

# Final Report



## **Offshore Wind Turbine**

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## 1.0 Executive Summary

The main purpose of our design project is to design a wind turbine that can successfully operate offshore. Additionally, we have added the dimension of autonomy to the design, which will allow the floating turbine to self-navigate to its selected location and self-orient when needed. With the final design selected, the process of detailed design, component analysis, materials procurement, and construction scheduling has been completed. Each component of the final design, including the turbine blades, generator, tower, foundation, and electric motors has been designed. Note, however, that some of these components have been designed with sufficient detail to allow for their manufacture, while other, less critical components (i.e., outside the main scope of our design project) have been sufficiently designed to allow for their informed selection from the commercial market.

## 2.0 Acknowledgement

There were many individuals that advised and guided our group and its members throughout the design process. The efforts of these individuals not only served to guide us through the design process, but also to continue our education in the principles of math, science and engineering. Each of them routinely made time, in their busy schedules, to meet with us and provide us with substantive feedback. Our sponsor, Dr. Sungmoon Jung, not only provided us with a challenging, inspiring, and innovative design project, he made himself available for weekly “sponsor meetings”. He continually provided us with positive feedback and encouragement, while asking the hard questions that pushed us to learn and improve our ideas and designs. Our mentor, Dr. Kumar, guided us through some of the more difficult aerodynamic issues, which ultimately helped shape the final design. Our Senior Design instructors, Dr. Amin and Dr. Frank, continually provided outlines and guidance regarding the deliverables and presentations. Dr. Faruque and Dr. Graber also provided valuable input that helped shape the size and shape of the final turbine design.

## 3.0 Project Overview

### **3.1 Sponsor Requirements**

The energy potential of offshore wind farms is much greater than that of land based farms thanks to the reduced surface roughness of the sea. For some states the entire electricity could come from offshore wind farms. With such enormous energy potential, offshore wind turbines will contribute to the national energy security.

Although the floating offshore wind turbine has advantages, the cost is still prohibitive. The most important project objective is to reduce the cost compared to existing ideas. The approach is not limited to innovative design --you may come up with innovative construction method, logistics, or any other approach that you can think of.

### **3.2 Scope**

The scope for the offshore wind turbine is related to location and water depth. The location should be sufficiently far from shore such that surface effects from land are immaterial leaving only those from the ocean surface. Water depth should be deep enough to be considered “deep water” (i.e., greater than or equal to 60m).

### **3.3 Goal**

The purpose of this project is to expand a future renewable resource in the hopes of making it available for the commercial market. The largest problem facing the current development is expense. If it were able to have grid parity, the benefits from offshore wind power would grow the renewable energy market tremendously. The largest cost components, of an offshore wind turbine system, are the foundation and overall construction. The primary goal is to

modify existing designs to minimize cost, while maximizing output and sustainability with the goal of reaching a leveled cost of electricity with respect to total grid production.

### 3.4 Constraints

**Time Management:** The Floating Wind Turbine must be designed, built and tested before the last week of the spring semester (as of now April 25<sup>th</sup> 2014). Time management will be necessary in order to batch and cure the concrete foundation, build the steel structure and manufacture the blades and gears before the project deadline. Proper scheduling will be essential to the overall success of the Floating Wind Turbine.

**Budget:** As of now our budget is 2,000 dollars that is being supplied by Dr. Jung’s research grant. Supplies will also be donated from Florida Rock and Cives Steel which will alleviate some of the financial burden from acquiring materials. Blades, gears, motors and sensors will be restricted to the 2,000 dollar budget. The team will track expenditures in order to stay on budget and provide a quality product with a marginal cost.

**Team members:** The team consists of seven members from three disciplines of engineering. There are three mechanical, three civil and one electrical engineering majors assigned to this project. It is imperative that the three disciplines communicate and schedule effectively amongst each other to make the Floating Wind Turbine a reality. Due to differing schedules, the team must overcome scheduling conflicts and resolve a meeting time once a week that can accommodate the team. This is critical to meet objectives and benchmarks determined by faculty and the team members.

In order to overcome scheduling conflicts, much of the work will be broken into task that will completed remotely by the team members. Proper file organization will minimize confusion and ease collaboration of report writing. Drop box and the File Exchange in the EEL4911 Blackboard Course site will be utilized to share, retain and organize documents.

Task will be tracked and benchmarks will be set using a Gantt Chart created in Microsoft Project. The specified timeline will be utilized to track progress, goals, due dates. This timeline will govern the progression of the project.

## 4.0 Design and Analysis

From the dynamic point of view, a wind turbine is a complex structure to design reliably for a given service lifetime. In fact, the fatigue loading of a wind turbine is more severe than that experienced by helicopters, aircraft wings and car engines. The reason is not only the magnitude of the forces but also the number of load cycles that the structure has to withstand during its lifetime of 20 or more years (Figure 4.0) (1).

### 4.1 Turbine Blades

The magnitude and direction of loading play important roles in determining the design characteristics for a wind turbine’s individual components. With regards to the turbine blades, much of the wind’s energy is converted into rotational energy, which is then converted into electrical energy via the onboard generator. However, when the wind’s

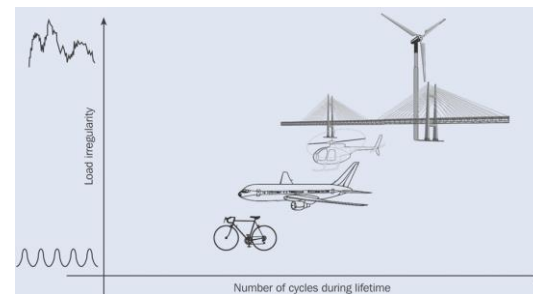


Figure 4.0: Number of lifetime cycles (1)

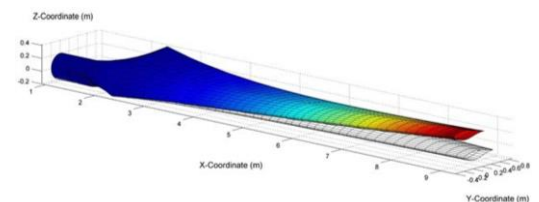


Figure 4.1: Tip deflection (1)

direction is not normal to the blades' rotation, especially in the circumstance of a wind gust, the blades can experience additional wind loading. This additional wind loading, above what is required to rotate the blades, can cause the blades to deflect, which is known as *tip deflection*,  $\delta$  (see Figure 4.1).

### 4.1.1 Wind Turbine Blade Geometry

The overall amount of deflection is important as it relates to the yield strength of the material used to fabricate the blade. To account for the worst case scenario (and to simplify the necessary calculations), it will be assumed that

all of the wind's energy, from a gust, causes the blade to deflect (this scenario might occur when the turbine is at its maximum rotation, which would mean that the additional wind load, from a gust, could not be translated

into rotational energy, but would have to be absorbed by the blades via their deflection). In this case, the following equations would be used to calculate the force of the wind and the deflection of a given blade. To further simply the calculations, the blade's cross sectional area will be approximated as a hollow ellipse. See Figures 4.2 and 4.3.

### 4.1.2 Turbine Blade Design Requirements

Table 4.1 outlines the design requirements for a wind turbine blade, specifically related to resisting deflection caused by wind loading, while practically maintaining lightweight. Stiffness relates to deflection, while toughness relates to the practical consideration that a blade must be able to sustain impacts (e.g., from bird strikes) without fracturing, which will help in the final material selection.

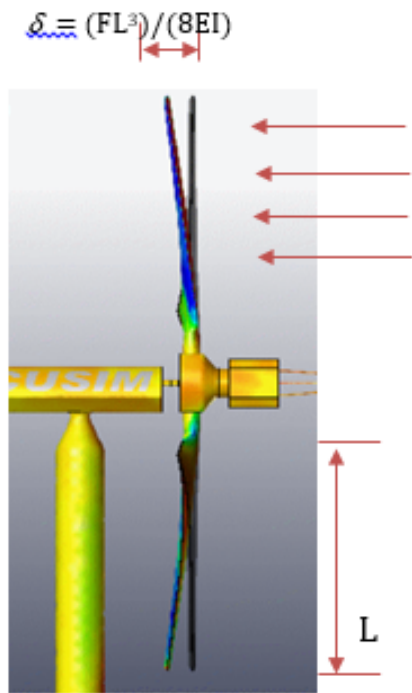


Figure 4.2: Profile view with wind loading and deflection (1).

$$F_{wind} = \frac{1}{2} \rho v^2 C_d A_s$$

Where:  $\rho$  = Air density, 1.29 kg/m<sup>3</sup>

$v$  = Wind velocity

$C_d$  = Coefficient of drag

$A_s$  = Frontal surface area (what the wind "sees")

$F_{wind}$  = Wind force

$L$  = Blade length

$E$  = Elastic modulus

$I$  = Moment of inertia

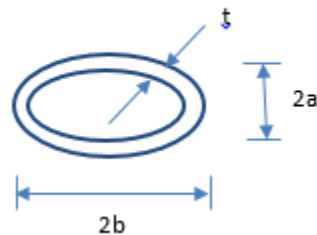


Figure 4.3: Cross-sectional view of a wind turbine blade modeled as a hollow ellipse. The cross-section affects the moment equations  $Z$  and  $I$ , along with surface area  $A_s$ , which are as follows:

$$Z = \frac{\pi}{4} a^2 t (1 + 3b/a)$$

$$I = \frac{\pi}{4} a^3 t (1 + 3b/a)$$

$$A_s = L 2b$$

$$A_c = \pi(a + b)t$$

**Table 4.1** Design Requirements (FCOFV)

Function	Turbine Blade—meaning light, stiff beam
Constraints	Length, $L$ specified Bending Stiffness, $S$ specified Toughness $G > 1 \text{ kJ/m}^2$
Objective	Minimize the Mass, $m$
Free Variables	Wall Thickness, $t$ Choice of Material

#### 4.1.3 Materials Index, $M$ , for Turbine Blade

For a given length,  $L$ , the required stiffness,  $S^*$  is adjusted by altering the wall thickness,  $t$ . The quantities  $S^*$ ,  $L$ , and  $C$  are all specified or constant; the best materials for a light, stiff beam (with a hollow, elliptical cross section) are those with the largest values of index  $M$ . The materials index,  $M$  will be used, in the next section, to compile a list of the best possible materials to be used for a wind turbine blade.

$$m = AL\rho$$

$$S = \frac{CEI}{L^3} \geq S^*$$

$$I = \frac{\pi}{4} a^3 t \left(1 + \frac{3b}{a}\right)$$

$$t = \frac{4SL^3}{\pi a^3 \left(1 + \frac{3b}{a}\right) CE}$$

$$m = \left( \frac{4SL^3(a+b)}{a^3 \left(1 + \frac{3b}{a}\right) C} \right) (L) \left( \frac{\rho}{E} \right)$$

$$M = \frac{E}{\rho}$$

#### 4.1.4 Materials for Wind Turbine Blades

The materials in Table 4.2 came from a graph that plotted *Young's Modulus,  $E$*  against *Density,  $\rho$*  (2). Given the design requirements laid-out in Table 3.1, these are the best materials that can be used to fabricate a lightweight, stiff turbine blade.

**Table 4.2** Materials for Wind Turbine Blades

Material	Index $M$ (GPa/(Mg/m <sup>3</sup> ))	Comment
Wood Parallel to the Grain	11.7 – 14.7	Traditional material for airboat propellers; inexpensive; natural variability
CFRP	46.7 – 133.3	As good as good with more control over properties
Ceramics	35 - 95	Good $M$ , but low toughness and high cost

#### 4.1.5 Values for Turbine Blade Calculations

Based on the average value of wind velocities, from wind gusts in areas where wind farms have been constructed in the US, a value of 20 m/s (47 mph) has been selected for the following calculations (3). Also, Tables 4.3, 4.4 and 4.5 contain the material properties, design characteristics, and geometric values, respectively, for the selected materials in Table 4.2 and the given blade geometry and equations from section 4.1.1.

**Table 4.3** Material Properties (average values)

Material	E (GPa)	$\sigma_y$ (MPa)	$\rho$ (kg/m <sup>3</sup> )
Wood Parallel to the Grain	13	50	700
CFRP	110	800	1550
Ceramics	86	1197	2485

**Table 4.4** Dimensions of Blade and Wind Speed (average values based on Fig. 1.2)

2a (m)	2b (m)	L (m)	$C_d$ (ellipse, turbulent)	v (m/s)
0.9	1.8	9	0.20	45

**Table 4.5** Geometric Values

t (m)	$A_s$ (m <sup>2</sup> )	$A_c$ (m <sup>2</sup> )	I (m <sup>4</sup> )	Z (m <sup>3</sup> )
0.00079	16.2	0.003350	0.000396	0.000879
0.00159	16.2	0.006743	0.000797	0.001770
0.00635	16.2	0.026931	0.003181	0.007069

#### 4.1.6 Final Values and Selection

Using the values from Tables 4.3, 4.4, and 4.5, along with the equations from section 4.1.1 (repeated here), the following calculations values can be determined. The final results are tabulated in Table 4.6.

Deflection:  $\delta = (F_{wind} L^3)/(8EI)$

Wind Load:  $F_{wind} = \frac{1}{2} \rho v^2 C_d A_s$

$F_{wind} = 4232 \text{ N}$

Min. Yield Strength:  $\sigma_{ymin} = (F_{wind} L)/(2Z)$



**Table 4.6** Final Values

Material	$\delta$ (m)	$\sigma$ min (Pa)	$\sigma_y$ (Pa)	m (kg)
Wood Parallel to the Grain	-	-	5.00E+07	-
t1	7.50E-02	2.17E+07	-	21
t2	3.72E-02	1.08E+07	-	42
t3	9.32E-03	2.69E+06	-	170
CFRP	-	-	8.00E+08	-
t1	8.86E-03	2.17E+07	-	47
t2	4.40E-03	1.08E+07	-	94
t3	1.10E-03	2.69E+06	-	376
Ceramics	-	-	1.20E+09	-
t1	1.13E-02	2.17E+07	-	75
t2	5.63E-03	1.08E+07	-	151
t3	1.41E-03	2.69E+06	-	602

**FINAL SELECTION:** CFRP at a thickness of 0.79mm (t1)

Based on a thorough analysis of the materials selected for a wind turbine blade, keeping in mind the primary objective of a light, stiff material that is also tough, **the best material available is CFRP** at a thickness of 0.79mm. CFRP, at 0.79mm thick, has a minimal deflection of 0.886cm, while allowing more control over its properties than wood and being tougher than ceramics. This selection is reinforced by the fact that CFRP is a typical and widely used material in the fabrication of today’s wind turbine blades.

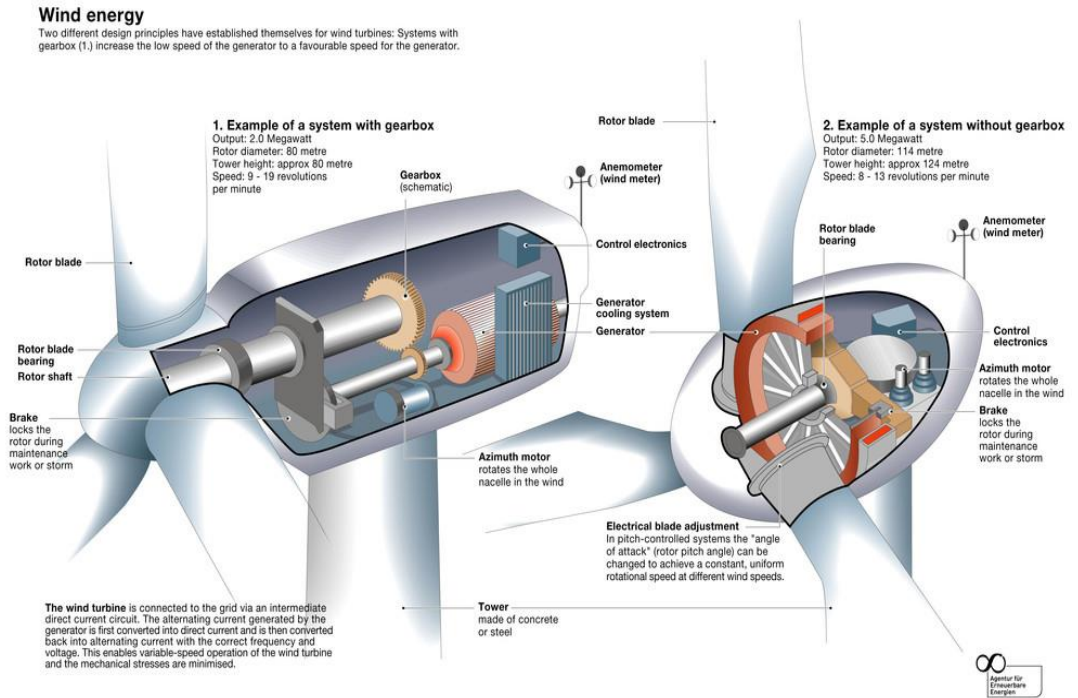
## 4.2 Generator

When looking at today’s wind turbine designs we see that there are two main concepts in generating power. In both concepts they consist of a generator, the difference being uses a gearbox or direct drive. When breaking down both concepts we see many fundamental differences.

In Gearbox design, we typically see a 6 phase, 6 pole induction generator that requires 1500+ rpm synchronous speed in 50 Hz, while it requires 1800+ rpm synchronous speed in 60 Hz. These gearbox, work well in on-shore application as they are easy accessible and maintenance is not too much of a burden, however when looking at off-shore applications we see that the task is a bit more of a challenge and in return presents a higher cost. On the other hand, using gearboxes in off-shore applications isn’t all bad. We see that in today’s technology most applications do use gearboxes because they can produce such high voltage potential, increase the rpm up to synchronous speeds, and allow a wider range of wind speeds. Typically in induction generator with a gearbox we see a range of 1800-1860 rpm before having to put the turbine into stall phase. Although this may sound like an ideal design there are many flaws in using gearboxes and an ideal induction generator. For example, with gearboxes weight becomes an important fact which was not a problem on land. Increase weight, impacts the structure of the base which in turn increases the cost. When looking at an induction generator another burden that plays a role is a needed external excitation. This excitation roughly consumes about 20% of the power before being able to synchronous and pump out power to the grid. Another factor as mentioned above is maintenance. It costs a significant amount to have a skilled professional go out on a boat and climb up to perform maintenance or fix a problem. In all, there are positives and negatives in gearboxes that do allow the creation of power back onto the grid.

In direct drive designs, we typically see an excitation static generator, induction generator or a permanent magnet generator. In floating offshore designs it is more efficient to use a permanent magnet generator for direct drive because of its size and reliability. A permanent magnet generator is roughly 4 meters, compared to a excitation static generator which is 8 meters. When comparing an induction generator and its need for multiple poles to use such lower rpms it is inefficient to use. For example, an induction generator would need to use 80+ poles resulting in a bigger, more expensive, and less efficient generator. Therefore with the purpose of reducing the load, permanent magnet would be the ideal option in direct drive. Permanent magnet generators are relatively easy to manufacture and assembly with the rotor is cheaper compared to induction generators. Using permanent magnets also eliminate the need for brushes and external excitation sources. In direct drive permanent magnet designs, there is a 20% energy savings because of its self-excitation and losses across the gearbox are now disregarded. Permanent magnet generators allows for size reduce on the base, which reduces the cost of materials, and also is more reliable and longer lasting than most generators of equal power output. Another added benefit of direct drive is now gearbox maintenance can be ignored, resulting in further saving in commissioning, erection, and contingency. Although there are many pros for direct drive permanent magnet generators there are some

down sides as well. Permanent magnet generators are more costly due to the market and its rare earth metals that create the magnetic field. Due to new innovations in the past two years, including reducing the size and efficiency, prices are slowly beginning to drop. As innovation increases and more permanent magnets hit the market they will drastically reduce in price. Another problem that could arise is the rotor becoming demagnetized thus resulting in a shift of the poles and lack of the creation of power. Because this technology is rather new, there is no case where this has happened yet, but it is always a small possibility. In all, there are solutions and challenges that direct drive permanent magnet generators give to the creation of power in offshore wind applications. (4)



Power Generation	Maintenance (0.3)	Weight (0.3)	Initial Cost (0.2)	Efficiency (0.2)	Totals
Gearbox	5	4	6	6	5.1
Direct Drive	8	6	4	8	6.7

After using the decision matrix, the answer between direct drive versus using a gearbox is to go with the direct drive design. Although the direct drive route is initially more expensive, looking at the long term picture it is cheaper with only requiring two services a year. Direct drive also provides more reliability and a greater life span up to 20 years, while offering easier assembly during the erection phase of the project. Looking at the comparison of a gearbox with induction generator versus a direct drive permanent magnet generator, it is seen that permanent magnet generators offer the best solution to bring down cost with improved efficiency in the future.

When deciding what the generator would output the team used the equation  $P=1/2\rho Av^3$ . Calculating the area of 9 meter blades the clear choice was using two 100kW permanent magnet generators that cost's \$14,240 for our two tower design. The specs of these generators are a start-up speed of 3m/s and a survival speed of 40 m/s with a weight of 2400 Kg each. These specs were designed to ensure a low start-up speed and making its survival speed was large enough that there were no safety concerns.

### 4.3 Tower

#### 4.3.1 Turbine Tower

When designing an offshore wind turbine, all structural components are classified into one of three categories regarding safety. The classes are based on risk level for personal injury, pollution, economic consequences and negligible risk to human life. Because the tower can delay the entire construction of a turbine, and because it is such a large investment, it must be designed according to the high safety class. The tower can fail due to fatigue, cracking, buckling, shearing, or stresses due to welding. A tree diagram of faults is pictured below.

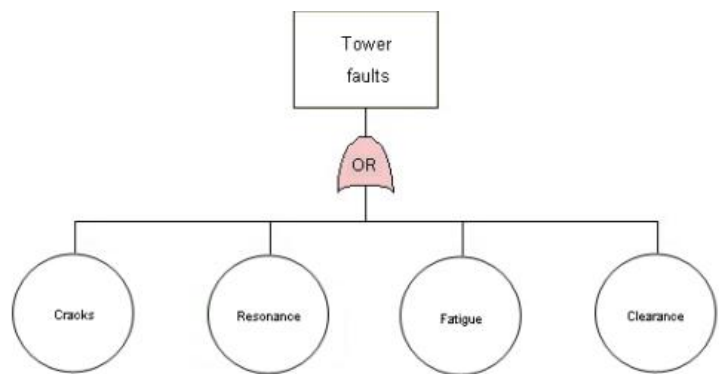


Figure 4.3.1 Tower Faults

#### 4.3.2 Wind Turbine Tower Geometry

The most important function of the tower is to support the weight of the nacelle and the blades and carry the loads generated from the operation of the turbine. The structural components of the tower are very important and have significant effects on the systems performance and response. The general shape of any tower has a very high height to width ratio, causing this structural component to be the most sensitive to wind loading. For this project, two designs were considered: steel lattice tower and steel tubular column.

Research was done on each of these designs and revealed the following. Lattice towers entail a specific assembly order to attain a specific structural strength and stiffness using the least amount of material. The steel is used most efficiently and results in a very light weight tower.

The ability to assemble this tower on site allows it to be used for extremely tall wind turbines. It has a lower initial cost than steel column



Figure 4.2.2 Photographs of lattice tower (left) and steel tubular tower

towers but requires more maintenance due to its abundance of connections, which could become costly over time. Most existing wind turbines are built with steel columns. The advantages include the enclosed cavity which provides more shelter for maintenance work and electrical component housing, assembly efficiency and aesthetic impact. It has been established in the industry that the largest steel column diameter that can be transported is 4.3 meters in diameter; this would be the most significant reason to design a lattice structure over a steel tubular beam. Based on this information and the size of the turbine to be designed, the steel column was selected. The following section will explicitly depict the design process carried out for the wind turbine tower. The Design of Offshore Wind Turbine Structures OFFSHORE STANDARD DNV-OS-J101 was referenced to design the tower. According to this standard, “The design of a structural system, its components and details shall, as far as possible, satisfy the following requirements:

- resistance against relevant mechanical, physical and chemical deterioration is achieved
- fabrication and construction comply with relevant, recognized techniques and practice
- inspection, maintenance and repair are possible.

Structures and structural components shall possess ductile resistance unless the specified purpose requires otherwise. Structural connections are, in general, to be designed with the aim to minimize stress concentrations and reduce complex stress flow patterns. As far as possible, transmission of high tensile stresses through the thickness of plates during welding, block assembly and operation shall be avoided. In cases where transmission of high tensile stresses through the thickness occurs, structural material with proven through-thickness properties shall be used.” [2011 DNV pg 26]

### 4.3.3 Design of the Tower

American Society of Civil Engineers has published ASCE 7-10 Minimum Design Loads for Buildings and other structures. This code and methodology was adopted:

“Steps to Determine Wind Loads for Enclosed, Partially Enclosed and Open Buildings of All Heights

- **Step 1: Determine risk category of building or other structure, see Table 1.5-1**

**Table 1.5-1 Risk Category of Buildings and Other Structures for Flood, Wind, Snow, Earthquake, and Ice Loads**

Use or Occupancy of Buildings and Structures	Risk Category
Buildings and other structures that represent a low risk to human life in the event of failure	I
All buildings and other structures except those listed in Risk Categories I, III, and IV	II
Buildings and other structures, the failure of which could pose a substantial risk to human life.	III
Buildings and other structures, not included in Risk Category IV, with potential to cause a substantial economic impact and/or mass disruption of day-to-day civilian life in the event of failure.	
Buildings and other structures not included in Risk Category IV (including, but not limited to, facilities that manufacture, process, handle, store, use, or dispose of such substances as hazardous fuels, hazardous chemicals, hazardous waste, or explosives) containing toxic or explosive substances where their quantity exceeds a threshold quantity established by the authority having jurisdiction and is sufficient to pose a threat to the public if released.	
Buildings and other structures designated as essential facilities.	IV
Buildings and other structures, the failure of which could pose a substantial hazard to the community.	
Buildings and other structures (including, but not limited to, facilities that manufacture, process, handle, store, use, or dispose of such substances as hazardous fuels, hazardous chemicals, or hazardous waste) containing sufficient quantities of highly toxic substances where the quantity exceeds a threshold quantity established by the authority having jurisdiction to be dangerous to the public if released and is sufficient to pose a threat to the public if released. <sup>a</sup>	
Buildings and other structures required to maintain the functionality of other Risk Category IV structures.	

- Step 2: Determine the basic wind speed,  $V$ , for the applicable risk category, see Figure 26.5-1A, B or C

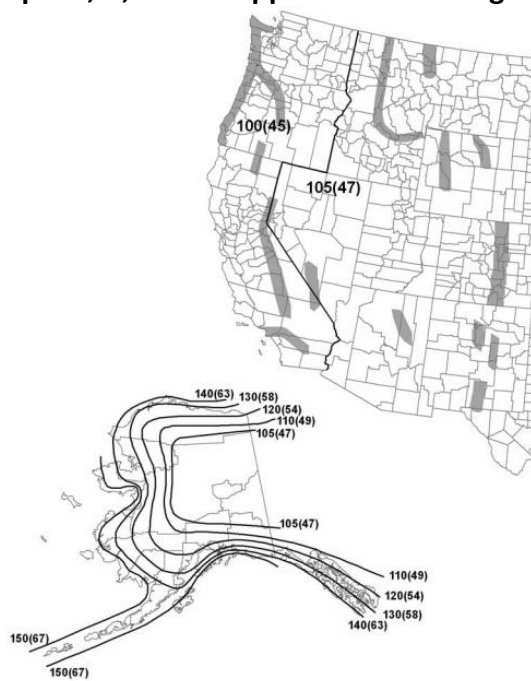


Figure 26.5-1C Basic Wind Speeds for Occupancy Category I Buildings and Other Structures.

- Step 3: Determine wind load parameters:
  - Wind directionality factor,  $K_d$ , see Section 26.6 and Table 26.6-1

Structure Type	Directionality Factor $K_d^*$
<b>Buildings</b>	
Main Wind Force Resisting System	0.85
Components and Cladding	0.85
<b>Arched Roofs</b>	0.85
<b>Chimneys, Tanks, and Similar Structures</b>	
Square	0.90
Hexagonal	0.95
Round	0.95
<b>Solid Freestanding Walls and Solid Freestanding and Attached Signs</b>	0.85
<b>Open Signs and Lattice Framework</b>	0.85
<b>Trussed Towers</b>	
Triangular, square, rectangular	0.85
All other cross sections	0.95



- Step 5: Determine velocity pressure  $q_z$  or  $q_h$  Eq. 27.3-1

Velocity pressure,  $q_z$ , evaluated at height  $z$  shall be calculated by the following equation:

$$q_z = 0.00256K_zK_dK_gV^2 \text{ (lb/ft}^2\text{)} \quad (27.3-1)$$

[In SI:  $q_z = 0.613K_zK_dK_gV^2$  (N/m<sup>2</sup>);  $V$  in m/s]

where

$K_d$  = wind directionality factor, see Section 26.6

$K_z$  = velocity pressure exposure coefficient, see Section 27.3.1

$K_g$  = topographic factor defined, see Section 26.8.2

$V$  = basic wind speed, see Section 26.5

MATHCAD CALCULATIONS:

$$K_d := 0.95 \quad K_{ZT} := 1 \quad Z := 66 \quad c_1 := 6.62 \quad c_2 := 1273$$

$$\alpha := c_1 \cdot Z^{-0.133} = 3.792 \quad Z_g := Z^{0.125} \cdot c_2 = 2.149 \times 10^3$$

$$K_Z := 2.01 \left( \frac{Z}{Z_g} \right)^{\frac{2}{\alpha}} = 0.32 \quad v := 160\text{mph} \quad v_{up} := 50\text{mph}$$

$$q_{zup} := 0.00256 \cdot K_Z \cdot K_{ZT} \cdot K_d \cdot v_{up}^2 = 4.19 \frac{\text{ft}^2}{\text{s}^2}$$

$$q_z := 4.19 \frac{\text{lb}}{\text{ft}^2}$$

#### 4.3.4 Materials for Wind Turbine Tower

### Steel Design

Due to the combined Flexural and Axial Loading, the Column and Chapter H sections were referenced in the AISC Steel Manual.

$$A_{\text{Axial}}_{\text{load}} = 1.692 \times 10^4 \text{ lb}$$

$$D_{\text{Rotor}} := 30 \text{ ft}$$

$$A_{\text{Rotor}} := \left(\frac{\pi}{4}\right) \left(D_{\text{Rotor}}^2\right) = 706.858 \text{ ft}^2$$

$$P_{\text{Rotor}} := A_{\text{Rotor}} \cdot q_z = 2.962 \times 10^3 \text{ lb}$$

$$D_{\text{out}} := 24 \text{ in}$$

$$D_{\text{in}} := 23 \text{ in}$$

$$t := 0.50 \text{ in}$$

#### Steel Selection

A618 Grade I

$F_y := 50 \text{ ksi}$

$F_u := 70 \text{ ksi}$

$E := 29000 \text{ ksi}$

$1 \text{ ksi} = 1 \times 10^3 \text{ psi}$

$$A_1 := \pi \frac{\left(D_{\text{out}}^2 - D_{\text{in}}^2\right)}{4} = 0.256 \text{ ft}^2$$

### Torsional Shear Constant

$$C_1 := \pi \frac{\left(D_{\text{out}} - t\right)^2}{2} = 6.024 \text{ ft}^2$$

### Polar Moment of Inertia

$$I_1 := \pi \frac{\left(D_{\text{out}}^4 - D_{\text{in}}^4\right)}{64} = 0.123 \text{ ft}^4$$



## Radius of Gyration

$$r_1 := \left( \frac{I_1}{A_1} \right)^{\frac{1}{2}} = 0.693 \text{ ft}$$

**Effective Length Determine using Table C-A-7.1**

$$K_1 := 0.6$$

**Laterally Unbraced Length**

$$L_1 := 792 \text{ in}$$

$$\text{Slender}_{\text{Ratio}1} := K_1 \cdot \frac{L_1}{r_1} = 57.181$$

$$F_{e1} := \frac{(\pi^2 \cdot E)}{\text{Slender}_{\text{Ratio}1}^2} = 8.754 \times 10^4 \text{ psi}$$

$$F_{\text{cr.Axial}1} := \left( 0.658 \frac{F_y}{F_{e1}} \right) \cdot F_y = 3.937 \times 10^4 \text{ psi}$$

$$P_{n1} := F_{\text{cr.Axial}1} \cdot A_1 = 1.453 \times 10^6 \text{ lbf}$$

Axial Load According to LRFD

$$\text{AXIAL}_{\text{LRFD}} := \text{Axial}_{\text{load}} \cdot 1.6 = 2.707 \times 10^4 \text{ lb}$$

**The Critical Axial Load is greater than the required Axial load.**

$M_{\max} := 200 \text{ kip}\cdot\text{ft}$  M.max was calculated by Hand

$$S := \pi \frac{(D_{\text{out}}^4 - D_{\text{in}}^4)}{32D_{\text{out}}} = \blacksquare$$

$$1 \text{ in}^3 = 4.329 \times 10^{-3} \text{ gal}$$

$$M_n := \left[ F_y + \frac{(0.021E)}{\left( \frac{D_{\text{out}}}{t} \right)} \right] \cdot 212.52 \text{ in}^3 = 3.572 \times 10^7 \frac{\text{ft}^2 \cdot \text{lb}}{\text{s}^2}$$

$$\phi M_n = 0.9 \left[ F_y + \frac{(0.021E)}{\left( \frac{D_{\text{out}}}{t} \right)} \right] \cdot 212.52 \text{ in}^3 = 1000 \text{ kip}\cdot\text{ft}$$

**The designed max moment is substantially greater than the required moment.**

#### 4.3.5 Final Values and Selection

The A616 Grade 1 steel column will be 66 feet tall with a diameter of 2 feet. The wall thickness is .5 inches, and it weighs 8,635 pounds.

### 4.4 Foundation

#### 4.4.1 Deck

The metal decking used was selected for weight, cost, and usability. Not structural support. Accessibility for maintenance crews was the main concern.

#### 4.4.2 Sub-Deck

The sub-deck rests on the truss framing and is made of W-shape beam members. This slab is continuously welded to 2.5 inch cap plate members on the truss framing. It was designed to translate the weight of the tower and the bending moment caused by wind hitting the tower to the truss frame below.

Dead Load = Weight of Wind Turbine

Design Dead Load = 200 psf which was determined using ASCE7 for Industrial Floors.

Max Moment = 403 kip-ft and was determined from the moment diagram.

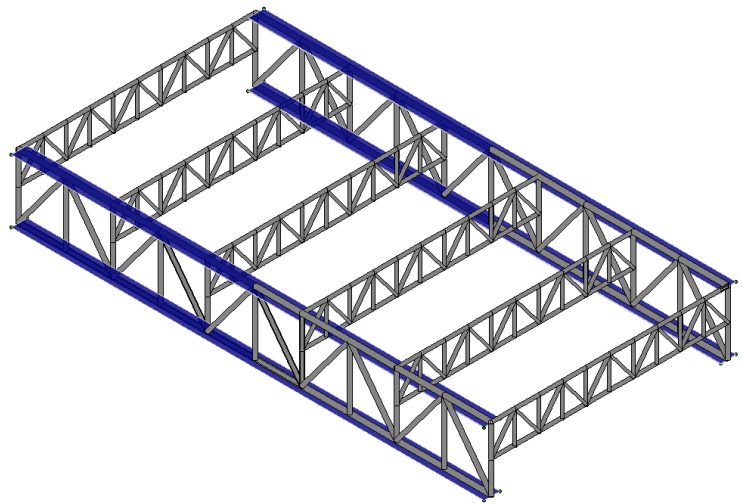
The supporting beam chosen for the deck is a W21x111. The steel chosen has a yield strength of 50 ksi. The Beam was chosen from Table 3-10 in the AISC Steel Manual. The beam is capable of holding a design load of 810 kip- ft. This provides a safety factor of 2 which is within the standard range of 1.5-3 for vessels.

Deck Beams weigh 252 kips

Allowable Deck weight including floor is 1000 kips.

#### 4.4.3 Truss Framing

The structural support of the turbine is comprised of a truss framing system and a sub-deck. The framing was designed, taking into account dead and live loads, for strength and fatigue. The live load due to wind hitting the blades and tower is the governing load on the framing and created a large strength requirement. Loads on the lateral bracing are due to ocean waves, thus, bracing trusses were designed for fatigue.

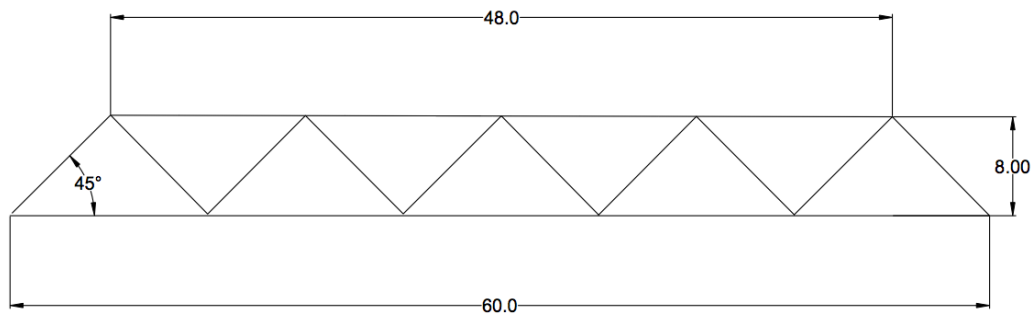


The truss frame system includes two parallel beam-trusses with six lateral bracing trusses. The trusses are comprised of circular tube structural members and are pin connected. Each Beam-Truss is capped by a 2.5 inch plate. The framing is connected to both the pontoons and deck by continuous welds with the cap plates, which are continuously welded to the sub-deck and pontoons.

This diagram shows the support trusses and truss bracing supporting the deck and turbine. The beam-trusses rest directly on the pontoons. The bracing trusses support the structure against lateral translation and deflection. The truss design is Warren B configuration.

The beam-trusses are comprised of round HSS16x0.625 members while the truss braces are round HSS5x0.25 members. The steel used for both is A500 Grade B steel with yield stress,  $F_y=42\text{ksi}$ , and fracture stress,  $F_u=58\text{ksi}$ . The cap plates are 2.5 inches thick using A36 steel with yield stress,  $F_y=36\text{ksi}$ , and fracture stress,  $F_u=58\text{ksi}$ .

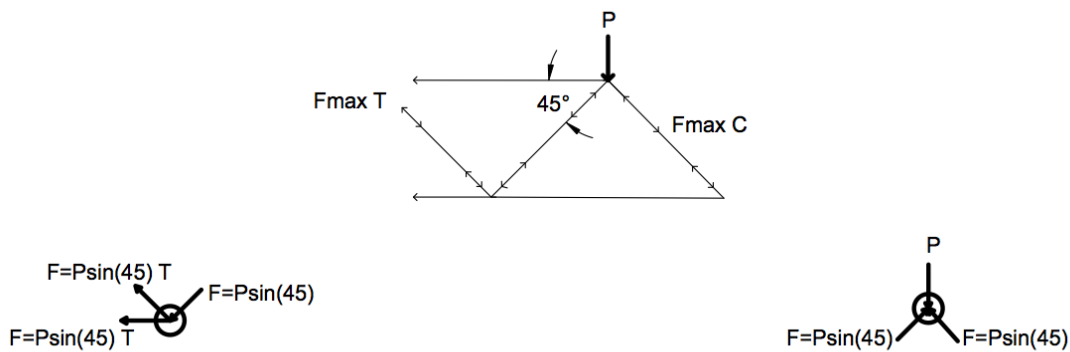
Below lies a diagram of the beam-trusses. (The bracing trusses are proportionally  $1/10^{\text{th}}$  the dimensions of the beam-trusses.)



Below

are the free

body diagram analyses accounting for the weight of the members above the support frame.



### Support Framing Member Design

**Design a circular HSS Shape for  $M_{max} = 397$  kip-ft  $P_{max} = 455$  kips** AISC Requirements: where  $K=0.65$   $L=20$ ft Using A500 Grade B Steel with  $F_y=42$ ksi and  $F_u=58$ ksi

(as recommended for rectangular HSS shapes) LRFD:  $M_u < \phi M_n$  In AISC Table 3-15 Try HSS16x0.625

$397$  kip-ft  $<$   $435$  kip-ft (ok)

Check For adequacy In:

$P_u < \phi P_n$  Effective Length:  $KL=(0.65)(26\text{ft}) = 17$  ft

In AISC Table 4-17 for HSS16x0.625

$455$  ksi  $<$   $1240$  ksi (OK)

#### Compression Analysis:

Slenderness ratio:  $KL/r=0.65(26 \times 12)/5.46= 37.1 < 200$  (OK)  $KL/r < 4.71(E/F_y)^{1/2}$   $37.1 < 4.71(29,000/46)^{1/2}$   $37.1 < 118.3$

$F_y/F_e < 2.25$   $42/208 < 2.25$   $0.20 < 2.25$  (OK)

#### Tension Analysis:

Yielding:

$P_n = F_{cr} A_g = (38.6)(28.1) = 1085$  kips  $\phi P_n = 0.9(1085) = 977$  kips  $>$   $455$  kips (OK)

$F_e=208$  ksi  $F_{cr}=38.6$  ksi

---

$$P_n = F_y A_g = 42 \text{ ksi} (28.1 \text{ in}^2) = 1180 \text{ kips} \quad \phi P_n = 0.9 (1180 \text{ kips}) = 1062 \text{ kips} > 455 \text{ kips (OK)}$$

---

Fracture:  $P_n = F_u A_e$

$$P_n = (58 \text{ ksi}) (3.275 \text{ in}^2) = 189.95 \text{ kips}$$

where,  $A_e = A_g U \quad A_e = 0.625 (5.24 \text{ in}^2) = 3.275 \text{ in}^2$

$$\phi P_n = 0.75 (189.95 \text{ kips}) = 142.5 \text{ kips} > 128 \text{ kips (OK)}$$

$$U = 1 - 0.375 = 0.625$$

---

*Use HSS16x0.625 shape @ 103 lb/ft (self weight) For bracing Use HSS5x0.250 shape @ 12.69 lb/ft*

#### **Weight Analysis:**

$$30 \text{ members @ } 26 \text{ ft @ } 103 \text{ lb/ft} + 75 \text{ members @ } 4 \text{ ft @ } 12.69 \text{ lb/ft} = 84.1 \text{ kips}$$

#### **4.4.4 Pontoon Design**

The pontoons are the main component to a stable platform. In order to increase stability, the pontoons have been designed to have a buoyancy ratio of 1.5 :1. This ratio allows the pontoons to be able to successfully float a load equivalent to half the weight of the entire structure. This buoyancy tolerance allows for the pontoons to be ballasted. The ballast allows the pontoons to take on water as needed to adjust the overall buoyancy of the structure. For example, by taking on water, the overall structure's center of gravity will be lowered which provides a structure that is more resistant to the overturning moment. By pumping out the water and decreasing the overall weight of the structure, the structure sits higher in the water, thus reducing drag. This will allow the structure to move through the water more efficiently.

The Buoyancy equation was the controlling design parameter that must be met. The formula below indicates that a positive number results in a floating number.

$$\text{Buoyancy} = (\text{Weight of displaced fluid}) - (\text{Weight of structure})$$

The Pontoon's Diameter were determined first by calculating the weight of the deck structure including the Wind Turbine and the allowable deck loading. Once the deck weight was determined, the amount of needed displaced water could be calculated. From this point, the method of guess and check was utilized to determine the pontoon diameter. Guess and check was chosen due to the change in pontoon weight as diameter changed. After optimization the following parameters and dimensions were defined and calculated for the pontoon using the below method.

Total Deck Weight = 1286 kips Deck<sub>weight</sub> := 1286kip Deck<sub>weightmetric</sub> := 590000kg

Water<sub>density</sub> :=  $1000 \frac{\text{kg}}{\text{m}^3}$  Steel<sub>Density</sub> :=  $7800 \frac{\text{kg}}{\text{m}^3}$  Pontoon<sub>Length</sub> := 60m

Pontoon<sub>Thickness</sub> := 0.0254m

Volume of water needed to diplace Weight of Deck = 590 m<sup>3</sup>

In order to displace this required volume of water the pontoon would need to have a diameter of 3.54m

Assume Diamter is 4m to determine the weight of the steel in the pontoon.

Volume of steel = 9.55m<sup>3</sup>

Weight of Steel = 75000 kg

Volume of Required Displaced water = 75 m<sup>3</sup>

Total Required Displaced volume = 665m<sup>3</sup> +

Total Volume Displaced (For 1 Pontoon) = 745m<sup>3</sup>

Buoyancy = (Weight of displaced fluid) - (Weight of structure)

Buoancy = (1000kg/m<sup>3</sup>)(745m<sup>3</sup>) - (590000kg + 75000 kg) = 230,000kg

Total Buoyancy for vessel = 1,050,000 kg

The vessel has approxiamte Buoyancy ratio of 1.5 to 1. It can be concluded that the vessel is positivly Boyant and thus will float.

One of the biggest contributors to the innovation of this turbine is the self-propelling propulsion system attached to the swath of the foundation. To start, a general understanding of the system needed to clear so a free body diagram was necessary. The figure below shows a free body diagram of how this issue was executed. Summing the forces in the horizontal direction is essential.

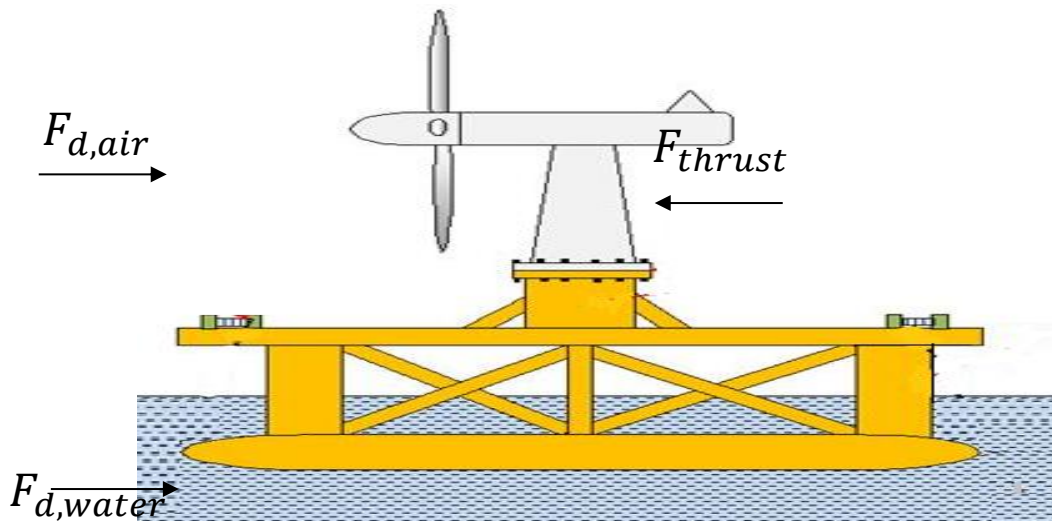


Figure 4.4.1 – Free Body Forces Breakdown

According to the figure, the amount of thrust forces needs to overcome all of the drag forces that are acting against it. Friction is another force and factor in this computation but it is so minimal that the component can be negated and assumed to be zero. From here the drag forces need to be calculated. The formula for analyzing drag forces is based on the equation:

$$F_d = \frac{1}{2} C_d v^2 A_c \rho \quad \text{(Equation 1)}$$

Therefore, based on the free body diagram:

$$F_{thrust} = F_{d,total} = F_{d,air} + F_{d,water} \quad \text{(Equation 2)}$$

Based on the final detail design for the full scale model, the following key parameters are used in order to calculate this equation. The traveling velocity of  $5 \frac{m}{s}$  was arbitrarily decided in order to perform these calculations. The speed at which the turbine travels is not a concern as long as it reaches its destination point. The table compares these parameters through thorough research or internal calculations based on the final design. Cross sectional areas were calculated based on the detail final designs of the foundation and structure, towers, hub/nacelle, and finally blades. The table is primarily set to evaluate and compare the major parameters between the air and the water. In other words, these components will reveal the most significant factors that go into the equation above.

**Table 4.1.1 – Free Body Forces Breakdown**

	Air	Water
Drag Coefficients	1.0	0.5
Fluid Density	$1.225 \frac{kg}{m^3}$	$1000 \frac{kg}{m^3}$
Cross Sectional Area	$118.2 m^2$	$13.366 m^2$

After researching and analyzing these parameters, it is very clear that drag force of the water is exponentially bigger than the drag force through the air. Clearly, the main contributing factor is the huge difference in the fluid density. Since the factor of the density of water is about 1000 times greater than air, this plays a huge factor in the calculations. The full calculations for this analysis are shown below using Mathcad software.

### THRUST REQUIRED FOR WIND TURBINE SWATH

$$F_{thrust} = F_{d\_air} + F_{d\_h20} + F_{fric} \quad V_{sw} = 5 \frac{m}{s} \quad F_{fric} = 0$$

#### ABOVE WATERLINE

$$\rho_{air} := 1.225 \frac{kg}{m^3} \quad C_{d\_above} := 1.0$$

Area 1)  $t_{deck} := 1m \quad d_{tower} := 2m \quad w_{outside} := 1m$

$$A_{1a} := t_{deck} \cdot (20m + d_{tower} + 2 \cdot w_{outside}) = 24 m^2$$

Area 2)  $h_{tower} := 20m$

$$A_{2a} := h_{tower} \cdot d_{tower} = 40 m^2$$

Area 3)  $r_{blade} := 9m \quad face_{blade} := 0.25m$

$$A_{3a} := r_{blade} \cdot face_{blade} = 2.25 m^2$$

Area 4)  $h_{above} := 4m \quad w_{above} := .1m$

$$A_{4a} := h_{above} \cdot w_{above} = 0.4 m^2$$

$$A_{frontal\_above} := A_{1a} + 2 \cdot A_{2a} + 6 \cdot A_{3a} + 2 \cdot A_{4a}$$

$$F_{d\_air} := \frac{1}{2} \cdot \rho_{air} \cdot V^2 \cdot C_{d\_above} \cdot A_{frontal\_above} = 1.811 \cdot kN$$

#### BELOW WATERLINE

$$\rho_{h20} := 1000 \frac{kg}{m^3} \quad C_{d1} := 0.4 \quad C_{d2} := 0.1 \quad C_{d\_below} := C_{d1} + C_{d2} = 0.5$$

Area 1)  $d_{swath} := 2m$

$$A_{1b} := 2 \cdot \frac{\pi \cdot d_{swath}^2}{4} = 6.283 m^2$$

Area 2)  $h_{below} := 4m$

$$w_{below} := .1m$$

$$A_{2b} := h_{below} \cdot w_{below} = 0.4 m^2$$

$$A_{frontal\_below} := 2A_{1b} + 2 \cdot A_{2b} = 13.366 m^2$$

$$F_{d\_h20} := \frac{1}{2} \cdot \rho_{h20} \cdot V^2 \cdot C_{d\_below} \cdot A_{frontal\_below} = 83.54 \cdot kN$$

#### TOTAL THRUST REQUIRED

$$F_{thrust} := F_{d\_air} + F_{d\_h20} + F_{fric} = 85.351 \cdot kN$$

$$F_{thrust} = 19187.732 \cdot lbf$$

#### TOTAL POWER REQUIRED(2 engines)

$$Power := \frac{F_{thrust}}{2} \cdot V = 286.145 \cdot hp$$

$$Power = 213.378 \cdot kW$$



After compiling and analyzing all of the calculations, it has been determined that the total amount of power that is needed to move the turbine out to its designated location is about two 286 HP motors. Knowing this, a 300HP Lincoln 1800 RPM three phase motor has been selected.

This motor was selected for several reasons. Most importantly, it produces the amount of power that will be needed to transport the entire system. Although the cost of this motor seems very expensive, this model in particular is much more cost effective compared to other existing 300 HP competitors. Another great aspect of this model is that it is a TEFC motor. TEFC stands for “Total Enclosed Fan Cooled” motor. The primary purpose of a TEFC is its ability to protect from environmental effects over a long period of time. It is commonly used in ordinary industrial situations. It offers tremendous protection against common hazards. The fan that is located in the back of the shaft is covered by the housing. It brings in air over the fins of the motor. At this stage, excess heat is removed and cooling occurs. This model also contains a water as well. It weighs approximately 3000 pounds by the structural design for the full scale model is able to absorb and support over a million pounds. An electric motor was a team decision to go with because of its self-sustaining power capability as well as environmentally friendly effect on its surroundings.



**Figure 4.4.2 – Motor Selection**

## 4.5 Autonomy

When looking at the wind turbine industry today there have been many different innovations to improve the product as a whole. From new generator concepts to the latest in blade designs, the wind power industry has accelerated faster than anyone could have imagined. Although these concepts are great improvements, there is a new idea that can revolutionize the way man-kind produces power. The future is autonomy, particularly in autonomous off-shore wind turbines.

When deciding how to control the autonomy, there are a ton of different aspects one must take into consideration, especially because of the high voltage electric motor being used. To help model how the autonomy would be manufactured, Tesla’s model of how they communicate with their motor was used.

In the autonomy package there are four main components: GPS, Power Stage, Controllers, and the filter stage. The language that is being used will be C programming and assembly to help make communication more efficient. The first component GPS is the main way, to communicate with the wind turbine and tell it where to go. The high level model of how this will work is a communication hub on land will send a signal to the wind turbine, and the hardware onboard will interpret the signal. From here the controller gives the motor instructions and navigated the wind turbine to its desired location.

Next is the power stage, one of the more complex components. The power stage is made of large semiconductors switch arrays. The switches will be composed one square inch by a quarter inch thing silicon insulated gate bipolar transistors (IGBTs). These arrays are the connected to the grid port or the motor depending whether the wind turbine is in commissioning or operation. Within each array, there will be more switches grouped into three pairs of half bridge rectifiers. During commissioning each of these bridges form a phase, and are connected to each phase of the 3-phase permanent magnet motor. During, operation however, there will only need to be two of these bridges active because there are only two ports in the AC line. To switch between operation and commissioning phases four relays will be used. These relays allow the switches to be connected to either the grid or connected to the motor.

The second largest component is the controllers on board. There are two types of controllers used: the digital signal processor (DSP) and the safety processor (SP). These controllers turn the switches on and off, up to 32,000 times per second. In this model the DSP is the primary controller, while the SP is the secondary. The DSP controls the torque and charge behavior of the motor and grid operation, while the SP monitors the current consistency, and other issues that need to be sent back to the communication hub.

The last component is the filter stage. The filter stage helps filter out the noise created by all the electronics. For instance, a large amount of the electrical noise is created during the power stage, and if this noise was to conduct back into the power lines it could interfere with the GPS, and other signals being sent onboard. If this problem was to occur, the wind turbine would essentially not know where it is. To create the filter, inductors will be placed between the IGBTs and the different port to avoid any interference. The language that is being used will be C programming and assembly to help make communication more efficient.

## 5.0 Prototype Details

### 5.1 Overall Construction

Below is an illustration showing the final prototype after building process has been completed. The major specifications of the prototype are listed:

Parameter	Dimension (inches)
Height of Tower	8 in.
Width of Deck	18 in.
Length of Deck	24 in.
Truss Height	8 in.
Pontoon Diameter	3 in.
Length of Propellers	3 in.
Diameter of Motor Cones	2 in.

The design criteria introduced by our sponsor at the beginning of the semester are as follows:

Autonomy-Static Location

Arduino Technology

Serviceability and Rotation Limit

Maximum Displacement of 10 deg.

Efficiency of Electricity Generated

Comparison Onshore vs. Offshore

The prototype includes an implementation of multiple ballast systems. The biggest reason for this addition to our product is because of its innovation for stability. One of the biggest scopes of our project is to introduce something that the market has yet to be applied to this technology. By adding more weight to the structure, the ballast allows the floating wind turbine to become more neutrally buoyant. There are four individual ballast systems, each capable of storing up to a half of pound of weight. Completely working in parallel with the Arduino



Figure 5.1– Prototype

microcontroller, the system and retrieve and extract water based on wind loads and wave activity. Although two pounds does not seem to play a huge factor, it correlates to 10% of the total weight of the turbine since the total weight of the turbine is about 20 pounds. The figure below shows a closer up version of this system.

Another innovative implementation into the prototype was attaching a sensor/pendulum onto the back of the decking. The purpose of this piece is to maintain pitch control. The pendulum is hooked up to the microcontroller, telling the turbine when wave activity is too strong so operating conditions are impossible. As you can see, a weight is attached to the bottom of the sensor which allows a pitch angle to be measured. In real world applications, this technology is extremely crucial based on the wave loads and wave conditions that this turbine will encounter in the middle of the ocean.



**Figure 5.2– Ballast System**



**Figure 5.3 – Pendulum**

## 5.2 Autonomy

Looking at the autonomy of the prototype, it uses an Arduino and a motor controller. In this setup instead of using GPS sensors to compile the data and send out the instructions, the prototype uses timing delays to simulate the erection and commissioning of the wind turbine. This was done because GPS, which would be ideal for full scale, has limitations and would be impossible to do pool testing of such a small scale. As a result of these limitations, the prototype used an Arduino with a motor controller to simulate what the turbine would look like going out in to the water and coming back.

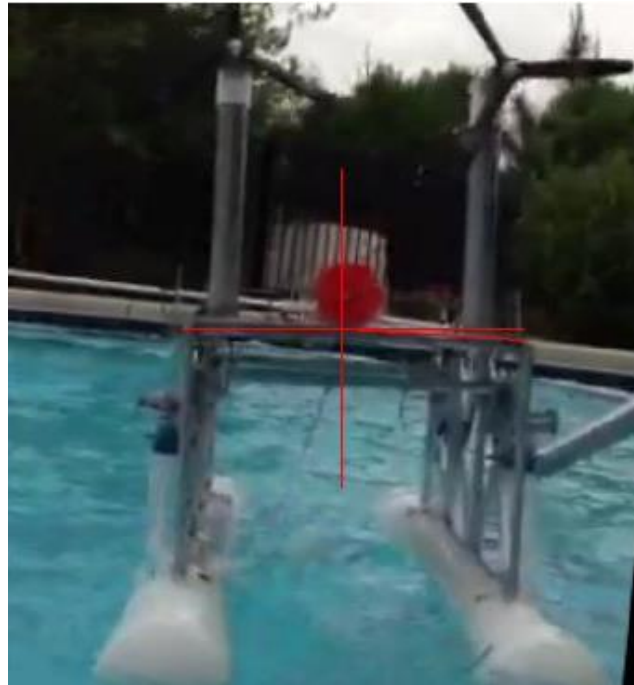
## 5.3 Testing

Deflection testing was conducted at a local pool in Tallahassee. The original testing was planned to be conducted using the wave pool at the college of engineering but the constructed prototype exceeded the allowable size thus other arrangements were made to conduct testing. Three measurements were taken, deflection/rotation about the x-axis due to wave activity, deflection/rotation about the y-axis due to wave activity and structural deflection due to wind.

### **Deflection about the X and Y axis**

Testing included producing consistent waves at a constant rate of time. Waves produced were approximately 2 inches. Due to the 1:100 scale, the 2 inch wave would be equivalent to a 17 foot hitting the full scale model. This is near the design limit of the full scale model and thus the 2 inch waves proved to be representative of unfavorable sea conditions.

When testing the deflection/rotation of the structure about the x axis, the front of the wind turbine was directed perpendicular toward the produced waves for 45 seconds. Each test was filmed. After examining the film frame by frame, the frame where the most deflection was detected imported into AUTOCADD to determine the angle of rotation by providing



reference lines. The tower orientation was then related to the plum reference lines. From there an angle could be measured between the rotated tower and its original position. The angle of rotation was approximately 4 degrees which was within the specified serviceability limit of 3-5 degrees for the structure. The measurements can be seen in the figure below.

When testing the deflection/rotation of the structure about the y axis, the side of the wind turbine was directed perpendicular toward the produced waves for 45 seconds. Each test was filmed. After examining the film frame by frame, the frame where the most deflection was detected imported into AUTOCADD to determine the angle of rotation by providing



reference lines. The deck orientation was then related to the level reference lines. From there an angle could be measured between the rotated deck and its original position. The angle of rotation was approximately 4 degrees which

was within the specified serviceability limit of 3-5 degrees for the structure. The measurements can be seen in the figure below.

## 6.0 Risk, Reliability, Environmental, & Safety Assessments

Potential risks and reliabilities are one of the most important factors that were taken into account when coming up with the final design for the offshore wind turbine. One risk that needs to be accounted is making sure that the blades will be stalled upon transporting out to the desired location. Not only this, but making sure that the transport period is under safe and steady wind conditions. Strong winds such as during hurricanes and tropical storms could create a very disruptive installation period. However, this judgment is something that can easily be projected and determined ahead of time so the decision should be relatively easy. One of the biggest features that has been introduced is making this structure completely autonomous, allowing the turbine to propel itself out to the desired location in deep water and being able to return to its original dock location. Comparing to existing technologies, this idea does not exist yet and we were asked to come up with an innovative design that appeals to customers but still finds a way to reduce total lifetime costs of the turbine. By doing this, installation costs have greatly reduced since the turbine will be programmed to propel out to the desired distance and be able to stay in that particular location. Installing turbines on mainland are much cheaper than in deep waters simply because oh how convenient it allows field workers to perform their day-to-day tasks. Not only this but maintenance costs have drastically decreased as well and will allow troubleshooting and rework to become much more accessible. By implementing autonomy, manufacturing companies will not have to pay field service workers to transport out to deep water and fix this turbine on site.

Obviously, the main purpose for wind turbines is to create large power output that is environmentally sustainable. The biggest and most positive aspect about this technology is that although initial costs are very expensive, the wind turbine will more than pay off itself during its entire estimated 25-30 year lifespan. This project is by far one of the more environmentally friendly that was offered from the FAMU-FSU College of Engineering. From a safety perspective, having an offshore wind turbine establishes a far less concern due to how far this is located off mainland. Based on the structural analysis, the foundation is able to hold an enormous amount of weight while still being able to float. Another great asset of the catamaran design is its ability to fight against strong wave loadings and currents. This greatly reduces the safety concern because the foundation is made to handle strong forces. Because of this, large boating manufactures and military and defense contractors have gone with this design because of how successful the material performs in deep water situations.

## 7.0 Design for Manufacturing, Reliability, and Cost

### 7.1 General

Throughout the design process the focus has been to reduce the cost of production and operation of an already existing technology. Wind turbine technology has progressed to allow for full operation offshore while still generating a profit for its operators. Furthermore, the technology has recently progressed to allow for full operation in ocean depths beyond the reach of traditional wind turbine structure through the use of floating structure. This floating structure allows for the very consistent and high wind speeds, which are found offshore, to be harnessed cost effectively.

The main purpose of our design project, from the beginning, was to design a floating wind turbine that can successfully operate offshore, in a cost effective manner. We did this through design innovations. These innovations were devised in order to solve problems that occurred during our analysis and development of ideas phase of the project. Starting out we fumbled with ideas related to the construction costs. We knew that the cost drivers would be related to the construction and installation. We set out to exhaust all cost reduction methods related to the construction

of the turbine. Our solution was to eliminate anchoring to the sea floor, as it was clearly the most costly part of construction.

The “replacement” for anchoring was a design innovation that turned into the keystone of this project and would allow for reduced assembly costs as well as eliminate installation. Autonomous navigation gave our design the capability to be assembled at dry-dock and propel its way to its assigned destination where it would maintain its position indefinitely, allowing for the turbine to operate.

The next evolution in our design was our transition to the design of a scale model. This model would be constructed as a replica of our theoretical design from the Fall semester and would apply all of the design innovations so that they could be tested for effectiveness. Due to issues that were encountered at the beginning of the Spring semester, the scope/goal of the project changed slightly with a new focus on design criteria and metrics to be accomplished. There will be objectives and obstacles that the scale model will need to be able to pass when the testing session towards the end of the semester. Currently, the main design criteria that will be tested include:

1. Turbine will maintain ability to remain "static" in one area when placed.
2. Turbine will produce X energy, with X efficiency.
3. Turbine tower will have a limit of 10 degrees maximum deflection from its designated plumb line.

The group will soon decide on quantitative values for radius size of floating zone, efficiency, and wind speeds. These criteria's have already been approved and reviewed by the team's sponsor. Criteria #3 will most likely be the most difficult challenge, due a limit known as Serviceability Limit. This is a new metric that has not been developed for floating wind turbines. It is being developed and tested by our design team so that our design guarantees satisfactory operating conditions for the wind turbine. Calculations for the full-scale model will need to be computed, to ensure that the scaled model prototype will function properly.

Throughout the design process we have made many additions to the floating wind turbine technology through our design innovations. Altogether we have added the dimension of autonomy to the design, which will allow the floating turbine to self-navigate to its selected location and self-orient when needed. With the final design selected, the process of detailed design, component analysis, materials procurement, and construction scheduling has been completed. Each component of the final design, including the turbine blades, generator, tower, foundation, and electric motors has been designed. Note, however, that some of these components have been designed with sufficient detail to allow for their manufacture, while other, less critical components (i.e., outside the main scope of our design project) have been sufficiently designed to allow for their informed selection from the commercial market.

## 7.2 Design for Manufacture

The design for our full scale model is shown in the figure below. A 100 KW permanent generator will be used to provide the necessary power. The main specifications are shown in the Figure 7.2.1.

The total width, across the entire platform of this model, is about 15 meters. The total depth is about 60 meters. Our innovative design was achieved with introducing an autonomous electrical program using processing microcontroller technology. Because of this, construction and manufacturing costs have been greatly reduced since everything can be assembled on dry dock. This technology uses timing delays as well as GPS capability and will be able to program to be able to send the turbine out to our desired location, drop anchor, and be able to remain in once particular location.

In terms of material used in this project, below is a bill of materials of the major components in the completion of this project. These materials were chosen to optimize performance from a mechanical and structural perspective. Electrically, most of the components were used to assemble our autonomous technology for the Arduino board. The biggest selection decision that was decided for the electrical calculations was making sure that the motors were stronger for both the power generation and propulsion system. The team decided to order multiple 6V DC motors that will be more than enough power to make our product autonomous as well as be able to power a LED.

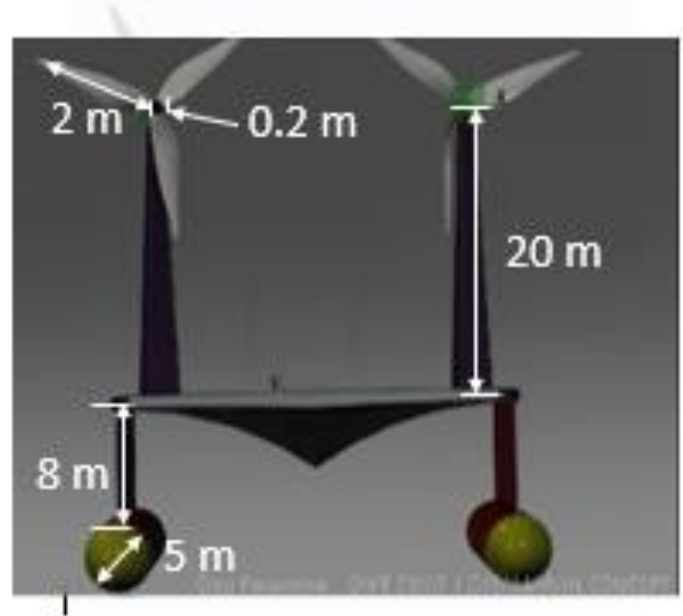


Figure 7.2.1. Offshore Wind Turbine Full Scale Design.

Table 1. Prototype Parts List.

Component	Item Name	Item Number	Distributor	Qty
Tower	1" x10', Galvanized Pipe	301337 Model # 565-1200HC	Home Depot	1
Decking	12"x24"x1/16", Al. Plate	3DRZ3	Grainger	1
Truss Decking	3/8" x 8', Aluminum Rod	6ALN0	Grainger	11
Floor	Mesh Screen	11811 Model # LAM	Lowes	3
Pontoon	PVC Pipe	To be determined	ASCE	1
Blades	Propeller	PKZ1015	Hobby Town	4
Blades	Propeller	EVOE0610P	Hobby Town	4
PVC Glue	PVC Cement	23467 Model # 31018L	Lowes	1

## Design Changes

For the full scale model, there are no expected design changes, but while building the scaled model, several features have been adapted to accommodate the prototype. The pontoons were initially designed to be four inches in diameter but have been reduced to three inches to reduce the buoyancy. Upon further testing, the platform was determined to be unstable therefore the pontoons have been elongated to increase stability to outside forces. The engine housing has also been modified to fit a three inch diameter pipe. The frame is consistent with the full scale and has provided the necessary rigidness to the structure. Exact Pontoon dimensions are still under development due to scaling issues between the full scale and model. The pontoon dimensions will be optimized based upon testing.

## Assembly Drawings and Instructions

The full scale model was too cumbersome to design full scale shop drawings and instructions. Instead a general construction method was developed. The Offshore wind Turbine is expected to be pieced together on a dry dock. Most if not all pieces will be prefabricated and assembled on site. The steel pontoons will provide the greatest challenge due to sheer size. The pontoons will be delivered in manageable sections and welded together. The structure and supporting deck will be set in place with welds. The engines will be set within the pontoons on brackets specifically designed for the engine. Once construction is complete, the dry dock can be flooded and the vessel is ready to operate.

## Challenges

Challenges expected in the full scale model include transportation of materials. DOT limits size and weight allowed on highways therefore pieces must be designed to accommodate DOT's regulations. Challenges encountered in the prototype build include buoyancy and stability issues. The vessel is very sensitive to added weight and therefore the buoyancy is affected greatly with little change in environment which then makes the platform unstable. Further testing is required to optimize the current prototype to overcome these obstacles.

## 7.3 Design for Reliability

For certain features of the offshore wind turbine, it must be determine which ones need special attention as far as ensuring reliable performance such as appropriate safety factors, risk assessment, potential failure modes (FMEA), long term survivability, and repair. Additionally, a strategy must be considered to address, as needed, a fail-safe approach, needed margin of safety, damage tolerance, prototype robustness, and other factors that could create hazard.

### Features Requiring Reliability

The key features requiring reliability are the pontoons, propulsion motors, turbine blades, and generators. Though there are many additional systems, onboard an offshore wind turbine, these systems, if they were to fail, would create the most severe hazards to the overall operation, safety, and performance of the platform.

### Pontoons

The consequences of pontoon failure would be catastrophic. A failure one or both of the pontoons would likely cause the entire offshore wind turbine to sink, resulting in a total loss of the platform. To ensure reliability of the pontoon system, design features that address safety factors, potential failure modes, and long term survivability were specified.

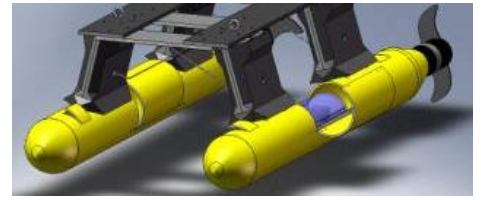


**Figure 7.3.1. Double-hull**



## Safety Factors

Because pontoon failure could result in a total loss of the platform, a safety factor of 1.2 was added to the design of the pontoons, that is, each pontoon is capable of providing 20% more buoyancy than required to float the platform. A safety factor of 1.2 was chosen because, in the event a pontoon is punctured, the bilge pumps would be able to evacuate the incoming water at a rate that would allow the platform to remain above the water surface (albeit lower than normal operating conditions), which would allow the platform to make an emergency return to dry-dock. The rate of flooding is based upon the damage that would likely occur in the designed-for location of operation and under normal operating conditions.



**Figure 7.3.2. Propulsion Motors.**

## Potential Failure Modes

A pontoon is likely to fail as a result of a foreign object puncturing the hull. As a result, each pontoon was designed with a double-hull.

## Long Term Survivability

For all practical purposes, the pontoons will spend the totality of their service life submerged in salt water—one of the most corrosive environments in the natural world. To increase long term survivability of the pontoons, each has been designed with zinc bars, which are mounted to the exterior surface of the pontoons and at regular intervals. The zinc bars will act as ‘sacrificial anodes’, that is, the salt water will erode the zinc bars before eroding the steel pontoons. Additionally, the zinc bars can be replaced at regular maintenance intervals.

## Propulsion Motors

The consequences of propulsion motor failure would cause the platform to stall while traveling to its location of operation or on a return trip to dry dock for maintenance/repairs. A failure one or both of the propulsion motors would likely cause the offshore wind turbine to float adrift, resulting in a possible damage to itself or nearby structures, such as offshore transformers. To ensure reliability of the propulsion motor system, design features that address risk factor, potential failure modes, and repair were specified.

## Risk Factor

Failure of one or both propulsion motors, in the first ten years, is approximately 20% and 10%, respectively. This results in a low overall risk factor, which means that no special design requirements were necessary, other than planning for the potential failure modes and the ability to make needed repairs.

## Potential Failure Modes

The primary mode of failure for a propulsion motor was determined to be flooding of the motor compartment within the pontoon. This potential failure mode is mitigated by the double hull design, the 1.2 factor of safety in the pontoon design, and the onboard bilge pumps.

## Repair

For all practical purposes, the propulsion motors will likely be serviced in dry dock. However, in the event that the motors fail and the platform is unable to return to dry dock, access to the motor compartment is safely provided from the surface of the platform and into the pontoon via a laddered access tube. The internal physical dimensions of the pontoon allow for emergency repairs to be made from within the pontoon.

## Turbine-Generator Assembly

The consequences of failure of the turbine-generator assembly would result in a complete loss of the offshore wind turbines primary purpose—energy production. To ensure reliability of each turbine-generator assembly, design features that address risk factor, potential failure modes, and repair were specified.

### Risk Factor

Failure of one or both turbine-generator assemblies, in the first ten years, is approximately 20% and 10%, respectively. This results in a low overall risk factor, which means that no special design requirements were necessary, other than planning for the potential failure modes and the ability to make needed repairs.

### Potential Failure Modes

The primary modes of failure for a turbine-generator assembly were determined to be overheating of the generator and foreign objects striking the turbine blades. These potential failure modes are mitigated by a braking system on the turbine shaft connected to the generator and carbon fiber blades.

### Repair

For all practical purposes, the turbine-generator assembly will likely be serviced in dry dock. However, in the event that these assemblies fail while the platform is at its operating location, access to the turbine-generator assembly is safely provided through the nacelle. The internal physical dimensions of the nacelle allow for emergency repairs to be made from within the nacelle.

## 8.0 Procurement & Budget

Procurement of required materials must be processed through the civil department of the FAMU-FSU College of Engineering. In order to streamline the process and stay on the specified schedule, a materials list including price quote, and distributor will be submitted to the Civil Department (Specifically Rosa Booker). This will allow the submission to be processed over the winter break. The process takes approximately three weeks. The material requested will then be available the first week of the spring semester (January 6-10, 2014). This is pertinent in order to start the construction of the wind turbine as scheduled.

The following list provides the materials requested, the material purpose, the dispenser, the unit price, and the estimated material cost.

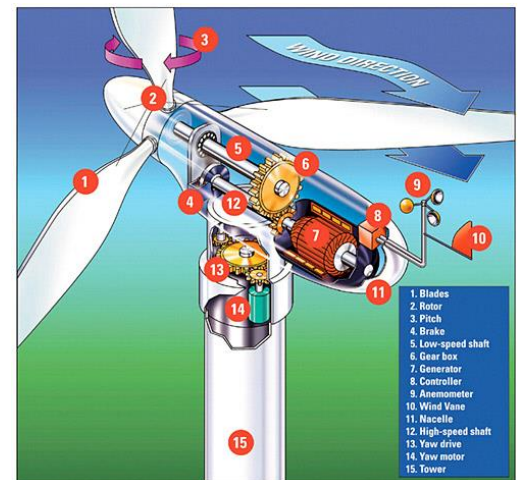


Figure 7.3.3. Turbine-Generator

Component	Item	Distributor	Unit Price (\$)	Quantity	Cost (\$)
Tower	1" Galvanized Pipe	Grainger	20.27	1	20.27
Decking	1/4" steel rod	Grainger	4.90	15	73.50
Floor	Mesh Screen	Home Depot	8.30	3	24.90
Pontoon	PVC Pipe	ASCE	Donated	1	0.00
Blades	Blade	Hobby Town	3.00	3	9.00
Electrical Components/Motor	--	Hobby Town	500.00	1	500.00
Protection/Sealant	Hydro-Dipping	Precision-Hydro	400.00	1	400.00
Generator	Generator	Sponsor	Donated	2	0.00
			<b>Total Approximate Cost:</b>		<b>1027.67</b>

From the table, an approximate total cost of \$1027.67 has been budgeted for construction. This value is well within the \$2000 budget provided by the sponsor. Unaccounted miscellaneous items will be purchased or obtained by donations on an as need basis.

The decking, floor and Tower will need to be welded. Once the supplies have arrived, an appointment will be setup with the machine shop to complete the welding. The machine shop will weld the trusses together according to shop drawings provided.

ITEM	QUANTITY	UNIT PRICE	TOTAL
DRIVE SHAFT	2	\$10.99	\$21.98
BOAT MOTOR	3	\$76.99	\$230.97
GENERATORS	2	\$14.50	\$29.00
TOWER	1	\$6.77	\$6.77
ALUMINUM DECKING	1	\$78.39	\$78.39
PVC CEMENT	1	\$4.44	\$4.44
ALUMINUM PLATE	1	\$36.05	\$36.05
ALUMINUM RODS	11	\$8.51	\$93.61
WIRE	1	\$12.19	\$12.19
3DR RADIO	1	\$88.99	\$88.99
ARDUPILOT ACCESSORY	1	\$10.59	\$10.59
POWER BATTERY PACK	1	\$38.47	\$38.47
1000 MW VIDEO AUDIO TRANSMITTER	1	\$133.00	\$133.00
JB WELD (WATER PACK)	3	\$6.97	\$20.91
VELCRO	2	\$4.68	\$9.36
JB WELD (APOXY)	4	\$4.98	\$19.92
WIRE CABLE	1	\$6.65	\$6.65
BREADBOARD AND ACCESSORIES	1	\$33.99	\$33.99
BATTERY PACK	1	\$31.99	\$31.99
PLATIC CONTAINERS	1	\$7.54	\$7.54
ALLIGATOR TEST LEADS	1	\$9.95	\$9.95
GPS	1	\$249.98	\$249.98
STRANDED WIRE	1	\$10.49	\$10.49
KEVLAR SPORTS LINE	2	\$6.93	\$13.86
BATTERY PACK	1	\$27.97	\$27.97
ZIP TIES	1	\$4.00	\$4.00
ARUINO ACCESORY	6	\$6.15	\$36.90
6 VOLT BOAT MOTOR	2	\$65.00	\$130.00
THUNDER TIGER MOTOR PROPUSLION	2	\$18.99	\$37.98
PROP	4	\$4.49	\$17.96
PROP	4	\$4.49	\$17.96
PROP	2	\$20.50	\$41.00
PROP	2	\$4.99	\$9.98
PROP	4	\$1.20	\$4.80
TOTAL=			\$1,527.64

## 9.0 Communications

Communications are an essential part to working together as a group, as well as, keeping in good contact with advisors. Especially with three different disciplines, staying in touch and up to date is important. Within the group, there is a communal Dropbox, email folder, and group text, to ensure everyone is on the same page. We also met for one hour (longer if necessary) every week. The communications with advisors included a biweekly meeting with Dr. Amin, Dr. Jung, Dr. Frank, and Dr. Shih. We communicated with these professors primarily through email. Also individual meetings with advisors are scheduled as needed. The group met with the main advisor, Dr. Jung for an hour every week he was available, to stay on track and ensure adherence to the expected outcomes. Furthermore, despite a slow start, the offshore wind turbine group found a productive system of communication and continued this imperative trend. There were a few minor hiccups in the last semester of the project, that were overcome by the creation of a group calendar that everyone had access to. Furthermore, within the group we used constructive criticism to bring the less talented presenters up to speed. Through peer evaluations, each individual member will see how well they actually were conveyed by their counterparts. Over the last eight months, the group has made several presentations and poster sessions, learned how to be respectful to each other, and communicate within multidisciplinary environment.

## 10.0 Conclusions

In conclusion, the main purpose of the design project is to design a wind turbine that can fully function and operate offshore. The design project was composed of many different concepts, several of which innovate the wind turbine industry. The biggest contribution that was added was a dimension of autonomy. Autonomy allows the floating turbine to self-navigate to its selected location as well as self-orient when needed. With the final design selected and the process of detailed design complete, all that is left is the prototype. A prototype has been constructed to demonstrate how the autonomy concept works, as well as how it could function as a whole. The other main component in demonstration will be power generation. The prototype demonstrates how power generation will be accomplished. Testing conditions were conducted in order to understand how the prototype would perform in terms of the designed criteria asked by our sponsor. We were given a budget of \$2000 and were all to perform all of this within that constraint as well. In all, this project brings a great piece of innovation to the offshore wind industry, and can be used in the future to change the way the world generates power.

## 11.0 Environmental and Safety Issues and Ethics

The environmental issues associated with this design are negligible as they are limited to the turbines affecting the flight path of birds. No other environmental impacts have been considered. Safety issues have been addressed by designing a safe ascension system for maintenance workers with harness line attachment points en route to the turbine. In addition, this design addresses the need for renewable turn switch power in an ethical manner.

With regard to the added propulsion design, energy required was constrained to be renewable in nature. While diesel is a viable and effective method, generation of wind energy is aimed at reducing pollution to the environment thus any included operation must also follow suit.

## 12.0 Recommendations for Future Work

There are four main recommendations for future work.

### Stability

Achieving neutral buoyancy proved to be much more challenging in practice than in theory. The primary recommendations for resolving this issue would be improving the ballast system and shortening the overall height. An improved ballast system would provide for finer weight adjustments and shorter trusses would lower the center of gravity.

### GPS v. Timing Delays

In practice, the turbine platform will autonomously travel to its designated location of operation via GPS and programmed coordinates. Timing delays were used to save time and as a proof of concept, but the next logical step is to test the code by using GPS. There are commercially available GPS systems that are compatible with this scale model and precise enough to detect position changes within a few feet (per Dr. Frank).

### Anchoring

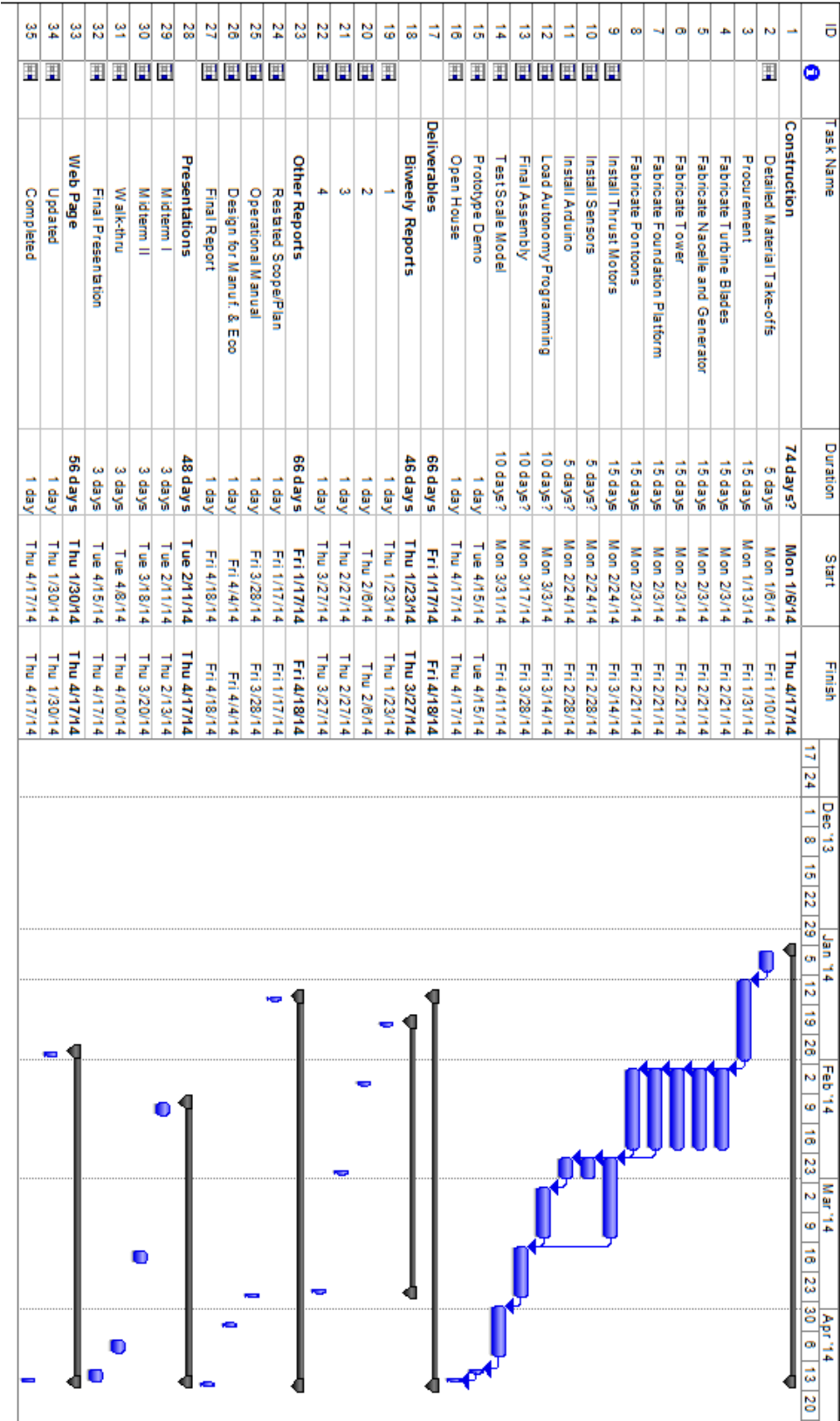
The motor was selected, connected to the Arduino, mounted to the platform, and an algorithm was written to control its operation, but it failed to perform properly. The reason for the failure of the anchoring system was that the weight used for the actual anchor was too heavy for the motor to retract. To resolve this issue a gear box is needed, which can be built relatively cheaply and used with the existing assembly.

### Adjust Portions

The stability tests showed that the turbine platform is stable and that the deflections are within the design parameters. However, this was achieved without the pontoons being fully submerged. Because the pontoons were not fully submerged, the entire platform was more susceptible to wave activity. If neutral buoyancy could be achieved, which would place the pontoons below the surface of the water, the overall stability of the current platform would likely greatly increase. This would allow for a smaller platform, which would reduce the amount of materials required and the overall cost of the platform assembly.

# 13.0 Gantt Chart, Resources, & Budget

## 12.1 Gantt Chart



## 12.2 Resources

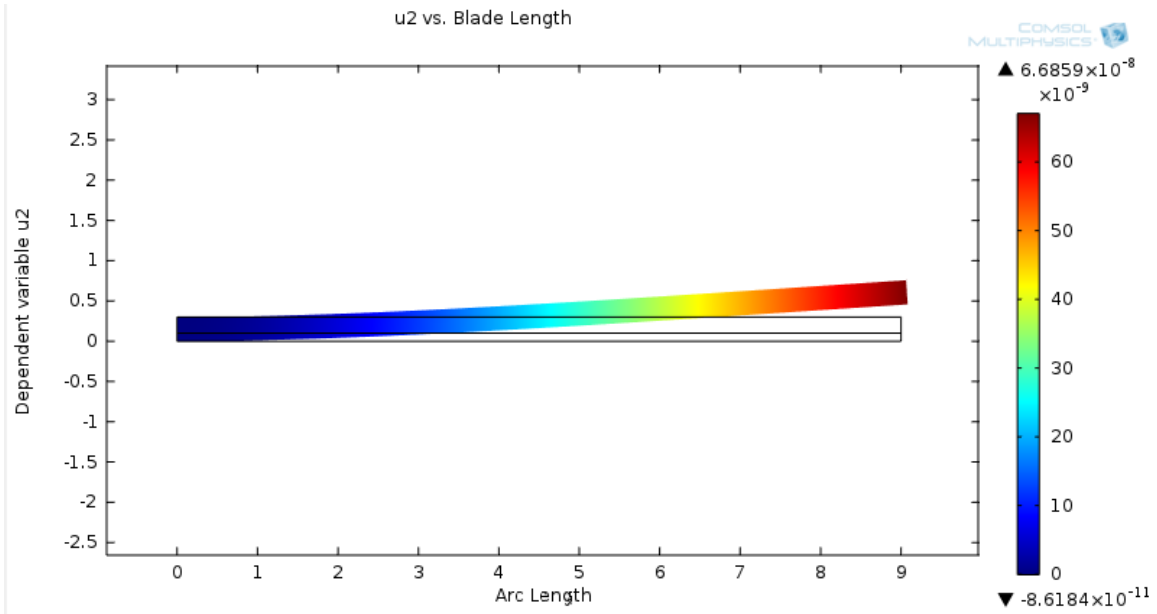
Our primary resources consist of computer programs, vendors, and fabricators. Fabricators often require electronic files of designed parts for manufacturing. Some of the programs we've used to meet this requirement are Pro-Engineer and AutoCAD. Many of our parts are available, on the commercial market, and can be purchased directly from such vendors as The Home Depot and RadioShack. The College of Engineering provides us with several skilled fabricators from which to choose. We will utilize the Machine Shop, operated by Jeremy, and the ME Lab, operated by Keith Larson.

## References

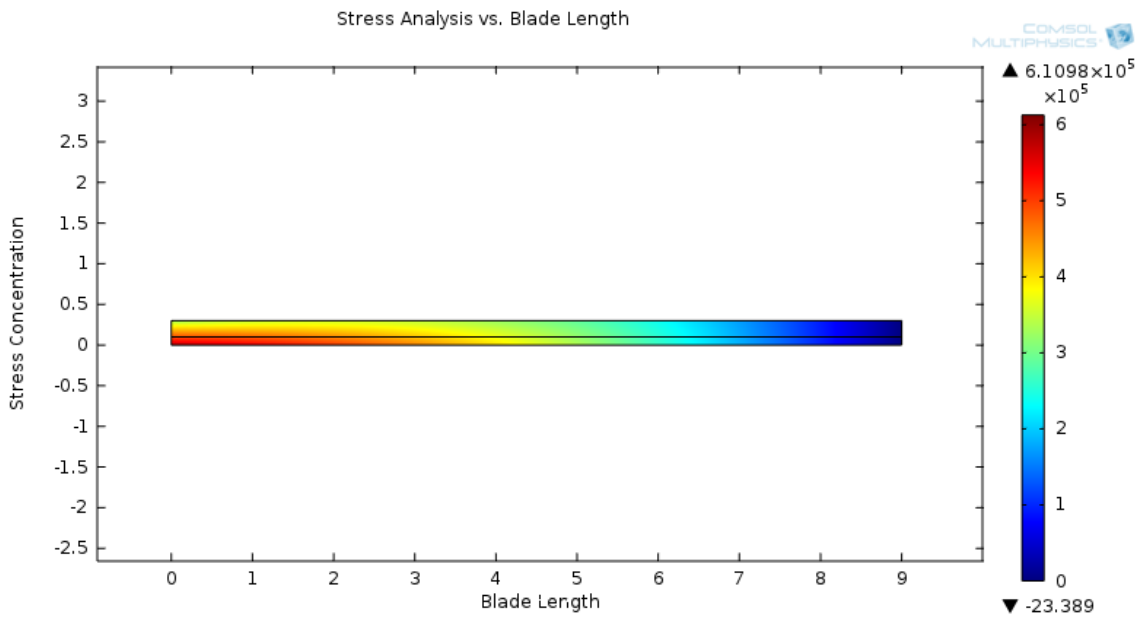
1. **Wind Energy the Facts.** *Wind Energy the Facts*. [Online] <http://www.wind-energy-the-facts.org/index-86.html>.
2. **Ashby, Michail F.** *Materials Selection in Mechanical Design* 4th Ed. s.l. : Elsevier Ltd., 2011.
3. **Los Vegas Sun.** *Gusty Winds*. [Online] <http://www.lasvegassun.com/news/2011/apr/07/high-wind-warning-issued-las-vegas/>.
4. **Agentur für Erneuerbare Energien.** [Online] <http://www.unendlich-viel-energie.de/en/details/browse/9/article/226/functioning-principles-of-a-wind-turbine.html>.
5. **leitwind.** [Online] <http://en.leitwind.com/Technology>.
6. **siemen.** [Online] <http://www.energy.siemens.com/hq/pool/hq/power-generation/renewables/wind-power/wind%20turbines/SWT-2.3-113-product-brochure.pdf>.
7. **obeki.** [Online] <http://www.obeki.com/en/productos/Permanent%20Magnet%20Generators%20and%20Motors.pdf>.
8. **academia.** [Online] [http://www.academia.edu/2339055/stability\\_of\\_tubular\\_wind\\_turbine\\_tower](http://www.academia.edu/2339055/stability_of_tubular_wind_turbine_tower).



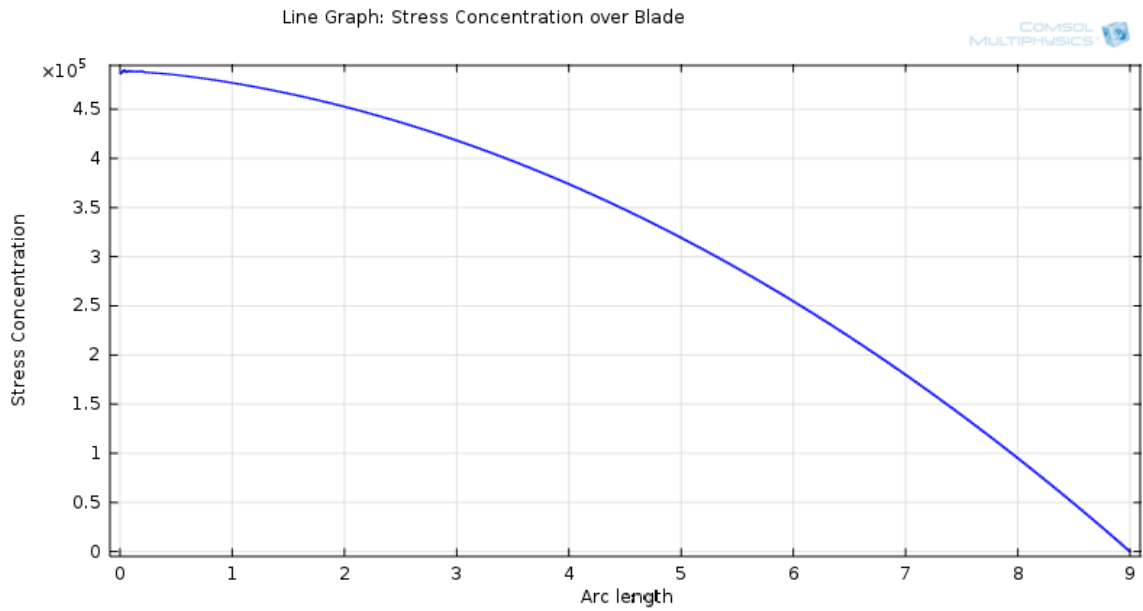
# Appendix



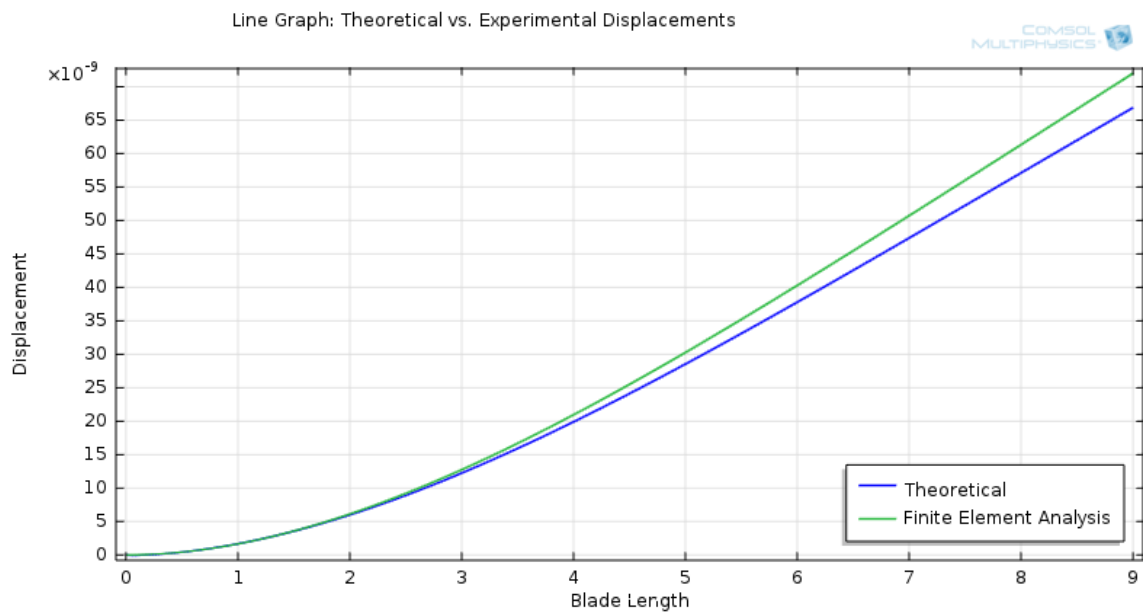
COMSOL Model Displacement Breakdown for Typical Cantilevers



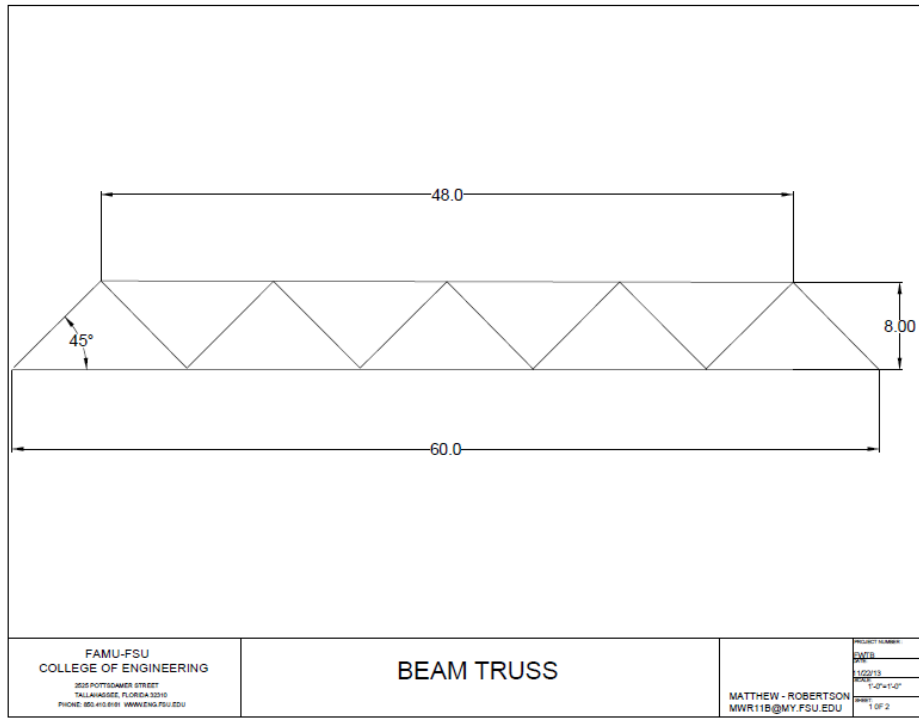
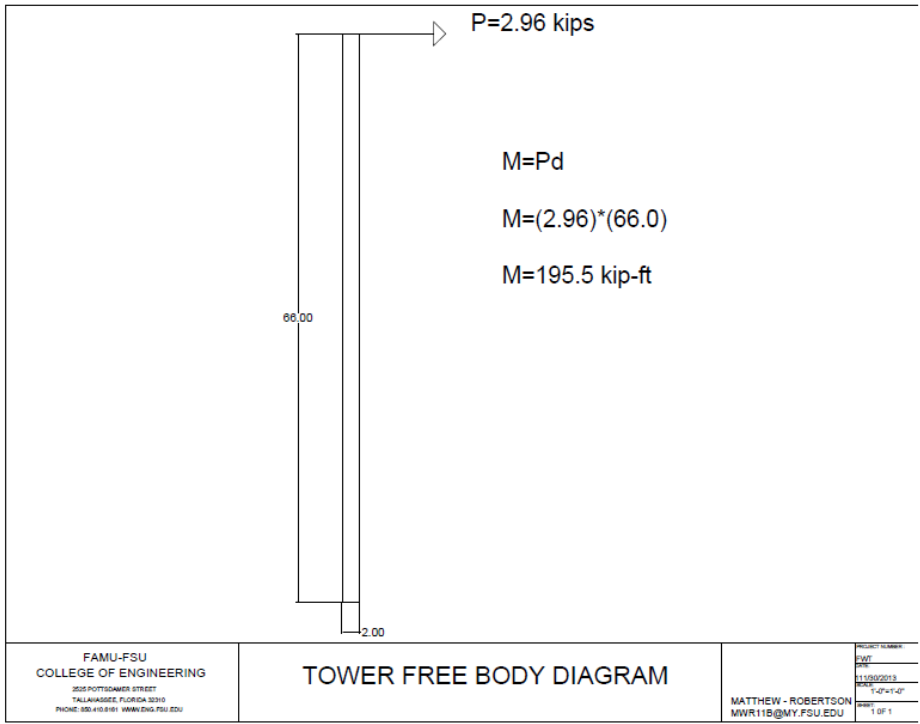
COMSOL Model Stress Concentration for Typical Cantilevers

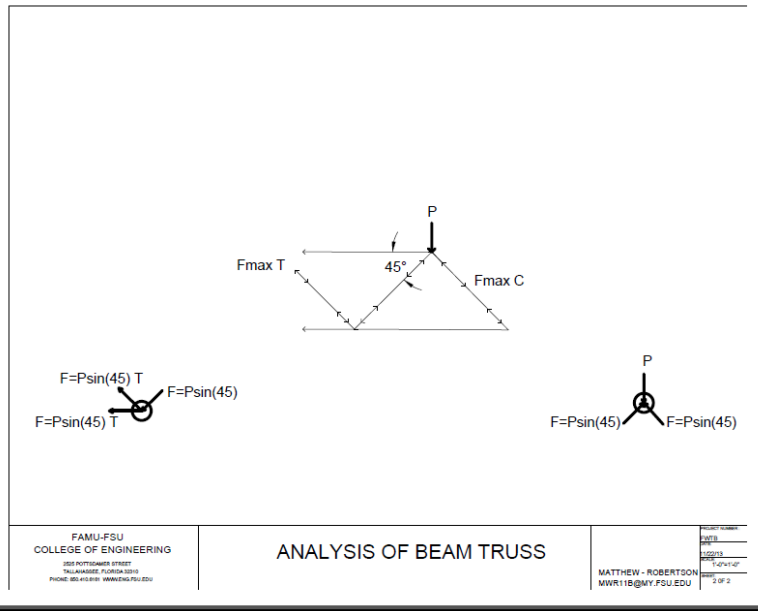


COMSOL Line Graph Stress Concentration for Typical Cantilevers



COMSOL Displacement Theoretical vs. Finite Element Analysis





Use HSS16x0.625 shape @103 lb/ft (self weight)  
 For bracing Use HSS5x0.250 shape @12.69 lb/ft

**Weight Analysis:**

30 members @ 26 ft @ 103 lb/ft + 75 members @ 4 ft @ 12.69 lb/ft = 84.1 kips

**Axial Load**

$$\text{Nacelle}_{\text{weight}} := 9000\text{lb}$$

$$\text{Blade}_{\text{weight}} := 7920\text{lb}$$

$$\text{Axial}_{\text{load}} := \text{Nacelle}_{\text{weight}} + \text{Blade}_{\text{weight}} = 1.692 \times 10^4 \text{ lb}$$

**Wind Load Determined using ASCE 7**

Directionality factor ( $K_d$ ) - Determined from Table 26.6.1

Design Velocity ( $v$ ) - Determined from graphic 26.5-1C

Topographic factor ( $K_{ZT}$ ) - Determined from 26.8-1

Velocity Pressure Coefficient ( $K_z$ ) - Determined from Table 26.6.1

Velocity Pressure ( $q_z$ ) - Determined by Equation 27.3-1

$$K_d := 0.95 \quad K_{ZT} := 1 \quad Z := 66 \quad c_1 := 6.62 \quad c_2 := 1273$$

$$\alpha := c_1 Z^{-0.133} = 3.792 \quad Z_g := Z^{0.125} \cdot c_2 = 2.149 \times 10^3$$

$$K_Z := 2.01 \left( \frac{Z}{Z_g} \right)^{\frac{2}{\alpha}} = 0.32 \quad v := 160\text{mph} \quad v_{\text{up}} := 50\text{mph}$$

$$q_{z\text{up}} := 0.00256 K_Z K_{ZT} K_d v_{\text{up}}^2 = 4.19 \frac{\text{ft}^2}{\text{s}^2}$$

$$q_z := 4.19 \frac{\text{lb}}{\text{ft}^2}$$

## Steel Design

Due to the combined Flexural and Axial Loading, the Column and Chapter H sections were referenced in the AISC Steel Manual.

$$Axial_{load} = 1.692 \times 10^4 \text{ lb}$$

$$D_{Rotor} := 30 \text{ ft}$$

$$A_{Rotor} := \left(\frac{\pi}{4}\right)(D_{Rotor}^2) = 706.858 \text{ ft}^2$$

$$P_{Rotor} := A_{Rotor} \cdot q_z = 2.962 \times 10^3 \text{ lb}$$

$$D_{out} := 24 \text{ in}$$

$$D_{in} := 23 \text{ in}$$

$$t := 0.50 \text{ in}$$

### Steel Selection

A618 Grade I

$$F_y := 50 \text{ ksi}$$

$$F_u := 70 \text{ ksi}$$

$$E := 29000 \text{ ksi}$$

$$1 \text{ ksi} = 1 \times 10^3 \text{ psi}$$

$$A_1 := \pi \frac{(D_{out}^2 - D_{in}^2)}{4} = 0.256 \text{ ft}^2$$

### Torsional Shear Constant

$$C1 := \pi \frac{(D_{out} - t)^2}{2} = 6.024 \text{ ft}^2$$

### Polar Moment of Inertia

$$I_1 := \pi \frac{(D_{out}^4 - D_{in}^4)}{64} = 0.123 \text{ ft}^4$$

### Radius of Gyration

$$r_1 := \left( \frac{I_1}{A_1} \right)^{\frac{1}{2}} = 0.693 \text{ ft}$$

Effective Length Determine using Table C-A-7.1

$$K_1 := 0.6$$

Laterally Unbraced Length

$$L_1 := 792 \text{ in}$$

$$\text{Slender}_{\text{Ratio1}} := K_1 \cdot \frac{L_1}{r_1} = 57.181$$

$$F_{e1} := \frac{(\pi^2 \cdot E)}{\text{Slender}_{\text{Ratio1}}^2} = 8.754 \times 10^4 \text{ psi}$$

$$F_{\text{Cr,Axial1}} := \left( 0.658 \frac{F_y}{F_{e1}} \right) \cdot F_y = 3.937 \times 10^4 \text{ psi}$$

$$P_{\text{nl}} := F_{\text{Cr,Axial1}} \cdot A_1 = 1.453 \times 10^6 \text{ lbf}$$

Axial Load According to LRFD

$$\text{AXIAL}_{\text{LRFD}} := \text{Axial}_{\text{load}} \cdot 1.6 = 2.707 \times 10^4 \text{ lb}$$

The Critical Axial Load is greater than the required Axial load.

$M_{\text{max}} := 200 \text{ kip} \cdot \text{ft}$   $M_{\text{max}}$  was calculated by Hand

$$S := \pi \frac{(D_{\text{out}}^4 - D_{\text{in}}^4)}{32 D_{\text{out}}} = \blacksquare$$

$$1 \text{ in}^3 = 4.329 \times 10^{-3} \text{ gal}$$

$$M_n := \left[ F_y + \frac{(0.021E)}{\left( \frac{D_{\text{out}}}{t} \right)} \right] \cdot 212.52 \text{ in}^3 = 3.572 \times 10^7 \frac{\text{ft}^2 \cdot \text{lb}}{\text{s}^2}$$

$$\phi M_n = 0.9 \left[ F_y + \frac{(0.021E)}{\left( \frac{D_{out}}{t} \right)} \right] \cdot 212.52 \text{in}^3 = 1000 \text{ kip-ft}$$

**The designed max moment is substantially greater than the required moment.**

## **Final Column Selection**

Column Height= 66 ft

Diameter = 2 ft

Wall Thickness = 0.5 in

Steel Grade: A618 Gr. 1

Weight of Column= 8635 lb

## **Boat Deck Design**

Dead Load = Weight of Wind Turbine

Design Dead Load = 200 psf which was determined using ASCE7 for Industrial Floors.

Max Moment = 403kip-ft and was determined from the moment diagram

The supporting beam chosen for the deck is a W21x111. The steel chosen has a yield strength of 50 ksi. The Beam was chosen from Table 3-10 in the AISC Steel Manual. The beam is capable of holding a design load of 810 kip-ft. This provides a safety factor of 2 which is within the standard range of 1.5-3 for vessels.

Deck Beams weigh 252 kips

Allowable Deck weight including floor is 1000 kips.

## Deck Support Design

Design a circular HSS Shape for  $M_{max} = 397$  kip-ft  $P_{max} = 455$  kips

AISC Requirements:

where  $K=0.65$   $L=20$ ft Using A500 Grade B Steel with  $F_y=42$ ksi and  $F_u=58$ ksi  
(as recommended for rectangular HSS shapes)

LRFD:  $M_u < \phi M_n$  In AISC Table 3-15 Try HSS16x0.625  
 $397$  kip-ft  $< 435$  kip-ft (ok)

Check For adequacy In:

$P_u < \phi P_n$  Effective Length:  $KL=(0.65)(20\text{ft}) = 13$  ft

In AISC Table 4-17 for HSS16x0.625

455 ksi  $<$  1240 ksi (OK)

Compression Analysis:

Slenderness ratio:  $KL/r=0.65(20 \times 12)/5.46= 37.1 < 200$  (OK)

$KL/r < 4.71(E/F_y)^{1/2}$

$37.1 < 4.71(29,000/46)^{1/2}$

$37.1 < 118.3$

$F_e=208$  ksi

$F_{cr}=38.6$  ksi

$F_y/F_e < 2.25$

$42/208 < 2.25$

$0.20 < 2.25$  (OK)

$P_n = F_{cr}A_g = (38.6)(28.1) = 1085$  kips

$\phi P_n = 0.9(1085) = 977$  kips  $> 455$  kips (OK)

Tension Analysis:

Yielding:

$P_n = F_y A_g = 42 \text{ksi}(28.1 \text{in}^2) = 1180$  kips

$\phi P_n = 0.9(1180 \text{kips}) = 1062$  kips  $> 455$  kips (OK)

Fracture:

$P_n = F_u A_e$

where,  $A_e = A_g U$   $U = 1 - 0.375 = 0.625$

$A_e = 0.625(5.24 \text{in}^2) = 3.275$  in<sup>2</sup>

$P_n = (58 \text{ksi})(3.275 \text{in}^2)$

$= 189.95$  kips



$$\phi P_n = 0.75(189.95 \text{ kips}) = 142.5 \text{ kips} > 128 \text{ kips (OK)}$$

Use HSS16x0.625 shape @103 lb/ft (self weight)  
For bracing Use HSS5x0.250 shape @12.69 lb/ft

#### Weight Analysis:

$$30 \text{ members @ } 26 \text{ ft @ } 103 \text{ lb/ft} + 75 \text{ members @ } 4 \text{ ft @ } 12.69 \text{ lb/ft} = 84.1 \text{ kips}$$

### Pontoon Dimensions

Pontoons will be modeled as cylinders for calculations to provide a factor of safety for thrust. Once required thrust is established, the pontoon will be optimized for optimal performance

$$\text{Total Deck Weight} = 1286 \text{ kips}$$

$$\text{Deck}_{\text{weight}} := 1286 \text{ kip}$$

$$\text{Deck}_{\text{weightmetric}} := 590000 \text{ kg}$$

$$\text{Water}_{\text{density}} := 1000 \frac{\text{kg}}{\text{m}^3}$$

$$\text{Steel}_{\text{Density}} := 7800 \frac{\text{kg}}{\text{m}^3}$$

$$\text{Pontoon}_{\text{Thickness}} := 0.0254 \text{ m}$$

$$\text{Pontoon}_{\text{Length}} := 60 \text{ m}$$

$$\text{Volume of water needed to displace Weight of Deck} = 590 \text{ m}^3$$

In order to displace this required volume of water the pontoon would need to have a diameter of 3.54m

Assume Diameter is 4m to determine the weight of the steel in the pontoon.

$$\text{Volume of steel} = 9.55 \text{ m}^3$$

$$\text{Weight of Steel} = 75000 \text{ kg}$$

$$\text{Volume of Required Displaced water} = 75 \text{ m}^3$$

$$\text{Total Required Displaced volume} = 685 \text{ m}^3$$

$$\text{Total Volume Displaced (For 1 Pontoon)} = 745 \text{ m}^3$$

$$\text{Buoyancy} = (\text{Weight of displaced fluid}) - (\text{Weight of structure})$$

Buoancy =  $(1000\text{kg}/\text{m}^3)(745\text{m}^3) - (590000\text{kg} + 75000\text{ kg}) = 230,000\text{kg}$

Total Buoyancy for vessel = 1,050,000 kg

The vessel has approxiamte Buoyancy ratio of 1.5 to 1. It can be concluded that the vessel is positvely Boyant and thus will float.

## Autonomy Code

```
#include <AFMotor.h>

AF_DCMotor motor1(1); //MOTOR12_64KHZ); // create motor #2, 64KHz pwm
AF_DCMotor motor2(2); //MOTOR12_64KHZ); // create motor #2, 64KHz pwm

void setup() {
  motor1.setSpeed(255); // set the speed to 200/255
  motor2.setSpeed(255); // set the speed to 200/255
}
void loop() {

  delay(10000);
  // Go Forward for 10 sec
  motor1.run(FORWARD); // turn it on going forward
  motor2.run(FORWARD); // turn it on going forward
  delay(10000);

//STOP
  motor1.run(RELEASE);
  motor2.run(RELEASE);
  delay(2000);
  //REVERSE
  motor1.run(BACKWARD); // turn it
  motor2.run(BACKWARD); // turn it
  delay(3000);

//STOP
  motor1.run(RELEASE);
  motor2.run(RELEASE);
  delay(1000);

//REVERSE
  motor1.run(BACKWARD); // turn it
  motor2.run(BACKWARD); // turn it
  delay(3000);
//BEGIN FIRST TURN (X3)
  // Turn arround
  motor1.run(BACKWARD); // turn it
  motor2.run(FORWARD); // turn it on going forward
  delay(6000);

//STOP
  motor1.run(RELEASE);
  motor2.run(RELEASE);
  delay(1000);

//REVERSE
  motor1.run(BACKWARD); // turn it on going Backward
```

```

motor2.run(BACKWARD); // turn it on going Backward
delay(1500);

// Turn around
motor1.run(BACKWARD); // turn it
motor2.run(FORWARD); // turn it on going forward
delay(6000);

//STOP
motor1.run(RELEASE);
motor2.run(RELEASE);
delay(1000);

//REVERSE
motor1.run(BACKWARD);
motor2.run(BACKWARD);
delay(1500);
// Turn around
motor1.run(BACKWARD);
motor2.run(FORWARD); // turn it on going forward
delay(6000);

//STOP
motor1.run(RELEASE);
motor2.run(RELEASE);
delay(1000);

//REVERSE
motor1.run(BACKWARD);
motor2.run(BACKWARD);
delay(1500);

//BEING SECOND TURN
// Turn around
motor1.run(BACKWARD);
motor2.run(FORWARD);
delay(6000);

//STOP
motor1.run(RELEASE);
motor2.run(RELEASE);
delay(1000);

//REVERSE
motor1.run(BACKWARD);
motor2.run(BACKWARD);
delay(1000);
//BEING THIRD TURN CURRENT FINAL
// Turn around
motor1.run(BACKWARD);
motor2.run(FORWARD); // turn it on going forward
delay(10000);

//STOP
motor1.run(RELEASE);
motor2.run(RELEASE);
delay(1000);

```

```
// Go Forward for 1 sec ONE MOTOR
motor1.run(RELEASE);
motor2.run(FORWARD);
delay(1000);

// Go Forward for 10 sec
motor1.run(FORWARD); // turn it on going forward
motor2.run(FORWARD); // turn it on going forward
delay(10000);

// Stop
motor1.run(RELEASE);
motor2.run(RELEASE);
while(1);
```