A Thesis

entitled

Model Development and Load Analysis of an Offshore Wind Turbine

by

Mohammad Masoomi

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the

Master of Science Degree in

Mechanical Engineering

Dr. Theo Keith, Committee Chair

Dr. Abdollah Afjeh, Committee Member

Dr. Terry Ng, Committee Member

Dr. Patricia R. Komuniecki, Dean

College of Graduate Studies

The University of Toledo

August 2014
An Abstract of

Model Development and Load Analysis of an Offshore Wind Turbine

by

Mohammad Masoomi

Submitted to the Graduate Faculty as partial fulfillment of the requirements for the

Master of Science Degree in

Mechanical Engineering

The University of Toledo

August 2014

The purpose of this thesis is to investigate the loadings on and motion of an offshore wind turbine. The three major components of an offshore wind turbine are the wind turbine, the platform and the mooring lines. The effects of these components on the motion of the wind turbine were investigated. The NREL-5 MW offshore baseline model wind turbine was chosen for this study. The selected platforms are the surface and submerged TLP platforms suggested by MIT/NREL.

Loadings on an offshore wind turbine are the result of three primary forces. Aerodynamic forces, hydrodynamic forces and forces from the mooring lines. To start with the loadings from the waves, hydrodynamic coefficients were determined. This was accomplished by using the WAMIT (Wave Analysis at MIT) computer program to determine the hydrodynamic coefficients. The computer code FAST (Fatigue, Aerodynamics, Structures, and Turbulence) was then used to determine the effects of the wind turbine and the wave loads. An equation of motion was developed that incorporated these coefficients. The steady aerodynamic force was derived using Bernoulli’s equation. In
order to add the force from the mooring lines, a new code had to be written. This code assumed that each mooring line remained in the elastic region. Moreover, a stiffness matrix was computed and incorporated into the equation of motion. In the final step, the three primary forces were combined to calculate the wind turbine motion for six degrees of freedom with and without aerodynamic loads.

To validate the theoretical results scale model tests were performed within an existing water channel. A wide range of waves with different amplitudes and frequencies were generated within the channel. Various model platforms were constructed and the hydrodynamic coefficients were derived to compare with theoretical results. Finally, a comparison was made of platform configurations with different aspect ratios and designs. It was found that a submerged platform has less movement compared with a surface-based platform with the same shape. Also, the effects of wind speed and water depth on the motion of wind turbine were studied. It was found that at larger depth, the maximum amplitude occurs at higher frequency. The justification being that the stiffness of the mooring line will decrease as depth increases.
Acknowledgements

I would like to express my deep gratitude to my master thesis advisors, Drs. Afjeh, Ng and Keith. I have learned many things since I became a Research Assistant on Dr. Afjeh’s Wind Energy Project. Dr. Afjeh spent much time guiding me through the project and helped me to find the right path. Dr. Ng’s technical guidance and insight about experimental procedures was extremely helpful. Also, it was my great pleasure to work under the supervision of Dr. Keith. His advice was not only helpful for the project, but also for my life. All three are hard-working professors and I was fortunate to work with them.

Special thanks to the Mechanical, Industrial and Manufacturing Engineering Graduate Program. Not only did I learn many new things, but also I was able to do my experiments in their facilities.

During my two year period at the University of Toledo, I made many friends who added color to my life. I have to acknowledge all my lab mates in the wind tunnel for their assistance with many aspects of my research, which are too numerous to list here.

Last but not least important, I owe more than thanks to my family members which includes my parents and sister, for their support and encouragement throughout my life. Without their support, it would have been impossible for me to finish my college and graduate education seamlessly.
# Table of Contents

Abstract ............................................................................................................................ iii  

Acknowledgements ........................................................................................................ v  

Table of Contents ......................................................................................................... vi  

List of Tables ................................................................................................................ ix  

List of Figures ............................................................................................................... x  

1 Introduction ................................................................................................................. 1  

2 Analysis ....................................................................................................................... 5  

2.1 Analysis of an Offshore Wind Turbine ..................................................................... 5  

2.1.1 Wind Turbine ....................................................................................................... 5  

2.1.2 Analysis of Floating Platforms .......................................................................... 5  

2.1.2.1 Water Plane Restoring Matrix .................................................................... 8  

2.1.2.2 Buoyant Restoring Matrix .......................................................................... 9  

2.1.3 Mooring Lines .................................................................................................... 9  

2.2 Loads on an Offshore Wind Turbine ........................................................................ 10  

2.2.1 Aerodynamic Loads ........................................................................................... 11  

2.2.1.1 Steady Aerodynamic Loads ...................................................................... 11  

2.3 Hydrodynamic Loads ............................................................................................. 11
2.3.1 Steady State Hydrodynamic Loads .................................................. 14
2.3.2 Hydrostatic Forces .......................................................................... 14
2.3.3 Excitation Forces and Moments ......................................................... 15
2.4 Body Motion ......................................................................................... 16
3 Experimental Facilities, Instrumentation and Measurements .................. 17
  3.1 Test Facilities ...................................................................................... 17
  3.2 Wave Maker ....................................................................................... 18
  3.3 Instrumentation .................................................................................. 20
    3.3.1 Load Cells .................................................................................. 20
    3.3.2 Camera ....................................................................................... 20
  3.4 Platform .............................................................................................. 21
  3.5 Post Processing of Data ........................................................................ 21
  3.6 Measurements ..................................................................................... 24
  3.7 Errors and Limitations ......................................................................... 25
4 Results and Discussion ............................................................................ 26
  4.1 Experimental Results .......................................................................... 26
  4.2 Simulation Results .............................................................................. 28
    4.2.1 Hydrodynamic Coefficients .......................................................... 28
    4.2.2 Wind Turbine Motion .................................................................... 34
    4.2.3 Water Depth Effect ....................................................................... 35
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2.4</td>
<td>Wind Speed Effect</td>
<td>44</td>
</tr>
<tr>
<td>4.2.5</td>
<td>Platform Effect</td>
<td>45</td>
</tr>
<tr>
<td>5</td>
<td>Conclusion</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>48</td>
</tr>
</tbody>
</table>
List of Tables

2.1 Properties Chosen for the NREL 5-MW Baseline Wind Turbine ......................6
2.2 Platform Properties of the MIT/NREL TLPs..................................................7
3.1 Scale Factors for Each Variable.................................................................24
3.2 Description of measured parameters.........................................................24
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Coordinate system</td>
<td>10</td>
</tr>
<tr>
<td>2.2</td>
<td>Loads on an offshore wind turbine</td>
<td>12</td>
</tr>
<tr>
<td>2.3</td>
<td>Different Wave Theories</td>
<td>15</td>
</tr>
<tr>
<td>3.1</td>
<td>Water Channel</td>
<td>18</td>
</tr>
<tr>
<td>3.2</td>
<td>Wave Maker</td>
<td>19</td>
</tr>
<tr>
<td>3.3</td>
<td>Connector</td>
<td>19</td>
</tr>
<tr>
<td>3.4</td>
<td>D. C Motor</td>
<td>20</td>
</tr>
<tr>
<td>3.5</td>
<td>Camera</td>
<td>23</td>
</tr>
<tr>
<td>4.1</td>
<td>Wave Force on a Single Cylinder (Wave Frequency = 1.2 Hz)</td>
<td>26</td>
</tr>
<tr>
<td>4.2</td>
<td>Wave Force on a Single Cylinder (Wave Frequency = 1.6 Hz)</td>
<td>27</td>
</tr>
<tr>
<td>4.3</td>
<td>Wave Force on a Single Cylinder (Wave Frequency = 2.1 Hz)</td>
<td>27</td>
</tr>
<tr>
<td>4.4</td>
<td>Added Mass Matrices, MIT/NREL TLP, Submerged</td>
<td>29</td>
</tr>
<tr>
<td>4.5</td>
<td>Damping Matrices, MIT/NREL TLP, Submerged</td>
<td>30</td>
</tr>
<tr>
<td>4.6</td>
<td>Exciting Forces, MIT/NREL TLP, Submerged</td>
<td>31</td>
</tr>
<tr>
<td>4.7</td>
<td>Added Mass Matrices, MIT/NREL TLP, Surface</td>
<td>32</td>
</tr>
<tr>
<td>4.8</td>
<td>Damping Matrices, MIT/NREL TLP, Surface</td>
<td>33</td>
</tr>
<tr>
<td>4.9</td>
<td>Exciting Forces, MIT/NREL TLP, Surface</td>
<td>34</td>
</tr>
<tr>
<td>4.10</td>
<td>Schematic Overview of Simulation</td>
<td>36</td>
</tr>
<tr>
<td>4.11</td>
<td>Submerged Platform in 60m Depth</td>
<td>37</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>--------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>4.12</td>
<td>Submerged Platform in 150m Depth</td>
<td>38</td>
</tr>
<tr>
<td>4.13</td>
<td>Submerged Platform in 450m Depth</td>
<td>39</td>
</tr>
<tr>
<td>4.14</td>
<td>Submerged Platform</td>
<td>40</td>
</tr>
<tr>
<td>4.15</td>
<td>Surface Platform in 60m Depth</td>
<td>41</td>
</tr>
<tr>
<td>4.16</td>
<td>Surface Platform in 150m Depth</td>
<td>42</td>
</tr>
<tr>
<td>4.17</td>
<td>Surface Platform in 450m Depth</td>
<td>43</td>
</tr>
<tr>
<td>4.18</td>
<td>Surface Platform</td>
<td>44</td>
</tr>
<tr>
<td>4.19</td>
<td>Submerged Platform</td>
<td>45</td>
</tr>
<tr>
<td>4.20</td>
<td>Submerged and Surface Platform</td>
<td>46</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

Wind power is among the fastest growing renewable power generation methods. Wind energy can be generated without pollution and it is inexhaustible. According to the U.S Department of Energy, in 2012 [1], wind energy became the number one source of new U.S. electricity generation for the first time – representing 43 percent of all new electric additions and accounting for $25 billion in U.S. investment. Last year, over 13 gigawatts (GW) of new wind power capacity were added to the U.S. grid – nearly double the wind capacity deployed in 2011. This tremendous growth helped America’s total wind power capacity surpass 60 GW at the end of 2012 – representing enough capacity to power more than 15 million homes annually, or as many homes as in the states of California and Washington combined. The country’s cumulative installed wind energy capacity has increased more than 22-fold since 2000 [1].

The first modern wind turbine was built in 1887 in Scotland. Since then considerable research has been done to improve different aspects of them. As wind turbines became more complex, new problems emerged. A significant problem was the lack of suitable land to erect wind turbines. In order to solve that problem it has been suggested building them offshore. The offshore wind turbine concept was first introduced
by Professor William E. Heronemus at the University of Massachusetts in 1972 [2]. As of 2013, there are no offshore wind farms in the United States, but projects are under development along the coast lines that include the Atlantic and Pacific Oceans and the Great Lakes.

There are numerous advantages in using offshore wind energy [3].

- The wind is stronger, with less turbulence intensity
- The complaint from locals could be avoided if the turbines are installed a sufficient distance from shore.
- There are lots of available spots which can be used for the installation of offshore wind

On the other hand, there are also several disadvantages that include [3],

- Offshore wind turbine is generally more expensive. It is due to the higher cost of installation, design and maintenance.
- In addition to the experiencing loads from the wind, they should withstand loading from extreme conditions such as sea storms. All of these would increase the complexity of designs.

Offshore wind turbines have three main elements: the wind turbine (the main structure), the platform and the mooring lines. The platform supports the wind turbine and limits its motion in all six degrees of freedom. In order to be able to design the platform, we need to know the force which is exerted on the platform by the wind turbine, the sea waves and the mooring lines.
Stability of the platform of a floating wind turbine can be achieved by three different methods. These methods include stabilizing from the water plane area, from the ballast and from the mooring lines [4]. Each of these methods will be discussed in this thesis.

Forces on the wind turbine are mainly due to the wind. In this study calculation of aerodynamic forces on the turbine was made using the computer code FAST [5] (Fatigue, Aerodynamics, Structures, and Turbulence), which was developed at NREL (National Renewable Energy Laboratory) and is publicly available. The first step in the computational procedure is to model the wind turbine with this software. In these studies, the NREL 5-MW wind turbine, which represents a typical state of the art multi megawatt turbine, was used as the model. Next the environmental conditions in which the wind turbine is going to operate were prescribed. Premier among the parameters that are important is the wind speed. Also, it should be noted whether the wind is steady or turbulent. This information allows the software to determine the aerodynamic force on the turbine.

The wave loads were calculated using the computer code WAMIT [6] (Wave Analysis at MIT). The first step in this load calculation is to model the geometry of the platform. The geometry can be described in two ways. One method is to represent the platform by an ensemble of flat quadrilateral panels [6]. In the second method the platform’s geometry may be represented by an explicit analytical formula [6]. Next the wave condition must be prescribed. The waves may be regular or irregular and periodic or non-periodic. Also, the free surface must be specified as an input to the software. This
is especially important when extreme waves need to be modeled and non-linear effects are not negligible. After all of this the software may be run to produce the results.

A subroutine was used for the calculation of the force from the mooring lines. The inputs for the subroutine are: the elastic modulus of the mooring line material, the water depth and the angle of each line.

Finally, another module was constructed in order to calculate the motion of the whole system in the time domain. The hydrodynamic and aerodynamic forces and the force from the mooring lines are inputs to this subprogram as are the mass, damping and stiffness matrices.

In addition to the simulation results, a series of experiments were conducted in order to verify the results. The experiments were performed within a water channel located in the laboratories of the Department of Mechanical, Industrial and Manufacturing Engineering (MIME) at the University of Toledo. A wide range of waves with different amplitude were generated. Also several scale model platforms were built and hydrodynamic coefficients were measured for them.

This thesis is described in five chapters. Following this initial introductory chapter, Chapter 2 describes the analysis that was utilized. The equations which govern the motion of the platform, mooring lines and wind turbine are all presented in this chapter. Chapter 3 presents the experimental apparatus and procedure. The results obtained and comparisons with the experimental data are presented in Chapter 4. The final chapter contains a summary of the findings of this research and presents a number of recommendations and for further research.
Chapter 2

Analysis

A floating offshore wind turbine has three main parts: the platform, the wind turbine and the mooring system. The platform and mooring system have different configurations in different design concepts. In the following sections the wind turbine, the platform and the mooring system chosen for this study will be described.

2.1 Analysis of an Offshore Wind Turbine
2.1.1 Wind Turbine
The wind turbine chosen for this study is the NREL-5 MW offshore baseline wind turbine model. The description of the wind turbine is given in Table 2.1 [7]. It has been estimated, [4], that a 5 MW wind turbine is the minimum power that a deep floating wind turbine must have in order to be cost effective to build. NREL (National Renewable Energy Laboratory) has studied conceptual versions of this size wind turbine [7] and modeled it using the computer code FAST (Fatigue, Aerodynamics, Structures, and Turbulence).

2.1.2 Analysis of Floating Platforms
In order to numerically study the effects of waves on the platform of an offshore wind turbine, added mass, damping and exciting force hydrodynamic coefficients are needed. The WAMIT (Wave Analysis at MIT) software was used to calculate these
coefficients. WAMIT is a Radiation/diffraction program developed for the analysis of the interaction of surface waves with off shore structures. The water depth can be infinite or finite. Either one or multiple interacting bodies can be analyzed. The bodies may be located on the free surface, submerged, or mounted on the sea bottom. A variety of options permit the dynamic analysis of bodies which may be freely floating, restrained, or fixed in position.

Table 2.1 Characteristics of the NREL 5-MW Baseline Wind Turbine Used in this Thesis. [7]

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Orientation</td>
<td>Upwind</td>
</tr>
<tr>
<td>Control</td>
<td>Variable speed, Collective pitch</td>
</tr>
<tr>
<td>Rotor Diameter/ Hub Diameter</td>
<td>126 m/ 3m</td>
</tr>
<tr>
<td>Hub Height</td>
<td>90 m</td>
</tr>
<tr>
<td>Max Rotor/Generator Speed</td>
<td>12.1 rpm/1,173.7 rpm</td>
</tr>
<tr>
<td>Maximum Tip Speed</td>
<td>80 m/s</td>
</tr>
<tr>
<td>Overhang/Shaft Tilt/Precone</td>
<td>5m/ 5° / -2.5°</td>
</tr>
<tr>
<td>Rotor Mass</td>
<td>110,000 Kg</td>
</tr>
<tr>
<td>Nacelle Mass</td>
<td>240,000 Kg</td>
</tr>
<tr>
<td>Tower Mass</td>
<td>347,460 Kg</td>
</tr>
</tbody>
</table>
Table 2.2 Platform Properties of the MIT/NREL TLPs [7]

<table>
<thead>
<tr>
<th>Property</th>
<th>Surface TLP (m)</th>
<th>Submerged TLP (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Cylinder Height</td>
<td>26</td>
<td>24</td>
</tr>
<tr>
<td>Tower Draft</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Installed Draft</td>
<td>22.75</td>
<td>36</td>
</tr>
<tr>
<td>Deck Clearance</td>
<td>3.25</td>
<td>-10</td>
</tr>
<tr>
<td>Center of Gravity</td>
<td>-12.01</td>
<td>-25.26</td>
</tr>
</tbody>
</table>

The geometry of the platform was defined using a GDF (Geometric Data File). It includes the Cartesian coordinates of each vertex of each panel, listed sequentially.

The added mass terms, Eqs.(2.1)- (2.4) and the damping coefficients, Eqs.(2.5)- (2.8), were non-dimensionalized by dividing the added mass by the product of the water density and the volume of submerged structure, i.e., \( \rho \cdot V \), and dividing the damping coefficients by the product of the density, the volume of submerged structure, and the wave frequency, i.e., \( \rho \cdot V \cdot \omega \). The dimensionless frequency was defined by multiplying the frequency by the square root of the characteristic dimension, \( R \), divided by the gravitational constant, \( g \), i.e., \( \sqrt{\frac{R}{g}} \).

\[
\bar{A}_{ij} = \frac{A_{ij}}{\rho_{\text{water}} L^k}
\] (2.1)
Here $A_{ij}$ and $B_{ij}$ are added mass and damping matrices, respectively. And $L$ is the characteristic length. The platform gains stiffness from three different sources. These sources are: the water plane, buoyancy and the mooring line [4].

In order to build the mass matrix for the platform, it is assumed that the center of mass of the structure on which the wind turbine sits is located at $(x_{CG}, y_{CG}, z_{CG})$.

### 2.1.2.1 Water Plane Restoring Matrix

When a platform rotates, the buoyancy force will decrease on one side and increase on the other side. This will cause the platform to rotate to its initial position. Because of symmetry the only non-zero entries in the water plane restoring matrix are the diagonal entries for heave, pitch and roll. The stiffness is given in Eqs. (2.9) – (2.11):

\[
C_{33,\text{water plane}} = \rho g \int \int dA = \rho g \pi R^2 
\]  
(2.9)

\[
C_{44,\text{water plane}} = \rho g \int \int x^2 dA = \frac{\rho g \pi R^4}{4} 
\]  
(2.10)

\[
C_{55,\text{water plane}} = \rho g \int \int y^2 dA = \frac{\rho g \pi R^4}{4} 
\]  
(2.11)
2.1.2.2 Buoyant Restoring Matrix

Also by lowering the center of gravity in comparison to the center of buoyancy, stiffness can be gained by the amount shown in Eqs. (2.12) - (2.14):

\[
\text{Center of buoyancy} = \frac{d}{2}
\]

\[
C_{44,\text{Buoyant}} = \frac{\rho g d m_{\text{buoyant}}}{2} - m_{\text{total}} g z_{\text{CG}}
\] (2.13)

\[
C_{55,\text{Buoyant}} = \frac{\rho g d m_{\text{buoyant}}}{2} - m_{\text{total}} g z_{\text{CG}}
\] (2.14)

2.1.3 Mooring Lines

Mooring lines provide stiffness to the system. There are several different types of mooring lines. The line which is chosen to be studied in this thesis is part of the Tension Leg Mooring System. Tension mooring systems contain several parallel tethers which are attached to the seabed. The important features of these tethers are the fact that they are in pre-tension. The great advantage of this design is that it gives good stiffness for vertical, pitching and rolling motions. In an offshore wind turbine usually three legs are used.

Throughout the analysis it was assumed that the mooring line is a straight and that it remained in the elastic region of the mooring line material and that the angle between the mooring line and an imaginary horizontal line is \( \theta \). The pre-tension of the mooring line is \( F_{\text{Tether}} \). For a small imaginary displacement in the x direction to the platform, we may write:

\[
dF = F_{\text{Tether}} (\cos(\theta + d\theta) - \cos(\theta - d\theta)) = -F_{\text{Tethers}} \sin(\theta) \, d\theta
\] (2.15)

\[
dx = L_{\text{Tether}} \sin(\theta) \cdot d\theta
\] (2.16)

\[
C_{11} = \frac{F_{\text{Tethers}}}{L_{\text{Tether}}}, \quad C_{22} = \frac{F_{\text{Tethers}}}{L_{\text{Tether}}}
\] (2.17)
In the z direction, we have:

\[
\Delta z = \frac{\Delta F L_{\text{Tether}}}{E_{\text{Tether}} A_{\text{Tether}}}, \quad c_{33} = \frac{E_{\text{Tether}} A_{\text{Tether}}}{L_{\text{Tether}}}
\]  \hspace{1cm} (2.18)

And by writing the equilibrium equation around the center we have

\[
c_{44} = \frac{2E_{\text{Tether}} A_{\text{Tether}}}{L_{\text{Tether}}} (R^2),
\]  \hspace{1cm} (2.19)

\[
c_{55} = \frac{2E_{\text{Tether}} A_{\text{Tether}}}{L_{\text{Tether}}} (R^2)
\]

\[
c_{66} = \frac{R^2}{L_{\text{Tether}}} (F_B - M_{11} g),
\]  \hspace{1cm} (2.20)

\[
c_{51} = c_{42} = -\frac{F_{\text{Tether}}}{L_{\text{Tether}}} T
\]

### 2.2 Loads on an Offshore Wind Turbine

The loading on an onshore wind turbine is dominated by aerodynamic loads. In an offshore wind turbine hydrodynamic loads play an important role, too. The other sources of force on an offshore wind turbine are loads from ice and the variation of mean sea level, which could have significant effects in some cases. In the following sections, information concerning these forces will be presented [8].
2.2.1 Aerodynamic Loads
The energy which is produced from a wind turbine is from the interaction of wind and the airfoils of each blade. The lift and drag forces are consequences of this interaction. The aerodynamic loads can be categorized in three parts [8]: steady aerodynamic forces, periodic aerodynamic forces and randomly fluctuating aerodynamic forces. In this study, only steady aerodynamic forces will be considered.

2.2.1.1 Steady Aerodynamic Loads
The steady aerodynamic load is generated by the mean wind speed. When the wind strikes the wind turbine, its velocity will fall. According to Bernoulli’s equation, when there is velocity discontinuity in the fluid, a pressure difference will appear. This pressure difference will act over the rotor area, A, and produces a thrust force that is given by,

\[ F_{\text{Thrust}} = A(P_\text{a} - P_\text{b}) = \frac{1}{2} \rho A(v_1^2 - v_2^2) \]  

(2.21)

This force also produces a moment about the origin. This moment can be calculated by:

\[ T = F_{\text{Thrust}}z_{\text{Hub}} \]  

(2.22)

These forces will push the wind turbine downwind as shown in Figure 2. In turn this will produce some tension in the mooring lines. Also, the moment will be balanced by the moment from the ballast, buoyancy and mooring lines.

2.3 Hydrodynamic Loads
The other important source of loads on an offshore wind turbine is hydrodynamic. The size of the hydrodynamic load depends on many factors, e.g., wave height, wave amplitude, wave frequency and wave speed. In the following section, the theory behind the calculation of the hydrodynamic loads will be briefly discussed [9].
Since it is assumed that the fluid is incompressible and inviscid, the velocity potential has to satisfy Laplace equation [9].

$$\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} + \frac{\partial^2 \Phi}{\partial z^2} = 0$$ \hspace{1cm} (2.23)

Also, the Bernoulli’s equation can be used to write the equation to find pressure, p.

$$p + \rho gz + \rho \frac{\partial \Phi}{\partial t} + \frac{\rho}{2} V^2 = C$$ \hspace{1cm} (2.24)

In order to solve these equations, boundary conditions must be prescribed. If there is the body moving with velocity $U$ , the boundary condition can be written as:
\[
\frac{\partial \phi}{\partial n} = u \cdot \vec{n} \quad (2.25)
\]

In the equation \( n \) denotes the direction along the normal to the body surface. If the body is fixed, Eq. (2.25) could simply be written as

\[
\frac{\partial \phi}{\partial n} = u \cdot \vec{n} \quad (2.26)
\]

And for the free-surface condition, the assumption is that a fluid particle will remain on free-surface. So after some derivation [10], the boundary condition on the free surface can be written as:

\[
\frac{\partial \zeta}{\partial t} + \frac{\partial \phi}{\partial x} \frac{\partial \zeta}{\partial x} + \frac{\partial \phi}{\partial y} \frac{\partial \zeta}{\partial y} - \frac{\partial \phi}{\partial z} = 0 \quad (2.27)
\]

Equations (2.24) and (2.27) are non-linear. In order to solve these equations, the problem was simplified by linearizing the free surface boundary condition. By this assumption, these equations can be written as:

\[
\frac{\partial \zeta}{\partial t} = \frac{\partial \phi}{\partial z} \quad (2.28)
\]

\[
g \zeta + \frac{\partial \phi}{\partial t} = 0 \quad (2.29)
\]

By combining Eqs. (2.28) and (2.29):

\[
\frac{\partial^2 \phi}{\partial t^2} + g \frac{\partial \phi}{\partial z} = 0 \quad (2.30)
\]

The region in which linear wave theory can be applied is shown in Figure 2. Linear theory can be safely used to analyze a floating wind turbine that is installed in deep water.

From these equations, the velocity potential and the wave potential can be written as:
\[ \phi = \frac{g^T z_a}{\omega} e^{ikx} \cos(\omega t - kx) \]  
(2.31)

\[ \zeta = z_a \sin(\omega t - kx) \]  
(2.32)

In the equations, \( z_a \) is wave amplitude. The equations for the velocity potential, pressures, velocities, and accelerations for plane progressive waves which satisfy the free-surface boundary condition can be found in Faltinsen [11].

### 2.3.1 Steady State Hydrodynamic Loads

The force on the platform from waves using linear wave theory can be formulated as.

\[ F_i^{\text{platform}}(t) = -A_{ij}(\omega) \ddot{\eta}_j - B_{ij}(\omega) \dot{\eta}_j - C_{ij} \eta_j + \rho g V_0 \delta_{i3} + AX_i(\omega, \beta) \]  
(2.33)

In Eq. (2.34), \( A \) is wave amplitude, \( \omega \) is wave frequency and \( \beta \) is its direction. \( A_{ij} \) and \( B_{ij} \) are 6 by 6 matrices of added mass and damping coefficients. \( \eta \) is 6 by 1 vector of displacement. \( C_{ij} \) is hydrostatic restoring matrix and \( X_i \) is 6 by 1 exciting force matrix.

### 2.3.2 Hydrostatic Forces

There are three types of hydrostatic forces that must be considered in the analysis: buoyancy force, restoring forces from water-plane area effects, and effects from the change of the COB (Center of Buoyancy) position.

The stiffness matrix for hydrostatic forces could be written as below.

\[
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \rho g A_0 & 0 & 0 & 0 \\
0 & 0 & 0 & \rho g \int_{A_0} y^2 \, dA + \rho g V_0 Z_{COB} & 0 & 0 \\
0 & 0 & 0 & 0 & \rho g \int_{A_0} x^2 \, dA + \rho g V_0 Z_{COB} & 0 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]  
(2.34)
2.3.3 Excitation Forces and Moments

When the waves strike the structure, they will exert a force on the structure. This force is generated from two different sources. The fluid around the structure is the superposition of the undisturbed fluid and the fluid involved with scattered waves from the structure. The forces due to undisturbed waves are called Froude-Kriloﬀ forces and the forces from
scattered waves are called the scattering forces or diffraction forces. The sum of these two forces is called the wave excitation force.

2.4 Body Motion
The module which calculates the motion of the structure is part of WAMIT. In this module it is possible to separately specify external mass, damping and stiffness matrices. This permits analysis of bodies which are not freely floating in waves. The input for this module is density of fluid, the mass and added mass matrices, damping matrix and stiffness matrix.
Chapter 3

Experimental Facilities, Instrumentation and Measurements

The purpose of the experiments contained within this thesis was to measure the force on a scaled platform which was exerted by waves with different frequencies and amplitudes. The experiments were conducted within a water tunnel at the University of Toledo. Waves were generated using a wave maker which was built for this study. Force measurements were done using a six-axis force/torque sensor. Each measurement was performed several times and confidence interval method was used to identify the reliability of the experiments.

3.1 Test Facilities
As stated earlier, all tests on the scale model platforms were conducted in a water tunnel, which consists of an 18 inch deep × 12 inch wide × 100 inch long water tank, Figure 3.1, shows a manually operated plank that acted as a simple wave generator. The depth of water in the flume was kept constant for all tests at 0.6 meters. The test section of the flume had a transparent side wall for model viewing. A video camera was used to capture the side view of the flume and observe the wave heights incident on the platform. A plunger-type wave maker was located about 30 inches upstream of the test model. The water tunnel was equipped with two pumps with the power of 560 Watts which circulated water to the system.
The flowing water of the flume had many disturbances in its upstream section, so honeycombs were placed at the entrance of the tunnel in order to reduce these disturbances.

3.2 Wave Maker
A wave generator capable of producing a range of frequencies and amplitudes was required. In order to accomplish this, a piston type wave generator was designed and built. The generator and connector are shown in Figs. 3.2 and 3.3. The assembly was driven by a D. C motor, Figure 3.4. The D.C motor is 1.5 horsepower and was built by WESLO INC. The motor would drive the wave maker up and down using the connector.

Figure 3.1- Water Channel
Figure 3.2 Wave Maker

Figure 3.3 Connector
The range of the frequencies and amplitudes of the waves that were produced was 1-10 Hz and 0-4 cm.

### 3.3 Instrumentation

#### 3.3.1 Load Cells

A six-axis force/torque sensor (Nano 25, serial number FT11132) manufactured by ATI Industrial Automation was used. The operating range of the load cell is 125 N in the x and y directions and 500 N in the z direction. The sensor could measure torque values of up to 3N-m in all 3 directions. The sensor’s output range is ±10V. These load cells were suitable for this experiment since they are sufficiently sensitive to capture the wave loads on the model structures. The National Instruments data acquisition hardware and software (LabView) were used to collect and process the sensor’s signals.

#### 3.3.2 Camera

There are many ways for measuring the wave height and wave length in the water tunnel. In this thesis, a photographic measurement technique was used. The PIVCAM 10-30
model 630046 was used for this purpose, Figure 3.5. The camera is capable of taking up to 25 frames per second. Using the camera’s Insight Software, measurements can be performed, producing very accurate results.

3.4 Platform
Scale-model platforms were constructed using ABS plastic as the primary structural material. The length of the platform is 26 cm and its radius is 11 cm.

3.5 Post Processing of Data
Because a full scale version of the floating wind turbine could not be run in the test facility, a scale model of it was built. In order to use the data obtained from experiments on the scale model, scaling of the results was necessary. There are two important non-dimensional numbers involved in this experiment: the Froude and Reynolds numbers.

The Reynolds number is defined as the ratio of inertia forces to viscous forces. As Reynolds number increases, effects of inertia increases compare to viscous forces. Equality in Reynolds number will ensure that viscous forces are correctly scaled. On the other hand, the Froude number is defined as the ratio of body’s inertia to gravitational force. Equality of the Froude Number between the model and the full scale version will ensure that gravity forces are correctly scaled. Considering the fact that surface waves are gravity-driven this equality will ensure that wave resistance is correctly scaled.

Fr-Re scaling can only be satisfied if the model is made full size.

Here the model is 1 and the Full Size is 2

\[ Re = \left( \frac{UL}{v} \right)_1 = \left( \frac{UL}{v} \right)_2 \] (3.1)
If \( v_1 = v_2 \) and since \( g = g_1 = g_2 \)

We see that \((UL)_1 = (UL)_2\) and \((\frac{v_2}{v_1})^2 = (\frac{l_1}{l_2})^2 = \frac{l_1}{l_2}\) Hence,

So, \( L_1^2 \cdot L_2 = L_2^2 \cdot L_1 \) Therefore, \( L_1 = L_2 \) and the model would have to be tested at full size which is not practical. The only other option would be to perform the tests with a fluid different from water.

In this study, because it is being performing at relatively high Reynolds numbers effects of viscous forces was neglected. So, in order to compare the results from scaled model to actual model the Froude number was kept the same [12].

First, a geometric scaling ratio was defined as

\[
\lambda = \frac{L_{FS}}{L_M} \tag{3.3}
\]

Where \( L_{FS} \) denotes the characteristic length of the full scale model and \( L_M \) denotes the characteristic length of the model. The Froude number is defined as:

\[
Fr = \frac{U}{\sqrt{gL}} \tag{3.4}
\]
In Eq. (3.4) \( U \) is the characteristic velocity, \( L \) is the characteristic length and \( g \) is the acceleration of gravity. The goal is to equalize the Froude number of the model with full scale platform. In order to accomplish that, we write [12]:

\[
\text{Fr}_m = \text{Fr}_fs \rightarrow U_{fs} = U_M \sqrt{\frac{L_{FS}}{L_M}}
\]  

Equation (3.5) can be written as:

\[
U_{fs} = U_M \sqrt{\lambda}
\]  

For other physical parameters, the same procedure can be done. For example, acceleration will change by a factor of 1, while force varies by the scale of \( \lambda^3 \). The full list of scaled properties is contained in Table 3.1.

The important issue in this analysis is that Reynolds number and Froude number of scale and full size platform could not be equalized at the same time.
3.6 Measurements
For the measurements, the scale model was put in the water channel and it was attached to the load cells. The measurements were done in three different frequencies. The results were gathered using ATI software.

The parameters that are measured are summarized in Table 3.2.

Table 3.1- Scale Factors for Each Variable

<table>
<thead>
<tr>
<th>Variable</th>
<th>Dimensions</th>
<th>Units</th>
<th>Scale Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>$L$</td>
<td>$m$</td>
<td>$\lambda$</td>
</tr>
<tr>
<td>Mass</td>
<td>$M$</td>
<td>Kg</td>
<td>$\lambda^3$</td>
</tr>
<tr>
<td>Angle</td>
<td>None</td>
<td>Rad</td>
<td>1</td>
</tr>
<tr>
<td>Acceleration</td>
<td>$L/T^2$</td>
<td>$m/S^2$</td>
<td>1</td>
</tr>
<tr>
<td>Angular Acceleration</td>
<td>$1/T^2$</td>
<td>$1/S^2$</td>
<td>$\lambda^{-1}$</td>
</tr>
<tr>
<td>Angular Velocity</td>
<td>$1/T$</td>
<td>$1/S$</td>
<td>$1/\sqrt{\lambda}$</td>
</tr>
<tr>
<td>Force</td>
<td>$(M*L)/T^2$</td>
<td>$(kg*m)/S^2$</td>
<td>$\lambda^3$</td>
</tr>
<tr>
<td>Wave Height</td>
<td>$L$</td>
<td>$m$</td>
<td>$\lambda$</td>
</tr>
<tr>
<td>Wave Period</td>
<td>$T$</td>
<td>$S$</td>
<td>$\sqrt{\lambda}$</td>
</tr>
<tr>
<td>Velocity</td>
<td>$L/T$</td>
<td>$m/S$</td>
<td>$\sqrt{\lambda}$</td>
</tr>
<tr>
<td>Moment of Inertia</td>
<td>$M*L^2$</td>
<td>$kg*m^2$</td>
<td>$\lambda^3$</td>
</tr>
</tbody>
</table>

Table 3.2-Description of measured parameters

<table>
<thead>
<tr>
<th>Measured Parameters</th>
<th>Units</th>
<th>Equipment Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force</td>
<td>N</td>
<td>Load Cell</td>
</tr>
<tr>
<td>Wave Frequency</td>
<td>Hz</td>
<td>Camera</td>
</tr>
<tr>
<td>Wave Amplitude</td>
<td>cm</td>
<td>Camera</td>
</tr>
</tbody>
</table>
3.7 Errors and Limitations

There are different source of errors in the experiment. One of them is error in measuring the force from load cells. Load cells could not measure the force exactly. Also the waves which produced in water channel are not only composed of one frequency.

One of the limitations of the experimental effort was that a full scale platform could not be used to perform the tests. Hence, a scale model of the platforms was built and the experiments were performed using them. The Froude and Reynolds numbers for both the scale model and the full size platform could not be satisfied simultaneously. Consequently, the experiments do not exactly represent the real case. Also, the frequencies of waves which were produced in the water channel were very limited.

It should be mentioned that the purpose of these experiments was not to precisely simulate the motion of a floating wind turbine. Rather, the tests were performed on reasonably close approximants of the offshore wind turbine platforms to validate the tools that were employed to calculate the forces on the platforms.
Chapter 4

Results and Discussion

In this section, results from the experiments and simulations are shown. First results of experiments that verified the WAMIT results are shown. Then hydrodynamic coefficients of platforms are presented. Finally, by using these data, motion of an offshore wind turbine are displayed.

4.1 Experimental Results
First we show the results for the single cylinder with the radius of 3 cm and length of 25 cm. The waves with different frequencies were generated and waves were measured and compared with theory.

![Figure 4.1 Wave Force on a Single Cylinder (Wave Frequency = 1.2 Hz)](image.png)
Figure 4.2 Wave Force on a Single Cylinder (Wave Frequency = 1.6 Hz)

Figure 4.3 Wave Force on a Single Cylinder (Wave Frequency = 2.1 Hz)
4.2 Simulation Results

4.2.1 Hydrodynamic Coefficients

Using the geometric data file for WAMIT software [6] a mesh was first created and the program was run to obtain hydrodynamic coefficients of the platforms which were studied in this thesis. The damping and added mass matrices are 6 by 6 and therefore have 36 components. Figure 4.4 - Figure 4.9 show these components for each matrix.

Plots of non-dimensional added mass for four different components are presented in Figure 4.4 and Figure 4.7. It is obvious from the figures that the added mass changes very little as frequency changes in a submerged platform, but that it changes drastically in the surface platform. The main reason is that waves act differently when they strike the surface of the platform at different frequencies.

Also, in Figure 4.5 and Figure 4.8, plots of non-dimensional damping coefficients are presented. The forces in the x and z directions and the moment in the y direction are shown in Figure 4.6 and Figure 4.9. The rise of the force in the x direction is due to waves impacting the surface of the platform.
Figure 4.4 Added Mass Matrices, MIT/NREL TLP, Submerged
Figure 4.5 Damping Matrices, MIT/NREL TLP, Submerged
Figure 4.6 Exciting Forces, MIT/NREL TLP, Submerged
Figure 4.7 Added Mass Matrices, MIT/NREL TLP, Surface
Figure 4.8 Damping Matrices, MIT/NREL TLP, Surface
Finally it was decided to determine how the variation of important system parameters affected the platform movement. A major consideration which is crucial in determining
the platform movement is whether the platform is submerged or whether it is surface piercing. In first case the loads on the platform will be reduced but on the other hand if the structure pierces the wave free surface it will gain stiffness and stability. The other important consideration which affects the movement of the platform is depth of the sea in which the wind turbine is positioned.

In order to simulate platform motion, we need to know the wind turbine properties. In order to acquire that information, the computer code FAST must be run for a particular operating point. FAST provided mass, damping and stiffness matrices. Also, by using WAMIT, we have the added mass and damping matrices for the platform. Finally, by adding the effects of the mooring line we could solve the equation of motion for the wind turbine.

In order to obtain this information, the FAST code was run to obtain the linearized mass, damping and stiffness matrices. The response was non-dimensionalized by dividing the motion by wave amplitude.

The whole simulation procedure is shown in Figure 4.10.

4.2.3 Water Depth Effect
To study the effect of water depth on the motion of wind turbine, the simulation was performed for several water depths. Floating wind turbines are mainly used at depths deeper than 50 m. Consequently, the first simulation depth was at 60 m. Results for depths of 150 m and 450 m were presented to show the effects of water depth. Results are presented in form of Response Amplitude Operators (RAO). RAO is the amplitude of motion of floating platform normalized per unit wave amplitude [6]. RAO in the x and y directions also rotation around z direction are presented in Figure 4.11 to Figure 4.18.
It is obvious that the maximum response occurs at the highest frequency, as the depth of water increases in both submerged and surface platform. The justification being that the stiffness of the mooring line will decrease as the depth increases. Hence, at larger depths the maximum amplitude occurs at a higher frequency.

Figure 4.10 Schematic Overview of Simulation
Figure 4.11 Submerged Platform in 60m Depth
Figure 4.12 Submerged Platform in 150m Depth
Figure 4.13 Submerged Platform in 450m Depth
Figure 4.14 Submerged Platform
Figure 4.15 Surface Platform in 60m Depth
Figure 4.16 Surface Platform in 150m Depth
Figure 4.17 Surface Platform in 450m Depth
4.2.4 Wind Speed Effect
In order to realize the effect of wind speed on wind turbine motion, the simulation was performed at several wind speeds. The results are presented at wind speeds of 9, 11.2, 15
and 25 m/s. According to [7], these wind speeds are located at regions 2, 2½ and 3. That means at the wind speed of 9 m/s, the wind turbine produces half of its rated power. At wind speed of 11.2 m/s, the wind turbine will work at its full capacity and at 15 m/s, is within region 3. Finally, at 25 m/s the wind turbine has reached its cut-out wind speed.

The displacement of wind turbine is shown in Figure 4.19.

![Figure 4.19 Submerged Platform](image)

### 4.2.5 Platform Effect

The effects of submerged and surface platform on the motion of wind turbine are shown in Figure 4.20.
Figure 4.20 Submerged and Surface Platform
Chapter 5

Conclusion

A three step method was developed and used to model the motion and loads on an offshore wind turbine. First, the FAST computer code was used to derive wind turbine properties, which include mass, damping and stiffness matrices. Also, FAST was used to derive the aerodynamic force on the wind turbine. Second, the WAMIT computer code was used to derive the hydrodynamic coefficients of the wind turbine’s platform. Finally, the developed data were used to solve the equation of motion for a floating offshore wind turbine. To determine the accuracy of the numerical solution results, a model of a wind turbine platform was developed and several experiments were performed on wind turbine models in a water channel using waves of controlled amplitude and frequency; empirical data was collected. The simulation and experimental results agreed well. Therefore, it was concluded that the proposed method for simulating the motion of floating wind turbine is adequate. Additionally, several experiments were performed to verify data computed using WAMIT.
References


[9] D. Matha, Model Development and Loads Analysis of an Offshore Wind Turbine on a Tension Leg Platform, with a Comparison to Other Floating Turbine Concepts,
University of Colorado - Boulder, April 2009.
