DESIGN OF SCALE-MODEL FLOATING WIND TURBINE:

SPAR BUOY

A Major Qualifying Project Report
submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
Degree of Bachelor of Science.

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Abstract

The goal of this project was to design and build a 100:1 scale model of a spar buoy floating wind turbine. This report details the design process used to create the spar buoy, as well as a mooring system. A preliminary design for adding rotating blades to the nacelle is also described. The components were modeled in SolidWorks, then machined using either a rapid prototyping machine or machine tools. A system of accelerometers, inclinometers, and load cells which were developed by a concurrent master’s thesis project was implemented into the model to collect data during the testing phase. Models were tested in fresh water to determine draft, buoyancy, and the spar-buoy response to differing wave heights and frequencies. One round of testing, conducted at Alden Research Laboratory in Holden, Massachusetts, was performed on the spar buoy while anchored to the base of the water flume. Future testing using the developed scale model will implement the rotating blades and model the gyroscopic and thrust effects on the spar buoy.
Acknowledgements

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1. Introduction

The world is reaching a pivotal period in its history. Since the 1960’s, people have begun to realize that our current dependence on fossil fuels needs to change, but no significant steps have been taken to cut consumption until very recently. The U.S. uses more oil than any other nation, and needs to lead the push toward renewable energy sources. We are nearing what has been deemed a critical point in the consumption of fossil fuels, as we have nearly used half of the fossil fuels resources available throughout the world.

Renewable energy is on the rise, but it is a very slow process. Figure 1 below shows that 8% of the energy consumption in the U.S. was renewable energy in 2009, compared with 7% in 2008. Of this, wind energy constitutes only 9% of the 2009 renewable energy, or 0.72% of the total energy consumption for the entire U.S. In 2008, wind energy accounted for about 7% of the renewable energy, or about 0.49% of total energy consumption. Also from Figure 1, 83% of all energy use in the U.S. comes from fossil fuels.

![Figure 1- Renewable Energy Consumption in the Nation’s Energy Supply, 2009 [1]](image-url)
One possible expansion of renewable energy is through floating wind turbines. Wind energy is a vast and relatively untapped resource. Offshore wind turbines have the potential to significantly decrease the use of fossil fuels, being thus of great benefit to the environment. Currently, almost all wind energy is harnessed through stationary wind platforms, either on land or in shallow water fixed to the ocean floor.

The idea of locating wind farms far offshore is not only to remove them from the horizon of the coast, but also to harness the strong winds that exist in the above the open sea waters. Figure 2 below shows the east coast of the U.S. and the amount of potential wind energy that could be harnessed from offshore wind turbine farms in those locations. The wind over the ocean is strong in many other places around the world, and these potential wind farms could become a catalyst for a global move towards renewable energy.

Figure 2 - Wind energy potential of the east coast in kilowatts [2]
Offshore wind turbines will also help decrease the transmission distance of many of the wind farms to major cities. Since there are a large number of cities which are located in coastal areas, and many of the current land based wind farms are found in the mid-western part of the country, the U.S. could greatly decrease the amount of money spent transporting the harvested energy to the cities that need it by installing offshore wind farms.

As the world shifts toward renewable energy resources, significant amounts of research will be needed to aid the continual development of these new energy resources in order to use them in a large scale setting such as wind farms. This MQP will study one specific design of the floating wind turbine concepts, the Spar Buoy. It will involve designing and manufacturing a 100:1 scale-model spar buoy platform, and performing tests in a water flume with the use of a wave generator at Alden Research Laboratory in Holden, MA. This will be done in order to analyze the turbine system’s response to different simulated ocean conditions. Finally, the team will draw conclusions on the feasibility of this design and determine any future improvements that can be made so that it can be implemented on wind farms.
2. Background

2.1. Wind Power

Wind power is defined as energy derived from the conversion of kinetic energy of moving air into useful forms such as electric energy for powering homes and industries. Wind energy is not only a renewable form of energy, but also a clean energy source, since it does not produce any harmful byproducts or emissions that can damage the environment. Wind energy is also an attractive form of energy generation, because it utilizes wind which is found abundantly in many areas of the world. It also does not require a large land-use footprint compared to other energy generation methods like hydroelectric generation. Hence, other activities such as agriculture can be carried out in the same location. These advantages make wind energy an ideal method of harnessing energy to augment or replace the power derived from the much more environmentally harmful fossil fuels.

Over the past few decades, technological improvements in the wind energy sector have led to a significant drop in the cost of producing electricity. Better siting procedures, more accurate wind maps and measurements, and larger, more efficient turbines, manufactured with better materials and production techniques have contributed to the significant increase in current wind turbine efficiency [16]. Wind energy does, however, face numerous hurdles such as noise and visual pollution, and relatively low generation efficiency. For example in the latter case, the generation capacity of nuclear plants in the US is approximately 98% while the capacity of wind turbines cannot exceed 59.3% according to the Betz’ law limit. Furthermore, there are concerns about the possible impact of the spinning blades on the avian and bat populations. These
drawbacks however, pale in comparison to the advantages that may be accrued from producing vast amounts of energy from wind.

2.2 Offshore Wind Power

Offshore wind power utilizes the vast wind energy resources found offshore to produce electricity. More accurate wind data collection shows that most of the wind resources lie off the coast, and this is evident in the US wind map in section 1 of this report. It is this abundance of wind resources offshore that has brought an increased interest in the development of electricity-generating wind facilities in open sea waters. Locating the wind facilities in the open ocean has many other benefits as well. Their distance from land may result in less of an aesthetic and noise problem, which comprises a good portion of the debate regarding the Cape Wind project off the coast of New England. The vast open space of the ocean provides ample room to place wind farms. This open space also results in faster and more unobstructed winds, which is the main contributing factor of the large wind resource offshore.

Currently, there is a renewed interest in the vast wind resources that exist off the coast of the United States. It is estimated this resource has a potential installed capacity of roughly 4.15 terawatts. According to the US Energy Information Administration (E.I.A), the net demand for electricity in 2008 in the US was roughly 744,151 GW, while installed generation capacity exceeded 900 GW. Therefore offshore wind resources could conceivably supply a large portion of the electricity supply. Table 1 shows the offshore wind resources available in square kilometers (km²) and potential installed capacity in (GW) of US states with shorelines. The areas considered had winds with average annual speeds greater than 7 meters-per-second (m/s).
## Table 1 - Offshore Wind Resources available off the US coast, in GW and km² [3]

<table>
<thead>
<tr>
<th>State</th>
<th>&gt; 7.0 m/s (Wind Speed at 90m)</th>
<th>Km²</th>
<th>GW</th>
</tr>
</thead>
<tbody>
<tr>
<td>California</td>
<td>117555</td>
<td>587.8</td>
<td></td>
</tr>
<tr>
<td>Connecticut</td>
<td>1272</td>
<td>6.4</td>
<td></td>
</tr>
<tr>
<td>Delaware</td>
<td>2940</td>
<td>14.7</td>
<td></td>
</tr>
<tr>
<td>Georgia</td>
<td>12085</td>
<td>60.4</td>
<td></td>
</tr>
<tr>
<td>Hawaii</td>
<td>127477</td>
<td>637.4</td>
<td></td>
</tr>
<tr>
<td>Illinois</td>
<td>4192</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>Indiana</td>
<td>584</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>Louisiana</td>
<td>63075</td>
<td>315.4</td>
<td></td>
</tr>
<tr>
<td>Maine</td>
<td>31311</td>
<td>156.6</td>
<td></td>
</tr>
<tr>
<td>Maryland</td>
<td>10756</td>
<td>53.8</td>
<td></td>
</tr>
<tr>
<td>Massachusetts</td>
<td>39997</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Michigan</td>
<td>96642</td>
<td>483.2</td>
<td></td>
</tr>
<tr>
<td>Minnesota</td>
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<td>20.5</td>
<td></td>
</tr>
<tr>
<td>New Hampshire</td>
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<tr>
<td>New Jersey</td>
<td>19935</td>
<td>99.7</td>
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<tr>
<td>New York</td>
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<tr>
<td>North Carolina</td>
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<td></td>
</tr>
<tr>
<td>Ohio</td>
<td>9237</td>
<td>46.2</td>
<td></td>
</tr>
<tr>
<td>Oregon</td>
<td>43894</td>
<td>219.5</td>
<td></td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>1924</td>
<td>9.6</td>
<td></td>
</tr>
<tr>
<td>Rhode Island</td>
<td>5126</td>
<td>25.6</td>
<td></td>
</tr>
<tr>
<td>South Carolina</td>
<td>26049</td>
<td>130.2</td>
<td></td>
</tr>
<tr>
<td>Texas</td>
<td>55671</td>
<td>278.4</td>
<td></td>
</tr>
<tr>
<td>Virginia</td>
<td>18890</td>
<td>94.4</td>
<td></td>
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<td></td>
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<tr>
<td>----------</td>
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<td>--------</td>
<td></td>
</tr>
<tr>
<td>Washington</td>
<td>24455</td>
<td>122.3</td>
<td></td>
</tr>
<tr>
<td>Wisconsin</td>
<td>23298</td>
<td>116.5</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>830064</strong></td>
<td><strong>4150.3</strong></td>
<td></td>
</tr>
</tbody>
</table>

2.3 Shallow Offshore Wind Turbines

Shallow offshore wind turbines consist of turbines that are installed in shallow waters close to the coast. In most cases, water depths suitable for their installation range between 30-80 meters. Most of the offshore wind turbines currently installed are of the bottom fixed type, similar to those used onshore. However, different depths require different foundations for stability. A monopole with a six meter diameter is usually used in waters up to 30 meters deep; in deeper waters of up to 80 meters, a tripod base or steel jacket is used for stability.

Currently, Europe is the world leader in installed offshore wind energy. The first wind farm placed in operation during 1991 and was located in Denmark, and as of June 2010, Europe had an installed capacity of 2396 MW [11]. There are 39 offshore wind farms presently installed with 100GW of new projects proposed or under construction.

Contrastingly, there are no offshore wind farms in the United States. All of the wind power produced in the United States comes from onshore wind farms with a generation capacity of 34,296MW in 2009 [14]. However in a report issued by the Department of Energy (DOE) in 2010, a plan was laid out to achieve 54 GW of offshore wind power by 2030 [12]. Most of the potential offshore farms are close to the major urban load centers that are found along the coasts where land for onshore wind farms is limited, and demand for energy is high. The first of these wind farms is the Cape Wind Project sited off the coast of Nantucket Sound in Massachusetts. This wind farm will be comprised of 130 wind turbines, producing up to 170 MW, to cover 75% of the electricity needs in Cape Cod, Martha’s Vineyard and Nantucket.
2.4 Developments in Floating Wind Turbines

The large wind resources found in deeper waters off the coast and the growing need for renewable energy sources have led to interest in the development of floating wind turbine facilities. Floating wind turbine facilities can be sited in deeper waters where large and less turbulent wind resources exist and where there is an abundance of open space. Since most designs do not require heavy concrete foundations, floating wind facilities offer a cost effective choice in capturing wind energy for water depths in excess of 50 meters. The floating designs also have an extra advantage of low decommissioning costs compared to conventional offshore wind turbines. This is because the floating structure does not have a large footprint on the seabed, since it uses mooring lines for anchorage. Floating wind turbine technologies have also benefited from floating technologies, pioneered and improved by the oil and gas industries.

There are currently several floating wind turbine designs that show the most promise for the advancement of offshore wind technology as shown in figure 3. These include the Tension Leg Platform (TLP), Shallow draft barge, and Spar buoy concepts. The TLP incorporates a tank with an intermediate aspect ratio (ratio between height and diameter) as compared to the other floating concepts. The TLP design achieves stability through the use of vertical mooring lines that are attached to tank legs and tensional by the reverse buoyancy of the tank. Thus, the platform is permanently moored by means of tethers attached at the corners of the structure. Another design is the shallow draft barge. The barge concept incorporates a tank design with lower aspect ratio and larger water plane area compared to the TLP and spar buoy designs. The barge concept achieves stability from the large water plane area-to-volume ratio that allows it to remain buoyant in water. The spar buoy model is designed for deeper waters of up to 300 meters. The spar buoy incorporates an elongated cylindrical tank with a high aspect ratio, which holds
ballast at the tank bottom. The ballast helps to lower the center of gravity of the tank and make it more stable. In addition, the spar buoy is moored to the ocean bed with either taut or catenary lines to provide further stability.

The TLP and Barge designs were the subjects of the MQP carried out in 2009 [10]. For the current project, our team designed, built, and analyzed a 100:1 scale prototype of the Spar Buoy concept. Of note are the differences in size and structural designs of their platforms.

Figure 3 - Floating Wind Turbine Designs [3].
2.4.1 Previous Scale Floating Wind Turbine Tests

2.4.1.1 WindFloat Floating Model

The WindFloat model comprises a three-legged floating foundation designed to support multi megawatt offshore wind turbines [13]. The foundation is designed to accommodate large wind turbines (5 MW and above), with minimum modifications made to the nacelle and rotor. As part of the plan in developing the prototype model, the designers carried out tests on scale models. The 1/105 scale model was fabricated out of acrylic [13]. The figure below shows the scale model with the different components listed.

![Scale model of the WindFloat floating system](image)

Figure 4 - Scale model of the WindFloat floating system

List with the components comprising the above floating wind turbine system, and their functions:
1. Floating columns with water-entrapment plates
2. Video camera: tracked the motion of light-emitting diodes placed on the model
3. Tower: made from acrylic piping
4. Loading cell: measured the axial force perpendicular to the tower
5. Foam board disk: attracts wind loads matching the design wind force
6. Electrical motor: modeled the gyroscopic effect
7. Turbine blades: modeled out of aluminum rods
8. End weights: helped in matching the design inertia.

To carry out the test, the model was placed in a floating tank using four soft springs and mooring lines. A plunger type wave maker produced the scale waves while a set of five large wind fans generated the required wind loading. A three-hour test was carried out to simulate a 100-year storm, with an associated wind of 25 m/s [13].

2.4.1.2 Statoil/ SINTEF Scale Tests.
Prior to the installation of Statoil’s Hywind full scale model, scale tests were carried out. Statoil had a scale model tested at the MARINTEK wave simulator, as shown in figure below, in collaboration with SINTEF Energy Research. A 47:1 model was used in the testing.
2.4.2 Previous Full Scale Floating Wind Turbine Tests

Despite the increased interest in Floating Wind Turbines, there have been few floating systems that have been subject to open sea trials. This is mainly due to the larger scale and resources that are needed to undergo such a turbine test. Consequently, most of the promising wind turbine models have been subject to limited scale model testing as described in the previous section.

2.4.2.1 Statoil’s Hywind

Statoil has made the most progress towards full scale testing. Statoil drew on their experience in the oil and gas sector to manufacture the first full scale floating wind turbine system in 2009. The model that was used in the test incorporated the Spar Buoy design that supported a 65-meter tall wind turbine that was rated at 2.3 MW. The turbine, also known as Hywind, can be used in waters 120 meters to 700 meters deep. The figure below shows the full scale prototype installed close to Karmøy Island of the coast of Norway.
2.4.2.2 Blue H Technologies

Blue H Technologies, from the Netherlands, also had a working prototype that first operated in the summer of 2008. An 80 kilowatt (kW) wind turbine was installed on the floating structure in the Strait of Otranto off the coast of Puglia in Italy. The floating design utilized in this case was a tri-floater with three buoyancy tanks. Blue H is currently working on a 2.4 MW full scale model in Brindisi, Italy as part of the Tricase offshore wind farm. The Tricase wind farm will have a nameplate capacity of 90MW. The following figure shows the prototype of the floating wind turbine that Blue H built.
2.4.3 Mooring Cable Configurations for the Spar Buoy Design

Offshore floating wind turbines are subject to a wide range of ocean conditions, ranging from calm, tranquil waters, to 100 kilometer-per-hour hurricane winds and considerably high waves that accompany them. It is thus imperative that the system be securely anchored to the ocean floor, so that the effects of severe weather and ocean conditions can be mitigated and not affect the overall performance of the turbine.

There are currently a few mooring configurations being studied by different companies and universities in Europe, US, and Japan, the two most widely known being the simple, zero-tension 3- or 4-cable catenary system, and the ballasted cable system. The zero-tensioned configuration consists of mooring lines attached to a particular location on the spar buoy tank, the most common ones being the center of gravity and the bottom surface [8], and to the ocean floor, by corrosion-protected cables. The second one, which is a variation of the single-layered and tensioned mooring lines, called the ballasted mooring configuration, is shown in the figure below [6].
This system consists of three or four tensioned cables attached to a location on the tank and fixed to the ocean floor. A weight is attached to each of the cables, decreasing the overall net vertical force acting on the system and thus increasing the tension on the catenaries, so that the system can be more resistant to outward forces in the heave direction. As an example of this cable system, Hywind, a Norwegian company currently conducting research on offshore floating wind turbines off the coast of Europe, has employed a “ballasted catenary layout that adds 60-tonne weights hanging from the midpoint of each anchor cable to provide additional tension.”[7] Sungho Lee has also suggested that a 70 ton weight be added to each cable for increased stability [6]. Therefore, in ocean regions where waters tend to be more agitated and prone to tropical storms or fierce winds, ballasted catenaries may be a very beneficial asset for stabilizing the wind turbine system.
3. MQP Objectives

This Major Qualifying Project had the following objectives:

- Conduct a literature review on floating wind turbines, particularly the spar buoy design;
- Design and build a 100:1 scale model of the spar buoy floating wind turbine;
- Incorporate new wireless instrumentation to measure inclination and acceleration of both the tower and the buoy, as well as measuring wave size and frequency. The electronics for this project were developed by Eric Murphy, a WPI graduate student;
- Test spar buoy model in wave flume at Alden Research Laboratory in Holden, MA;
  - Tests were conducted in January 2011, and an assessment of the spar buoy’s dynamical performance was made.
- Implement mooring lines and anchoring plates, securing the model to the floor during testing.
- Attach load cells to the anchoring plates so that cable tension could be measured during testing. Kazim Naqvi, a WPI graduate student, developed a method for attaching the load cells and was responsible for this system;
- Implement rotating turbine blades to tower and analyze how gyroscopic effects impact the stability of the system;
  - The rotating blades could further alter the stability of a floating wind turbine.
- Implement an aerodynamic drag disc and model air flow (using fans) to model the thrust force on the turbine rotor.
4. Design and Manufacture

4.1 Project Designs

This section explains the important decisions and procedures involved in designing the Spar Buoy floating wind turbine model, starting with the basic scaling of dimensions and mass calculations. The team referred to Sungho Lee’s S.M. Thesis [6], who analytically modeled the dynamics of the Spar Buoy turbine concept, incorporating his results and design parameters to construct this team’s own model. This study used the NREL baseline wind turbine, with a rotor diameter of 126 meters, a hub height of 90 meters and a total weight of 700 metric tons. The turbine is rated to produce 5 MW. For the floating platform system, a spar buoy design was used, with a draft of 60 meters and a diameter of 14 meters. Table 2 below shows the specific full-scale and model dimensions of the spar-buoy wind turbine system. For this project, the group used Froude scaling to scale down length measurements by 100:1, weights and forces by $10^6:1$ and $10^{10}:1$ for moments of inertia.

![Table 2 - 100:1 Scale Spar Buoy Floating Wind Turbine Design Parameters](image)

*MIT thesis stated these values based on using concrete as ballast material.

**Mass based on steel as ballast material.
4.2 Scaling of Dimensions

The purpose of this MQP is to construct and test a 100:1 scale model of a Floating Wind Turbine, using the Spar Buoy conceptual platform design. In performing the scaling operations, all length dimensions were scaled down by a factor of 100 and all weight values were scaled down by a factor of 1,000,000, since mass is directly proportional to the length cubed.

Figure 9 illustrates the spar buoy platform design with its main components. Each individual component labeled is discussed in detail in the following sections, and their SolidWorks drawings can be found in the Appendix. Figure 10 shows the full assembly view of the floating wind turbine.

![Figure 9 - Cross-sectional view of tank assembly](image)
4.3 Mass Calculations

This section explains all the calculations performed in the design procedures to determine ballast support characteristics, tank dimensioning, and weight limitations.

The group initially envisioned that the most adequate ballast configuration would consist of a layer of metal plates, which would sit at the bottom of the tank (and thus lower the center of mass location of the spar buoy to a greater distance below the water level), followed by a layer of sand above the plates. The amount of sand could be easily altered depending on the floating characteristics of the system once it is actually placed in water, and making the stabilizing work
easier. Based on this ballast set up, the team performed calculations for various ballast conditions in order to determine the amount of sand required, as well as the total ballast height.

The following ballast scenarios were studied:

1. Five aluminum plates, plus sand.
2. Five steel plates, plus sand.
3. Ten steel plates, plus sand.

Assuming a plate thickness of 0.6cm, outer diameter of 13cm, and inner diameter of 2.5cm, the volume of a single plate is then:

\[
V_{plate} = \frac{\pi D^2}{4} t = \frac{\pi (13 - 2.5)^2}{4} \times 0.6 = 51.95 \text{ cm}^3
\]  

(1)

Last year’s MQP report used aluminum plates for ballast support, and consequently this year’s team used these plates to estimate the mass of a single plate with the new specified dimensions. Last year’s plates had a volume of 161.28cm\(^3\) and a unit mass of 0.55kg. Thus, a plate with the above specified dimensions would have a mass of 0.1771kg.

The team then performed simple mass calculations to determine the amount of sand required as well as the specific ballast height. The table below contains the numerical results in each of the described scenarios (height values are tabulated with reference to the tank bottom, i.e., \(h = 0\) lies on the bottom surface of the tank and is measured positive in the upwards direction). The sand used in last year’s project had a density of 0.001599kg/cm\(^3\). The steel density was taken as an average result obtained from research on different types of steel, which was determined to be 0.00785kg/cm\(^3\). From the MIT thesis report [6], the total allowable mass
for the tank is 8.04243kg. Based on information given by Eric Murphy, the instrumentation
would have a mass of at most 0.5kg. Additionally, the team estimated the mass of the tank
structure itself to be 0.8kg.

Table 3 - Ballast Configuration Calculation Results

<table>
<thead>
<tr>
<th>Scenario</th>
<th>5 Al plates + sand</th>
<th>5 Steel plates + sand</th>
<th>10 Steel plates + sand</th>
<th>Steel plates only</th>
<th>Steel plates reconfigured</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Required mass of sand (kg)</td>
<td>5.8566</td>
<td>Required mass of sand (kg)</td>
<td>4.7032</td>
<td>Required mass of sand (kg)</td>
</tr>
<tr>
<td></td>
<td>Sand height (cm)</td>
<td>24.87</td>
<td>Sand height (cm)</td>
<td>19.97</td>
<td>Sand height (cm)</td>
</tr>
<tr>
<td></td>
<td>Total ballast height (cm)</td>
<td>27.87</td>
<td>Total ballast height (cm)</td>
<td>22.97</td>
<td>Total ballast height (cm)</td>
</tr>
<tr>
<td></td>
<td>Mass of single steel plate (kg)</td>
<td>0.4078</td>
<td>Required mass of sand (kg)</td>
<td>6.7424</td>
<td>Number of required plates</td>
</tr>
<tr>
<td></td>
<td>Number of required plates</td>
<td>16.53 ≈ 17</td>
<td>Total ballast height (cm)</td>
<td>10.2</td>
<td>Total ballast mass (kg)</td>
</tr>
<tr>
<td></td>
<td>Total ballast height (cm)</td>
<td>9.53</td>
<td>Total ballast height (cm)</td>
<td>9.53</td>
<td></td>
</tr>
</tbody>
</table>

As can be seen from the total ballast height results above, the only scenario that would be
adequate for this project’s design would be Option 3. According to Sungho Lee’s thesis report
[6], the center of gravity of the spar buoy should lie at approximately 39.68cm below the surface
of the tank, or 20.32cm above the bottom of the tank. In order to have all the ballast support
below the center of mass, scenario 3 would be the best option. However, there is only 20.32 –
17.31 = 2.99 cm of empty height space between the sand and the center of gravity (CG). Thus,
a better ballast configuration should be explored, such that it will leave the team with more space
between the ballast and the CG for possible component adjustments and positioning changes.
The spar buoy tank will have an instrumentation cylinder located inside and concentric with the symmetry axis of the tank, as shown previously in Figure 9. This cylinder will have a built-in platform to house part of the instrumentation, which needs to be strategically positioned at the system’s center of gravity. With this in mind, another ballast configuration was proposed. It consisted on extending this instrumentation cylinder along the entire length of the tank (roughly 60cm), and placing the metal plates and sand around it. The problem with this set-up was that a large amount of space which was previously being used by sand and/or plates would now remain empty, since the cylinder was hollow. Thus the calculated ballast height increased to a value much greater than the designed draft height of 60cm. A suggestion to solve this issue was to fill the hollow cylinder with sand to compensate for this loss of space, but this design seemed impractical and the team decided to explore other possible scenarios.

Since steel (0.00785 kg/cm³) is roughly three times denser than aluminum (0.0027 kg/cm³), it was decided to use steel for the metal plates. The team then studied the possibility of using only steel plates for ballasting. The results obtained have also been tabulated in Table 4 above as scenario 4.

As can be seen from Table 4, the ballast height is reduced to 10.2cm, which is significantly lower than the results for the sand-and-plates configurations.

In an effort to reduce the number of plates the team would need to manufacture, increasing the thickness of the plates from 0.6cm to 1.905cm (0.75 inches) was considered. This would yield a total of roughly 5 steel plates, with a new total ballast height of 9.5cm. This
scenario is displayed as option 5 in Table 3 above. After careful consideration and re-calculations, the team decided to pursue this particular configuration\(^1\).

### 4.4 Turbine Platform and System Components

The Spar Buoy tank is comprised of four main structural components as displayed in Figure 9: the outer tank casing (platform), the tank cover, the instrumentation cylinder, and the steel ballast plates. This section explains the design procedures involved in manufacturing each of these components, along with the mooring lines and their attachment to both the spar buoy and the anchor plates.

#### 4.4.1 Platform

To manufacture the parts required for assembling the tank (with the exception of the steel plates), the team used WPI’s Rapid Prototyping Machine, which manufactured the parts from ABS plastic. This machine had sizing limitations and could only manufacture parts that were less than 10in (width) x 10in (length) x 12in (height). The tank height was about 60cm (23.62in), thus the team designed two hollow cylindrical tubes, one with both ends open and the other with one end closed, so that when assembled they would have the desired length of 60cm. They were assembled using an inner ring which was about 0.01 inch smaller in diameter than the inner diameter of the platform. This allowed for a secure and tight fit between both halves of the tank. The figure below shows the above-described process.

\(^1\) As is explained in section 4.5, the team later decided it was safer to use only 4 steel plates when testing in the water, so that the water line was slightly above the cover lid and the draft approximately 60 cm. The total ballast mass was thus 5.1417 kg, as is shown in Table 2.
To ensure that the platform was fully waterproof, the team applied two layers of ABS cement to the insides of the tank. This cement acts as a water sealant and contains a combination of methyl ethyl ketone (MEK), acetone, and ABS solids, and is commonly used to coat ABS plastic materials for waterproofing.

The figures below are pictures of the actual spar buoy tank. The second picture shows the ABS cement coating on the inside of the tank (black layer).
Figure 12 - Photo of Spar Buoy tank (with cover and cable attachments)

Figure 13 - Inside of Spar Buoy tank, showing ABS cement glue layer in black
4.4.2 Instrumentation Cylinder

The instrumentation cylinder is a tube 45cm in length and 7cm in diameter that runs concentrically along the inside of the tank, as show in Figures 9 and 10. It has a platform located at the turbine’s center of mass (COM), 39.68cm below the top of the tank, which will house an accelerometer, a wireless card, and a micro-controller, as the name suggests. The reason for this platform to be placed at the model’s COM is that for the accelerometer’s readings to be accurate, it needs to be positioned correctly at the COM.

The manufacturing process for the cylinder was exactly the same as for the tank. Since it was longer than the allowable length for printing on the rapid prototyping machine, the cylinder had to be separated into halves and was joined together by an inner ring, just like the tank.

Below is a photo of the instrumentation cylinder, coated with two layers of ABS cement glue for water-tightness.

![Instrumentation cylinder with ABS cement coating](image)

*Figure 14 - Instrumentation cylinder with ABS cement coating*
4.4.3 Tank Cover

The tank cover was designed using the same basic cross-sectional sketch from last year’s MQP group [10]. Below is a sketch of this cross-section, with the new dimensions according to this year’s design requirements. All dimensions are in centimeters.

![Cross-sectional view of tank cover sketch](image)

*Figure 15 - Cross-sectional view of tank cover sketch*

The above sketch was revolved about the center axis to produce the solid shown in the photos below, from two different views.
The first figure shows two lips of height 0.64 cm and thickness 0.18 cm, where the rapid prototyping machine’s tolerance of 0.006 in has also been taken into account for an easier, more accurate fit. These correspond to the locking mechanism used to assemble the tank cover onto the outer tank and instrumentation cylinder. Compared with the cover design from last year’s MQP, this cover was roughly four times thicker (0.61 cm thick). The cover was purposely designed this way so that bending and buckling of walls are less likely to occur once the tower is assembled and attached to the top of the cover. Wall instability was a retarding factor to the progress of last year’s TLP design, mainly because the tank cover was too thin to bear the weight of the tower.

4.4.4 Ballast Plates

As discussed in the mass calculation section, the group determined that the five steel plates ballast idea was optimal for our design. After making that decision, the next step was to determine how large the plates should be. The team decided that the plates would be machined to a size just small enough to fit into the spar buoy. Eventually, the group settled on a thirteen centimeter diameter, with a two and a half centimeter diameter circular hole to easily add or
remove plates from the spar buoy. Later, the group added two small quarter inch diameter holes to bolt the plates down during machining so that they could not move.

Then the group moved on to the actual machining of the steel plates. This process took a long time because of the density of steel and the level of difficulty to machine. The team used the plate design obtained in SolidWorks and imported it into ESPRIT, subsequently adding all the cutting operations for manufacturing the circular disk with its holes. After this preliminary set-up had been completed, the team began work on machining the plates using the CNC machines located in Higgins Labs. There were a few minor issues while machining, including occasional changing of the tools, mostly due to overheating. After two full days of machining, the parts were completed and nearly ready to be used as ballast inside the spar buoy tank. All that was left was to coat these plates with a rust-protective paint, so that in case water leaked into the tank during testing, the plates would not rust as easily.

Below is a sketch of one of the plates used for ballasting, followed by a photo of all plates to be used in the actual model after the rust-protective spray had been applied.

*Figure 18 - SolidWorks sketch of one steel plate to be used as ballast*
4.4.5 Cables and Attachments

Before beginning the design of the spar buoy, the team consulted last year’s MQP members on the mooring cables they had utilized. The team also consulted Sungho Lee’s thesis report [6] on the physical characteristics of mooring cables he used for his numerical simulations. Once the axial stiffness was properly scaled down, it was found that the cables had similar characteristics to a nylon 6/6 cable. Nylon 6/6 has a superior ability to resist failure due to high stresses and can withstand tension forces greater than 10000 psi [9]. The cables used for this project were four feet in length and had a 1/8” diameter.

In designing the mooring cable attachments, the group envisioned a simple circular attachment that would be mounted onto the exterior wall of the spar buoy. After consulting several reports on spar buoy designs as well as the previous MQP report, it was determined that the cable attachment would be of the design that the group originally envisioned. Also, after further consultations with Professor Olinger, it was decided that three cable attachments were an adequate number for this project (last year’s Tension-Leg Platform design had four cable attachment points). The team arrived at this conclusion because the forces expected on the cable...
attachments did not warrant the addition of an excessive amount of cable attachments. It was also decided that the cable attachments would be designed using Solid Works and built in the Rapid Prototyping machine (RPM) using ABS plastic. Furthermore, the group concluded that the cable attachments were to be placed at the base of the spar buoy.

Some of the features of the cable attachment include a circular loop through which the mooring cable was attached to. The size of this loop was dictated by the thickness of the mooring cable selected for this design. Since the cables used were relatively thin, the team settled on a loop that was approximately ¼ of an inch in diameter. Another feature was the circular curvature of the attachment point with the spar buoy. The radius of this curve was 14 cm, which was the radius of the outer cylinder of the spar buoy. This allowed the cable attachment to fit in neatly and more securely to the outer cylinder.

Below is a sketch of the cable attachment, with the attachment hole in view.

![Figure 20 - SolidWorks sketch of mooring cable attachment](image)

Once the cable attachments were designed, the Solid Works sketches were submitted for printing in the RPM. Once completed, the group attached the cable attachments on the spar buoy.
using ABS cement. Beforehand, the team had measured and marked three equidistant points around the bottom of the base. These marks specified the points on which the cable attachments were to be positioned.

Below is a photo of the spar buoy tank with a cable attachment in view.

![Figure 21 - Zoomed view of mooring cable attachment](image)

However, this design proved to have a few drawbacks. The loop which was designed to hold and secure the cable did not perform as well as the team anticipated. Therefore, the team redesigned the cable fasteners with a new fastening screw hole as well as a mooring cable hole running vertically through the aft section of each of the cable fasteners. A summary of the team’s redesign is described in the following section.

**4.4.6 Modified Cable Attachments**

A modified cable attachment design was also developed to improve the method of securing the tether lines to the platform. These new attachments, shown below, should make for an easier method of attachment to the spar buoy, as well as easier to adjust once the spar buoy is in the water.
These new cable attachments are designed to feed the mooring line from the bottom through the top, while a screw is placed in the front and tightened until it secures the mooring line against the end of the hole. The screw hole stops far enough in that it goes through the mooring line hole, but doesn’t go completely through the entire attachment. This new design should make securing the mooring lines easier, as well as more secure.

There are now nine of these attachments to be placed at different locations along the height of the spar buoy as desired. The MQP team thought that the optimal location for these new cable attachments would be at the bottom of the spar buoy, at the center of gravity of the spar buoy, and at the center of buoyancy of the spar buoy. These locations were thought as optimal places to help find the most stabilized testing configuration of the spar buoy. These will need to be glued to the platform before any future testing can be conducted.

4.4.7 Anchoring Plates

With the introduction of mooring lines to the spar buoy, the team also had to design anchoring plates to keep the spar buoy in place while testing in Alden Laboratories. These anchoring plates would be placed on the bottom of the flume. It was determined that aluminum
was the most adequate option for manufacturing the plates and that met the needs of this project, both because of its price and ease of machining, along with the fact that it is corrosion-resistant.

The next step in this process was to size the plates. The team’s first decision was that because of the location where the mooring lines should be anchored, our group needed to use three separate plates, one for each mooring line. Then, the alignment of the buoy was finalized in an attempt to minimize the amount of force on any given line. The group decided that the easiest way to do this was to place one line directly downstream and the other two one hundred twenty degrees in either direction. This way the plates would be evenly spaced, and the spar buoy would only have a significant force downstream, so the main force will be evenly distributed among two plates. Finally, the group had to estimate the maximum force exerted on any plate, which the team estimated might approach the weight of the spar buoy if the force were only applied to one mooring line. After this conclusion, the team ordered three one inch thick, one foot by one foot plates, one for each of the mooring lines.

The next step was to machine the plates as needed with the help of graduate student Kazim Naqvi. Kazim also helped with ensuring that the method the team used for attaching the load cells and cables, and for lowering the anchoring plates onto the flume floor were the same as the ones for the TLP. An eyehook system was used for lowering the plates to the bottom of Alden Labs water flume, and adjusting the plates to achieve the correct tension in each mooring line.

Figure 23 shows the optimized test setup with the placement of anchoring plates on the water flume floor.
4.4.8 Full Assembly Views

Figure 9 shows a cross-sectional view of the full tank assembly, combining all of the above structures. Detailed drawings are included in the Appendix. This year’s MQP used the same tower designed and manufactured by the previous Floating Wind Turbines MQP. Figure 10 is a CAD model of the spar buoy fully assembled, including the mooring cable attachments, the tower, and a conceptual nacelle, leaving room for possibly installing a rotating set of blades to the tower in the future.

One concern this MQP team had throughout the design process was making sure that the spar buoy tank was 100% watertight. This is needed so that the instrumentation housed in the tank does not come in contact with water. If this were to happen, it would malfunction and data acquisition would not be possible. Taking in water will also change the tank’s ballast mass,
making it heavier, prone to sinking, and altering its stability. To ensure water-tightness, the team coated the inner surface of the outer tank and outer surface of the instrumentation cylinder with the ABS cement glue previously described. The group then placed the full assembly in the WPI water tank and left it there for a full day to make sure no leaks were present. This was a successful test and no water was let in.

However, the team did run into some water-tightness issues as the tank was accidentally dropped on the ground while being assembled to the tower. This fractured the outer layer of the tank casing at different locations around the cable attachment points. After another leakage test, it was determined that the tank was no longer watertight. Once again, the team sealed the leaks with ABS cement glue to reinforce any fractures. After this, a last leakage test was conducted and thankfully the tank was watertight once again.

Additionally, to ensure that no water would leak through the location where the two halves of the tank joined together, a layer of silicone glue was applied right on the groove between the two parts, as shown on the figure below. The tank was then submerged and, after a long period of time, it was observed that no water was entering the spar buoy along the junction.
4.5 Center of Mass Test

With all components of the wind turbine model manufactured, the tower was assembled onto the tank for a center of mass (COM) test. This test was done so that the actual location of the COM could be determined, since the accelerometer housed by the instrumentation cylinder must be located at the system’s COM. The figure below shows this simple test.
As can be seen from above, the assembly was placed horizontally on a table and laid to rest on a wooden bar, which was adjusted along the length of the tank until it was able to balance the entire assembly. This location was then measured and it was determined that the COM of the assembly was located at 17.9cm from the bottom of the tank, or 42.1cm from the top of the cover. Sungho Lee’s estimate for the COM was at 39.68cm from the cover top [6], which means this MQP’s design was very close in comparison to his calculated value, differing by approximately 6%.

4.6 Flotation Test

The team then conducted a simple flotation test to determine the inherent stability of the wind turbine system. This was done to ensure that the assembly was balanced and could float vertically upwards on its own. It was also conducted so that the team could determine the number of plates required to keep the water level of the tank approximately at the tank cover, corresponding to the desired draft height of 60 cm (see Table 2 on page 20), and whether or not this number matched the predicted value of five steel plates. The figure below shows this test.
Figure 26 - Spar Buoy Full Assembly Flotation Test.

This test was performed in the water tank located in Higgins Laboratories 016. It was initially conducted using five steel plates, as calculated in the ballast weight section of this report. However, five plates made the assembly too heavy, completely submerging it. The team then removed one plate and the resulting configuration is depicted on the figure above. As can be seen, the assembly was floating as desired, with the water level slightly under the tank cover. In response to this test, the team decided to use only four of the five steel plates for ballast during the tests at Alden Labs, so that the tank would not be fully underwater.

4.7 Design of Disk for Wind Modeling

In addition to the modeling of tether cables and the angular deflections of the floating wind turbine system, it is also of great interest to model the effects of wind on the turbine’s equilibrium. This is a very challenging task to say the least, because the 100:1 scaling factor used in this MQP’s design process would require wind speeds 100 times greater in magnitude than the
ones experienced in real life. Placing this concept into perspective, 10 mile-per-hour winds the prototype could potentially experience in open sea waters would equate to 1000 mile-per-hour winds for the scaled model! This is simply impossible.

In order to model the wind effects as simply and yet as accurately as is possible, this MQP team adopted the idea proposed by Roddier, Cermelli, Aubault, and Weinstein [13], in which a circular disk is placed in front of the rotating blades on the nacelle, and stands in between the blades and the fans, which blow the air perpendicular to the disk’s surface, as shown in Figure 27.

![Figure 27 - Wind modeling test of floating wind turbine.](image)

This MQP group then sized and designed its own disk to model the wind effects which were depicted in the picture above. The design the team came up with is illustrated in Figure 28.
The first step in sizing the disk was to estimate the thrust it would experience as a result of the wind blowing against its surface. This was done by first determining the thrust the prototype would experience using the following equation for an ideal Betz turbine:

$$T_{\text{prototype}} = \frac{4}{9} \rho_{\text{air}} V_{\text{air}}^2 A$$

where $\rho_{\text{air}} = 1.29 \text{ kg/m}^3$ is the density of air, $V_{\text{air}} = 30 \text{ knots} = 15.433 \text{ m/s}$ is an average wind speed the turbine might experience in open sea waters, and the diameter of the rotor was 126 meters [6]. The prototype thrust was then calculated to be $1.703 \times 10^6 N$.

The team then scaled this thrust value in order to estimate the thrust experienced by the 100:1 scale model. The scaling relation used was $T_{\text{model}} = \frac{T_{\text{prototype}}}{10^6}$ since thrust varies directly with mass, and mass is scaled down by a million. Therefore, $T_{\text{model}} = 1.703 \text{ N}$. 

Figure 28- SolidWorks model of new nacelle assembly with carbon fiber blades and foam disk
From the basic principles of aerodynamics, the thrust experienced by the modeling disk will be equal in magnitude to the drag the air exerts on it. Therefore, \( T_{model} = \frac{1}{2} \rho V^2 A C_d \), where \( C_d \) is the drag coefficient assumed to be 1.2.

Now, with all the quantities in this equation known, except for the area term (which is dependent on the diameter of disk and is the variable to be solved for) and the air speed, one can plot the diameter of the disk as a function of this air speed according to the following relation:

\[
D_{disk} = \sqrt{\frac{8 T_{model}}{\pi \rho \text{air} V_{air}^2 C_d}}
\]

Plotting this equation, the trend below is observed:

![Disk Diameter vs. Fan Air Speed](image)

Figure 29 - Plot of disk diameter as a function of fan air speed, for wind modeling.

To be able to determine the appropriate diameter of the disk, the group needed to decide on a fan to be used for testing, how many fans would be necessary, and thus determine the speed of the air generated by this particular fan. A medium-size industrial fan was found at WPI’s Gas Turbines Laboratory in Higgins Labs and was taken as a reference for this design process. Eric
Murphy, a WPI graduate student, measured the air speed produced by this fan, and his results are displayed in the table and graph below.

Table 4 - Air speed measurements performed on industrial fan to be used for wind modeling.

<table>
<thead>
<tr>
<th>Distance from fan (cm)</th>
<th>High (mph)</th>
<th>Low (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>9.3</td>
<td>7.4</td>
</tr>
<tr>
<td>50</td>
<td>8.1</td>
<td>5</td>
</tr>
<tr>
<td><strong>75</strong></td>
<td><strong>5.5</strong></td>
<td><strong>3.5</strong></td>
</tr>
<tr>
<td>100</td>
<td>5.2</td>
<td>3.5</td>
</tr>
<tr>
<td>125</td>
<td>5.2</td>
<td>3.5</td>
</tr>
<tr>
<td>150</td>
<td>5.2</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Figure 30 - Plot of air speed as a function of distance from industrial fan.

The highlighted row in the table corresponds to the selected distance from the fan at which the disk will be located. The “high” setting will be used, yielding a speed of 5.5 mph \( \approx 2.5 \, m/s \). Thus, from the equation for \( D_{\text{disk}} \), it can be determined that \( D_{\text{disk}} \approx 67 \, cm \).

One of the design constraints that needed to be taken into consideration is that the disk had to be as light as possible so that the total nacelle mass could stay as close to the desired 240
grams as specified in the MIT thesis report [6]. Consequently, the team chose to use insulation foam as the material for constructing this disk because it has low density and is easy to cut into the desired shape. This foam density was estimated to be 0.03 g/cm³ based on specifications outlined by the Home Depot hardware store. Thus, for a 67-cm disk, its mass would be roughly 67 grams, for a 0.25-inch thick disk. The graph below shows the relation between the mass of the disk and the air speed expected from the fan.

![Disk Mass vs. Fan Air Speed](image)

*Figure 31 - Plot of disk mass as a function of fan air speed.*

Unfortunately, due to time constraints, this year’s MQP team was not able to manufacture the disk. This task, along with the subsequent wind modeling tests, is left for future project teams which will be continuing the work on the spar buoy floating wind turbine.

**4.8 Blades and Motors for Wind Modeling**

With the design of the circular disk for air modeling complete, the team looked into the appropriate motors and blade design. The team first measured the nacelle and its components to determine the suitable weight of the electric motor. The electric motor was to be used to create
the gyroscopic effects produced by turning turbine blades. According to the NREL baseline 5MW wind turbine weights, the nacelle weight was set at 240,000 kg [15]. When scaled down using our $10^6$:1 weight scale, the new scaled down weight came to 240 g. After measuring the weight of the nacelle components, accelerometer, inclinometer, and wiring at the nacelle, it was discovered that the maximum weight allowable for the motor was 110 g. The maximum allowable space was 60mm by 60mm. The motor the team chose had to fit these dimensions while producing an RPM of 120 to properly model the scaled down rotation speeds.

The team decided to use the TURNIGY AerodriveXp SK28-36 750 model motor, selecting this particular piece because it best fit all the size and performance criteria. The motor specifications of the model are listed in Table 5 below accompanied by an illustration.

<table>
<thead>
<tr>
<th>Table 5 - Design specifications for the SK28-36 750 model motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kv (rpm/v)</td>
</tr>
<tr>
<td>Weight (g)</td>
</tr>
<tr>
<td>Max Current (A)</td>
</tr>
<tr>
<td>Resistance (mh)</td>
</tr>
<tr>
<td>Max Voltage (V)</td>
</tr>
<tr>
<td>Power (W)</td>
</tr>
<tr>
<td>Shaft A (mm)</td>
</tr>
<tr>
<td>Length (mm)</td>
</tr>
<tr>
<td>Diameter (mm)</td>
</tr>
<tr>
<td>Total Length (mm)</td>
</tr>
</tbody>
</table>
Once the motor choice was decided upon, the team then modeled the rotor. Three materials were chosen for the initial analysis of the blades: wood, aluminum, and carbon fiber. Carbon fiber was further divided into solid and hollow blade types (hollow cylindrical tubes of carbon fiber). The prototype rotor weight was 110 tons [15] which when scaled down using our $10^6$:1 scale, changed to 110g. Given the light target weight and the required strength needed for the turbine blades, the team chose the hollow carbon fiber for use as the blade material. The team used a carbon fiber rod with an outer diameter of 0.00477 meters, an inner diameter of 0.00295 meters. The length of the blade was set to 0.63m. The team calculated the length by referring to the baseline rotor diameter of 126m [15]. The team then divided this figure by two to find the radius, and then the 100:1 scale to further scale down the length. The result of these calculations was a length of .63m. To calculate the volume of the rod, the following volume equation was used:

$$V = \pi h(R^2 - r^2)$$
where \( h \) is the rod length, \( R \) is the outer radius, and \( r \) is the inner radius of the tube. Using the manufacturer’s calculated carbon fiber density of 1330 kg/m\(^3\), the team was able to find the mass of the blade to be 0.036985523 kg which was approximately close to the scaled down weight of one blade.

However, to properly model the turbine length, the blades would require a moment of inertia equal to that of the prototype when scaled down. To calculate the moment of inertia, the following equation was used

\[
I = \frac{1}{3} ML^2
\]

where, \( I \) stands for moment of inertia, \( M \) for mass and \( L \) for length. The calculated moment of inertia of the full scale prototype blades were 48,510,000 kg.m\(^2\). When scaled down, the moment of inertia was converted to 0.004851 kg.m\(^2\). The scaling factor used was \( T_{model} = \frac{T_{prototype}}{10^9} \). In order to match the moment of inertia of the hollow carbon fiber tubing to that of the prototype blade, the team used a rod with a length of 0.63m. The weight and moment calculations were performed in Microsoft Excel. The table below shows a comparison of the weights and moments for the three materials.

<table>
<thead>
<tr>
<th></th>
<th>Aluminum</th>
<th>Wood</th>
<th>Carbon Fiber (hollow)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length (m)</strong></td>
<td>0.63</td>
<td>0.63</td>
<td>0.63</td>
</tr>
<tr>
<td><strong>Radius (m)</strong></td>
<td>0.007</td>
<td>Width:0.05 Height: 0.01</td>
<td>Outer Radius: 0.00477 Inner Radius: 0.00295</td>
</tr>
<tr>
<td><strong>Volume (m(^3))</strong></td>
<td>9.6969 x 10(^7)</td>
<td>0.00032</td>
<td>2.78 x 10(^3)</td>
</tr>
<tr>
<td><strong>Density (kg/m(^3))</strong></td>
<td>2700</td>
<td>800</td>
<td>1330</td>
</tr>
<tr>
<td><strong>Mass (kg)</strong></td>
<td>0.267</td>
<td>0.252</td>
<td>0.0369</td>
</tr>
</tbody>
</table>
4.9 Design Modifications

After the team performed the COM test, it was determined that the actual location of the COM was 42.1cm from the cover, roughly 6.1% off from Lee’s [6] predicted value. This would affect the location of the instrumentation platform, which has to be located at the system’s COM so that the accelerometer readings are accurate. After having manufactured all of the tank’s components for preliminary tests early on in the project, the team had to then redesign the instrumentation cylinder taking this change into consideration and reprint the parts.

Another design modification that was done simultaneously to the above platform location change was in regards to the diameter of the instrumentation cylinder. The initial inner diameter was 7cm, which was confirmed by Eric Murphy to be large enough to house the instruments. However, this value turned out to be slightly smaller than the group expected. So the team redesigned the cylinder to an outer diameter of 7.874cm so that all the instruments (accelerometer, wireless card, and micro-controller) would fit tightly and securely inside.

The aforementioned design modifications made to the instrumentation cylinder also affected the tank cover design, changing the diameter of the inner lip which allows for a secure fit between the cylinder and the cover. Since the cover also had already been printed early on in the project, the team placed another order and reprinted it to meet these specifications.

Additionally, a modification to the wind turbine’s ballast configuration was also made. This came about after the team conducted its first floatation test on the model, where it became apparent that 5 steel plates made the system significantly heavier than desired, despite the calculations done above, plunging the tank completely underwater. By trial and error, it was then
determined that 4 plates was the ideal number so that the waterline was slightly below the tank cover, and the draft was approximately 60cm, as desired.

**4.10 Design of Testing Configuration**

To accomplish the goals of this MQP, the team tested the wind turbine model in a water flume provided by Alden Research Laboratory in Holden, MA. This 6-foot by 6-foot water tunnel was used to generate 100:1 scale waves, simulating sea conditions a floating wind turbine might experience during its lifetime out in the ocean. The water height used was 50 inches. Below is a picture of the flume.

![Figure 33 - Water flume used for testing, located at Alden Labs in Holden, MA](image)

In order to ensure a quick and easy set-up of the group’s testing apparatus once the testing day at Alden Labs arrived, the team designed an optimal testing configuration for the
zero-tension catenaries, using the flume’s space as best as possible. A picture of this setup can be seen in Figure 23, and a detailed, dimensioned drawing in the Appendix.

The optimal design for this setup allowed the team to place two aluminum anchoring plates upstream of the turbine and the remaining one downstream. Thus, if the wind turbine is carried downstream with the waves, there would be two plates pulling it back to its original position. The two upstream anchoring plates were symmetrically distributed along the flume floor, located 4.12cm from the flume walls and 108.12cm from the downstream plate.
5. Testing

There were two distinct phases of testing. The first phase was conducted in a water tank in Higgins Laboratories 016. The testing of the water-tightness of the spar buoy and the test to determine the height at which the fully assembled spar buoy floated at when submerged in water were outlined earlier in this report. One of the last necessary tests to perform was whether instrumentation (inclinometers and accelerometers) data acquisition software was operational. This test, performed by graduate student Eric Murphy working on a concurrent project, allowed the MQP team to see that all the data would be collected and that there would not be any major issues once the team traveled to Alden Research Laboratories. It also gave the team a chance to see the new wireless testing configuration, which removed the need for an umbilical cable between the floating platform and the laptop computer to transfer data. An umbilical cable would affect the platform dynamics under wave loading.

The final testing phase was conducted in Alden Research Laboratories in Holden, Massachusetts in a 6 foot by 6 foot flume. This flume has a wave generator that allows for varying wave frequencies and amplitudes. Wave amplitudes were conducted with 3 or 4 inch amplitude waves (peak to peak). Because of the modifications to the testing configurations, water did not get into the tank at all during the actual data acquisition phase.

The majority of the testing was done on a different design of floating wind turbine called a tension leg platform (TLP). This design was originally studied by last year’s floating wind turbine MQP team. This year, the TLP design was being run in a concurrent project by graduate student Kazim Naqvi. The entire first day of testing consisted of setting up the instrumentation and making sure everything was ready for the next day. The next two days of testing were spent...
performing 80 test runs with varying wave amplitudes and frequencies, as well as a varying ballast weight.

The fourth day of testing was spent almost entirely switching from the TLP to the spar buoy. The base plate for the TLP was removed, and a lot of time was spent checking again to make sure the spar buoy was water tight before any instrumentation was used. All the testing done that day was on a freely floating spar buoy.

The final day of testing was spent testing an anchored spar buoy. The MQP team ran about 67 tests of varying wave amplitudes (0 – 7.5 cm in height), frequencies (0.5-1.5s periods), as well as varying the ballast weight (1.02-5.14 kg). The data of these tests is analyzed in the next section.
6. Results

Data collection from the Alden Labs was performed using a LabVIEW interface for the inclinometer, accelerometers and load cells. It received data wirelessly from the aforementioned instrumentation. Figure 34 and 35 below show screenshots of LabVIEW of the TLP and spar buoy and model respectively for typical runs.

Figure 34 - LabVIEW screenshot of TLP testing
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The screen layouts that the team used for both of the prototypes were identical. The load cell readings were displayed in two ways. The first display method was through the use of a numerical output. The numerical moment and force quantities that the load cells collected were displayed at the top of the screen. The second display method was through the graph just below the load cell numerical displays. The inclinometer gave out readings on the graph below. The graph showed the degrees off of the vertical, one in the x-direction and the other y-direction. There was a more adverse rotation about the z direction than the TLP test since the lines were sagging and not taught.

The floating test also used two accelerometers. One accelerometer was mounted at the top of the tower at the nacelle, and the other was mounted above the cover of the tank. This was the approximate position of the center of gravity. The two accelerometers measure the
acceleration in the z, y and z directions. The x and y had more significant accelerations in the spar buoy compared to the TLP mainly due to the more sagging cable comparatively. The z direction acceleration was significant as the wave action brought about a substantial vertical movement.

Lastly, a float type gauge was used in the experiment. This provided an accurate measurement of the wave height for LabVIEW. This device used a small buoyant ball on a thin metal rod that was connected to a rotating joint on a potentiometer. This joint allowed the ball to rise and fall with each passing wave and measure the amplitude of the waves on the graph at the bottom right-hand side of the screen.

Below is a collection of graphs compiled from LabVIEW. The graphs illustrate the nacelle acceleration, center of gravity acceleration, wave height and the nacelle inclination. By comparing the graphs of all tests we were able to correlate the effects of the different wave heights and the dynamic forces on the floating system.
These graphs are of test run 79. In this particular test, the total wave amplitude was approximately 2.25 inches. This height translates to 18.75 foot (5.71 m) full scale waves using our 100:1 scale. As seen from the accelerations graphs, the waves had more significant impact on the nacelle than the center of gravity position, with the latter being the most stable.
7. Conclusions

The rise in demand and use of renewable energy sources has been attributed to the increasingly scarce supply of fossil fuels. Additionally, utilization of fossil fuels to produce energy produces byproducts that are harmful to the environment. Wind energy output has increased significantly as renewable energy use has risen. However, with the introduction of floating platform technology, wind energy stands to make more advances as turbines are moved to offshore locations with much greater wind speeds. The floating wind turbine platform may in the future play a significant role in meeting world energy needs.

This MQP designed and constructed a spar buoy floating wind turbine platform concept. Additionally, the team members were involved in the testing of the tension Leg Platform (TLP) design. Both the TLP and Spar Buoy scale models were equipped with inclinometers and accelerometers for data collection during testing. The tests were carried out in water tanks at the WPI’s Higgins Laboratories as well as a flume with a wave generator at the Alden Research Labs in Holden, MA. These tests replicated various conditions from calm weather to hurricane storms. Based on the test results, both models were able to stay afloat in all conditions.

A great deal of work needs to be done in the future to improve on the spar buoy wind turbine model. Improvements should be made to the spar buoy model especially on the ballasting system and cable attachments. Also, more work should be spent in water proofing both of the models with emphasis given to the cover, the tower attachment points and the cable attachment points. A more detailed discussion on future work is found in the following section.
8. Future Work

The goal of this MQP was to design, build, and test a 100:1 model of a Floating Wind Turbine, using the spar buoy as the platform design. For next year’s project, the team suggests modeling wind and gyroscopic effects in the presence of a rotating set of turbine blades, in addition to the existing methods for modeling the tension on the spar buoy tether lines. In the case of the wind modeling, this group performed basic thrust calculations to size a disk that can be placed in front of the turbine blades and serve to analyze how wind affects the pitching angle of the turbine, as described in the design chapter. Next year’s group can manufacture the disk as specified above and develop a shaft system to attach it to the turbine hub. They can then take the full modified system to Alden Labs for a more extensive and detailed testing session. As for the gyroscopic effects due to rotating blades, this MQP has also developed all of the preliminary design procedures for manufacturing the blades, as can be seen in the design section of this report. Future groups can purchase the required materials, manufacture them to the specified dimensions, assemble them onto the tower and nacelle, and, after incorporating the suggested motor for rotation, perform new tests at Alden Labs.

Additionally, due to the unfortunate accident described earlier of dropping the platform, a few dents were discovered on the part. This required the team to add several additional ABS sealant layers to the inside of the platform, adding unnecessary and undesired weight to the system. Therefore, it is highly encouraged that future teams reprint the platform parts and reassemble them, applying a thin layer of ABS sealant to the inside of the tank and taking extra care not to damage the parts.

Furthermore, a modified cable attachment design was also proposed to improve the method of securing the tether lines to the platform. There are now nine of these attachments to be
placed at different locations along the height of the spar buoy as desired. These will need to be glued to the platform before any future testing can be made.

Also, next year’s MQP team can analyze the effects of a ballasted tether system on the turbine’s stability. Unfortunately, due to time constraints, this year’s team was unable to fully design a ballasted configuration (see Figure 8) or test it in Alden Labs. It is advised that further research be made into this mooring system so that it can be accurately designed and tested, comparing the new data with the one presented in this MQP report.

Finally, wind modeling and gyroscopic effects should be introduced and observed how they affect the stability of the system. The first step to introducing new wind modeling and gyroscopic effects is to calculate the current nacelle weight and the potential new weight. The weight of the nacelle for the testing configuration in Alden was 245 grams. Of this mass, 145 grams were the instrumentation and the case that held it. This means that to keep the same weight for the nacelle, the motor, blades, and disk would all have to weigh a total of 100 grams. This is basically impossible based on the size of the disk required and on the maximum velocity that can be achieved. The MQP team decided that if all the weights were minimized as much as possible, than the weight of the new nacelle should not affect the data too drastically.
References

14. "Wind." U.S. Energy Information Administration. URL:

   <http://www.energiasrenovables.ciemat.es/adjuntos_documentos/NUSA2.pdf>

Figure 37 - SolidWorks drawing of tank cover (all dimensions in cm)
Figure 38 - SolidWorks drawing of Spar Buoy Tank Assembly (all dimensions in cm)
Figure 39 - SolidWorks drawing of modified cable attachments (all dimensions in cm)
Figure 40 - SolidWorks drawing of platform assembly (all dimensions in cm)
Figure 41 - Spar Buoy Testing Configuration (all dimensions in cm)