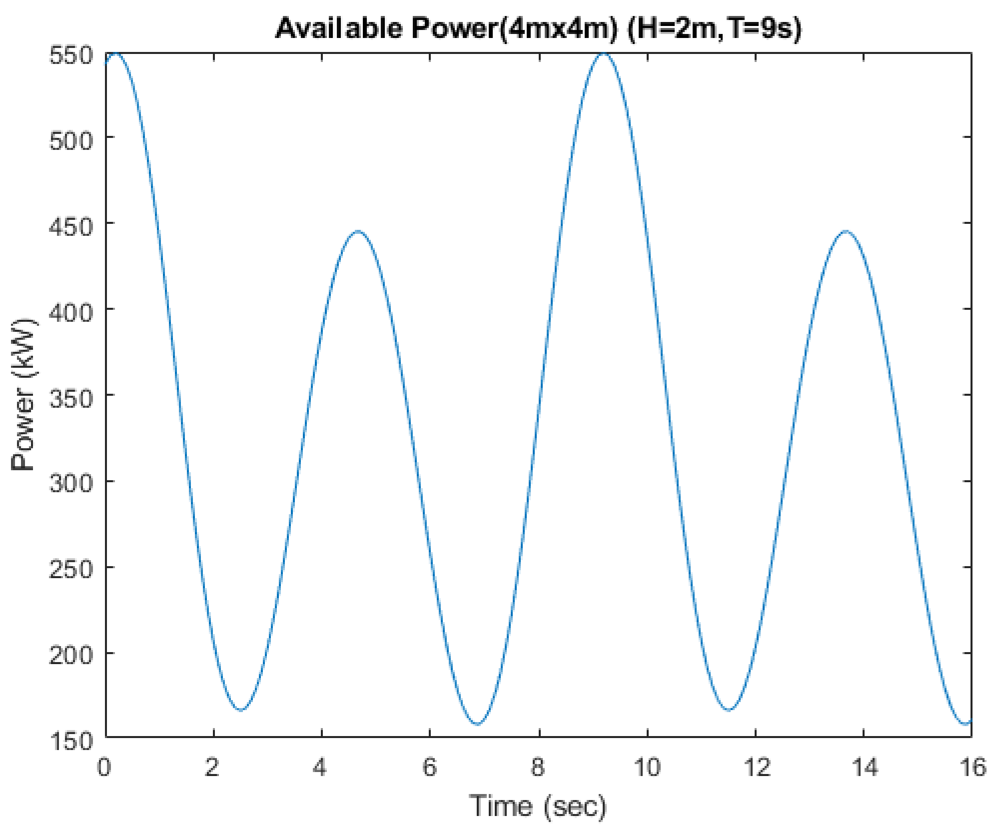

Available Power(4mx4m) (H=2m,T=4s)
Power (kW)
Time (sec)
220
200
180
160
140
120
100
80
60
0
2
4
6
8
10
12
14
16

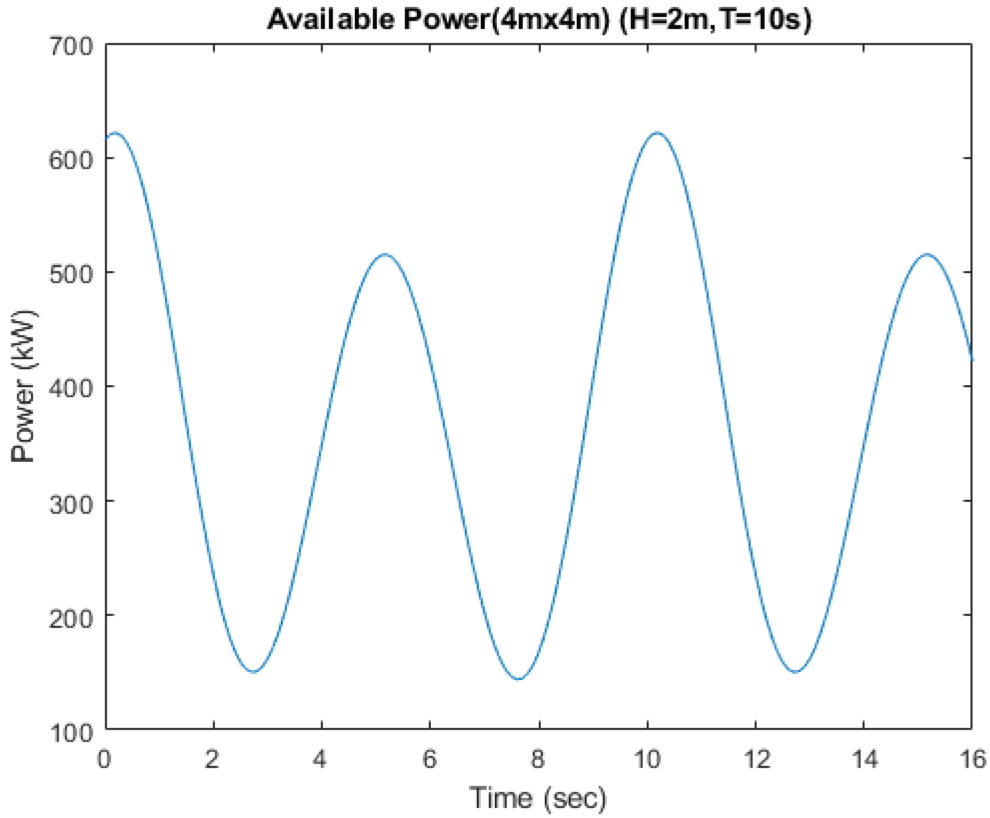

Available Power(4mx4m) (H=2m,T=5s)
Power (kW)
Time (sec)
240
220
200
180
160
140
120
100
0
2
4
6
8
10
12
14
16

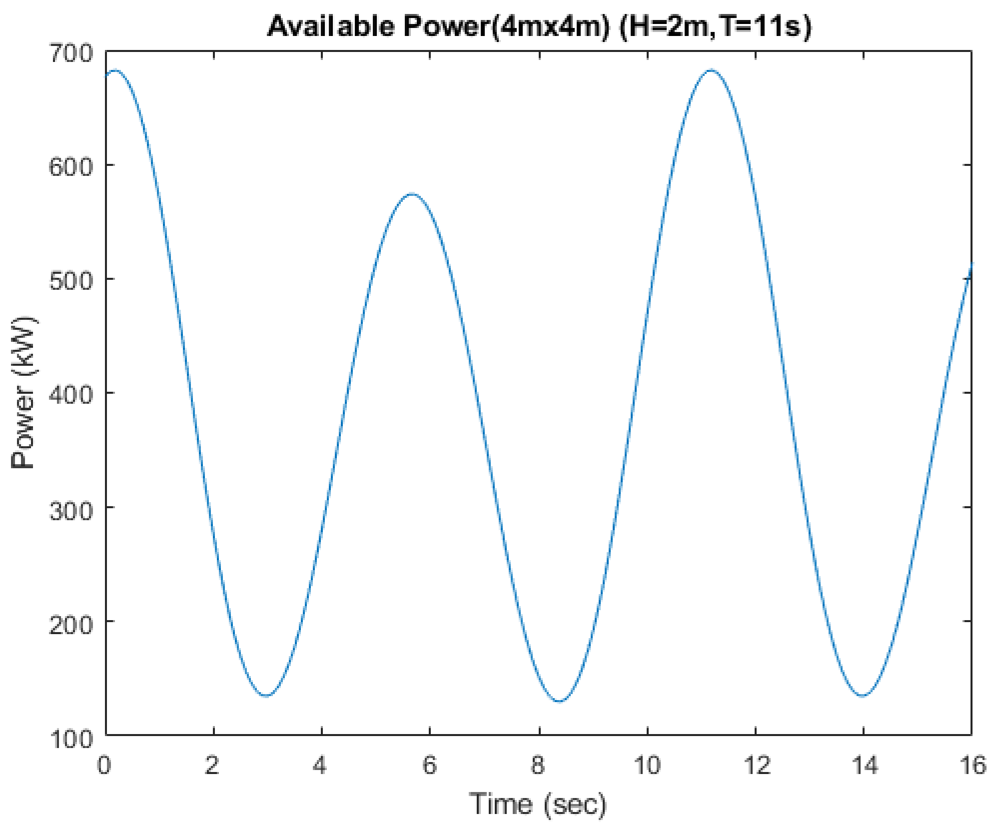

Available Power(4mx4m) (H=2m,T=6s)
Power (kW)
Time (sec)
300
250
200
150
0
2
4
6
8
10
12
14
16

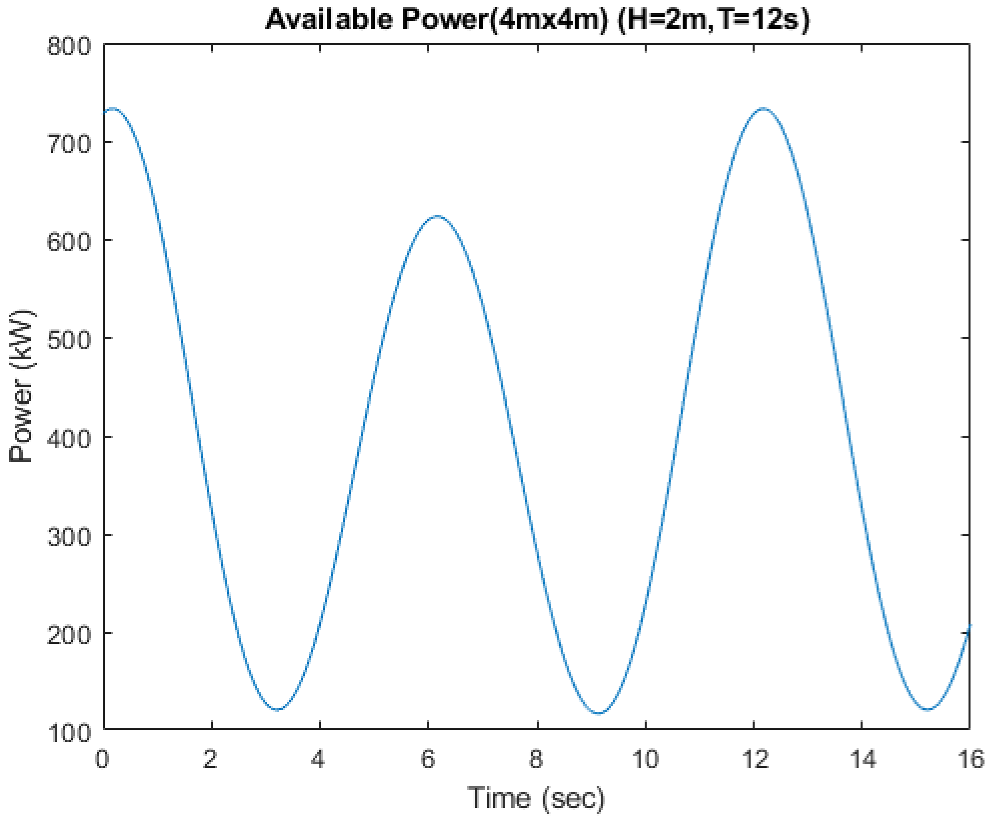

Available Power(4mx4m) (H=2m,T=7s)
Power (kW)
Time (sec)
400
350
300
250
200
150
0
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=2m,T=8s)
Power (kW)
500
450
400
350
300
250
200
150
0
2
4
6
8
10
12
14
16
Time (sec)

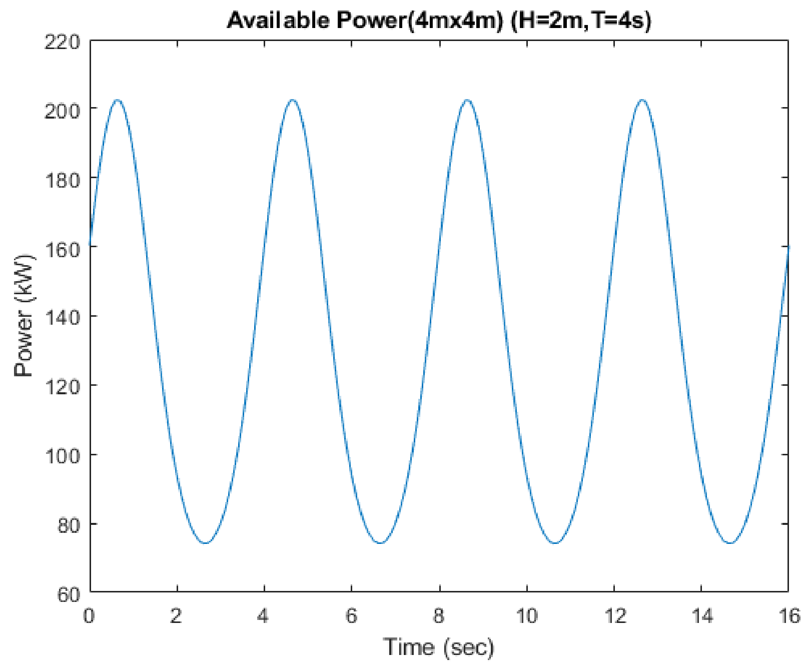

Available Power(4mx4m) (H=2m,T=9s)
Power (kW)
550
500
450
400
350
300
250
200
150
0
2
4
6
8
10
12
14
16
Time (sec)

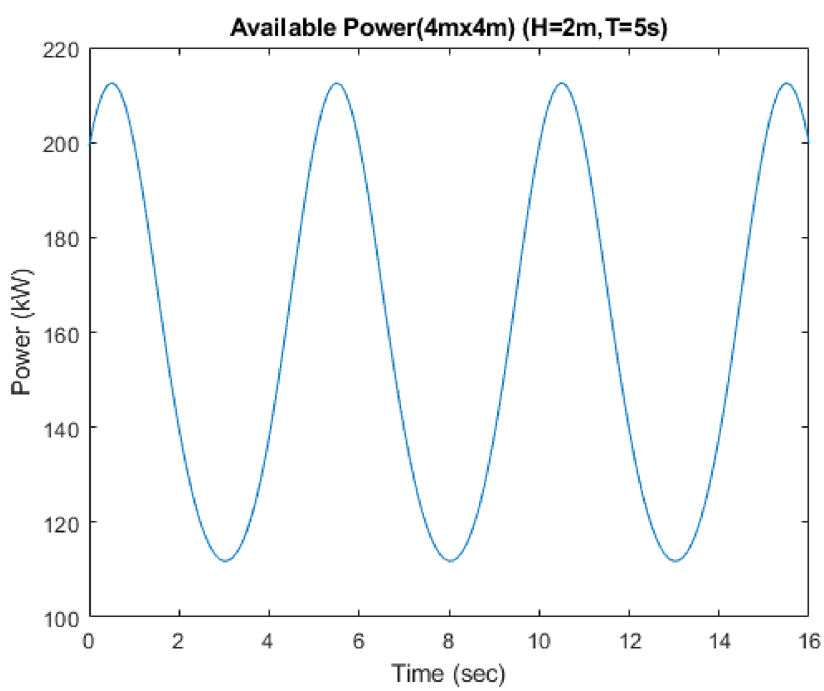

Available Power(4mx4m) (H=2m,T=10s)
Power (kW)
700
600
500
400
300
200
100
0
2
4
6
8
10
12
14
16
Time (sec)

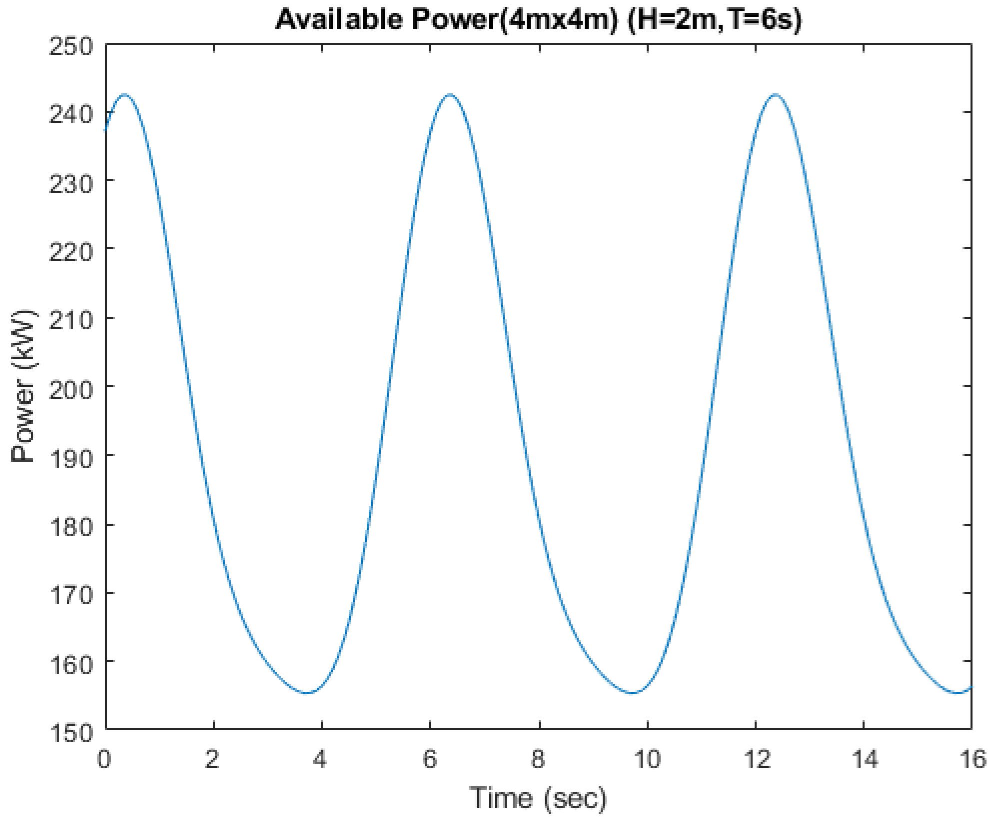

Available Power(4mx4m) (H=2m,T=11s)
Power (kW)
700
600
500
400
300
200
100
0
2
4
6
8
10
12
14
16
Time (sec)

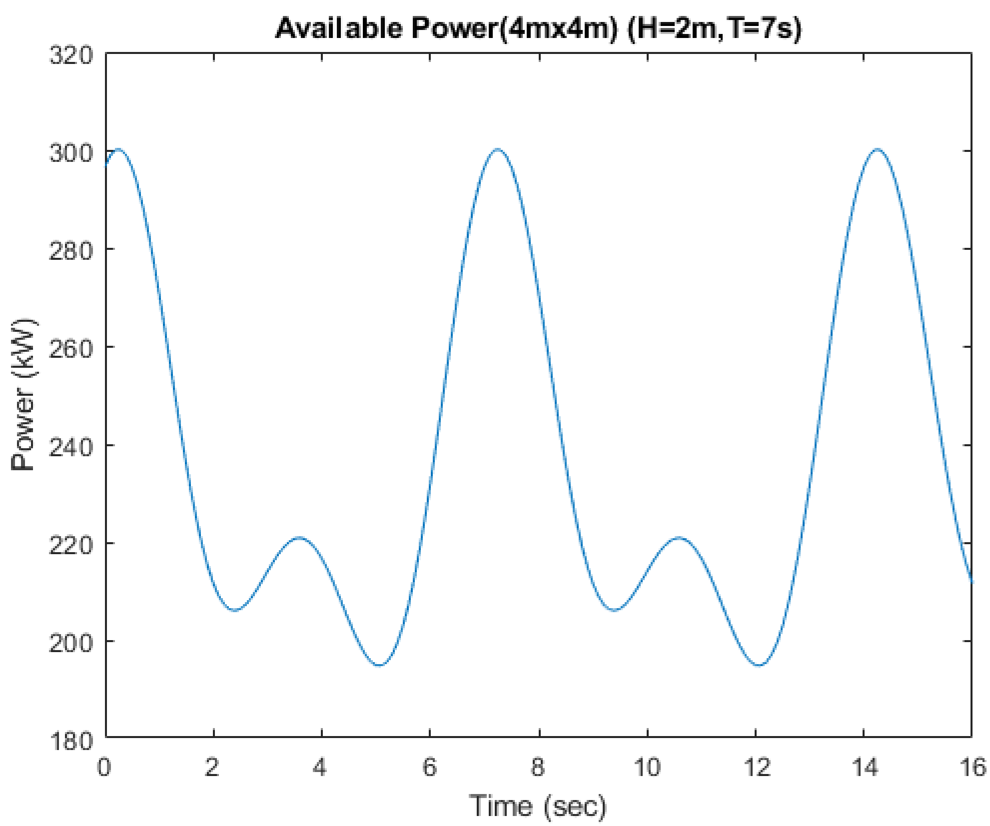

Available Power(4mx4m) (H=2m,T=12s)
Power (kW)
800
700
600
500
400
300
200
100
0
2
4
6
8
10
12
14
16
Time (sec)

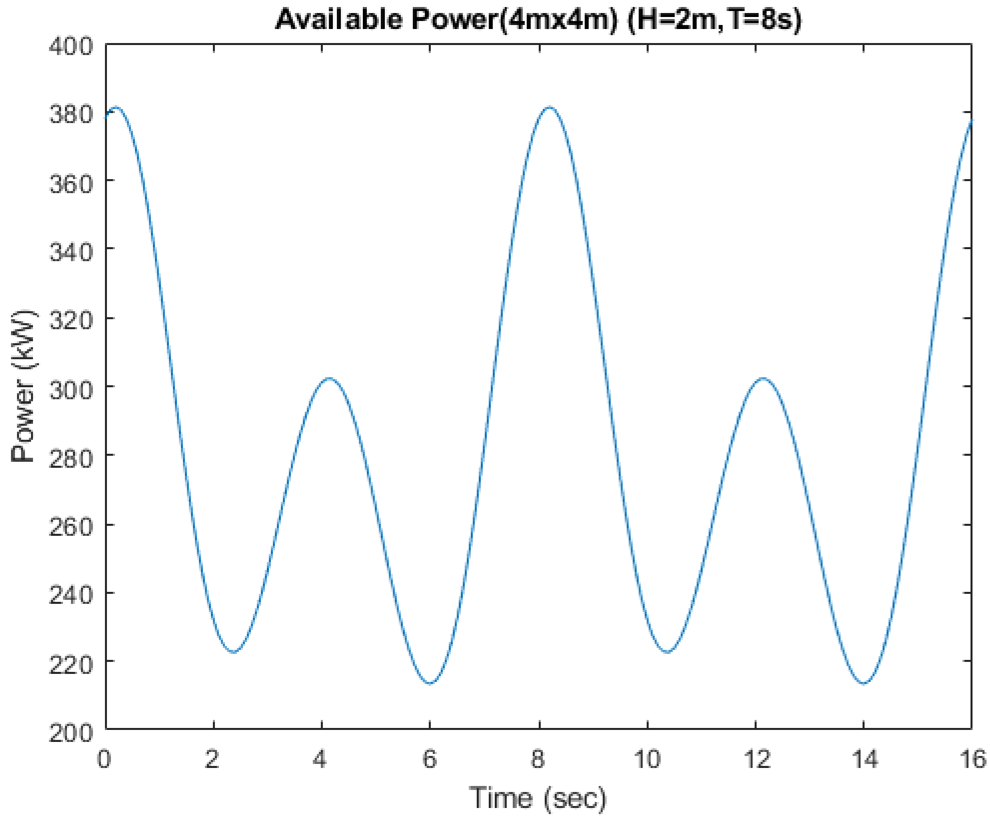
H=2 m, h=26 m

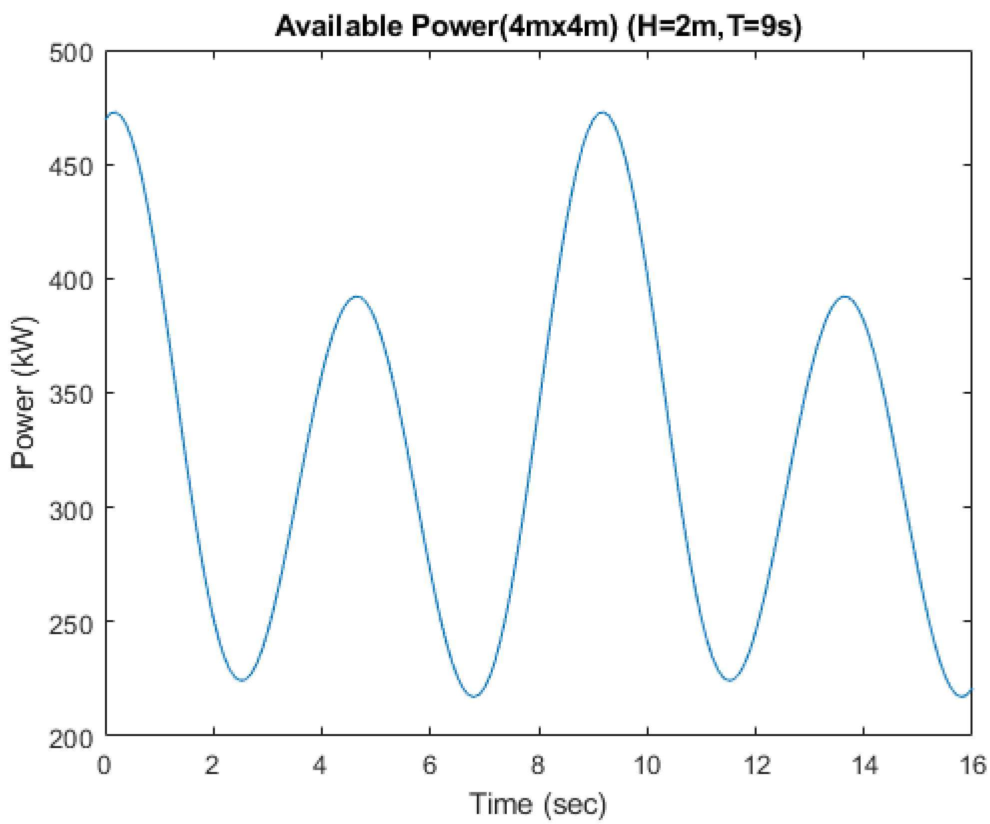

Available Power(4mx4m) (H=2m,T=4s)
Power (kW)
Time (sec)
220
200
180
160
140
120
100
80
60
0
2
4
6
8
10
12
14
16

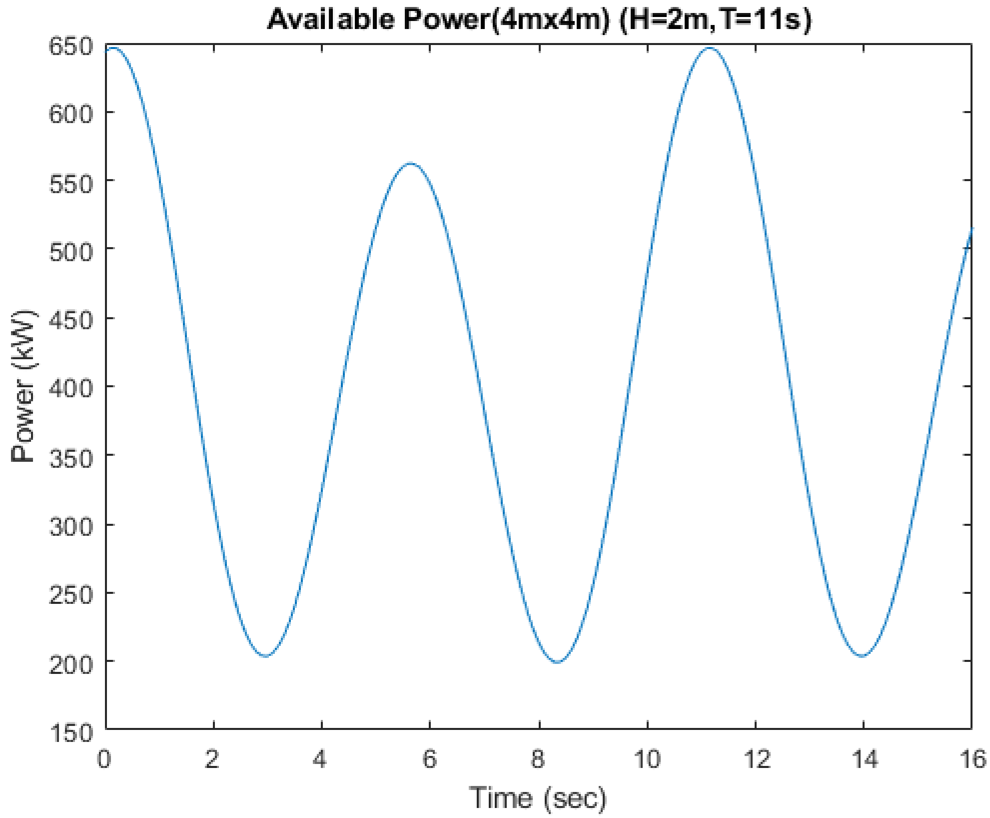

Available Power(4mx4m) (H=2m,T=5s)
Power (kW)
Time (sec)
220
200
180
160
140
120
100
0
2
4
6
8
10
12
14
16

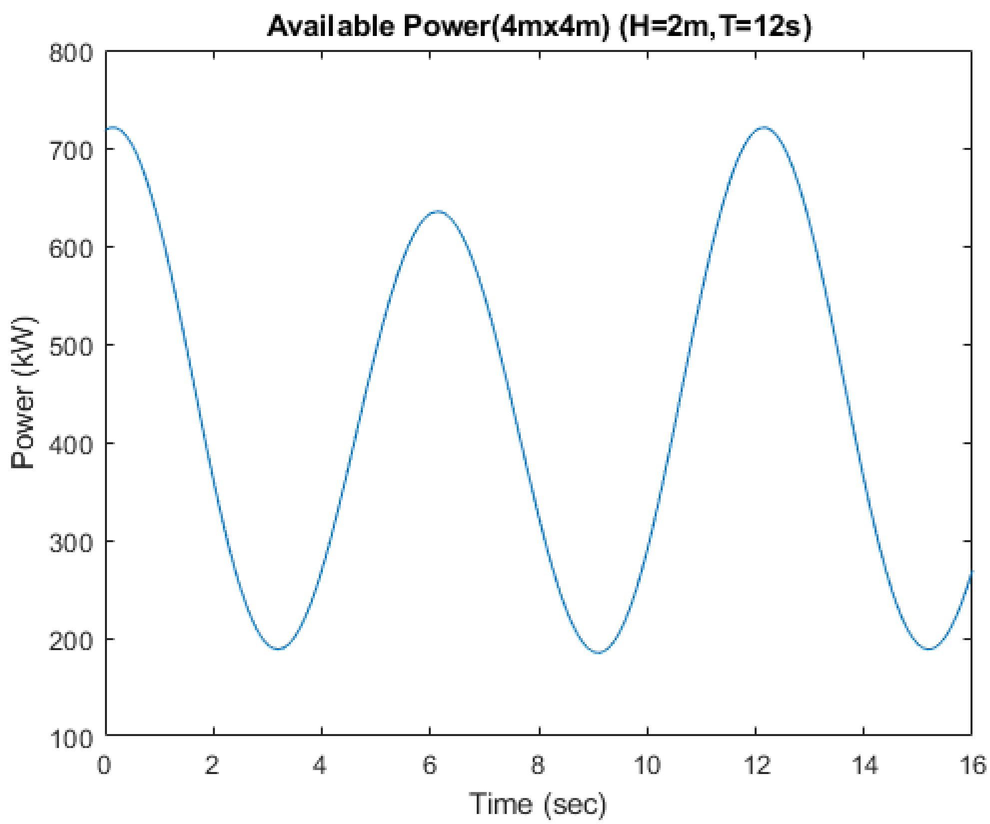

Available Power(4mx4m) (H=2m,T=6s)
Power (kW)
250
240
230
220
210
200
190
180
170
160
150
0
2
4
6
8
10
12
14
16
Time (sec)


Available Power(4mx4m) (H=2m,T=7s)
Power (kW)
320
300
280
260
240
220
200
180
0
2
4
6
8
10
12
14
16
Time (sec)

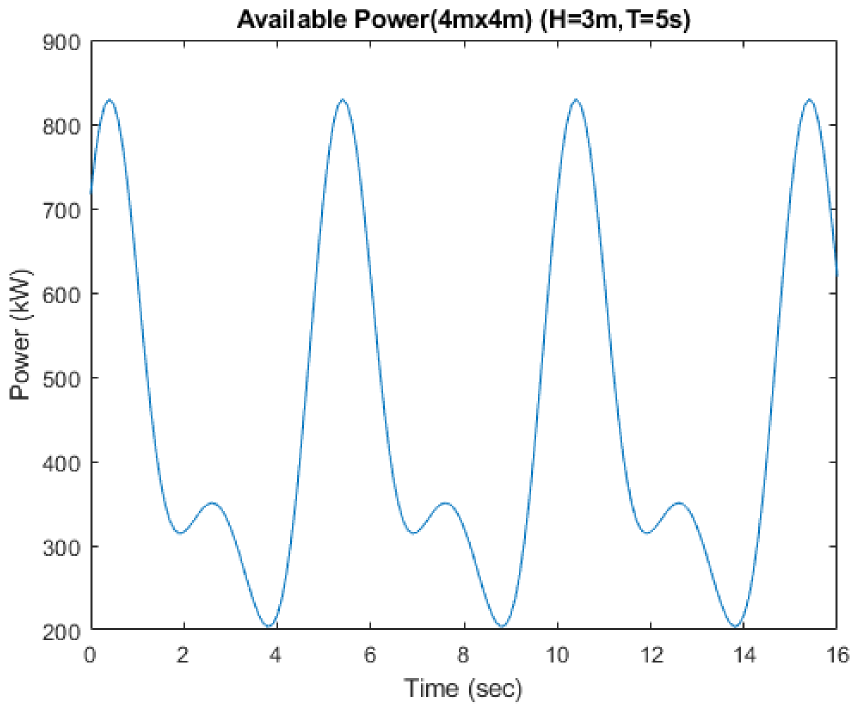

Available Power(4mx4m) (H=2m,T=8s)
Power (kW)
400
380
360
340
320
300
280
260
240
220
200
0
2
4
6
8
10
12
14
16
Time (sec)

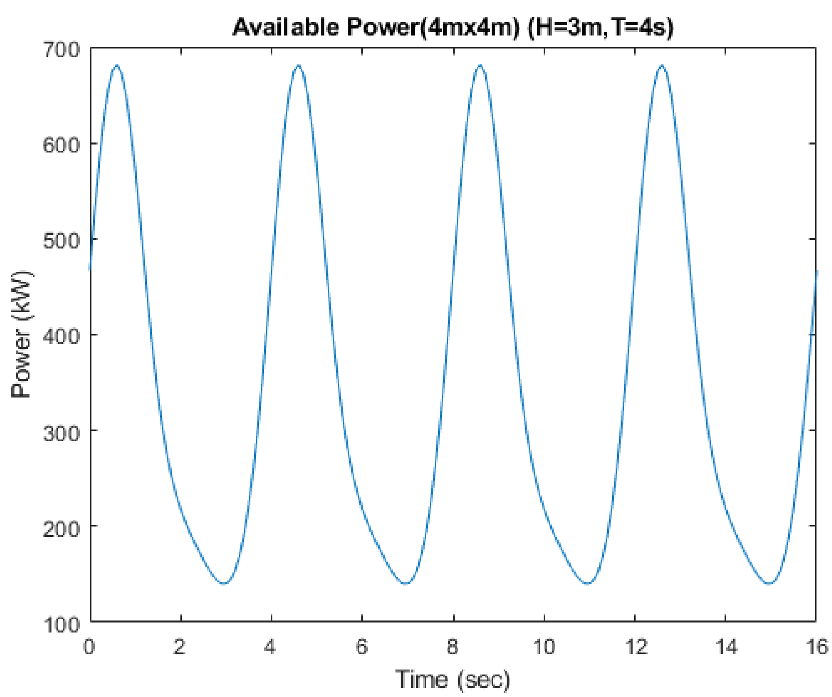

Available Power(4mx4m) (H=2m,T=9s)
Power (kW)
500
450
400
350
300
250
200
0
2
4
6
8
10
12
14
16
Time (sec)

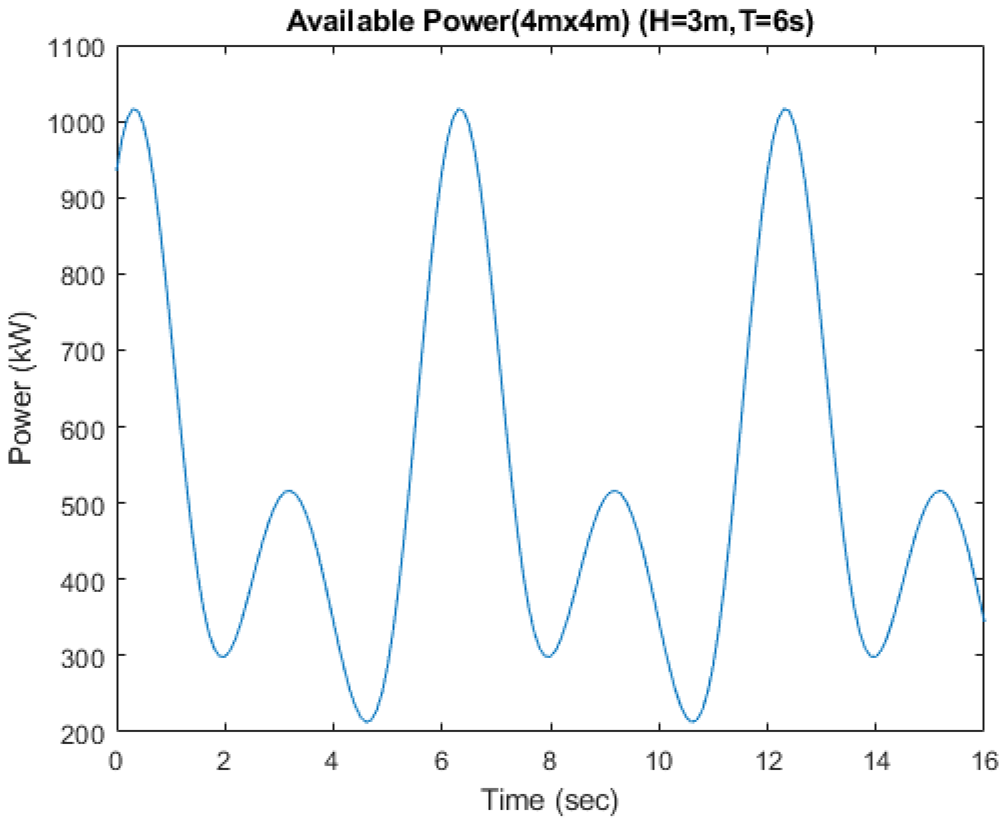

Available Power(4mx4m) (H=2m,T=11s)
Power (kW)
650
600
550
500
450
400
350
300
250
200
150
0
2
4
6
8
10
12
14
16
Time (sec)

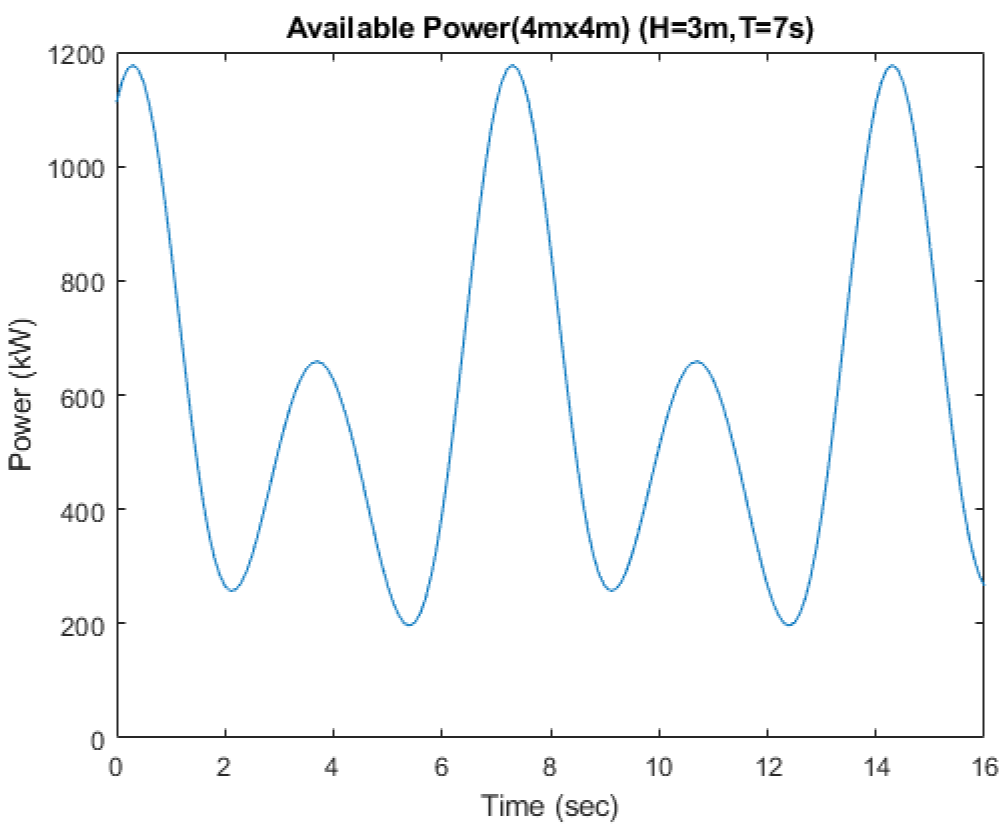

Available Power(4mx4m) (H=2m,T=12s)
Power (kW)
800
700
600
500
400
300
200
100
0
2
4
6
8
10
12
14
16
Time (sec)

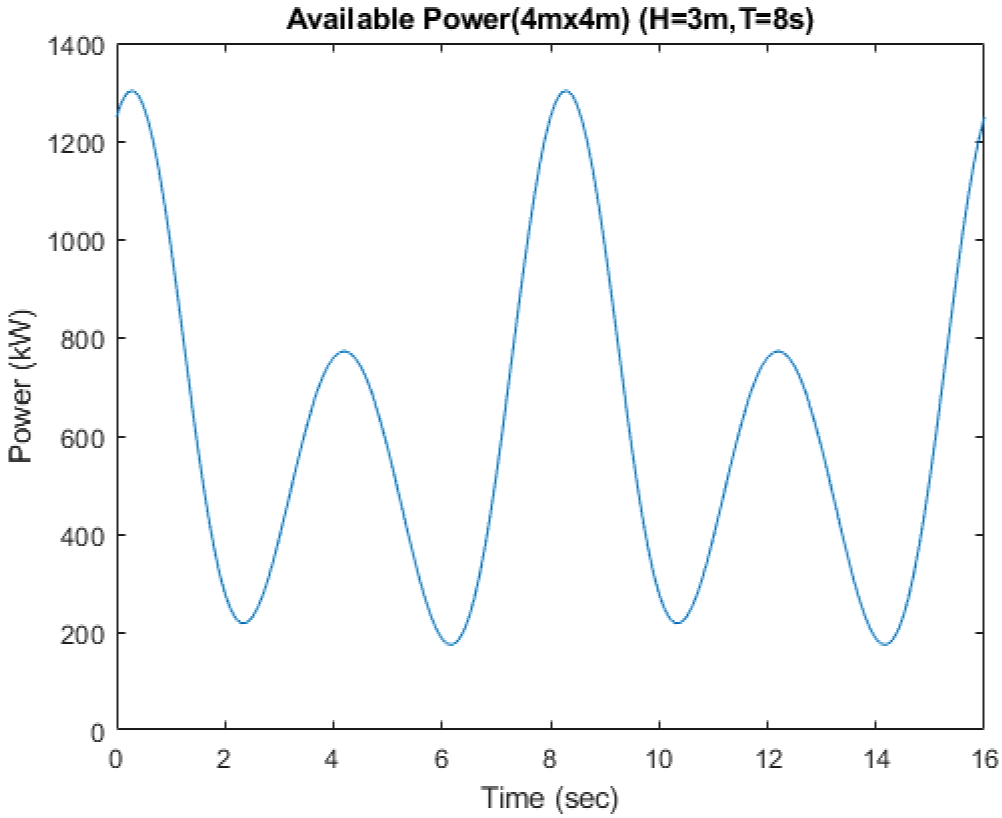
H=3 m, h=8 m

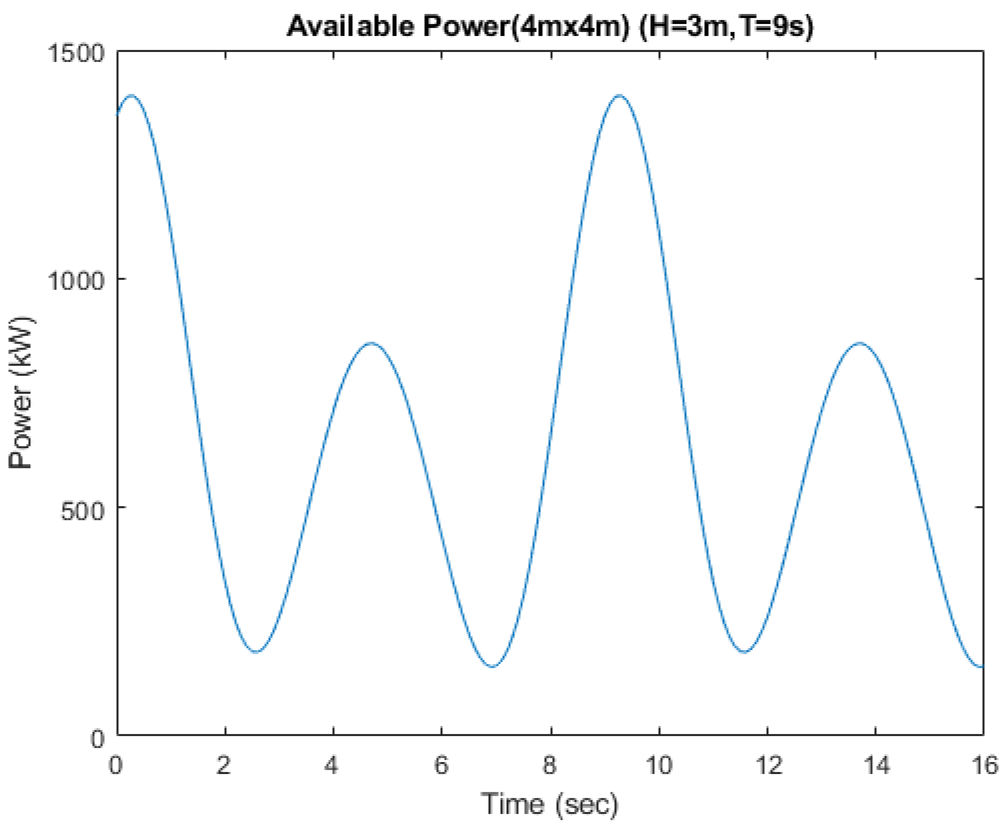

Available Power(4mx4m) (H=3m,T=5s)
900
800
700
600
500
400
300
200
Power (kW)
0
2
4
6
8
10
12
14
16
Time (sec)

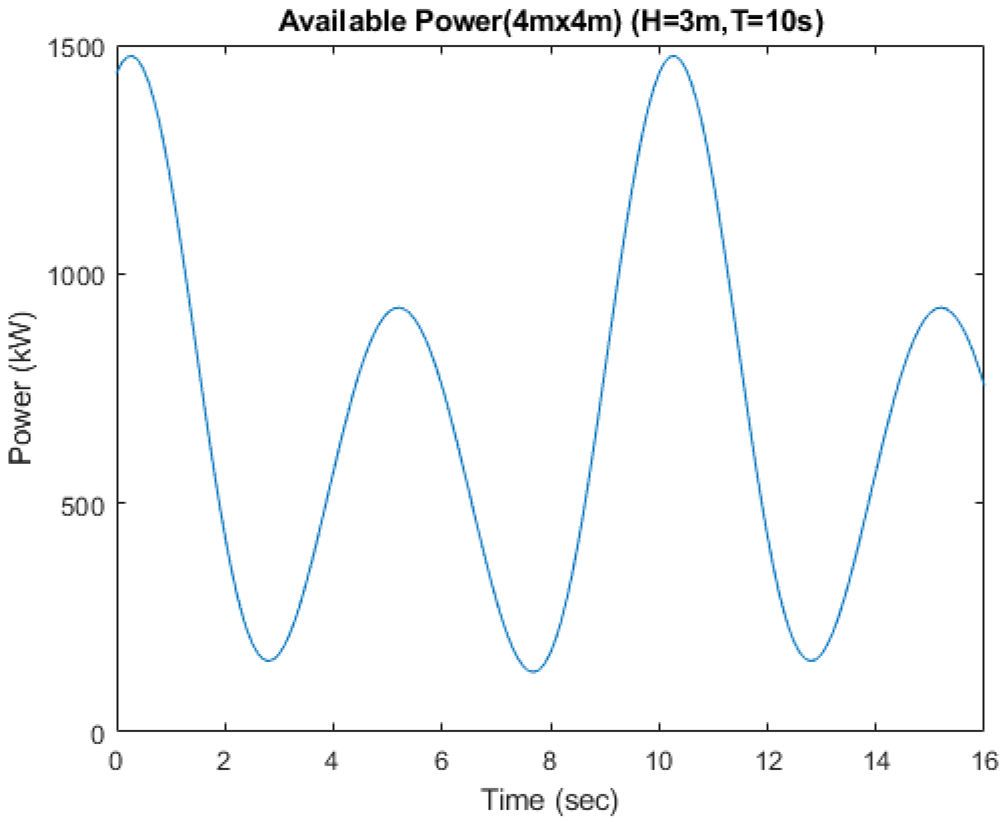

Available Power(4mx4m) (H=3m,T=4s)
700
600
500
400
300
200
100
Power (kW)
0
2
4
6
8
10
12
14
16
Time (sec)

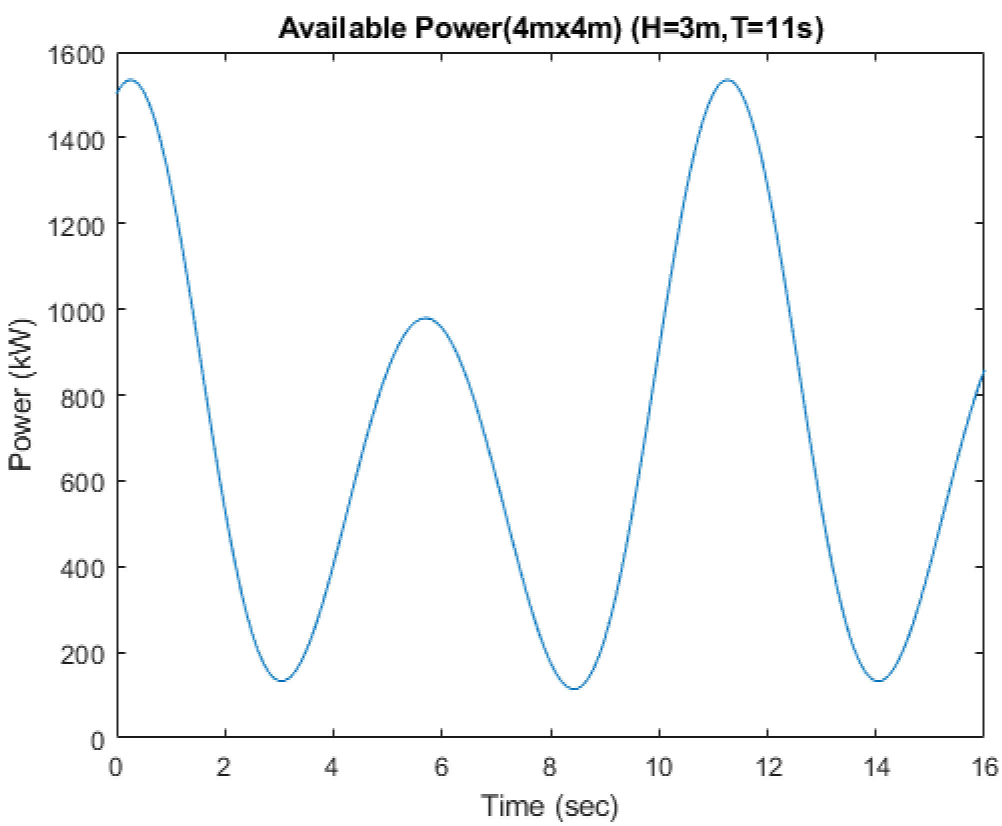

Available Power(4mx4m) (H=3m,T=6s)
Power (kW)
1100
1000
900
800
700
600
500
400
300
200
0
2
4
6
8
10
12
14
16
Time (sec)

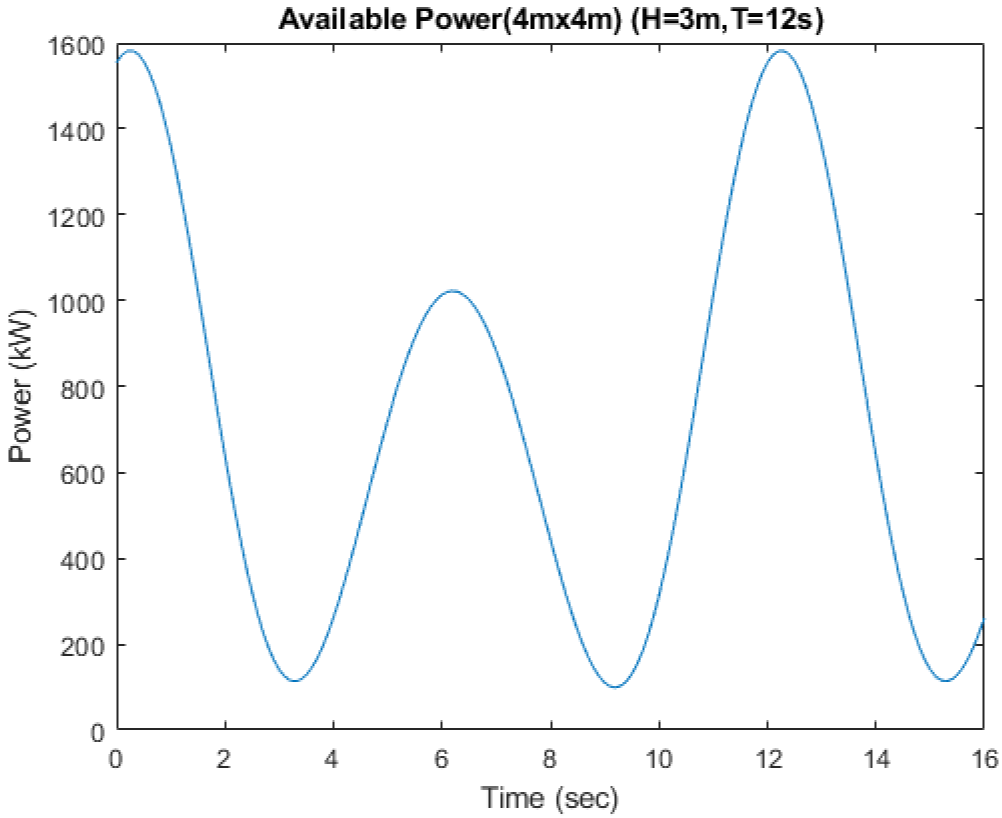

Available Power(4mx4m) (H=3m,T=7s)
Power (kW)
1200
1000
800
600
400
200
0
0
2
4
6
8
10
12
14
16
Time (sec)


Available Power(4mx4m) (H=3m,T=8s)
Power (kW)
1400
1200
1000
800
600
400
200
0
0
2
4
6
8
10
12
14
16
Time (sec)

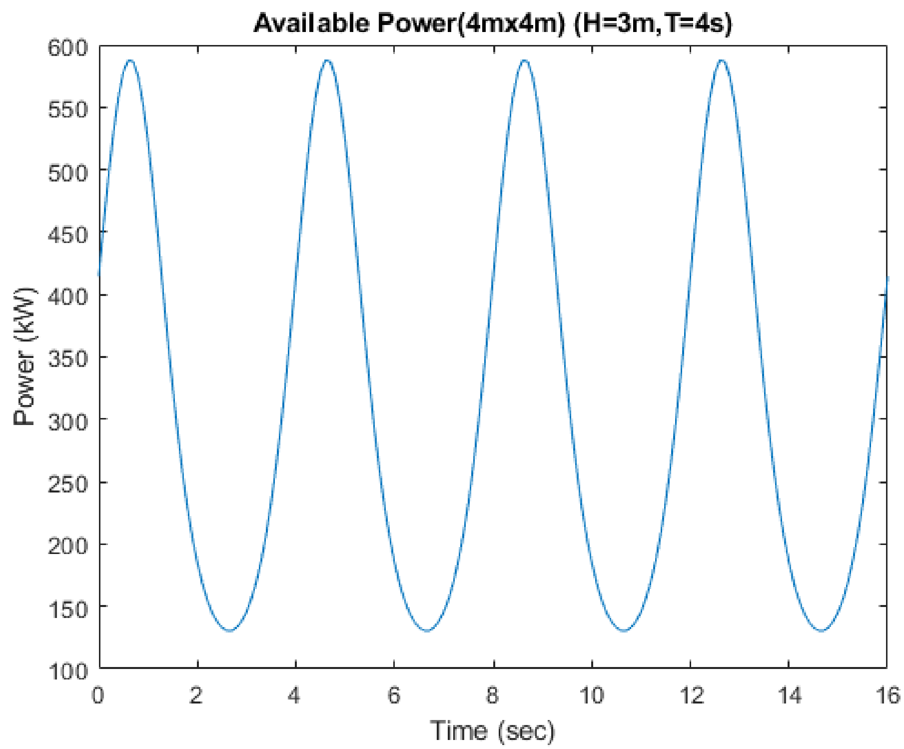

Available Power(4mx4m) (H=3m,T=9s)
Power (kW)
1500
1000
500
0
0
2
4
6
8
10
12
14
16
Time (sec)


Available Power(4mx4m) (H=3m,T=10s)
1500
1000
500
0
Power (kW)
0
2
4
6
8
10
12
14
16
Time (sec)

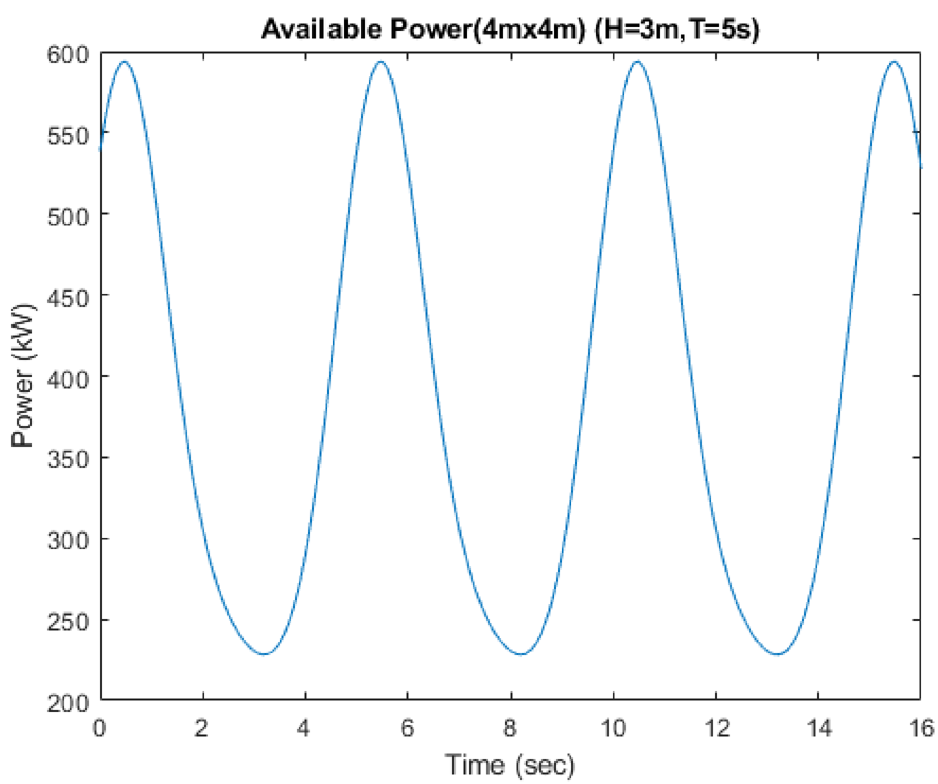

Available Power(4mx4m) (H=3m,T=11s)
1600
1400
1200
1000
800
600
400
200
0
Power (kW)
0
2
4
6
8
10
12
14
16
Time (sec)


Available Power(4mx4m) (H=3m,T=12s)
Power (kW)
1600
1400
1200
1000
800
600
400
200
0
0
2
4
6
8
10
12
14
16
Time (sec)

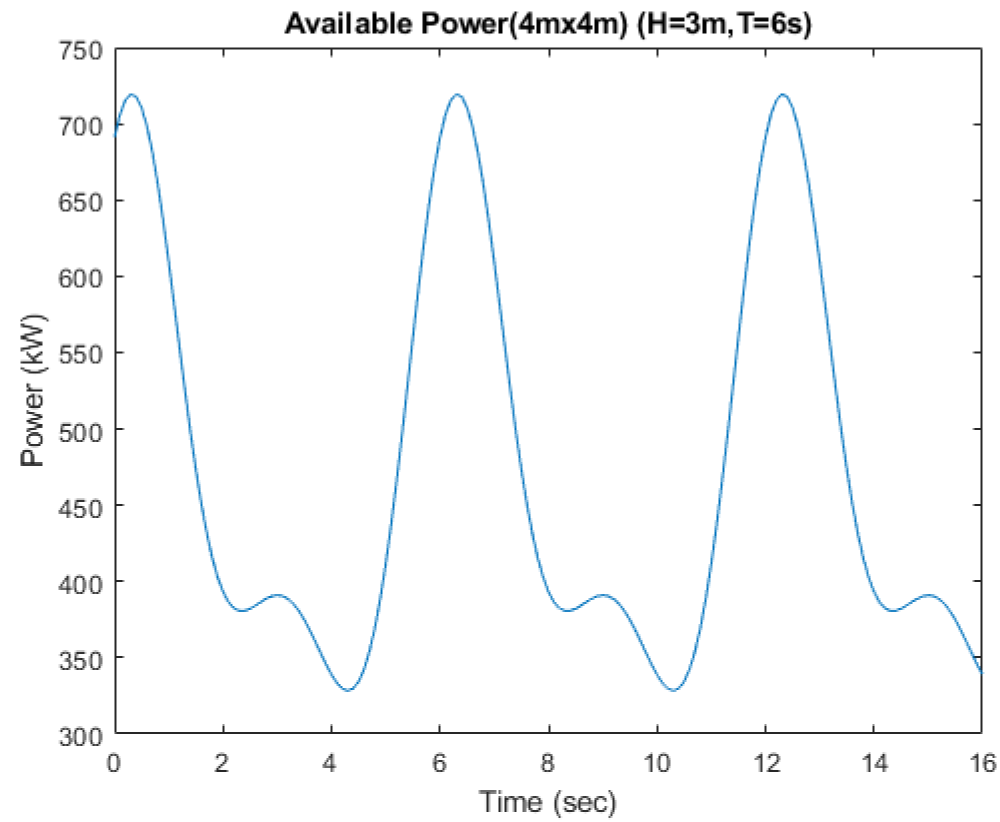
H=3 m, h=17 m

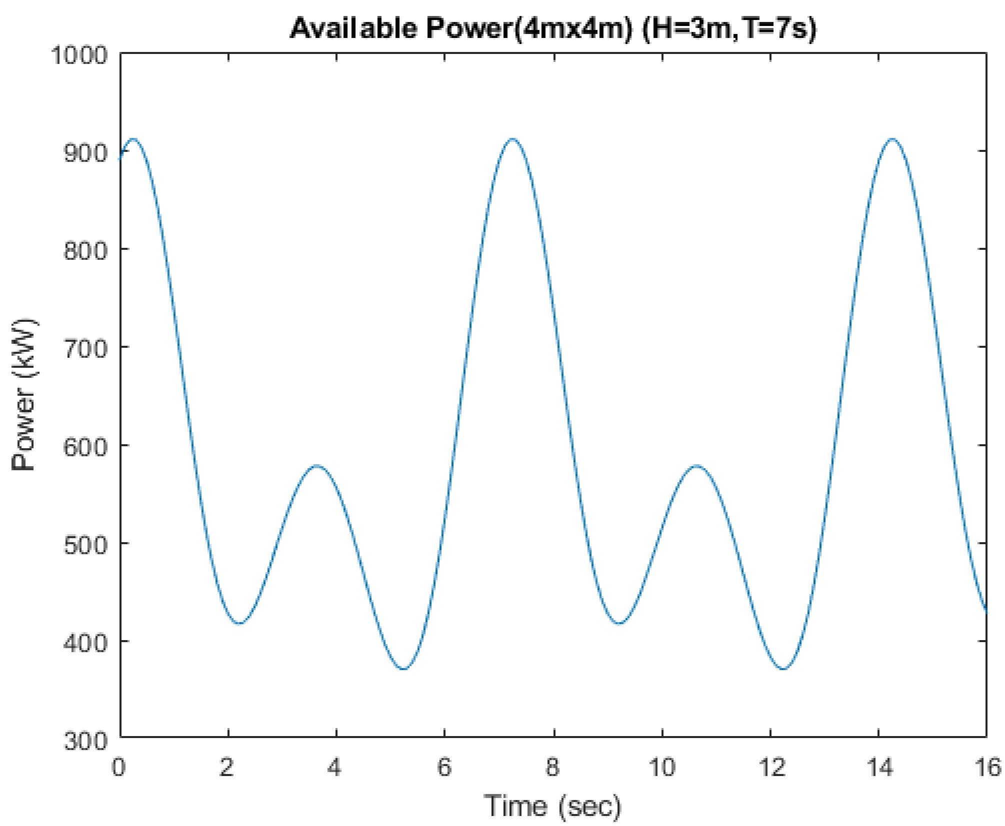


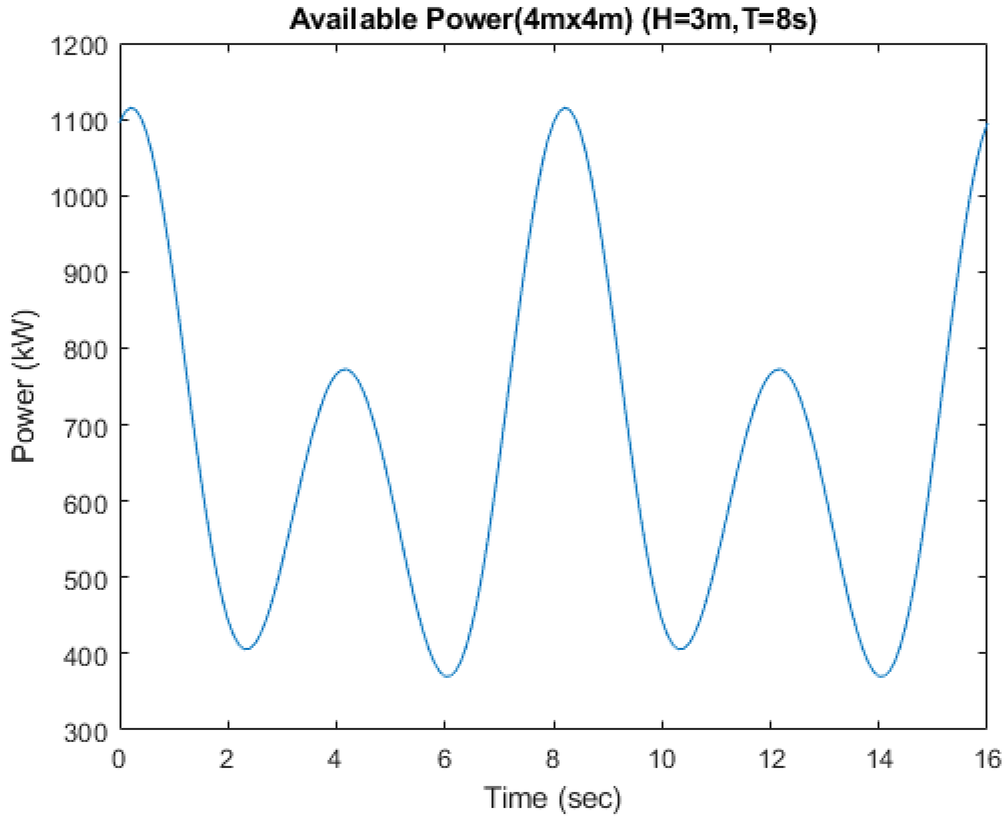
Available Power(4mx4m) (H=3m,T=4s)
Power (kW)
Time (sec)

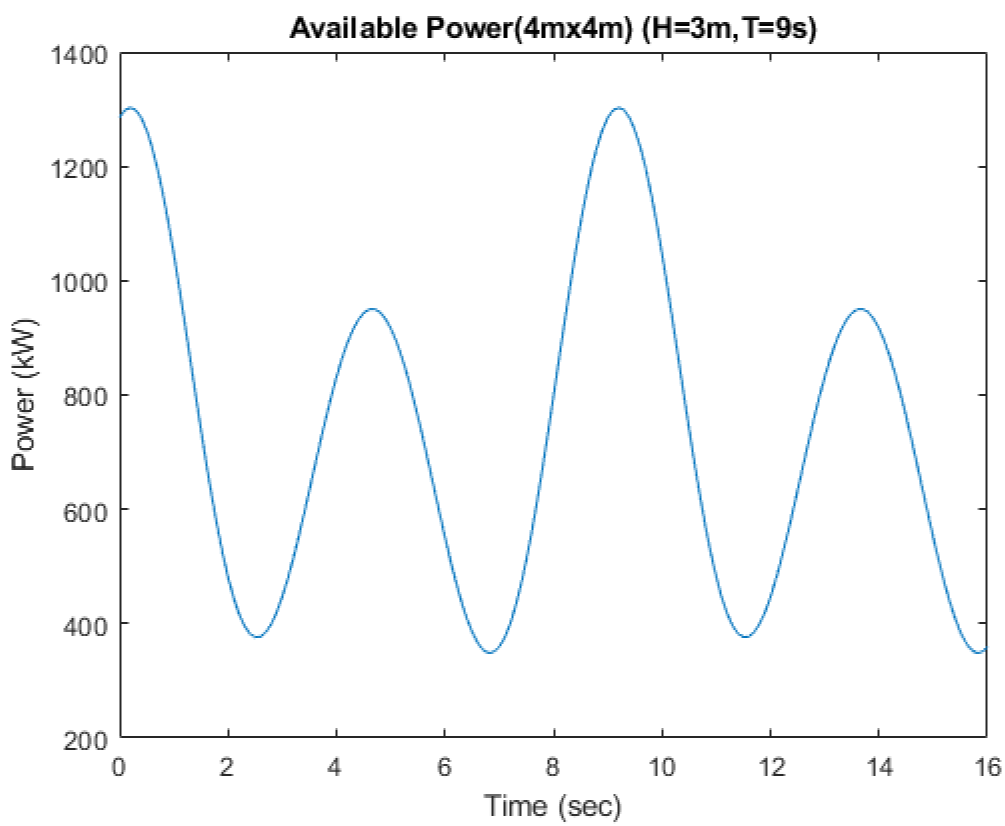


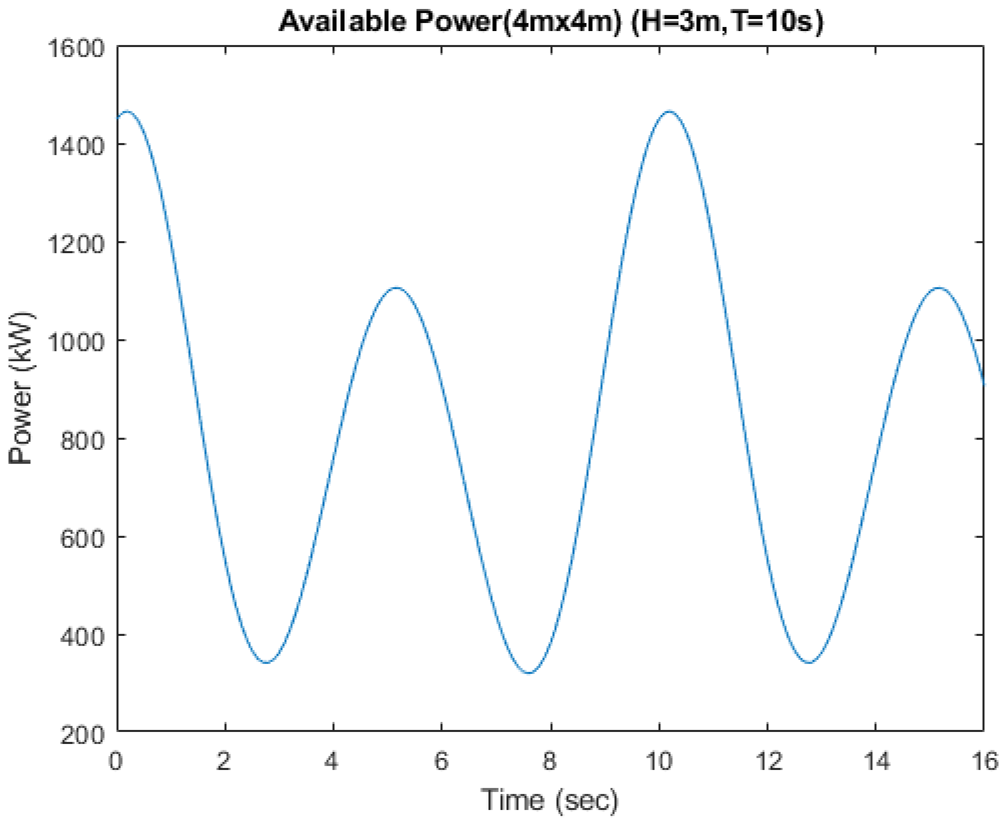
Available Power(4mx4m) (H=3m,T=5s)
Power (kW)
Time (sec)

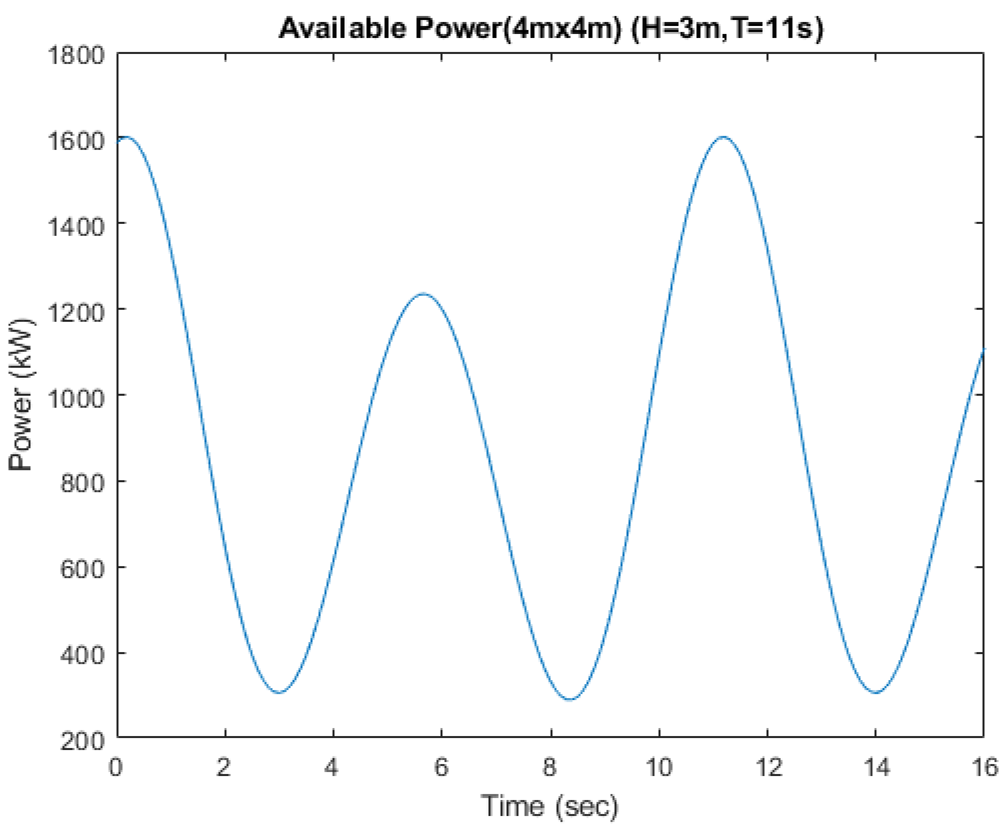

Available Power(4mx4m) (H=3m,T=6s)
Power (kW)
Time (sec)
750
700
650
600
550
500
450
400
350
300
0
2
4
6
8
10
12
14
16

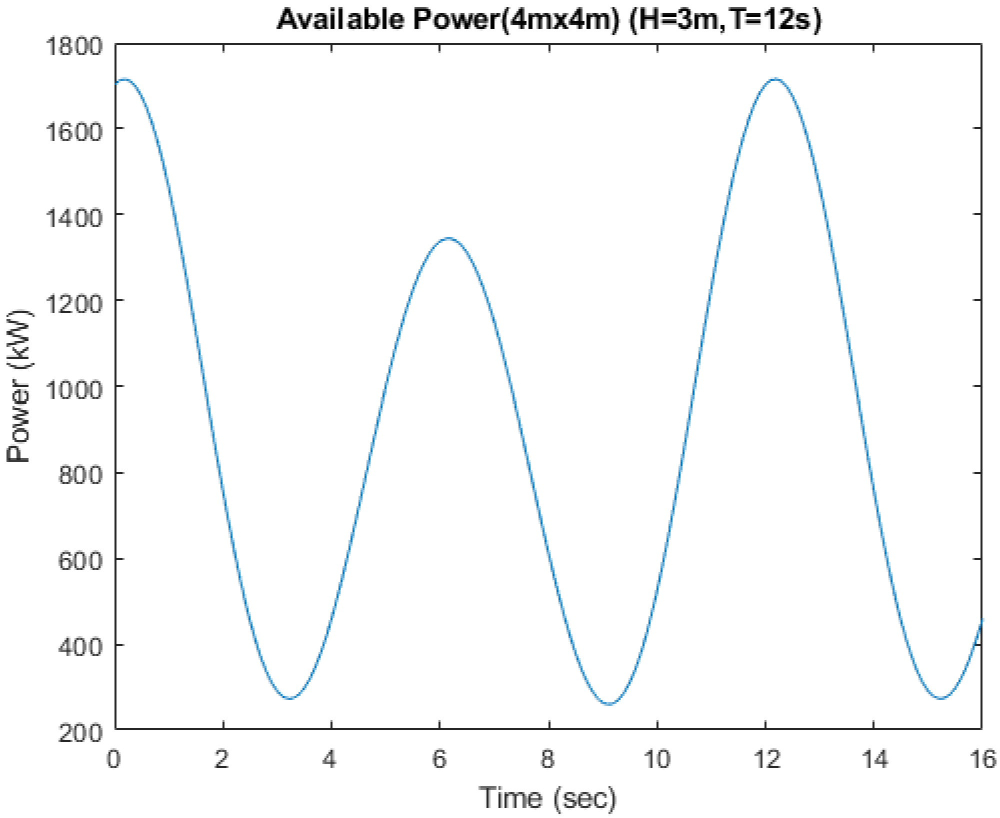

Available Power(4mx4m) (H=3m,T=7s)
Power (kW)
Time (sec)
1000
900
800
700
600
500
400
300
0
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=3m,T=8s)
Power (kW)
1200
1100
1000
900
800
700
600
500
400
300
0
2
4
6
8
10
12
14
16
Time (sec)

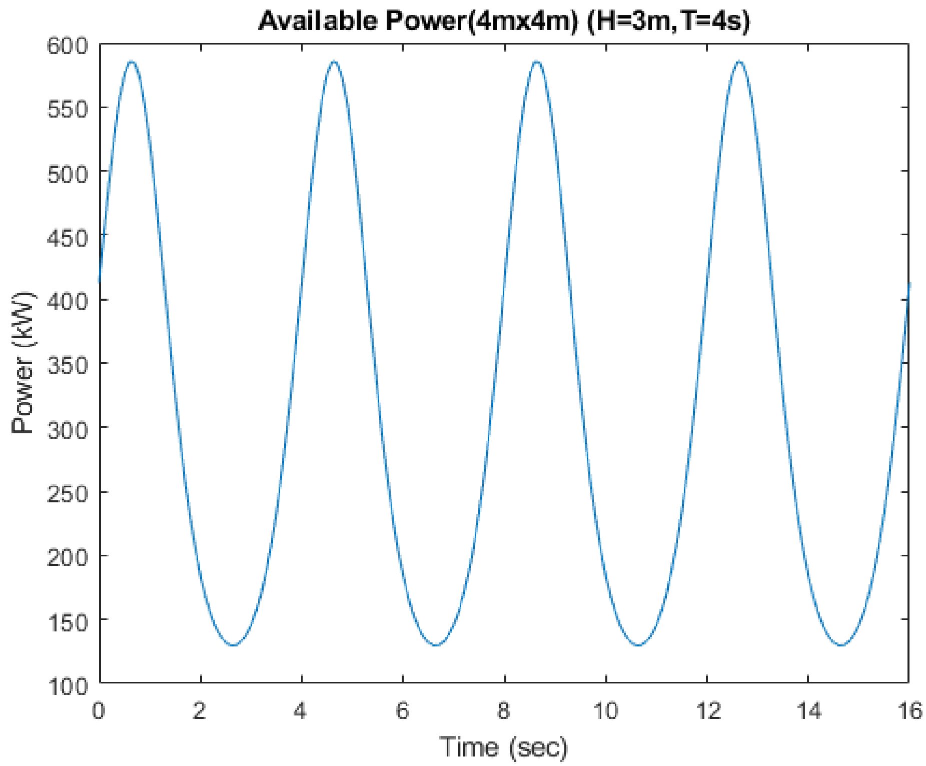

Available Power(4mx4m) (H=3m,T=9s)
Power (kW)
1400
1200
1000
800
600
400
200
0
2
4
6
8
10
12
14
16
Time (sec)

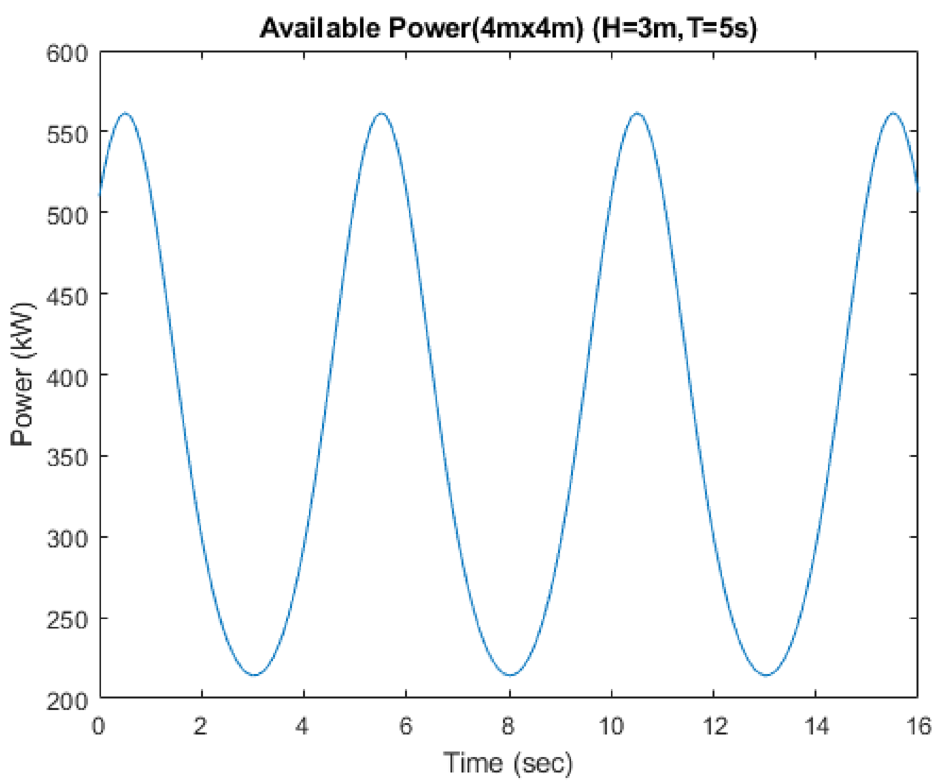

Available Power(4mx4m) (H=3m,T=10s)
Power (kW)
1600
1400
1200
1000
800
600
400
200
0
2
4
6
8
10
12
14
16
Time (sec)

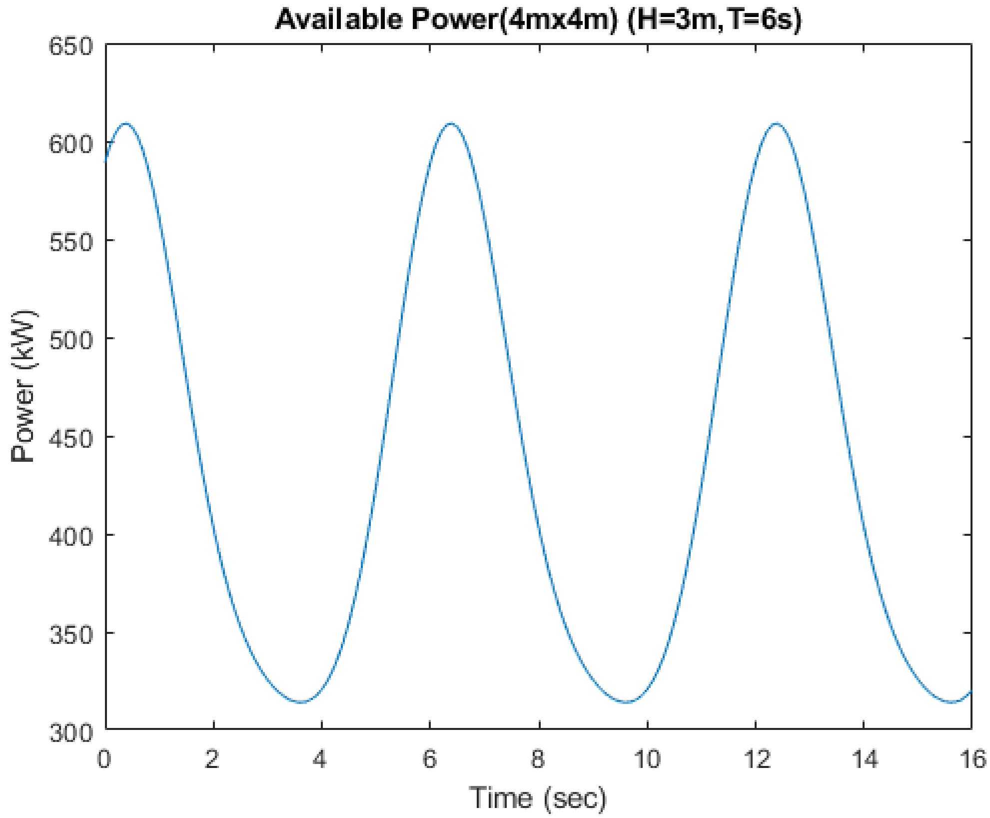

Available Power(4mx4m) (H=3m,T=11s)
Power (kW)
1800
1600
1400
1200
1000
800
600
400
200
0
2
4
6
8
10
12
14
16
Time (sec)

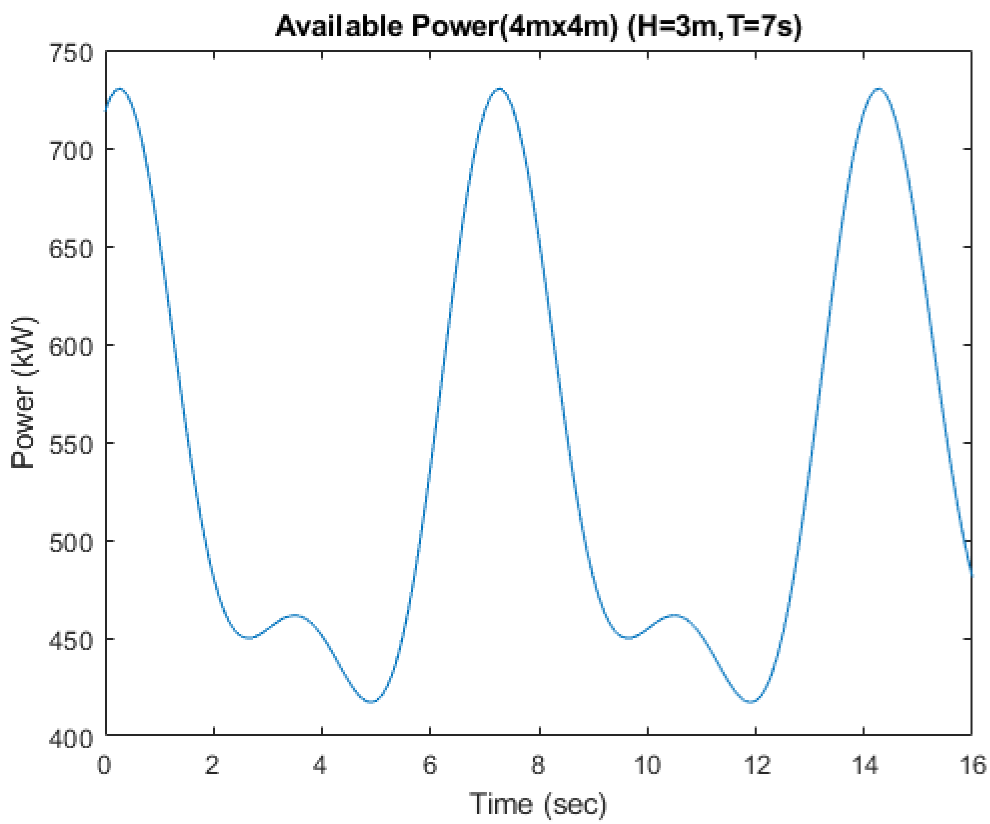

Available Power(4mx4m) (H=3m,T=12s)
Power (kW)
1800
1600
1400
1200
1000
800
600
400
200
0
2
4
6
8
10
12
14
16
Time (sec)

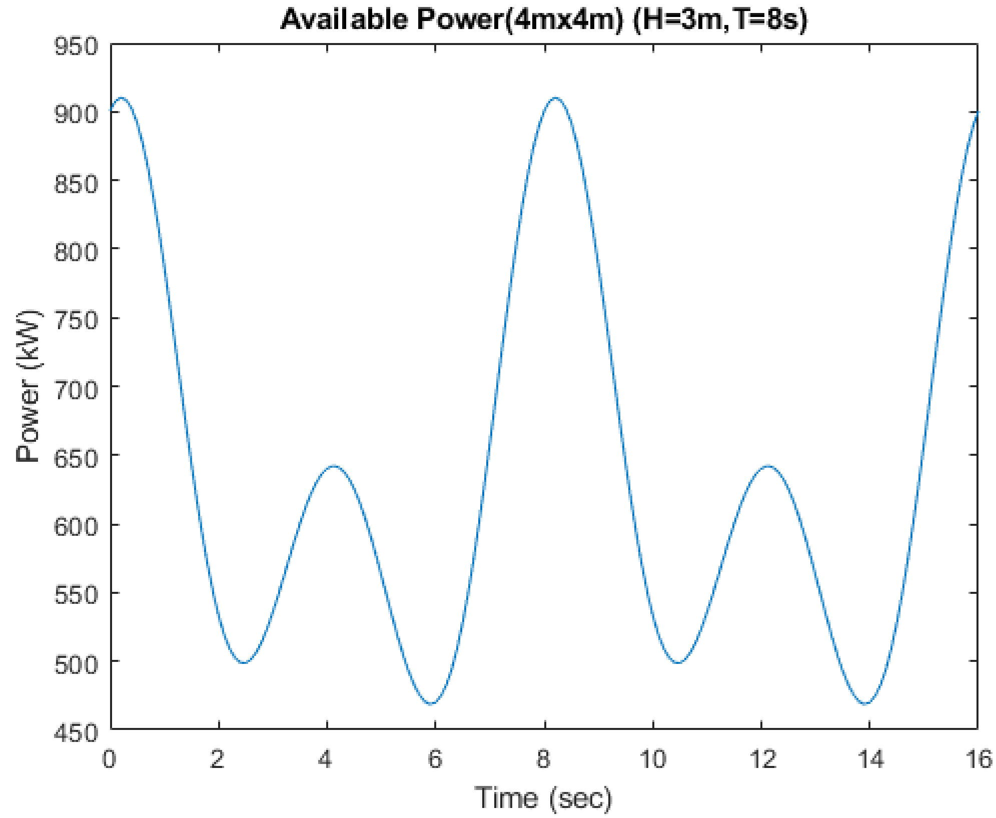
<u>H=3 m, h=26 m</u>


Available Power(4mx4m) (H=3m,T=4s)
Power (kW)
Time (sec)
600
550
500
450
400
350
300
250
200
150
100
0
2
4
6
8
10
12
14
16

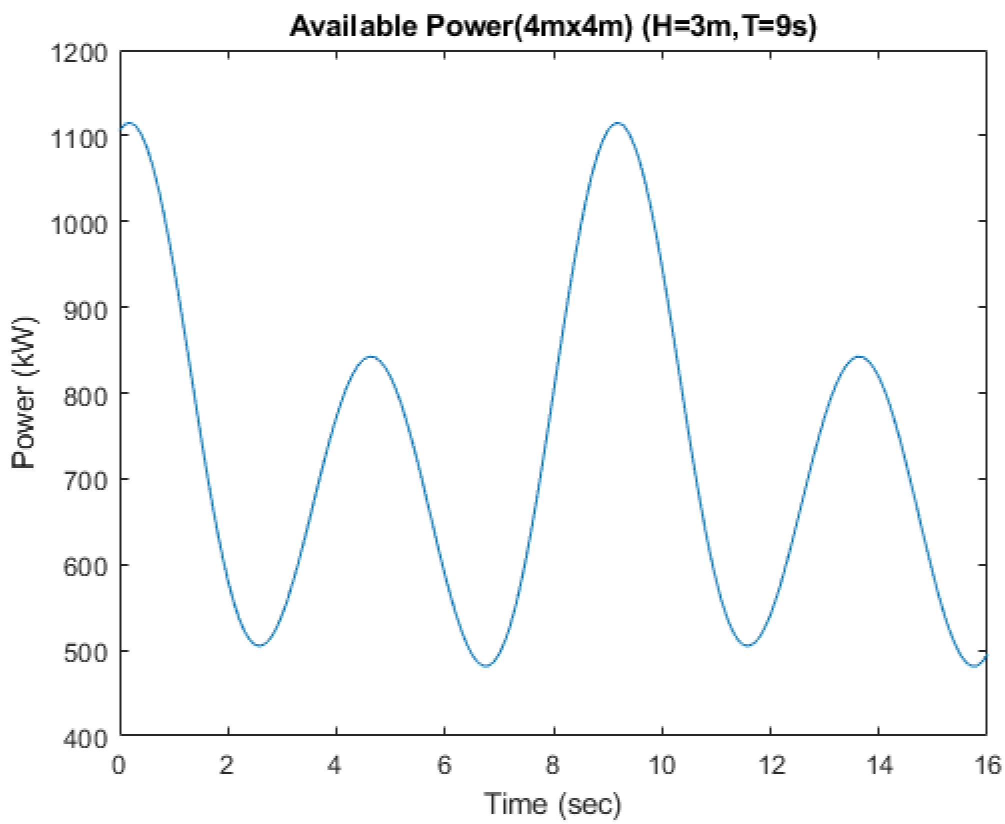

Available Power(4mx4m) (H=3m,T=5s)
Power (kW)
Time (sec)
600
550
500
450
400
350
300
250
200
0
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=3m,T=6s)
Power (kW)
Time (sec)
650
600
550
500
450
400
350
300
0
2
4
6
8
10
12
14
16

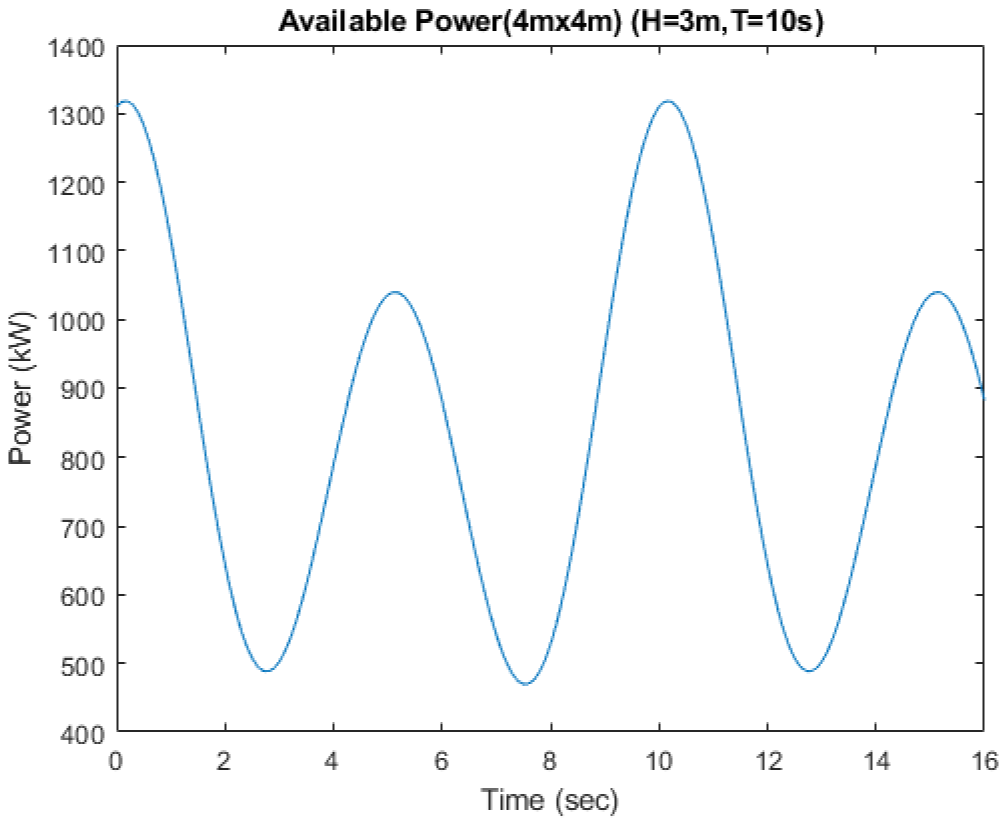

Available Power(4mx4m) (H=3m,T=7s)
Power (kW)
Time (sec)
750
700
650
600
550
500
450
400
0
2
4
6
8
10
12
14
16



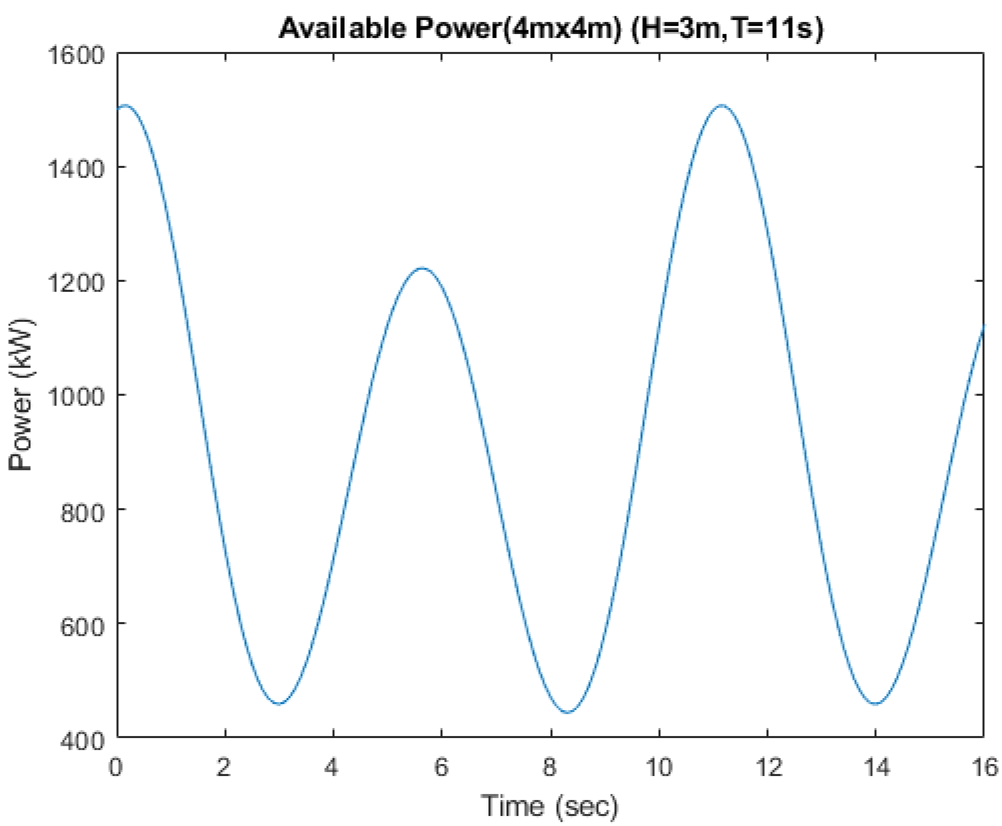
Available Power(4mx4m) (H=3m,T=8s)
Power (kW)
Time (sec)
950
900
850
800
750
700
650
600
550
500
450
0
2
4
6
8
10
12
14
16



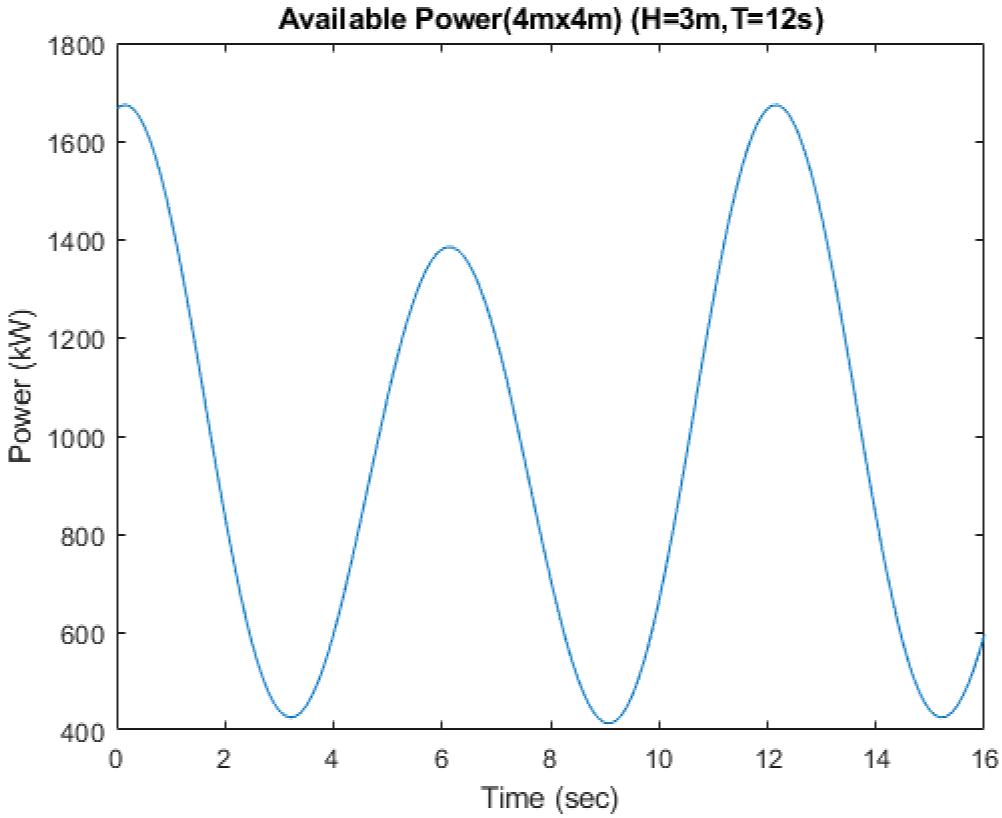
Available Power(4mx4m) (H=3m,T=9s)
Power (kW)
Time (sec)
1200
1100
1000
900
800
700
600
500
400
0
2
4
6
8
10
12
14
16



Available Power(4mx4m) (H=3m,T=10s)
Power (kW)
Time (sec)
1400
1300
1200
1100
1000
900
800
700
600
500
400
0
2
4
6
8
10
12
14
16



Available Power(4mx4m) (H=3m,T=11s)
Power (kW)
Time (sec)
1600
1400
1200
1000
800
600
400
0
2
4
6
8
10
12
14
16


Available Power(4mx4m) (H=3m,T=12s)
Power (kW)
Time (sec)
1800
1600
1400
1200
1000
800
600
400
0
2
4
6
8
10
12
14
16