UNIVERSITY OF NEW HAMPSHIRE

Development of a 10kW Wind Turbine Buoy

FLoating Offshore Wind Energy (FLOWE)

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DEDICATION

We would like to dedicate this project to our Mechanical Engineering Administrative Assistant, Tracey Harvey for her support and patience over the past four long years.

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NOMENCLATURE

A_i	Interior Cross-Sectional Area
A_o	Exterior Cross-Sectional Area
d_{fs}	Full scale length dimension
D_i	Interior Diameter
d_m	Model length dimension
D_o	Exterior Diameter
COB	Center of buoyancy
COM	Center of mass
f	Wave Frequency
Fb	Freeboard
F_B	Buoyancy Force
F_{fs}	Full scale force
F_m	Model force
Fr_{fs}	Full scale Froude Number
Fr_m	Model Froude Number
g	Gravitational constant
F_{wind}	Wind force
H	Height
gm	Metacentric height
H_B	Height of Component Below n
H_n	Height of Component
I	Area Moment of Inertia
M	Mass
M_{fs}	Model Moment
M_m	Full scale moment
T	Wave Period
t_{fs}	Full scale time
t_m	Model time
U_f	Full scale velocity
UM	Upsetting moment
U_m	Model velocity
VCG_c	Vertical Center of Gravity of Individual Component
VCG_m	Vertical Center of Mass of Individual Component
VCG_v	Vertical Center of Volume of Individual Component
V_i	Interior Volume
V_m	Material Volume
V_o	Exterior Volume
Vol_{fs}	Full scale volume
Vol_m	Model volume
W_{fs}	Full scale weight
W_m	Model weight
λ	Wavelength
ρ_s	Density of Steel
ρ_{sw}	Density of Water
Wr	Weight required to fully submerged buoy
θ_{rad}	Tipping angle in radians
θ_{deg}	Tipping angle in degrees

ABSTRACT

DEVELOPMENT OF A 10KW WIND TURBINE BUOY

by

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A design for a buoy capable of supporting a 10 kilowatt wind turbine and its tower was developed to operate at the University of New Hampshire's Center of Ocean Renewable Energy (CORE) testing site located off the Isles of Shoals, New Hampshire. The buoy was designed to be the first offshore wind turbine in the United States and while being able to operate under hurricane conditions. To evaluate ocean response, two Froude-scaled models were constructed, tested, and compared at the Ocean Engineering wave tank at the University of New Hampshire. Full scale construction and deployment is scheduled to happen within the next year.

CHAPTER I

INTRODUCTION

1. BACKGROUND

Developing new ways to produce sustainable energy is one of the greatest challenges engineers face today. The harnessing of wind power is not a new idea; think back to the first time a sail was used to power a boat. Wind energy today is converted into usable electrical power with wind turbines. Building these turbines on land or close to shore comes with potential problems from inconsistent winds that do not allow them to perform at their optimum efficiency as well as other problems. These issues can be avoided by placing them in the open ocean. The University of New Hampshire Floating Offshore Wind Energy (FLOWE) team was created to begin the design process of a floating offshore wind turbine buoy, similar to that shown in Figure 1.1.

Figure 1.1 –StatoilHydro Model

Wind turbines are often placed on vast wind farms that can take up large amounts of usable land. Wind flow is disrupted by large cities and land formations, causing it to become turbulent. New wind farms are also often opposed by nearby residents because they interrupt the natural views of the surrounding land. These problems are why floating offshore wind turbines are an up and coming way to produce power from wind energy. They are to be placed in the open ocean; far enough from the shore to avoid disruptions. Wind speeds are more consistent and reach their highest speeds offshore allowing the turbines to output the most power. Because the turbines float, they are able to be moored far enough from the shore to be out of sight. Finally, an open ocean wind farm will take up space that is otherwise unusable.

2. GOALS AND OBJECTIVES

The objective of the FLOWE team is to design a buoy to support a 10 kilowatt wind turbine and its tower. The buoy must be capable of surviving hurricane conditions, including 9 meter waves and 50 centimeter per second currents. It will be moored in 52 meters of water at an existing test site. In the upcoming years, a full scale prototype will be constructed and deployed at UNH's Center of Ocean Renewable Energy (CORE) testing site at the Isles of Shoals of the coast of Portsmouth, NH. Before a prototype can be manufactured, the buoy must be modeled and tested in the UNH wave/tow tank.

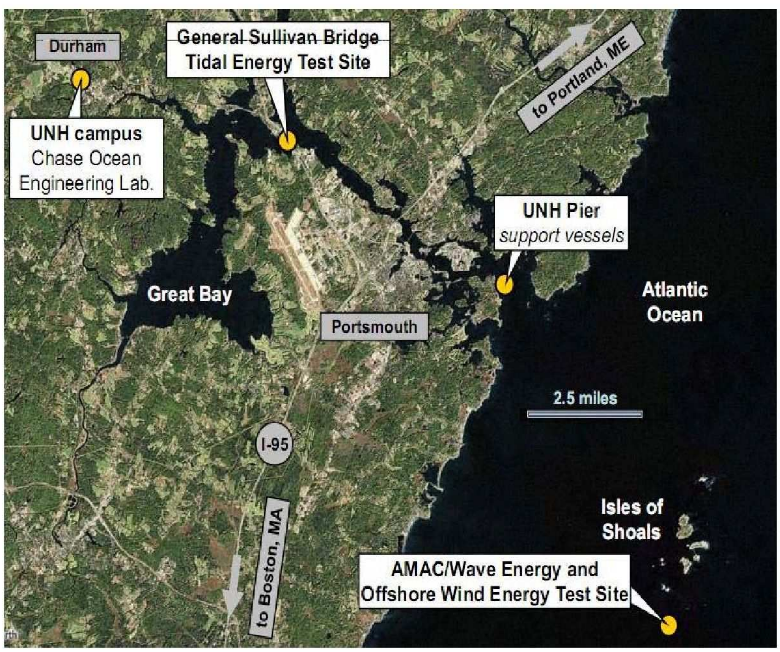

Figure 1.2 - Map of UNH Campus and Test Sites

3. APPROACH

This objective will be obtained by first researching buoy design concepts and previous CORE projects. Based on these findings, a hydrostatic model will be designed. The design will then be Froude-scaled to find dimensions for a model to fit the UNH wave/tow tank for testing. Preliminary design alternatives will be proposed and a final design will be chosen to move forward. A CAD design will be created to confirm the calculated weights and center of mass. Wave theory will then be utilized to determine the size of waves to be generated by the UNH wave/tow tank to best represent the CORE test site.

A model of the buoy will be fabricated to the Froude-scaled dimensions. Once finished, the model will be tested statically through a free-release test to demonstrate the heave and pitch behavior of the full-scale prototype. The maximum tipping angle due to the maximum wind force will be found by connecting a weight to the top of the model with a line through a pulley to simulate the buoy's reaction to a 10 kN wind force. The model will also be tested dynamically with waves generated in the UNH wave/tow tank according to the wave theory calculations. Finally, results will be analyzed and presented.

CHAPTER II

DESIGN

1. DESIGN CRITERIA

The goal of this project was to design a buoy to support a 10 kW turbine. Several criteria must be accounted for during the design process. The buoy must withstand 9 meter tall waves, hurricane winds that may exceed 70 kilometers per hour, as well as current speeds up to 50 centimeters per second. Once the design criterion was set, the design process began with buoy type selection.

The two major designs for buoys are the spar type design and the wave follower design. In Figure 2.1 below the design on the left depicts a spar buoy with cantenary mooring system. The design on the right is a barge or wave follower buoy.

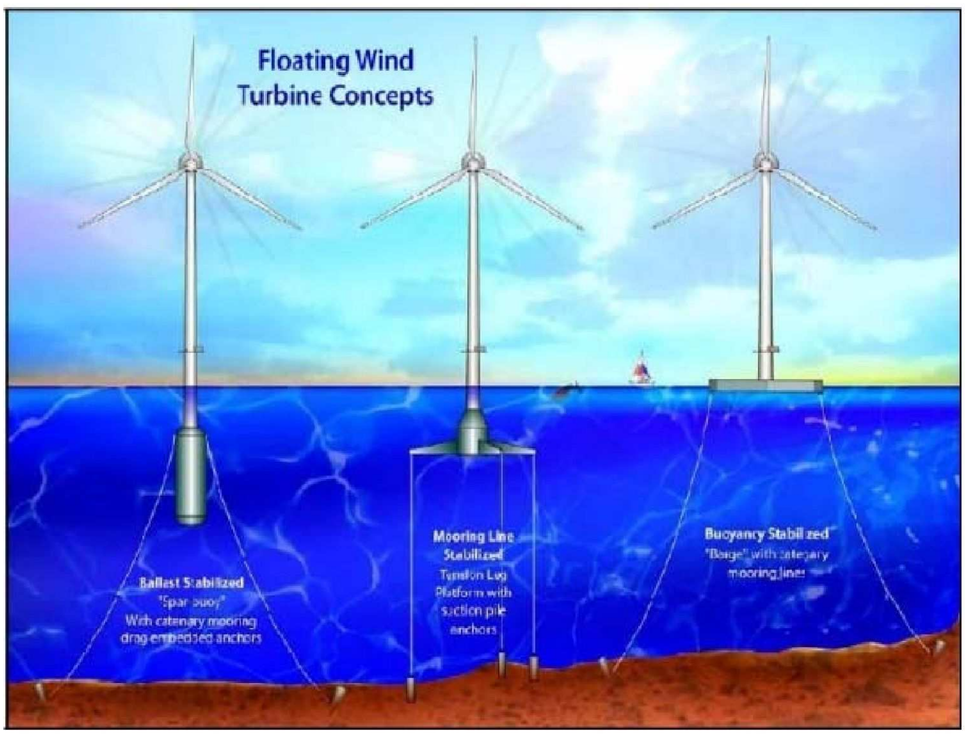

Figure 2.1 – Floating Turbine Concepts

The selected buoy type for our design was a spar buoy with catenary drag embedded mooring. The advantage of a spar design over a wave follower buoy is the drastically smaller water plane area. The water plane area is the cross-sectional area of the buoy at the waterline. As water plane area decreases, so does excitation of the buoy. With this knowledge, two spar buoys were designed to compare different aspects of geometry and their relationship to wave excitation and wind force.

2. CALCULATIONS

In order to evaluate the designs, an excel spreadsheet was designed to account for all components of the buoys. Both buoys were cylindrical in shape therefore most calculations were based around circular areas and moments of inertia. Each spar was designed as a steel pipe with 0.5 inch thick walls. On either end of the open pipe, 0.5 inch caps would be welded in order to seal the pipe air tight. For each component of the buoy a series of calculations was completed. With a selected height, exterior diameter and thickness of each component, interior and exterior cross sectional areas were calculated using equation (2.1) and (2.2).

$$A_i = \frac{\pi {D_i}^2}{4} \tag{2.1}$$

$$A_o = \frac{\pi {D_o}^2}{4} \tag{2.2}$$

Interior and exterior volumes were then calculated by multiplying the height by the calculated areas

$$V_i = A_i * H \tag{2.3}$$

$$V_o = A_o * H \tag{2.4}$$

By subtracting the two volumes, the material volume for the each section

$$V_m = V_o - V_i \tag{2.5}$$

The area moment of inertia was calculated for each component using equation (2.6)

$$I = \frac{\pi}{64} * (D_o^4 - D_i^4) \tag{2.6}$$

Mass was calculated next by multiplying the density of steel times the material volume for each component. The only exception was the concrete section of the ballast, which was multiplied times the density of concrete instead of steel.

$$M = V_m * \rho_s \tag{2.7}$$

The vertical center of gravity was found for each component, this was used find the center of mass as well as the center of buoyancy for the entire design.

$$VCG_c = \frac{1}{2}H_c + \Sigma \mathrm{H_b} \tag{2.8}$$

$$VCG_m = VCG_c * M \tag{2.9}$$

$$VCG_v = VCG_c * V_o \tag{2.10}$$

When calculating the VGG_c for the gussets, the 1/2 would be replaced by 1/3 to compensate for their triangular shape. The vertical center of mass was then divided by the total mass of the buoy to find its COM (center of mass). The vertical center for volume was divided by the total exterior volume to find the COB (center of buoyancy).

$$COM = VCG_m/\Sigma M \tag{2.11}$$

$$COB = VCG_v/\Sigma \mathrm{V_o} \tag{2.12}$$

The next calculation was the buoyancy force caused by completely submerging the buoy. This force was calculated using equation (2.13).

$$F_B = \Sigma V_o * \rho_{sw} * g \tag{2.13}$$

The weight force in Newtons was calculated using equation (2.14).

$$F_w = \Sigma M * g \tag{2.14}$$

The difference between buoyancy and weight force is considered the weight required to fully submerge the buoy.

$$w_r = F_B - F_w \tag{2.15}$$

With this excessive buoyancy force the freeboard may be calculated.

$$fb = \frac{w_r}{g * \rho_{sw} * WPL} \tag{2.16}$$

As previously stated in the criteria it was important that the design would survive hurricane force winds. The maximum acceptable tipping angle for the design was set a 5°. In order to find the force that would be acting on the turbine blades a calculation was done to scale up the forces done in a previous study.

In the experiment done by Utsunomiya and his colleges, the steady horizontal force acting on the model was 29.4 N. Froude scaling was used in order to find the force acting on the full scale model by multiplying the 29.4 N force by the scale factor cubed. This force was then multiplied by the ratio of the blade diameters squared. The resulting 2865 N force would act on the 10 kW turbine blades. To account for a worst case scenario, a force of 10 kN was also calculated.

In order to calculate the tipping caused by wind force, the metacentric height must be found. This value is the sum of the distance between the COB and COM and the area moment of inertia over the water plane area as seen below.

$$gm = \frac{I}{\Sigma V_o} + (COB - COM) \tag{2.17}$$

Upsetting moment is the force acting on the turbine blades times the length of the buoy to the mooring connection.

$$UM = F_{wind} * \Sigma H \tag{2.18}$$

∑H will change as the mooring location changes. When the mooring is attached at the bottom of the ballast ∑H will be the total height of the entire structure. If the mooring is attached at the water line ∑H will be equal to the tower height plus the freeboard.

The tipping angle can then be found using the following equation.

$$\Theta_{rad} = \arcsin\left(\frac{UM}{F_w * gm}\right) \tag{2.19}$$

This can then be converted to degrees to display the tipping angle in degrees.

$$\Theta_{deg} = \Theta_{rad} * \frac{180}{\pi} \tag{2.20}$$

Once the tipping angles were found and all were within the criteria, components could then be finalized.

Table 2.1 – Dimensions of Design 1

#	Name	Height (meter)	Outer Diameter (meter)	Inner Diameter (meter)	Mass (kilogram)	VCG (meter)
1	Spar Cap	0.01	4	-	939.6	23.040
2	Spar	6	4	2.9746	7375.3	20.035
3	Spar Cap 2	0.01	4	-	939.6	17.030
4	Spar Gusset	1.635	1.5	0.0127 (thickness)	978.0	16.53
5	Free Flooding Pipe	12	1	0.9746	3339.6	11.025
6	Hole	-	0.49	-	-	-
7	Ballast Gusset	1.635	0.75	0.0127 (thickness)	489.0	5.570
8	Ballast Cap	0.01	2.5	-	498.4	5.019
9	Ballast	5	2.5	-	60935.6	2.513
10	Ballast Cap 2	0.01	2.5	-	489.4	0.006

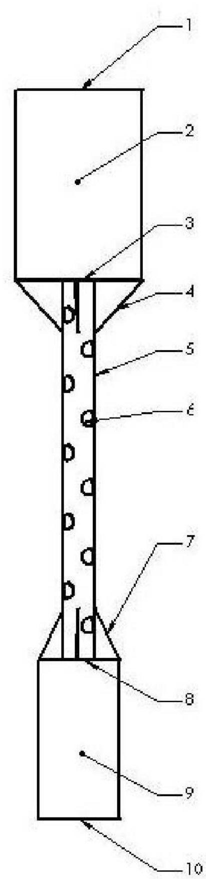

Figure 2.1 – Drawing of Design 1 with Labeled Components

Table 2.2 – Dimensions of Design 2

#	Name	Height (meter)	Outer Diameter (meter)	Inner Diameter (meter)	Mass (kilogram)	VCG (meter)
1	Upper Spar Cap	0.0127	2	-	313.2	21.557
2	Upper Spar	10	2	1.9746	6224.2	16.551
3	Upper Spar Gusset	1.25	0.5	0.0127 (thickness)	124.6	11.967
4	Lower Spar Cap	0.0127	3	-	704.7	11.544
5	Lower Spar	5	3	2.9746	4678.1	9.038
6	Lower Spar Cap 2	0.0127	3	-	704.7	6.532
7	Lower Spar Gusset	1.25	1	0.0127 (thickness)	249.23	6.109
8	Free Flooding Pipe	5	1	0.9746	1391.5	4.025
9	Hole	-	0.444	-	-	-
10	Ballast Gusset	1.25	1.5	0.0127 (thickness)	373.9	1.942
11	Ballast Cap	0.0127	4	-	1252.8	1.519
12	Ballast	1.5	4	-	44839.4	0.763
13	Ballast Cap 2	0.0127	4	-	1252.8	0.00645

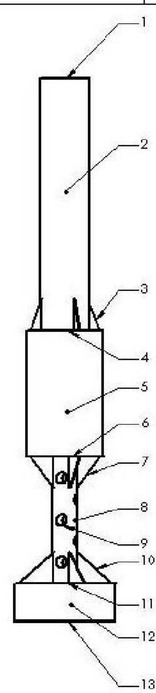

Figure 2.2 – Drawing of Design 2 with Labeled Components

CHAPTER III

MODEL FABRICATION

1. FROUDE SCALING

Once the full-scaled model was designed, it was necessary to design the model for testing. Using the actual ocean depth of 52 meters and the UNH tow tank depth of 2.44 meters, Froude scaling was used to scale down the full-scale design so the model could be tested in the UNH wave/tow tank. The following equations show the steps taken in the Froude scaling process. [Swift, 2009].

$$Fr_{fs} = \frac{U_{fs}}{\sqrt{gd_{fs}}} = Fr_m = \frac{U_m}{\sqrt{gd_m}} \qquad (3.1)$$

Since the buoy has no velocity, equations were simplified to on include variables of time and length, shown below in eaquation (3.2).

$$T_{fs}/T_m = \sqrt{d_{fs}/d_m} \qquad (3.2)$$

Then, from geometric similitude,

$$Vol_{fs}/Vol_m = \left({}^{d_{fs}}\!/\!{}_{d_m}\right)^3 \qquad (3.3)$$

From Archimedes principle,

$$\left({}^{d_{fs}}\!/\!{}_{d_m}\right)^3 = \left({}^{W_{fs}}\!/\!{}_{W_m}\right) = \left({}^{m_{fs}}\!/\!{}_{m_m}\right) = \left({}^{F_{fs}}\!/\!{}_{F_m}\right) \qquad (3.4)$$

Since the test site is at a depth of 52 meters and the tank is at a depth of 2.44 meters, $\left({}^{d_{fs}}\!/\!{}_{d_m}\right)$ was found to be 21.31. Therefore, with this ratio, it was possible to calculate model weight and height of each component of the buoy. The total height of the design 1 model was found to be 76.7 inches with a total weight of 17.5 pounds. The total height of the design 2 model was found to be 62.93 inches with a total weight of 14.97 pounds.

And finally, since Moment = Force * Distance

$$\left(\frac{M_{fs}}{M_m} \right) = \left(\frac{d_{fs}}{d_m} \right)^4 \tag{3.5}$$

This made it possible to calculate the upsetting moment on the buoys. The following table shows the final calculated dimensions of each buoy model compared to the actual measured dimensions. The accuracy of the scale used was to the nearest 0.2 pounds.

Table 3.1 - Calculated dimensions compared to measured dimensions for Design 1 and 2

	Design 1		**Design 2**	
	Calculated	Measured	Calculated	Measured
Total Height	76.70 inches	78 inches	62.93 inches	65.6 inches
Total Weight	17.50 pounds	17.6 pounds	14.97 pounds	15.2 pounds
C.O.M Location from bottom	10.79 inches	10.91 inches	7.56 inches	7.605 inches
C.O.B Location from bottom	32.09 inches	32.457 inches	18.96 inches	18.961 inches
Freeboard Measured from top	3.74 inches	3.951 inches	13.13 inches	13.09 inches

2. PROCEDURE/METHODS

After the model design was complete, each buoy was built with respect to its corresponding dimensions. The modeling process was, for the most part, the same for each buoy. First, the free-flooding PVC pipe was cut to specifications and holes were drilled to scale. Acrylic gussets were then cut and attached to PVC for support. The spar was shaped out of closed-cell blue foam and fit onto the gussets. Concrete was the then poured into a mold and the PVC was set in with threaded rods for extra reinforcement. Bondo auto-body repair putty was then applied to the foam spar and concrete ballast. When hardened, the putty was sanded down until the surface was smooth. A layer of white latex masonry paint was then applied to the buoy for waterproofing. A final coat of white semi-gloss paint was applied to the buoy to give it a shiny white texture. Refer to Figure 3.1.

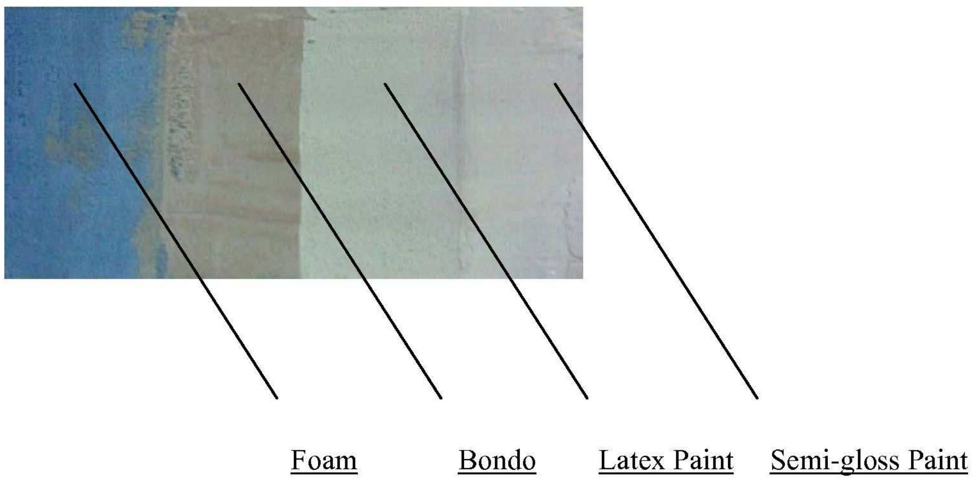

Figure 3.1 – Layers of Spar Construction

During the building process, each buoy's weight and center of mass was periodically checked to make sure values were consistent with calculated Froude-scaled values. Both buoys were specifically designed underweight since it is easier to add weight while keeping the model geometrically similar to the prototype, than to remove weight. In both buoys, the center of mass was calculated to be within the free-flooding PVC pipe. The center of mass was measured by placing the buoy, lengthwise, on a knife edge and observing at which point the buoy would not tip. Once the center of mass was correctly matched up to the calculated value, lead pellets were hot glued around that spot (inside the free-flooding pipe) until the weights were consistent with the Froude-scaled values.

A wooden dowel rod was cut with respect to the scaled down tower length. A scaled down windmill was also constructed out of blue foam and coated with white latex paint. The windmill was constructed completely for visual purposes, only to show how big the turbine blades were in regards to the tower and buoy. It did not generate any power. Once the buoy models were constructed, they were ready to be put in the tank for testing and analysis. The figures below show the completed 21.31:1 scale buoy models.

Figure 3.2 - Design 1 Model at 21.31 Scale

Figure 3.3 - Design 2 Model at 21.31 Scale

CHAPTER IV

MOORING

1. TENSION LEG VS. CATENARY

There are two types of mooring systems; tension leg and catenary. These two types strictly depend on the mooring scope, which is the ratio of mooring line length to the water depth. A small scope results in a tension leg (taut) moor, while a large scope results in a catenary (slack) moor. In reality, however, there are many complex varieties of these types, such as those for subsurface buoys, but for simplicity reasons, the focus was only on the two.

(a) Tension Leg

In tension leg mooring systems, the cable(s) stay in constant tension (as seen in figure 4.1). First off, a buoy could be anchored with a single tension leg attached to the bottom center of the ballast. This allows the buoy to rise and fall with the tides without the problem of overturning. As water depths increase the buoy watch circle or radius of travel increases, so additional mooring lines will be needed in order to keep the buoy in place. A trimoor (three point moor) would greatly reduce the buoy watch circle; however, the anchors would face both vertical and horizontal forces acting on them from wave motion. Also, under storm conditions there is high static tension acting on the lines from the strong currents [Berteaux, 1991]. Tension leg moorings generally have a small seabed footprint since the lines are in constant tension from the buoy to the anchors in the seabed.

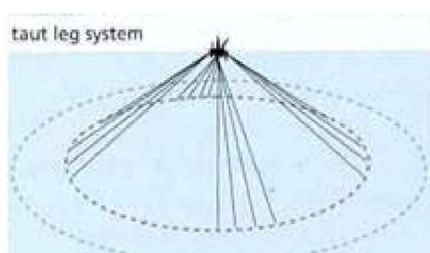

Figure 4.1 - Tension Leg Mooring System

(b) Catenary

In catenary mooring systems, heavier cables are used to allow for slack in the lines (shown in figure 4.2). Typically, a heavier type of chain is used for the line; however, to reduce costs, a portion of the chain can be replaced with a type of wire rope. The heavy chain provides a substantial amount of tension at the attachment to the buoy.

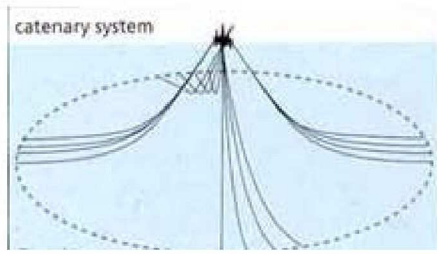

Figure 4.2 - Catenary Mooring System

The main advantage in catenary mooring is that the anchors only need to withstand horizontal forces acting on them rather than both vertical and horizontal forces. However, the disadvantage is that the system has a large footprint and needs a considerable amount of more cable than tension leg moorings. In deeper water the weight of the lines also starts to play a role in the buoyancy force of the buoy so this type of mooring is not suited for very deep water. Since the test site at the Isles of Shoals, NH is only 52 meters in depth, the catenary type mooring system was used.

2. POSITION AND NUMBER OF LINES

Through research, it was determined that the buoy will be moored at the waterline in order to reduce tipping and to keep the turbine as upright as possible, maximizing efficiency. It was also determined that the full scale buoy will use three mooring lines spaced at 120° to increase stability while reducing the cost and footprint of the lines. However, due to wave tank width limitations, it was only possible to attach one mooring line to the buoy during testing. This was possible because wave motion would only be disrupting the buoy from one direction therefore only one line was needed to act against that motion.

3. MATERIAL

Next in the design process of the mooring system, was the type of material to be used in order to construct the cables which attach the buoy to the anchor. For buoys of this size, it is common for a plow embedment anchor to be used. A heavy chain will be considered for at least part of the mooring line. If the line was made out of a durable chain, the risk of damage from shark bites and other biological attacks is greatly lowered, but a much stronger vertical force would then be applied to the lines from the weight of the chain and environmental damages may increase. A study conducted by Williams and Betcher in 1996, showed that by using an all chain mooring line, there is a 7% increase in marine vegetation disturbance from the seabed chain scour over using a chain to rope mooring line. This however, depends strongly on the size and density of the chain [Williams and Betcher, 1996].

Figure 4.3, *4.4*, and *4.5* show different configurations for mooring lines.

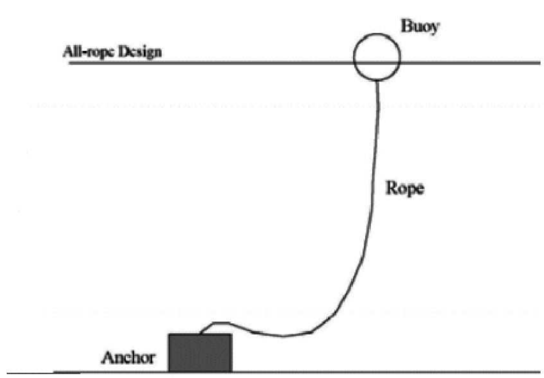

Figure 4.3 - All Rope Buoy Mooring Design

Above, Figure 4.3 shows a rope mooring line, connected from the buoy to the anchor. The problem with this, however, is that a rope is not as heavy and forfeits the line's ability to rest on the seabed. This might allow vertical forces to push up on the rope, causing the need of a heavier and more expensive anchor.

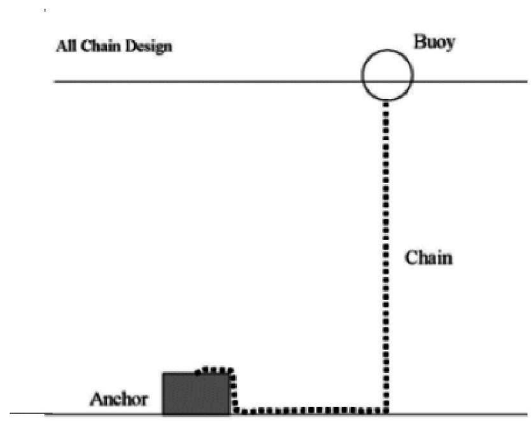

Figure 4.4 - All Chain Buoy Mooring Design

In Figure 4.4 above, only a chain is used to connect the buoy to the anchor. This is the most durable design for a mooring line, however since the line is made of only chain, weight becomes a serious issue.

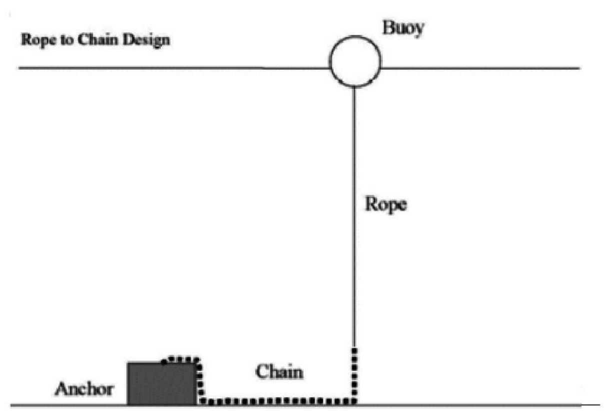

Figure 4.5 - Rope and Chain Buoy Mooring Design

Finally, in Figure 4.5, the mooring line was split into two materials, a chain and a type of rope. This proves to be the best design for the mooring system since it will minimize weight, while still using a chain to rest on the seabed.

4. MODEL

From Chad A. Turmelle's thesis from 2007, it was found that a typical chain for this full scale application is a 90 foot portion of 1 inch steel stud link chain. Chad's values were adjusted using the calculated 21.31:1 scale instead of his 20.7:1 scale. This chain portion was scaled to 50.7 inches. Chain with the appropriate length to weight ratio could not be found, so small lead sheet squares were attached to the chain until the desired weight was reached. The full scale line used in this application is a 525.7 inch long

2 inch thick Spectra ™ line. The line used in the model had no elastic properties so the line was cut in half and connected by a 20 inch rubber section to simulate the full scale elasticity. A 25 pound lead weight was used to model the full scale plow embedment anchor. The weight was heavy enough to remain stationary during dynamic wave testing. A picture of the modeled mooring system can be found below.

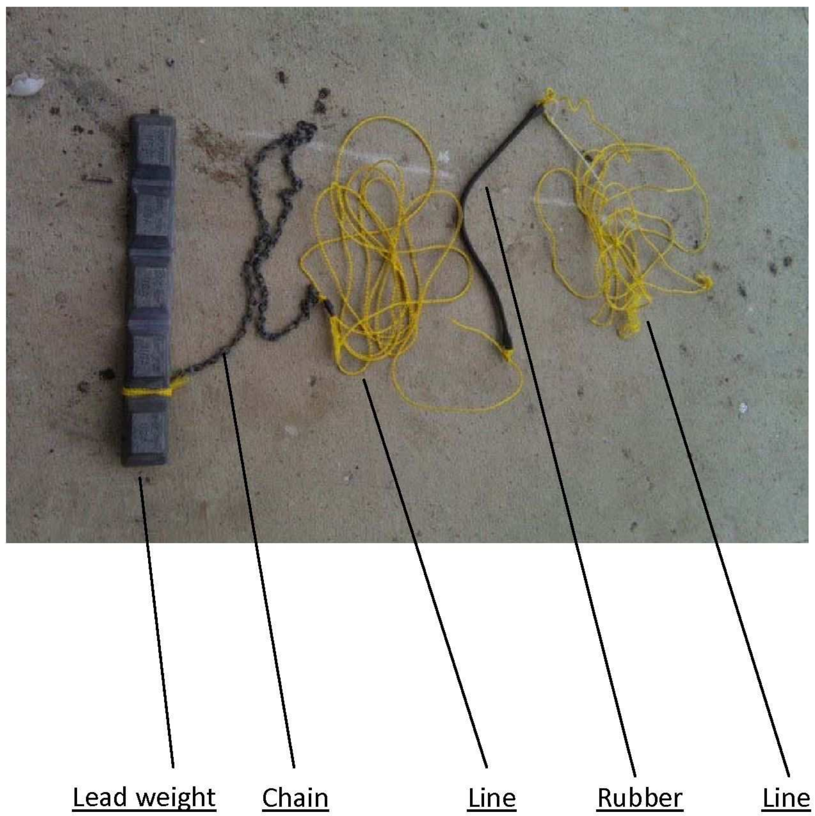

Figure 4.6 - Mooring System Model

CHAPTER V

TESTING AND RESULTS

1. EXPERIMENTAL METHODOLOGY

Both static and dynamic testing was performed on each scaled model in the UNH wave/tow tank in order to determine specific characteristics and behaviors of each design. For static testing (testing without the presence of waves) free-release tests were conducted for both pitch and heave to obtain values for pitch and heave natural periods. These values are effective in determining buoy motion in a large range of sea states as well as predicting the overall behavior and stability of each design as well as assisting in analyzing dynamic test results. Wave testing or dynamic testing is still in the process as being performed and will be ongoing after the completion of this paper. Dynamic testing will be performed to determine the pitch, heave, and surge Response Amplitude Operators (RAO) or transfer functions of both designs.

To determine each design's damped natural period/frequency a series of free-release testing was performed. Free-release testing is conducted by displacing each model from equilibrium state and observing the time response motion due to the displacement. The model oscillates between the equilibrium position; vertical motion for heave testing and angular motion for pitch testing. By plotting these oscillations it is possible to obtain the damped natural period and frequencie for each model. By measuring the crest to crest distances for each response natural periods are obtained and the natural frequencies are the reciprocals of those values.

Wave testing is ongoing and being conducted to obtain the heave, pitch, and surge RAOs or transfer function for each design model. Heave is displacement in the vertical direction, surge is in the horizontal direction, and pitch is angular displacement. The RAOs are defined as the ratio of buoy response, or amplitude to the wave forcing.

The heave RAO is defined as

$$HeaveRAO = \frac{HeaveAMP_{buoy}}{HeaveAMP_{wave}} \qquad (5.1)$$

where $\text{HeaveAMP}_{\text{buoy}}$ is the heave amplitude of buoy motion and $\text{HeaveAMP}_{\text{wave}}$ is the wave heave amplitude.

Wave heave amplitude is defined as

$$HeaveAMP_{wave} = \frac{H}{2} \tag{5.2}$$

It is predicted that the surge amplitude will be difficult to measure experimentally [Trumelle, 2007] with that in mind surge RAO will be determined through a relation to wave heave amplitude

$$.SurgeRAO = HeaveAMP_{wave}\left[\frac{cosh\left(\left(\frac{2\pi}{\lambda}\right)h\right)}{sinh\left(\left(\frac{2\pi}{\lambda}\right)h\right)}\right] \tag{5.3}$$

A similar relation will be used to determine pitch RAOs.

$$PitchRAO = \frac{PitchAMP_{buoy}}{HeaveAMP_{wave}\left(\frac{2\pi}{\lambda}\right)} \tag{5.4}$$

A series of five varying regular wave inputs will be used. These inputs have been decided based upon data collected at the test site and encompass the range of sea conditions found on site.

(a) Optical Positioning Instrumentation and Evaluation Software (OPIE)

Data for both wave and free-release testing was recorded using UNH's Optical Positioning Instrumentation and Evaluation Software (OPIE), which is a MATLAB® based program. OPIE records data by making use of a camera that captures movement up to 30 frames per second. This camera is placed perpendicular to the buoy while testing is performed. The OPIE software takes the sequence captured and tracks two points or tracking dots at a time on a model by recognizing contrast, thus each model was painted white with black tracking dots. As OPIE follows these tracking dots it measures angular movement, vertical and horizontal movement, velocity, and acceleration all with respect to time. These values are placed into arrays by OPIE that can be easily be loaded into a MATLAB® workspace for analysis.

(b) Experimental Procedure

Free-Release

Aset of at least four free release tests were performed for each model in order to find an average response. Tests were conducted in the UNH wave/tow tank with the buoy in the window on the side of the tank so that OPIE's camera could capture the movement. The OPIE capture sequence was started a few moments before displacement in order to have an initial position at equilibrium.

To displace the models for heave testing, they were pushed vertically into the water less than 2 inches and released. Pitch testing was performed by displacing the models by a horizontal angle less than 15 degrees and then they were released.

Dynamic (Regular Waves)

In order to keep the buoy models within OPIE's view frame during wave testing a mooring line will be added to the model. Only a single mooring line is needed because the waves act on the buoy in only one direction within the tank and that is the only force that needs to be opposed in order to keep the buoys in place.

A series of 5 tests are to be performed with a range of regular waves to try and capture the characteristics of the full scale site. These parameters, shown below in Table 5.1 along with their scaled up values were chosen using data collected from the full scale test site. Wave generation will be started a few moments before data collection to ensure that a steady state is reached by each buoy before the capture sequence begins.

Table 5.1 - Regular Wave Inputs for UNH Wave/Tow Tank

	MODEL INPUTS				FULL SCALE INPUTS			
#	T_m(sec)	H_m(m)	f_m(Hz)	λ_m(m)	T_{fs}(sec)	H_{fs}(m)	f_{fs}(Hz)	λ_{fs}(m)
1	0.888	0.0215	1.126	1.231	3.996	0.458	0.250	26.237
2	1.530	0.3610	0.654	3.655	6.885	7.693	0.145	77.889
3	1.604	0.1912	0.601	4.323	7.488	4.075	0.134	92.130
4	2.000	0.2870	0.500	6.245	9.000	6.116	0.111	133.092
5	2.440	0.0360	0.410	9.295	10.980	0.767	0.091	198.095

2. DATA ANALYSIS AND DISCUSSION

(a) Free-Release

Data collected from OPIE during free-release testing was imported into MATLAB® in the form of arrays. For the heave test data vertical movement of the buoys was plotted against time and for the pitch test data the horizontal angular displacement of the buoys was plotted versus time. Each set of data was averaged together to obtain an average time response and damped natural period for each displacement. Typical data for heave tests on each model is shown below in Figure 5.1.

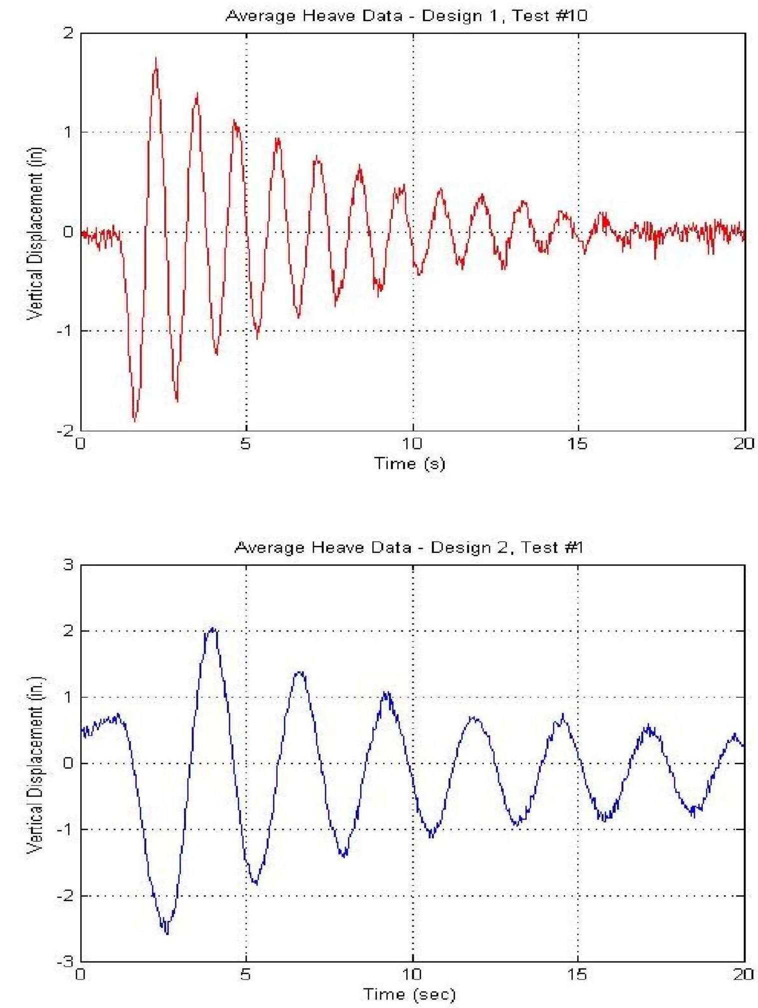

Figure 5.1 - Average Heave Free-Release Test Data from each Model (Design 1 and Design 2)

Looking at these plots, is it easy to see that design 2 has a much slower response to wave excitation. This illustrates that design 2 oscillates slower about the equilibrium position and takes a much larger amount of time to damp out the motion. Comparing the two plots design 1 settles back to equilibrium at approximately 16 seconds while design 2 is still noticeably disturbed at that time. This difference can be attributed to the difference in metacentric height and waterplane area between the models.

The first peak represents the initial displacement of the model; the proceeding 6 peaks were used to obtain peak to peak distances for the plot. These distances were used to acquire the damped natural periods (T_d) of each test. The natural periods of each individual test were averaged together to find one value and scaled back up to represent the expected full scale natural periods for both heave and pitch. Damped natural periods for both models and full scale buoys are shown in Table 5.2.

Table 5.2- Damped natural periods for heave and pitch on buoy models and full scale design.

	Td_m (sec)	**Td_{fs} (sec)**
Heave (design 1)	1.110	4.995
Heave (design 2)	2.580	11.610
Pitch (design 1)	0.923	4.154
Pitch (design 2)	1.987	8.901

(b) ***Dynamic (Regular Waves)***

Regrettably, at the time this report was written, sufficient data had not been collected due to mechanical and electric problems with the wave maker for the UNH wave/tow tank. Few tests had been performed therefore there was not enough data to find and analyze RAOs and other dynamic characteristics.

CHAPTER VI

FUTURE WORK

Future FLOWE teams will be designing the internal components of the buoy. Equipment must be placed inside the buoy to monitor and store energy generated by the turbine. The two designs were provided to allow for more flexibility in equipment size and placement so that the design that will best fit their needs can be chosen.

Within the next year, CORE will install a wind turbine with a 25-foot blade diameter on a 60-foot tower floating in 170 feet of water at the UNH test site.

Once the design aspects of the project have been finished in the coming years, a full scale buoy prototype will be fabricated and deployed for testing at the Isle of Shoals, NH. The ultimate goal of FLOWE is to provide one of the first US designs of a deep-water wind turbine.

CHAPTER VII

CONCLUSION

The design, model construction, and test analysis of two buoys capable of supporting a 10 kilowatt wind turbine in hurricane conditions was completed. The buoys were initially designed under full scale conditions. Corresponding heights, weights, forces, moments, and other dimensions were scaled down using Froude-scaling to be able to fabricate the models. A catenary mooring system was chosen, designed, and fabricated. The physical scale models were then subjected to free-release and regular wave testing. From the physical model testing it was found design 1 has a considerably fast time response to disturbances, damping out around 16 seconds during free release testing while design 2 damps out well beyond 25 seconds. Although it seems that design 1 may be the better option, because of design 2's slower response it responds better to wave excitation. That being said, in hurricane conditions design 1 may oscillate a considerable amount more than design 2.

The full scale buoy is scheduled to be constructed and deployed within the next year. All internal components, such as electronics and the turbine generator, need to be designed. While deployed at the site, the buoy will collect wind data and determine the amount of power that can be generated from the wind. Once data is collected, there are hopes to design a much larger buoy in turbine, similar to the 2.3 Megawatt device deployed off the coast of Norway.

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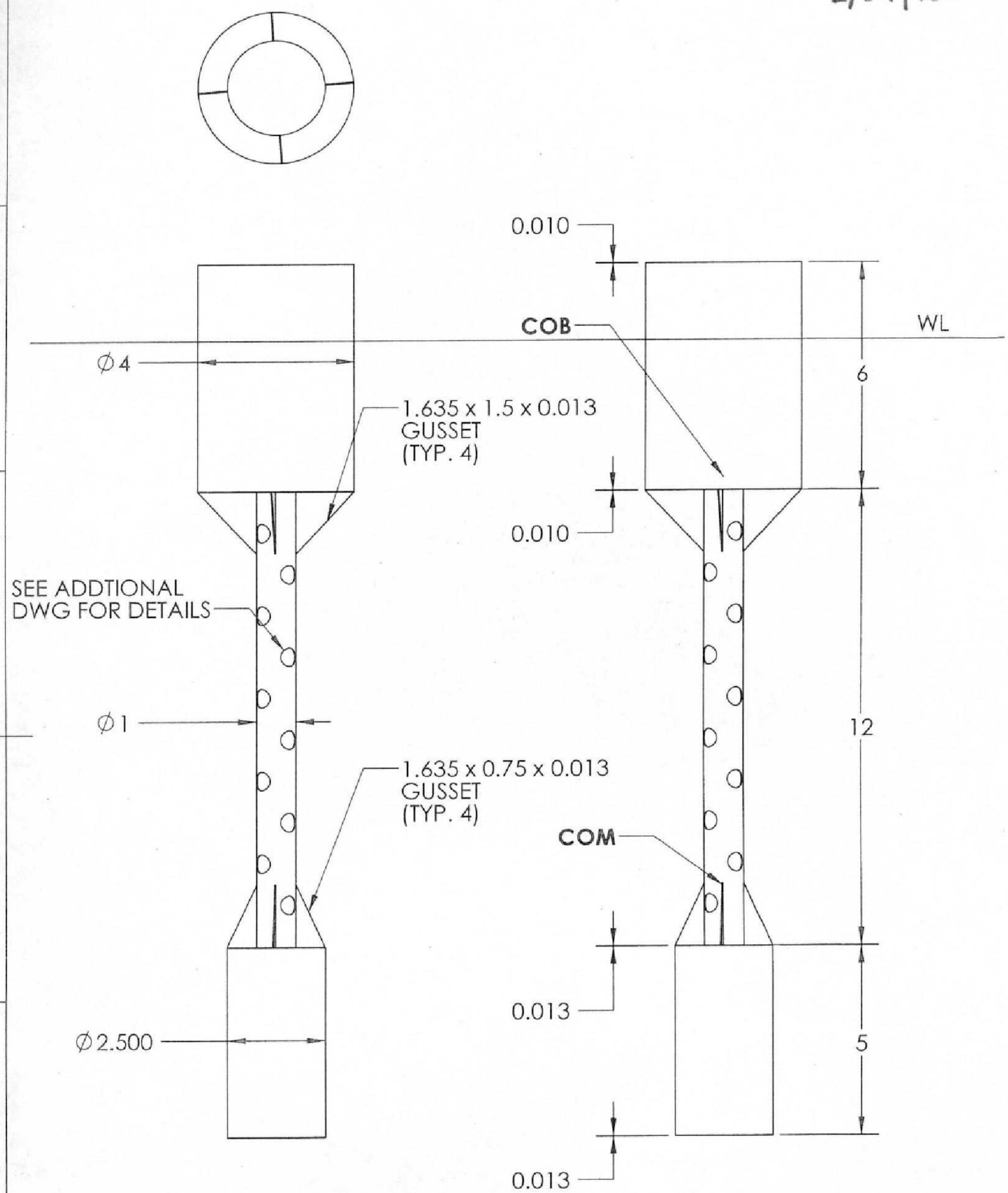
APPENDIX

2/24/10



BUOYANCY FORCE = 1009174 N
WEIGHT = 75150 N
WEIGHT REQ = 257024 N
COB = 17.369 m
COM = 5.830 m
GM = 11.542 m
FREEBOARD = 2.033 m
TIPPING ANGLE = 2.74 DEG

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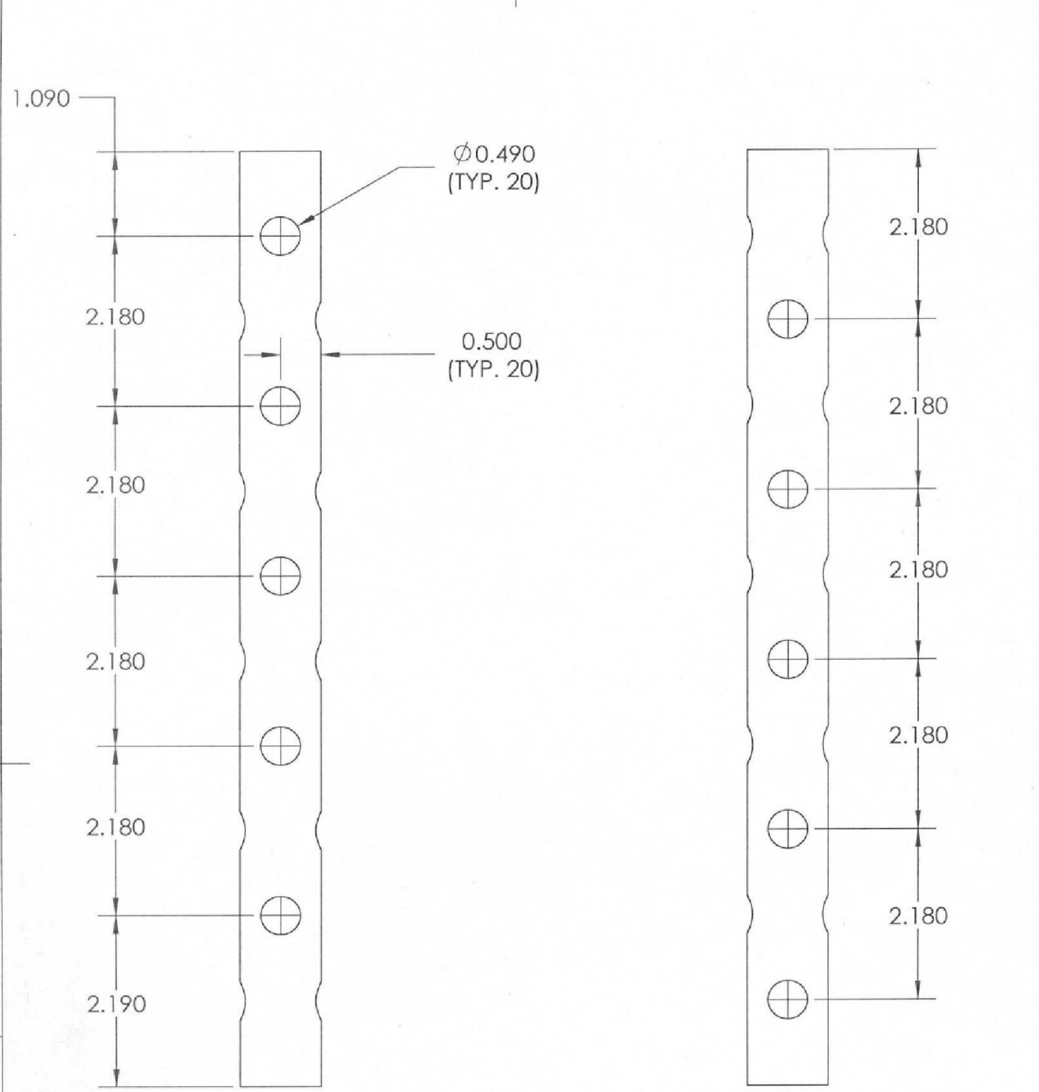

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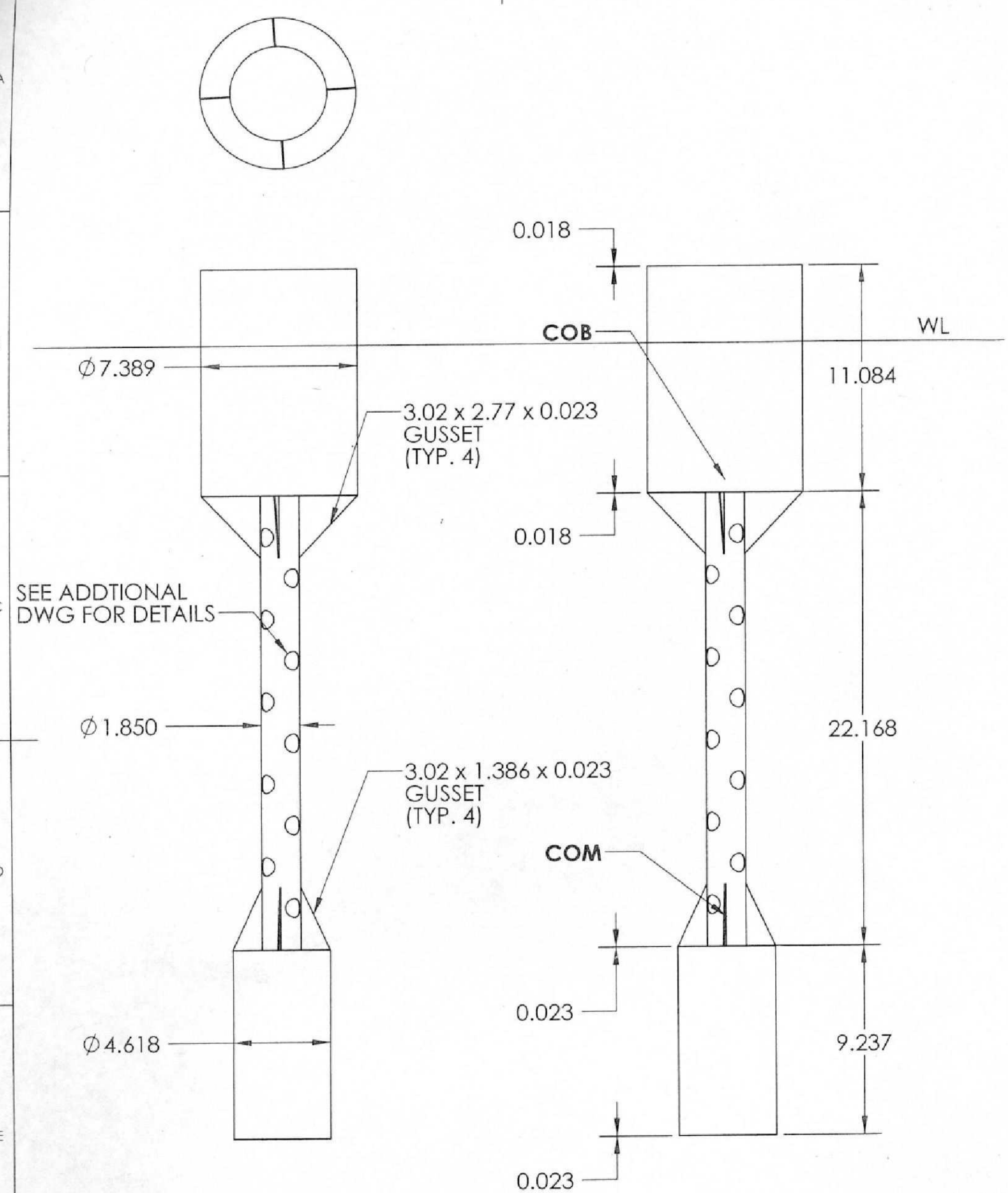

BUOYANCY FORCE = 23.38 LBS [104 N]
WEIGHT = 17.5 LBS[77.78 N]
WEIGHT REQ = 5.97 LBS Ø4.618 [26.55 N]
COB = 32.087 IN [0.815 m]
COM = 10.771 IN[0.274 m]
GM = 21.321 IN [0.542 m]
FREEBOARD = 3.756 IN[0.095 m]
TIPPING ANGLE = 2.74 DEG

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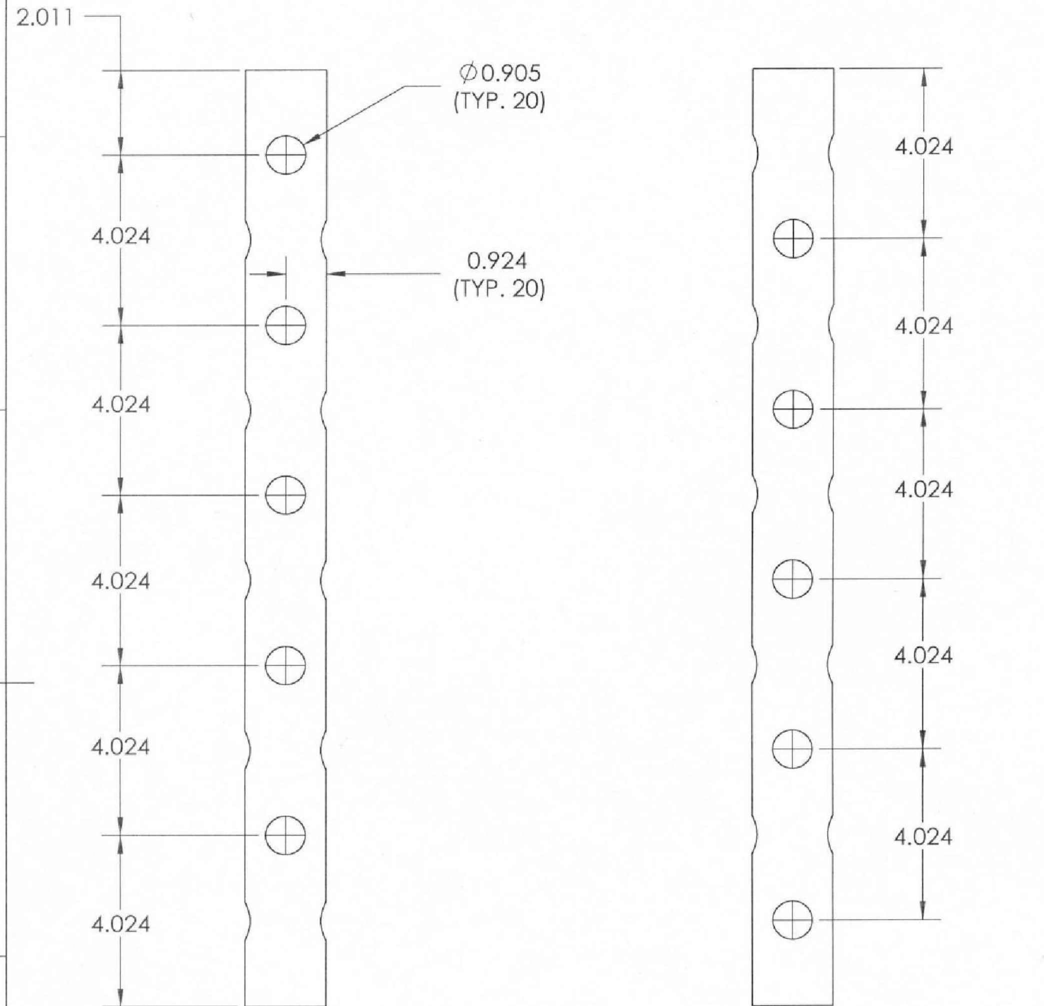

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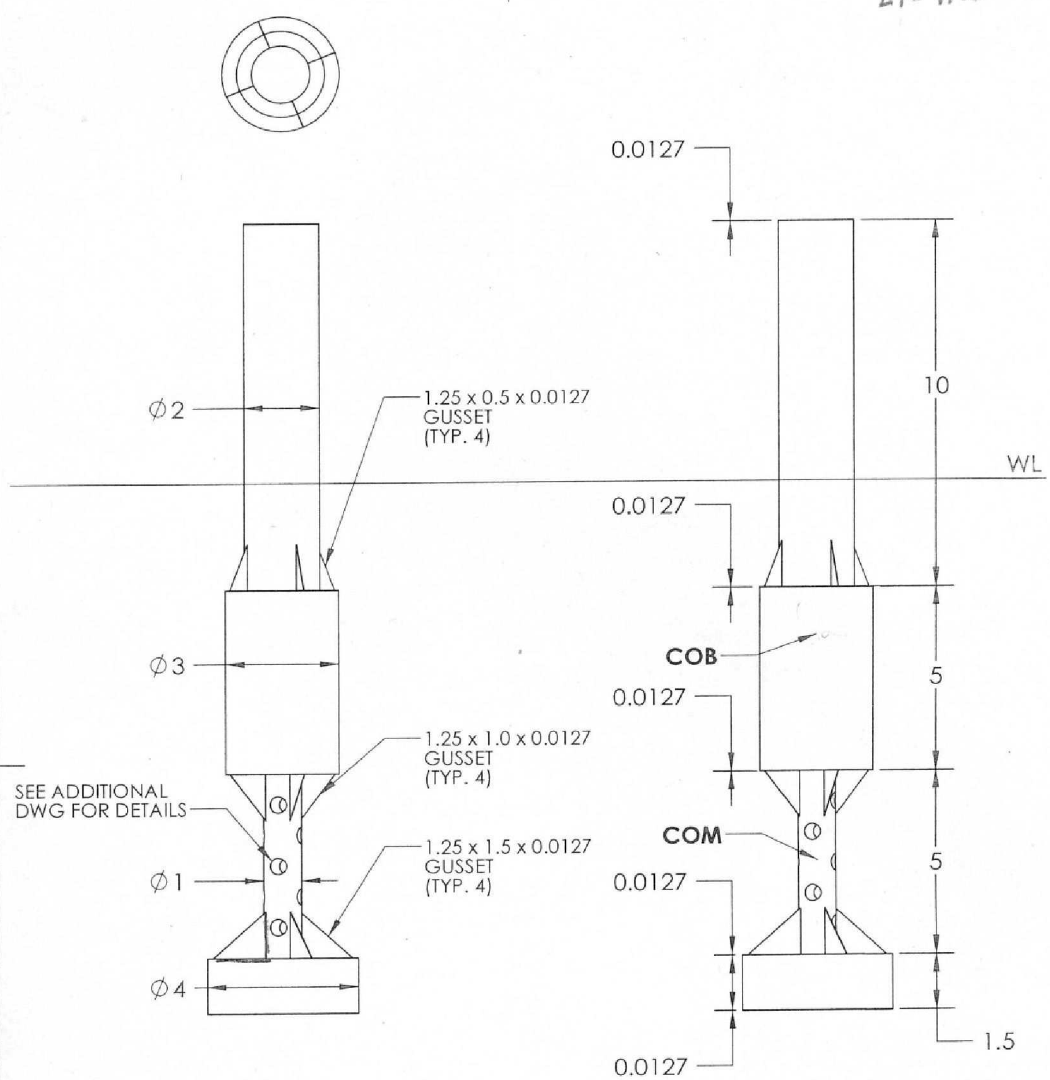
Design 1						
Full Scale						
Total Height	41.544	m	136.3	ft		
Total Weight	76703.1	kg	169101.3	lb	752150.116	N
Buoyancy Force	102913.9	kg	226886.4	lb	1009174.128	N
COM	5.83	m from bottom	19.13	ft from bottom		
COB	17.369	m from bottom	56.98	ft from bottom		
Freeboard	2.033	m	6.67	ft		
Worst Case Tipping Angle	2.74	degrees	2.74	degrees		
Individual Dimensions						
	Material	Height (m)	OD (m)	ID (m)	Weight (kg)	
Ballast	0.5" Steel encased Concrete	5.025	2.5	2.481	61914.399	
Free Pipe	Steel	12	1	0.9746	3339.613	
Spar	0.5" Steel	6.019	4	3.975	9254.537	
Tower	Steel Truss	18			1350	
Hub	Turbine	0.5			600	
Froude Scaled 1 : 21.311						
Total Height	76.73	in				
Total Weight	17.463	lbs				
Buoyancy Force	23.431	lbs				
COM	10.79	in				
COB	32.09	in				
Freeboard	3.74	in				
Worst Case Tipping Angle	2.74	degrees				
Individual Dimensions (Based off full scaled weight)						
	Material	Height (in)	OD (in)	Weight (lbs)		
Ballast	Concrete	9.24	4.618	13.245		
Free Pipe	Steel	22.17	1.85	0.759		
Spar	Steel	11.1	7.389	1.676		
Tower	Steel	33.25		0.307		
Hub		0.91		0.137		
Total		**75.76**		**16.124**		
Model Dimensions (Actual materials and weights)						
	Material	Height (in)	OD (in)	Weight (lbs)		
Ballast	Concrete	9.24	4.618	13.245		
Free Pipe	PVC	22.17	1.85	0.848		
Spar	Foam	11.1	7.389	0.5434		
Tower	Copper	33.25		0.307		
Hub				0.137		
Gussets	Steel			0.00261		
Total		**75.76**		**15.0804**		

2/24/10



BUOYANCY FORCE = 869818 N
WEIGHT = 645098 N
WEIGHT REQ = 224719 N
COB = 10.26 m
COM = 4.09 m
GM = 6.17 m
FREEBOARD = 7.1 m
TIPPING ANGLE = 4.9 DEG

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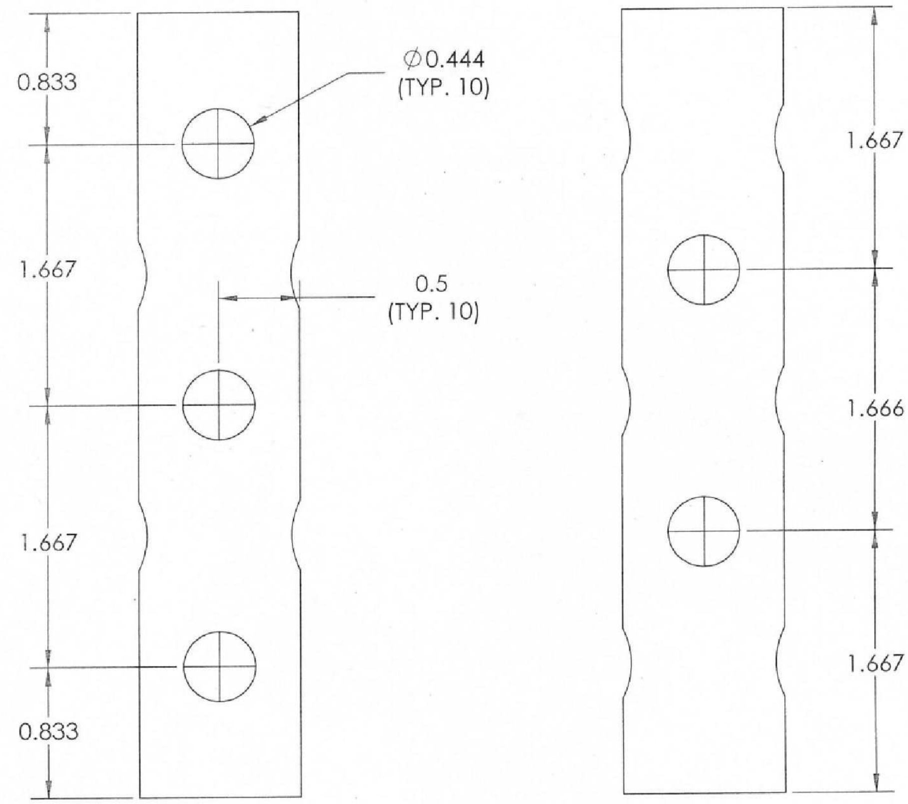

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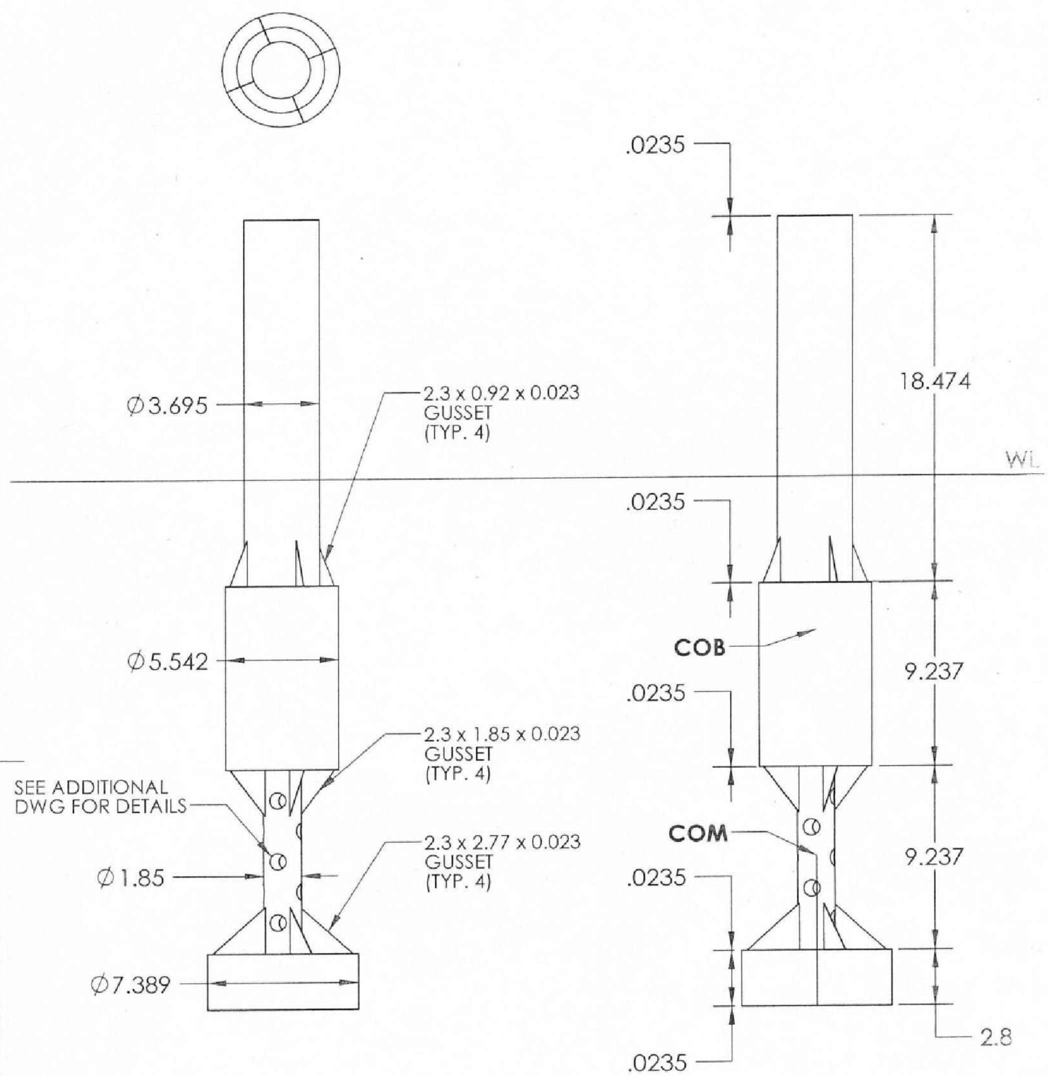

BUOYANCY FORCE = 20.2 LBS [89.86 N]
WEIGHT = 14.98 LBS [66.65 N]
WEIGHT REQ = 5.22 LBS [23.22 N]
COB = 18.97 IN [0.482 m]
COM = 7.48 IN [0.19 m]
GM = 11.37 IN [0.289 m]
FREEBOARD = 13.0 IN [0.33 m]
TIPPING ANGLE = 4.9 DEG

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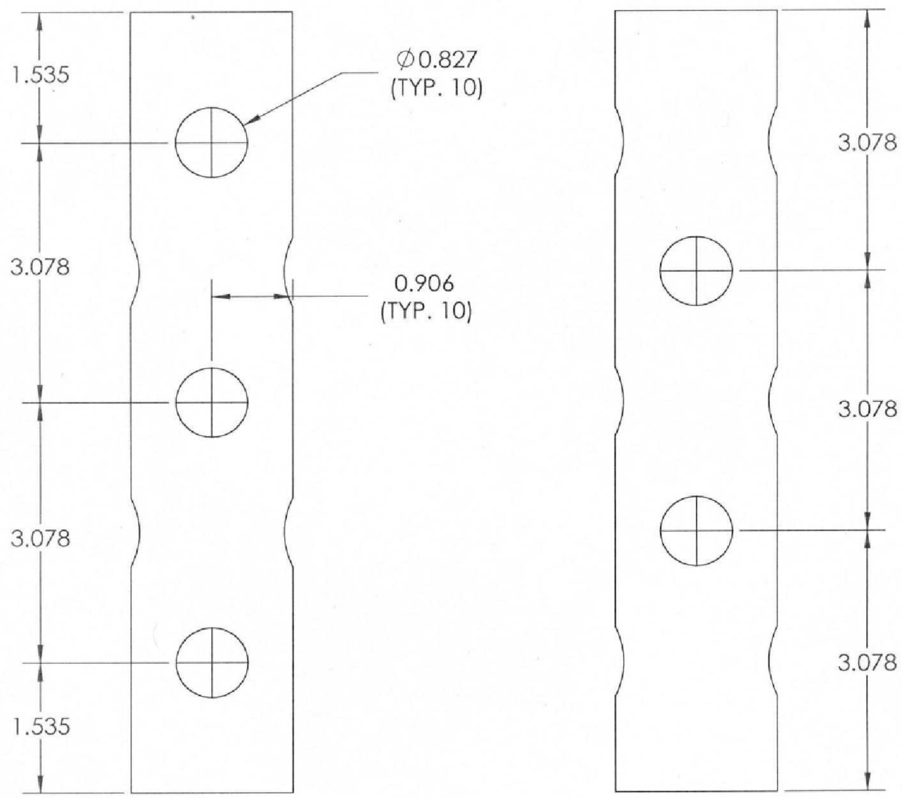

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Design 2

Full Scale

Total Height	34.0635	m
Total Weight	645098.4324	N
Buoyancy Force	869817.8322	N
COM	4.0912	m
COB	10.2636	m
Freeboard	7.107	m
Worst Case Tipping Angle	4.907	degrees

Individual Dimensions

	Material	Height (m)	OD (m)	t (m)	Weight (kg)
Ballast	Steel, Concrete	1.5	4	0.0127	1873.24
Free Pipe	Steel	5	1	0.0127	1391.51
Spar	Steel	5	3	0.0127	704.7
Shaft	Steel	10	2	0.0127	6224.25
Tower	Steel	12			1350
Hub	Turbine		0.5		600

Froude Scaled 1 : 21.311

Total Height	62.926	in
Total Weight	14.97	lbs
Buoyancy Force	20.195	lbs
COM	7.558	in
COB	18.96	in
Freeboard	13.13	in
Worst Case Tipping Angle	4.9	degrees

Froude Individual Dimensions

	Material	Height (in)	OD (in)	Weight (lbs)
Ballast	Concrete	2.771	7.34	10.17
Free Pipe	Steel	9.236	1.847	0.315
Spar	Steel	9.237	5.542	1.06
Shaft	Steel	18.47	3.694	1.42
Tower	Steel	22.17	0	0.31
Hub		0	0.924	0.14

Model Dimensions

	Material	Height (in)	OD (in)	Weight (lbs)		
Ballast	Concrete	2.771	7.34	10.17		
Free Pipe	PVC	9.236	1.847	0.42	0.0425	lbs/in^3
Spar	Foam	9.237	5.542	0.36	0.00162	lbs/in^3
Shaft	Foam	18.47	3.694	0.32	0.00162	lbs/in^3

```
%Design 1
%Static Testing (Pitch and Heave Responses)/ Dynamic Testing




figure  %1 Heave Test 8
plot(T8h,Y8h,'b')
xlabel('Time (s)')
ylabel('Vertical Displacement (in.)')
title('Average Heave Data - Design 1, Test #8 ')
%legend('Test 8','location','southeast')
axis([0 25 -1 1])
set(gca,'ytick',[-1,-0.5,0,0.5,1])
grid


figure %2 Heave Test 10
plot(T10h,Y10h-1.104,'r')
xlabel('Time (s)')
ylabel('Vertical Displacement (in)')
title('Average Heave Data - Design 1')
%legend('Test 10','location','southeast')
axis([0 20 -2 2])
set(gca,'xtick',[0,5,10,15,20])
set(gca,'ytick',[-2,-1,0,1,2])
grid



figure %3 Pitch Test 1
plot(T1p,Theta1p,'r')
xlabel('Time (s)')
ylabel('Angle of displacement (deg)')
title('Average Pitch Data - Design 1, Test #1 ')
legend('Test 1','location','southeast')
axis([0 25 -95 -87])


figure %4 Pitch Test 3
plot(T3p,Theta3p,'g')
xlabel('Time (s)')
ylabel('Angle of displacement (deg)')
title('Average Pitch Data - Design 1, Test #3 ')
legend('Test 3','location','southeast')
axis([0 8 -95 -87])


figure %5 Pitch Test 4
plot(T4p,Theta4p,'g')
xlabel('Time (s)')
ylabel('Angle of displacement (deg)')
title('Average Pitch Data - Design 1, Test #4 ')
```

```
legend('Test 4','location','southeast')
axis([0 8 -95 -87])


figure %6 Pitch Test 5
plot(T5p,Theta5p,'g')
xlabel('Time (s)')
ylabel('Angle of displacement (deg)')
title('Average Pitch Data - Design 1, Test #5 ')
legend('Test 5','location','southeast')
axis([0 8 -95 -87])


%For Poster Presentation
figure % Heave Test 10
subplot(T10h,Y10h-1.104,'r')
xlabel('Time (s)')
ylabel('Vertical Displacement (in)')
title('Average Heave Data - Design')
axis([0 20 -3 3])
set(gca,'xtick',[0,5,10,15,20])
set(gca,'ytick',[-2,-1,0,1,2])
subplot(T1h_2,Y1h_2+.2,'b')
%xlabel('Time (s)')
%ylabel('Vertical Displacement (in)')
%title('Average Heave Data - Design')
%legend('Design 1','Design 2','location','southeast')
%axis([0 20 -3 3])
%set(gca,'xtick',[0,5,10,15,20])
%set(gca,'ytick',[-2,-1,0,1,2])
grid
```

```
%Design 2
%Static Testing (Pitch and Heave Responses)/ Dynamic Testing


figure %1 Heave Test 1
plot(T1h,Y1h+0.5,'b')
xlabel('Time (sec)')
ylabel('Vertical Displacement (in.)')
title('Average Heave Data - Design 2, Test #1')
%legend('Test 2','location','southeast')
axis([0 20 -3 3])
set(gca,'xtick',[0,5,10,15,20])
set(gca,'ytick',[-3,-2,-1,0,1,2,3])
grid


figure %2 Heave Test 2
plot(T2h,Y2h,'r')
xlabel('Time (s)')
ylabel('Vertical Displacement (in)')
title('Average Heave Data - Design 2, Test #2 ')
%legend('Test 2','location','southeast')
axis([0 20 -2 2])
set(gca,'xtick',[0,5,10,15,20])
set(gca,'ytick',[-2,-1,0,1,2])
grid


figure %3 Pitch Test 1
plot(T1p,Theta1p,'r')
xlabel('Time (s)')
ylabel('Displacement Angle (deg.)')
title('Average Pitch Data - Design 2, Test #1 ')
%legend('Test 2','location','southeast')
%axis([0 20 -2 2])
%set(gca,'xtick',[0,5,10,15,20])
%set(gca,'ytick',[-2,-1,0,1,2])
grid


figure %4 Pitch Test 2
plot(T2p,Theta2p,'b')
xlabel('Time (s)')
ylabel('Displacement Angle (deg.)')
title('Average Pitch Data - Design 2, Test #2 ')
%legend('Test 2','location','southeast')
%axis([0 20 -2 2])
%set(gca,'xtick',[0,5,10,15,20])
%set(gca,'ytick',[-2,-1,0,1,2])
grid


figure %5 Pitch Test 3
plot(T3p,Theta3p,'g')
xlabel('Time (s)')
```

```
ylabel('Displacement Angle (deg.)')
title('Average Pitch Data - Design 2, Test #3 ')
%legend('Test 2','location','southeast')
%axis([0 20 -2 2])
%set(gca,'xtick',[0,5,10,15,20])
%set(gca,'ytick',[-2,-1,0,1,2])
grid


figure %6 Pitch Test 4
plot(T4p,Theta4p,'r')
xlabel('Time (s)')
ylabel('Displacement Angle (deg.)')
title('Average Pitch Data - Design 2, Test #4 ')
%legend('Test 2','location','southeast')
%axis([0 20 -2 2])
%set(gca,'xtick',[0,5,10,15,20])
%set(gca,'ytick',[-2,-1,0,1,2])
grid
```