Improving the Dynamics and Efficiency of the PowerBuoy System 9/20/12

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Summer 2012

Keywords: Fill-in Plates, Coefficient of Drag

ABSTRACT

This paper covers one of two projects completed during my 10 week summer internship at MBARI. Using aluminum plates to fill in existing gaps in the Submerged Plates component of the PowerBuoy System, the water plane surface area and coefficient of drag of the Submerged Plate are both increased, resulting in a decrease in its vertical motion during deployments. Doing so improves efficiency of the PowerBuoy by allowing more of the potential wave energy to be captured by the Power Take Off unit.

INTRODUCTION

Although it might seem that the scope of this paper is limited to the Submerged Plate component of the PowerBuoy System, an understanding of the whole of the PowerBuoy System and its functionality is required to realize the driving motivation behind the increased water plane surface area and coefficient of drag of the Submerged Plate. The PowerBuoy System is composed of three parts; the Buoy, the PTO, and the Submerged Plate, each of which are labeled in Figure 1 below.

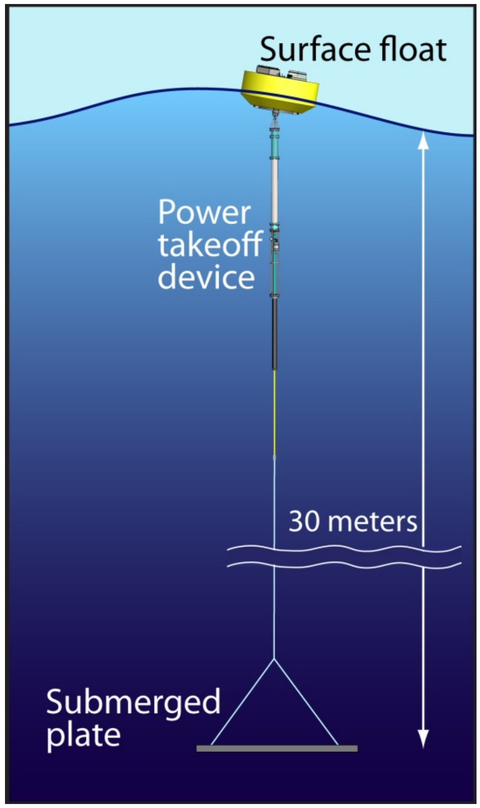


Figure 1: Representation of the deployed PowerBuoy

The Buoy, which floats on the ocean surface, undergoes vertical motion in conjunction of the waves. The Submerged Plate, because of its large surface area and how deep below the ocean surface it is, should have no vertical motion. The Pneumatic Spring absorbs the relative motion between the Buoy and the Submerged Plate, and inside the PTO the spring turns a hydraulic motor which powers an electric generator. So, obviously, the greater the relative motion between the Buoy and the Submerged Plate, the more electricity can be generated. Analysis of deployment data reveals that, in fact, the Submerged Plate does not completely resist vertical motion. Because of this, the maximum amount of potential wave energy is not harnessed, hindering the achievable efficiency of the overall system.

There are two ways to increase the Submerged Plate's resistance to vertical motion, to submerge it deeper underwater, and to increase the drag force that opposes vertical motion. Both options have been considered. In fact, during the July 2012 deployment, the Submerged Plate was 55 meters below the ocean surface, almost twice the depth indicated in Figure 1. The project described in this paper involved tackles the second option, using 12 aluminum plates to fill in existing gaps in the Submerged Plate in order to increase the water plane surface area, A, and the coefficient of drag, C_D, both of which, independently, result in an increase drag force acting on the plate. This modification was then tested in the MBARI test tank and test data analysis revealed that, in fact, both A and C_D were increased. The newly modified plate will be ready for the next deployment.

MATERIALS AND METHODS

Deployment Data Analysis

In order to justify filling in the existing gaps in the Submerged Plate, it is necessary to first confirm that the Submerged Plate is, in fact, undergoing vertical motion. In order to do so, data collected during deployment is analyzed in order to determine the vertical motion of the Submerged Plate. Although there is no instrumentation that directly measures the position of the Submerged Plate, its position can be calculated using the positional data of the Buoy and the piston within the PTO. Mounted on the top of the Buoy is a Crossbow 400 IMU which records, amongst other data, the vertical velocity of the Buoy at a 10 Hz rate. Inside the PTO a string potentiometer is used to record the linear motion of the hydraulic piston, also at a 10 Hz rate. Using MATLAB, the Buoy vertical velocity data can be integrated with respect to time to give Buoy vertical position as a function of time. The difference between the Buoy vertical motion and the PTO piston linear motion gives the Submerged Plate vertical motion, under two assumptions; that the PTO hangs vertically, and that any elongation of the tether connecting the PTO and submerged Plate is negligible. The MATLAB code used to do these calculations can be found in the Appendix of this report. The resultant data is plotted in Figures 2 and 3 below.

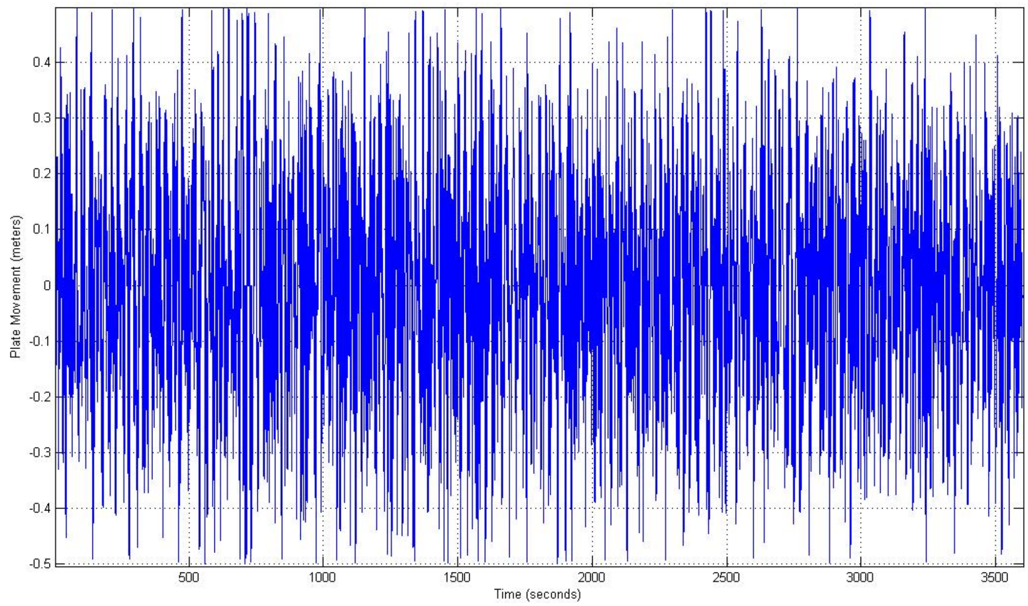


Figure 2: Submerged Plate Movement during July 2012 Deployment

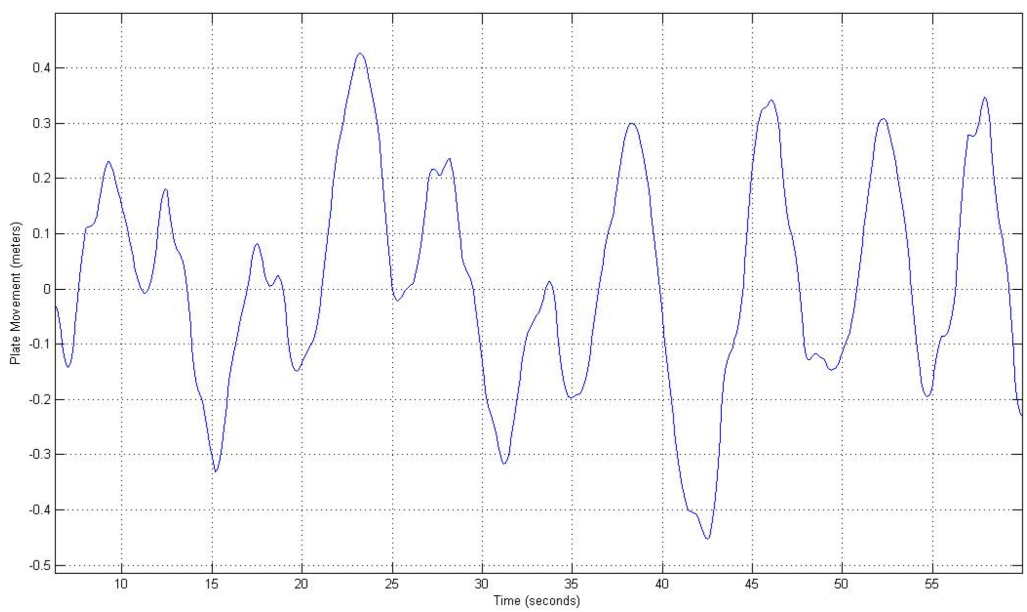


Figure 3: Submerged Plate Movement during July 2012 Deployment

Figures 2 and 3 represent data from a particularly rough sea state day. Notice that Figure 2 covers only one hour of data but because of the 10 Hz data collection rate, 36000 data points are seen on this plot, making it quite cluttered. Therefore, Figure 3, which contains the data from the first minute from the same hour used in Figure 2, is included to more clearly show the waveform. Notice that in Figure 2 there is a peak-to-peak amplitude of a full meter. This clearly shows that the Submerged Plate is not resisting vertical motion and is thus hampering maximum achievable efficiency of the PowerBuoy. Thus fill-in plates are not only justified but necessitated.

Fill-in Plate Considerations and Feasibility Testing

There were many considerations to take into account when designing the fill in plates. Namely the dimensions, material, attachment method, and attachment position of the fill in plates were considered. Design criteria include a stress and displacement 4:1 safety factor for a 10,000 lb load uniformly distributed across the entire Submerged Plate water plane surface area. As long as this safety factor is achieved, the fill in plates should be as light as possible. Weight is a factor of dimensions and material. The attachment method, using through bolts instead of welding, was chosen to facilitate easy of removal and modification if necessary. The length and width of the fill-in plates is determined by the size of the gaps they are filling. The length exactly matches the length of the length of the gap, and the width allows for a 1.25 inch overlap on both sides. The resulting length and width of the plates are 51.5 inches and 13.25 inches respectively. That means the surface area of one plate is 682.375 in^2, which is 3.07% of the total water plane surface area (Submerged Plate and 12 fill-in plates) which is 22232 in^2. Thus the load applied to a single fill-in plate is 307 lbs, 3.07% of 10000 lbs. The Thickness of the fill-in plates was minimized to reduce weight. The attachment position, on top v. under the rectangular tubes of the Submerged Plate has an effect on the distribution of stress on the bolts across the fill-in plate and Submerged Plate rectangular tube overlap.

Using SolidWorks Simulation, different configuration of thickness, material (ASTM A36 steel v. 6061 T6 Aluminum), and attachment position were tested to ensure they met the stress and deflection safety factor. Table 1 below shows all configurations tested and the resulting data.

Material, Thickness, Position	Yield Strength (psi)	Max Von Mises Stress (psi)	Max Displacement (in)	Weight (lbs)	Total Weight (lbs)
Al, 1/8, under	39885.4	31460.7	0.2305	8	96
Al, 3/16, under	39885.4	14170.3	0.06921	12	144
Al, ¼, under	39885.4	8409.1	0.0296	16	192
Al, 1/8, over	39885.4	1185.3	0.007422	8	96
Al, 3/16, over	39885.4	551.2	0.002319	12	144
Al, ¼, over	39885.4	311.1	0.001015	16	192
Steel, 1/8, under	36259.4	34888.8	0.08229	23.267	279.204
Steel, 3/16, under	36259.4	15625.4	0.02468	34.9	418.8
Steel, ¼, under	36259.4	9195.7	0.01054	46.534	558.408
Steel, 1/8, over	36259.4	1195.9	0.002582	23.267	279.204
Steel, 3/16, over	36259.4	545.5	0.0008054	34.9	418.8
Steel, ¼, over	36259.4	312.1	0.0003525	46.534	558.408

Table 1: All fill-in plate configurations considered and the resulting data from a SolidWorks Simulation of a 307 lb load uniformly distributed over a 51.5 in x 13.25 in rectangular plate.

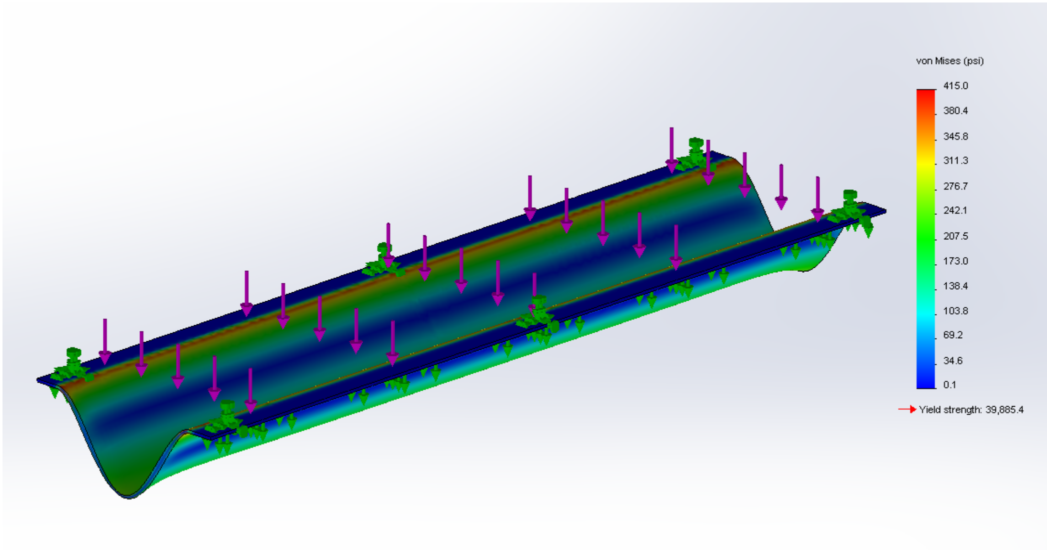


Figure 4: Screen Capture of the SolidWorks Simulation of a 307 lb load uniformly distributed over a 51.5 in x 13.25 in x 0.1875 in 6061 T6 Aluminum rectangular plate with fixed geometries at the 6 hole locations and roller/slider fixture 1.25 inches along each long edge.

Figure 4 gives an example of the stress distribution across one of the configurations tested. As Table 1 shows, the lightest configuration while still maintaining at least a 4:1 safety factor is 3/16 inch thick 6061 T6 Aluminum Plate positioned on top of the Submerged Plate rectangular tubes. This configuration would be appropriate for all twelve fill-in plates. Next, SolidWorks Simulation was used to test how these fill-in plates would affect the Submerged Plate when attached. The same 10000 lb load was uniformly distributed to the entirety of the water plane surface area of the Submerged Plate with and without the fill in plates attached. The resulting displacements for each case were compared. Figures 5 and 6 below show the results. See appendix for engineering drawings of the fill-in plate and the Submerged Plate and fill-in plate assembly.

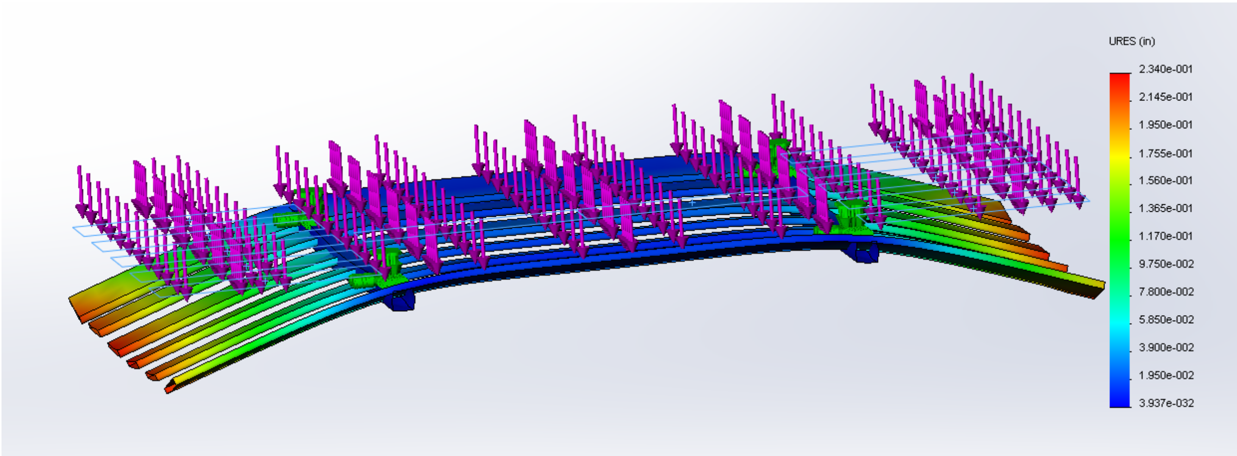


Figure 5: Displacement of Submerged Plate without Fill-In Plates under a 10000 lb Uniformly Distributed Load

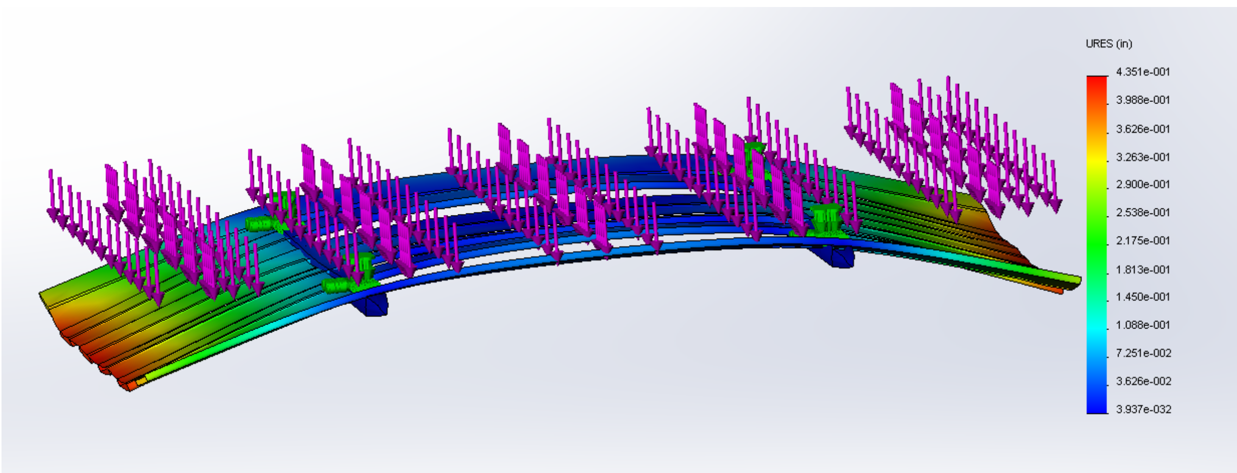


Figure 6: Displacement of Submerged Plate with the 12 Fill-In Plates under a 10000 lb Uniformly Distributed Load

As seen in Figures 5 and 6, the maximum displacement of the Submerged Plate with the fill-in plates attached is almost double that of the Submerged Plate without the fill-in plates. However, a maximum displacement of 0.4351 inches is acceptable. This concludes the fill-in plate feasibility tests. Next the plates were fabricated and added to the Submerged Plate.

Fill-in Plate Fabrication

The materials for the fill-in plates were ordered from Lusk Metals & Plastics. Each plate was cut to size, and the through holes for the bolts were drilled in house. 17/64 inch diameter holes were drilled to allow for an appropriate clearance hole for ¼ inch bolts. Because there are 6 bolts for each plate, each bolt experience a load of 307/6 lbs = 51.16 lbs. Bolts with a tensile strength of 70000 lbs/in^2 were ordered from McMaster-Carr. ¼ inch diameter bolts have an area of .049 in^2, resulting in a tensile strength of 3403 lbs. This well exceeds the load it experiences, so ¼ inch bolts are appropriate for this application. Hole positions were then transferred to the Submerged Plate and, using an electromagnetic portable drill press, holes were drilled through the rectangular tubes of the Submerged Plate.

RESULTS

Testing in the MBARI test tank

Once the fill-in plates had been attached to the Submerged Plate, it became necessary to test the new Submerged Plate configuration to measure and determine the new coefficient of drag, C_D. The experimental set up consisted of a hydraulic ram suspended vertically from the crane above the test tank. Between the crane and the ram a load cell was used to record force over time. A string potentiometer was used to record the vertical motion of the hydraulic piston, which was capable of a 72 inch stroke. The Submerged Plate was suspended from the end of the hydraulic piston, and was pushed a pulled through the water while a Dataq DI-710 Data Logger was used to record force and position data at a 10Hz rate. Three tests were conducted on each of the two Submerged Plate configurations, with and without the fill-in plates. The 3 tests were an 18 inch amplitude sinusoidal motion at varying periods, a 36 inch amplitude sinusoidal motion, using the full stroke of the piston, at varying periods, and a range of constant speed linear motion tests. Plots of all the data collected can be found in the Appendix. With force and position data from the sinusoidal motion tests, it was possible to calculate the coefficient of drag, C_D, and added mass, μ, resulting from the inertia added to a system as it accelerates through the volume of surrounding water as it moves through it. Figure 7 below shows a free body diagram of the Submerged Plate during testing.

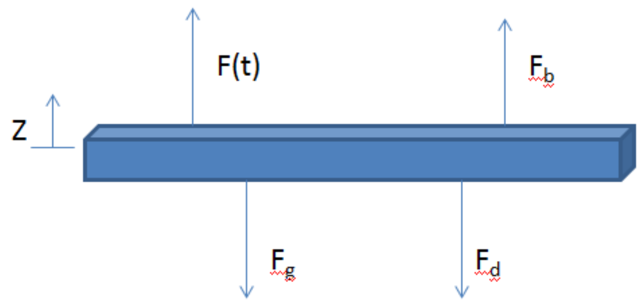


Figure 7: Free body diagram of the Submerged Plate during testing

F(t) and Z(t), vertical position, are recorded values. Z(t) can be differentiated with respect to time to give velocity and acceleration, $\dot{Z}(t)$ and $\ddot{Z}(t)$ respectively. The other forces, buoyancy force, gravitational force, and drag force, are known. $F_b = \rho \cdot V \cdot g$, $F_g = m \cdot g$, and $F_d = \frac{1}{2} \cdot A \cdot C_D \cdot \rho \cdot \dot{Z}^2$. V = submerged volume of the plate, ρ = density of water, m = mass of the plate, g is the gravitational constant, and A = surface area of the plate orthogonal to the direction of motion. Using Newton's law of motion, $\Sigma F = M \cdot \ddot{Z}$, a single equation of motion were all but two variables are not known or measured is found. Notice that $M = m + \mu$ accounts for the added mass. Rearranging and combining like terms, the equation of motion becomes $\mu \cdot \ddot{Z}(t) + \frac{1}{2} \cdot A \cdot C_D \cdot \rho \cdot \dot{Z}(t)^2 = F(t) + \rho \cdot V \cdot g - m(\ddot{Z}(t)+g)$. Because there are two unknowns are thousands of data points, the method of least squares is used to solve for the overdefined unknowns C_D and μ. The matrix representation of the least squares solution is show below.

$$\begin{bmatrix} \ddot{Z}(t_1) & \frac{1}{2}A\rho(\dot{Z}(t_1))^2 \\ \ddot{Z}(t_2) & \frac{1}{2}A\rho(\dot{Z}(t_2))^2 \\ \vdots & \vdots \\ \ddot{Z}(t_n) & \frac{1}{2}A\rho(\dot{Z}(t_n))^2 \end{bmatrix} \begin{bmatrix} \mu \\ C_D \end{bmatrix} = \begin{bmatrix} f(t_1) + \rho V g - m(\ddot{Z}(t_1)+g) \\ f(t_2) + \rho V g - m(\ddot{Z}(t_2)+g) \\ \vdots \\ f(t_n) + \rho V g - m(\ddot{Z}(t_n)+g) \end{bmatrix}$$

MATLAB was used to solve for this matrix equation. See Appendix for the MATLAB script used. The results of each of the three tests were compared for the two cases of the Submerged Plate with or without the fill-in plates. Figures 8 and 9 show the results of the half amplitude test without and with the plates respectively. Figures 10 and 11 show the results of the full amplitude tests without and with the plates respectively. Figures 12 and 13 show the results of the constant speed tests without and with the plates respectively. For the constant speed test, $\ddot{Z}(t)=0$ and thus $\mu=0$. Therefore the equation of motion becomes $F(t) + \rho \cdot V \cdot g - m \cdot g = \frac{1}{2} \cdot A \cdot C_D \cdot \rho \cdot \dot{Z}(t)^2$. The only unknown to be solved is C_D. Because of the range of constants speed tested, this test was useful in calculating C_D as a function of speed.

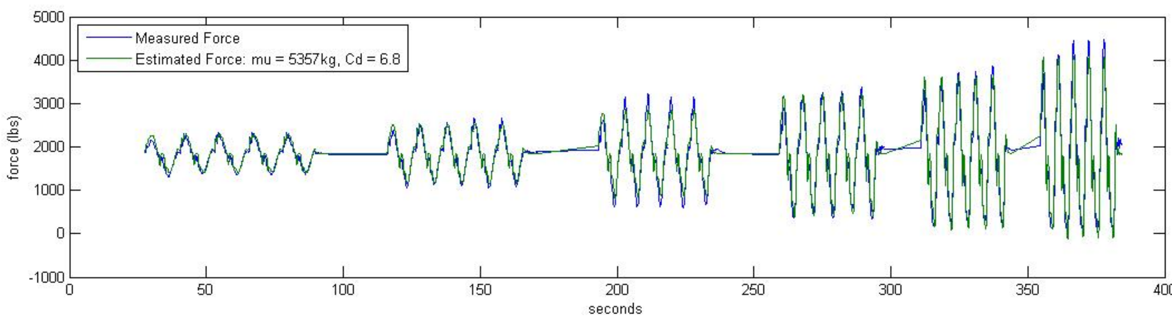


Figure 8: Results of the half amplitude test without the plates

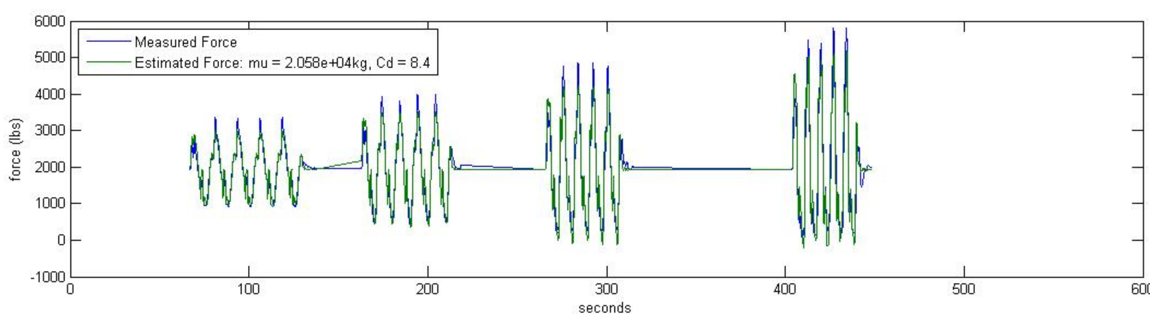


Figure 9: Results of the half amplitude test with the plates

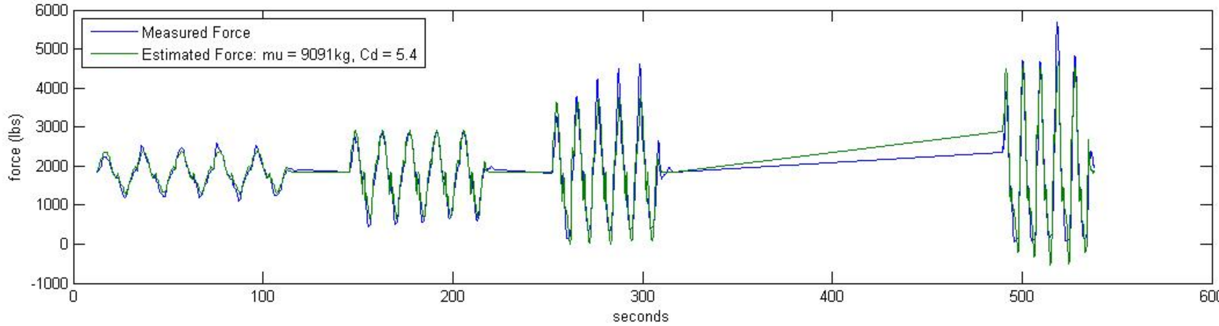


Figure 10: Results of the full amplitude test without the plates

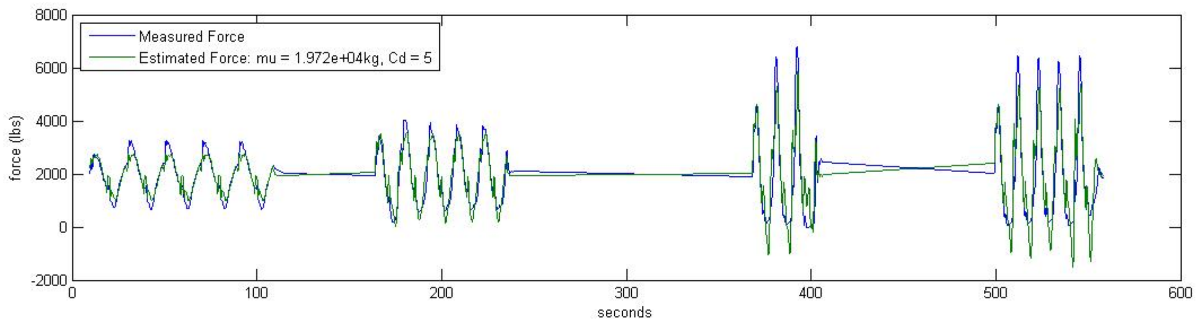


Figure 11: Results of the full amplitude test with the plates

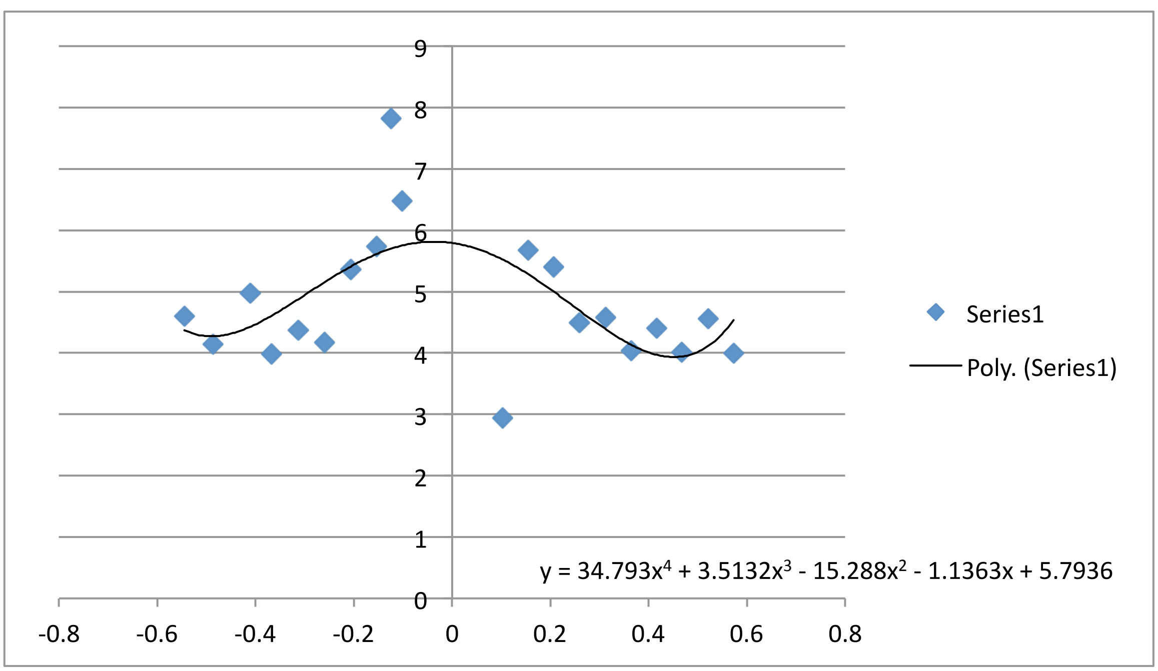


Figure 12: C_D as a function of speed withouth the plates

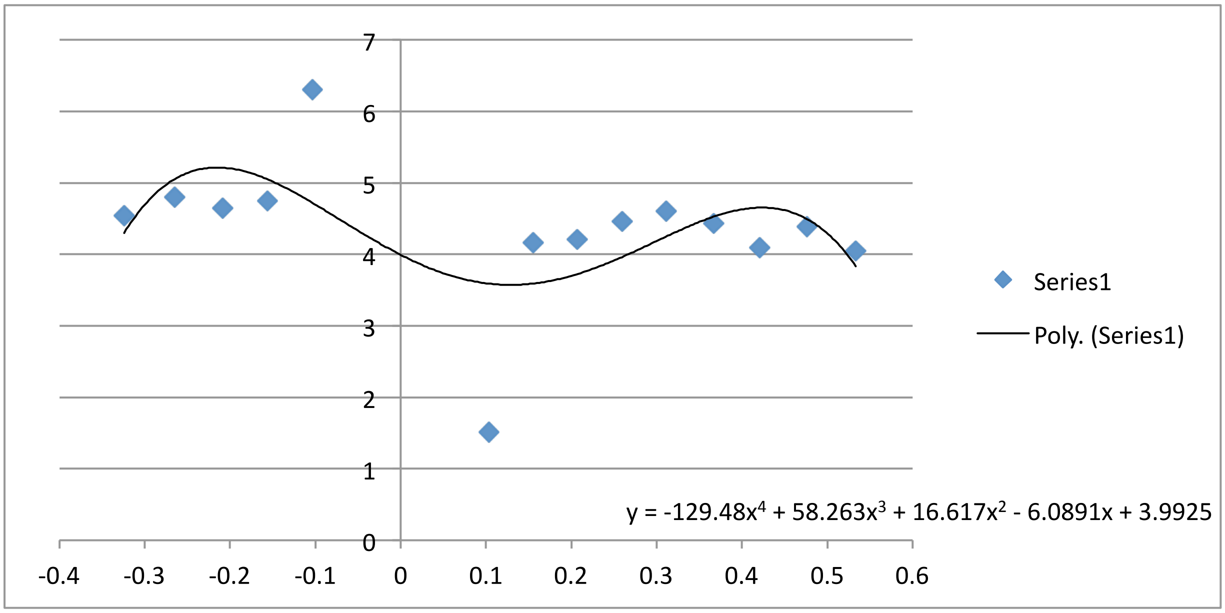


Figure 13: C_D as a function of time with the plates

DISCUSSION

As seen in the figures above, there are some inconsistencies between the results of the half and full amplitude test. For the half amplitude case, the addition of the fill in plates resulted in an increase in C_D and μ, as anticipated. For the full amplitude case, however, μ increased but C_D decreased slightly. This result was not expected and draws some concerns. While it was initially assumed that a full amplitude test was a closer representation of a real deployment scenario, analysing the deployment data from the June 2012 deployment shows that the submerged plate experiences sinusoilal motion with amplitudes closer to the half amplitude than the full, especially on days of less intense wave states. Still, changing the magnitude of the amplitude of the sinusoidal oscillation should not reverse the effect of the coifficent of drag, even if it is not representation of a real life case.

One explationation for this odd test result could be the size of the test tank relative to the amplitude. For the half amlitude case, the test tank is large enough that boundary conditions of the test tanks walls interfering with the water motion can be ignored. For the full amplitude case, however, the midpoint of the range of motion remained the same, so at full stroke the submerged plate was 18 inches closer to the test tank floor than in the half amlitude test. It is possible that the distance between the test tank floor and the submerged palte when the ram is full extended, about a meter, in not negligable and that boundary conditoins must be condsidered when forming the equations of motion for the plate. Not accouting for the boundary conditions could explain the inconsistencise between the test result.

For the analysis of C_D as a funciton of time, it is quite evident that there are outlying data points in both the half and full amplitude cases, interfering with the fitted curve shown. Still it can be seen that as the magnitude of the speed increases, C_D steadies out to a constant value, between 4 and 5 in both cases. This results is more evident in the test including the fill-in plates. The of C_D vaule is more consistent with the full amplitude sinusoidal test results, as the half amplitude sinsoidal test produced values of C_D ranging for 6.8 to 8.4, depending on the inclusion of the fill in plates.

CONCLUSIONS/RECOMMENDATIONS

Comparing the results of the half and full amplitude tests, it is evident that there is interference from the size of the test tank relative to the Submerged Plate in the test data. Still, we know that the Submerged Plate should resist vertical motion with a larger water plane surface area, and this will be confirmed when data from the next deployment in November of 2012 is compared to deployment data from July 2012.

ACKNOWLEDGEMENTS

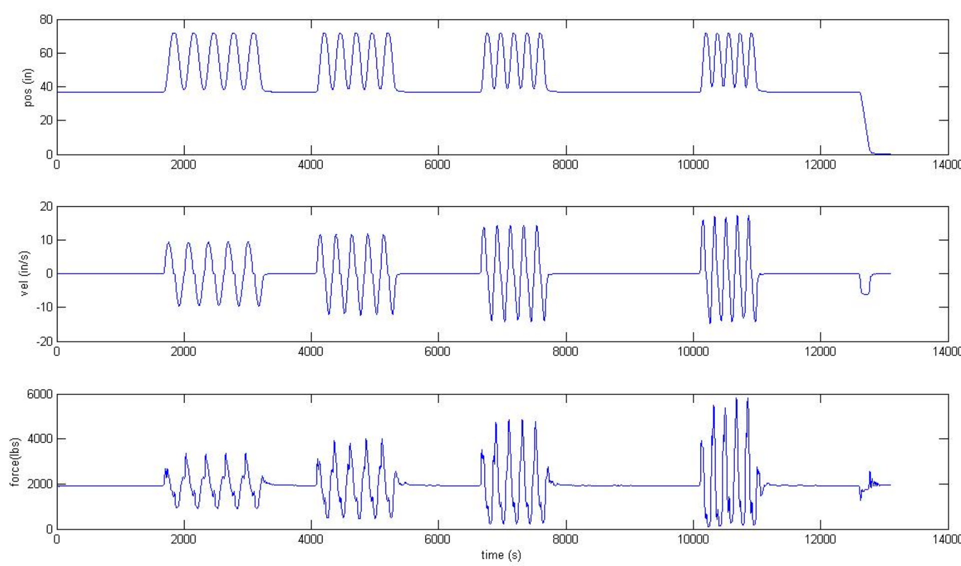
I would like to thank my mentors Andrew Hamilton and Francois Cazenave for all of their support and guidance through my internship. I learned much and more about marine science and the business decisions specific to engineering under their tutelage.

Thank you George Matsumoto and Linda Kuntz for organizing and facilitating the summer internship program. Without you, this experience would not have been possible.

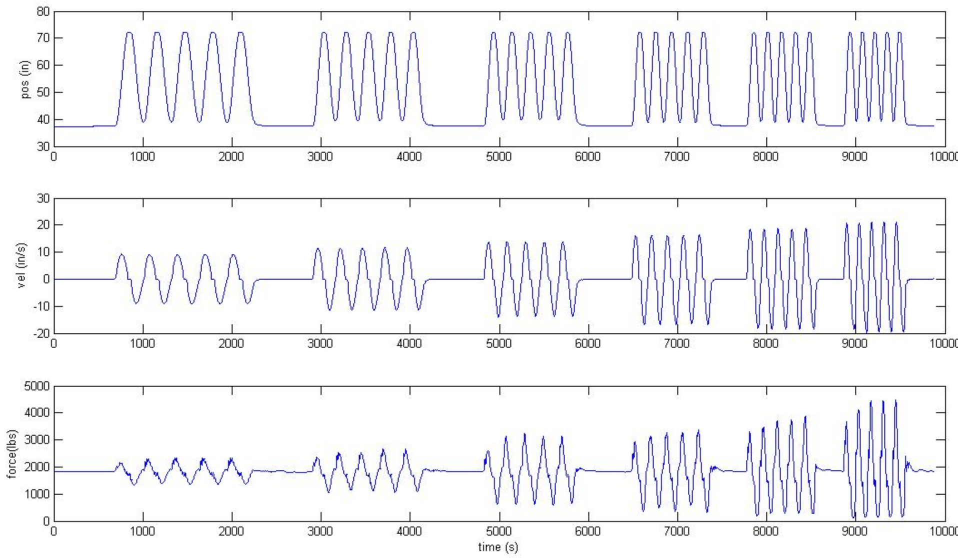
Finally, I would like to thank the following individuals: John Ferreira, Frank Flores, Larry Bird, Jim Scholfield, Jacob Ellena, Paolo Olmos, and Rob McEwen, for their guidance and contributions to different aspects of my project ranging from fabrication to FEA feasibility testing to data analysis using MATLAB.

APPENDIX

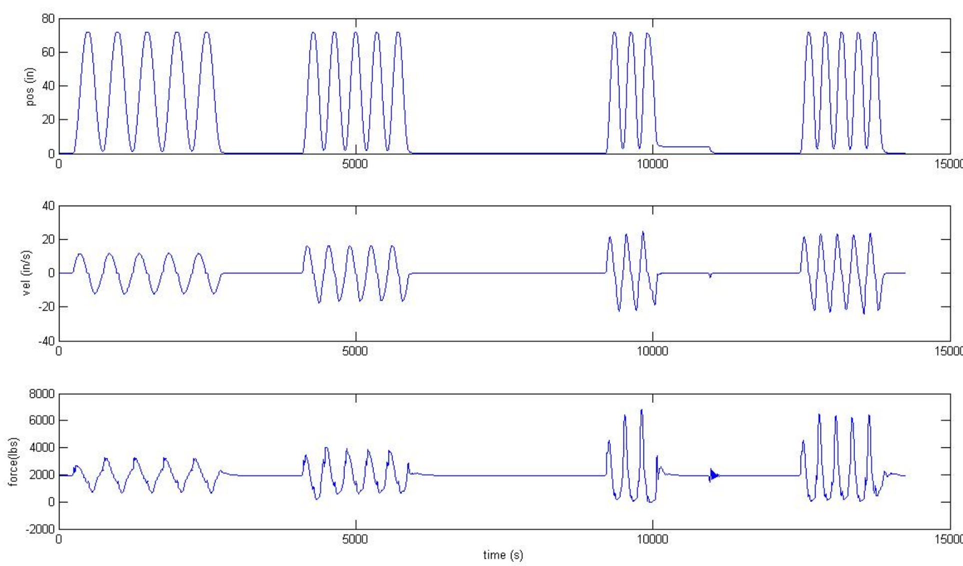
Test Data Plots



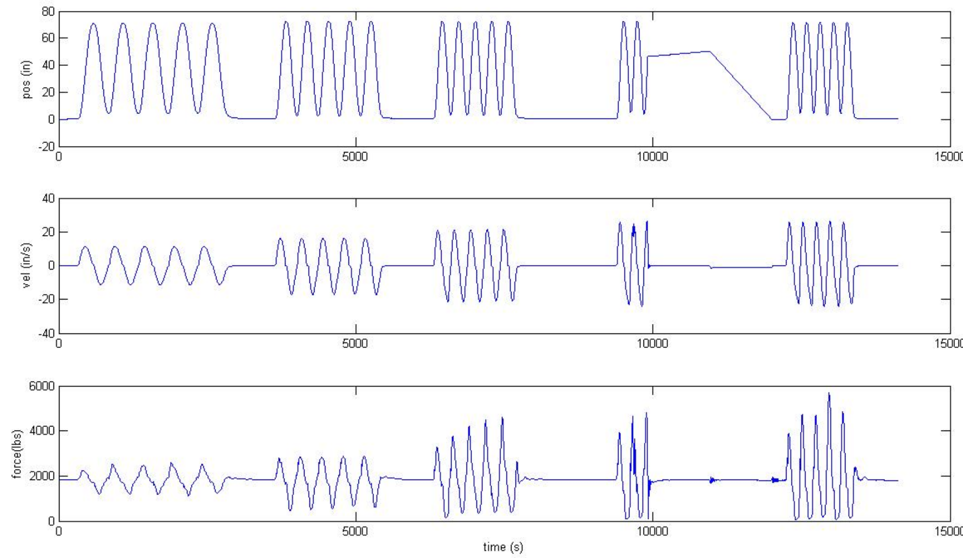
18-Inch Amplitude Test with Plates



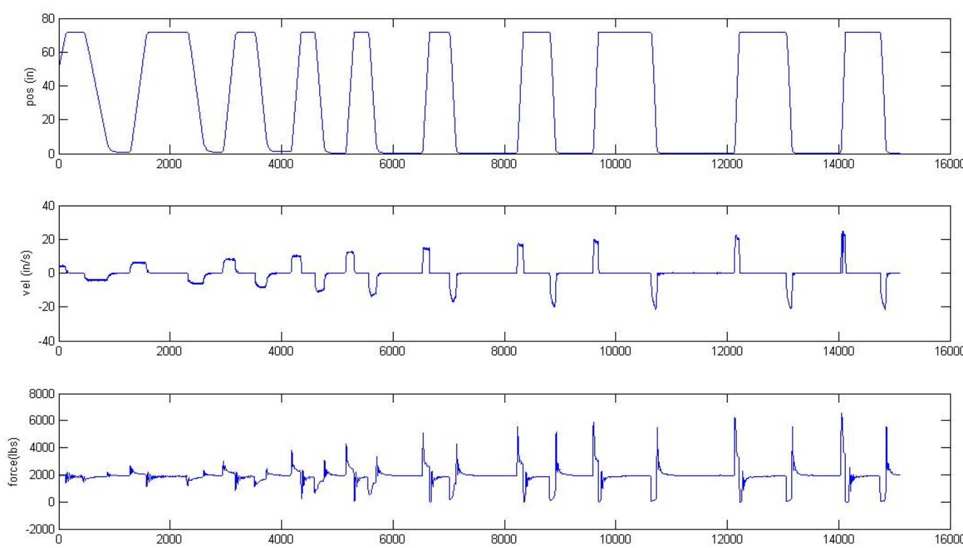
18-inch amplitude without plates



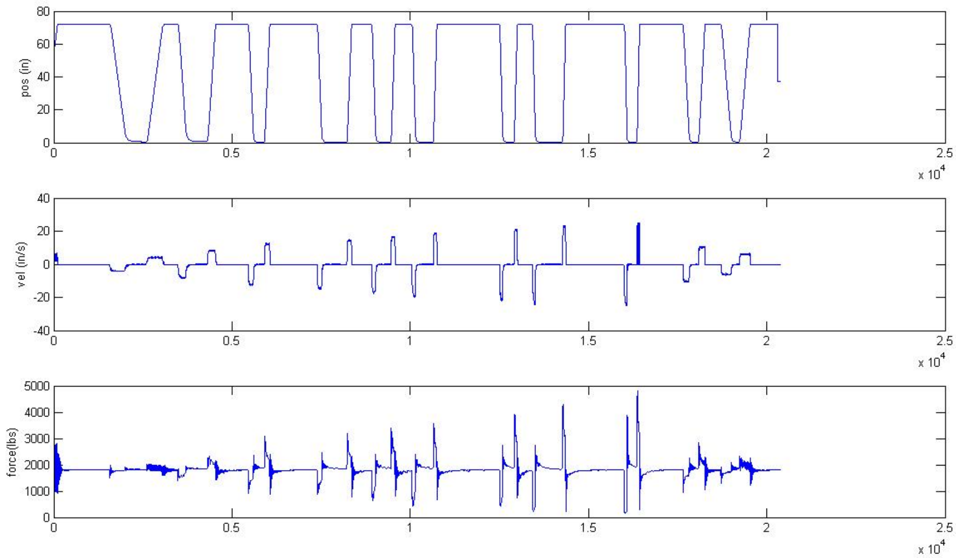
36-inch amplitude with plates



36-Inch Amplitude Test without Plates



Constant Speed Test with Plates



Constant Speed Test without Plates

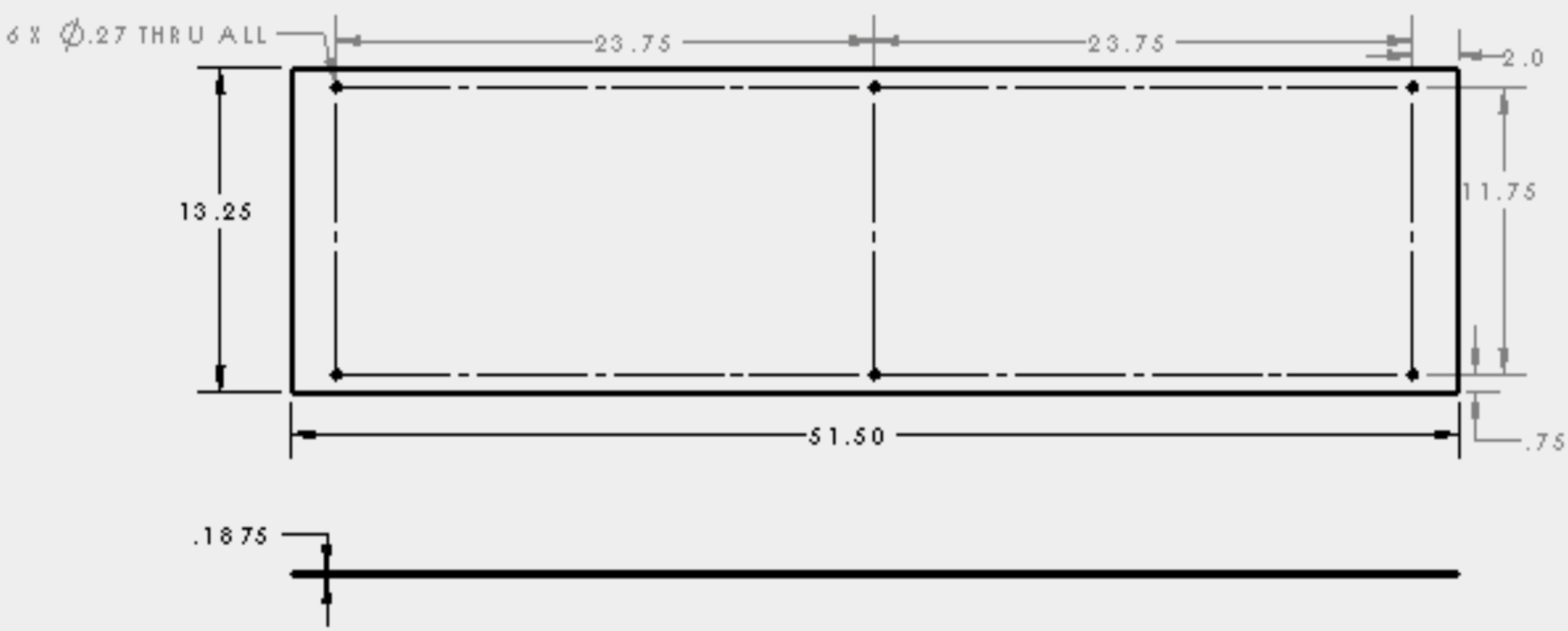
Deployment Data MATLAB Code

```
load('D000011_120626_211507.mat')

PistonVel = diff(PistonDistance)./diff(time);
PistonVel = [PistonVel 0];
BuoyVel = downVelocity*39.4;
PlateVel = BuoyVel + PistonVel;
%plot(time-time(1),PlateVel)
%hist(PlateVel)
PlateVel = PlateVel-mean(PlateVel);
detrend(PlateVel)
PlatePos = cumtrapz(time-time(1),PlateVel);
%plot(time-time(1),PlatePos)
[bb,aa]=butter(5,1/35/5,'high');
platePosFilt = filtfilt(bb,aa,PlatePos);
PlatePosition=0.0254*platePosFilt;
for i=1:length(PlatePosition)
    if PlatePosition(i)>=.5
        PlatePosition(i)=0;
    end
    if PlatePosition(i)<=-.5
        PlatePosition(i)=0;
    end
end
figure;plot(time-time(1),PlatePosition);grid on
xlabel('Time (seconds)')
ylabel('Plate Movement (meters)')
```

Test data MATLAB code

```
close all
clear all


data = load('wPlates-A36-sin.csv');
%%"Inch","lbf","PSI","PSI","Volt","degC","degC","cm"
dt = .04;

t = data(:,1);
pos = data(:,2);
force = data(:,3);


clear data;

vel = [0; diff(pos)/dt];
idx = find(vel > 30); %Remove outliers due to starting and stopping
logging.
vel(idx) = 0;
%Filter numerical derivatives to smooth.
b = ones(1,8)/8;
a = [1];
vel = filtfilt(b,a,vel);

accel = [0; diff(vel)/dt];
idx = find(accel > 30); %Remove outliers due to starting and stopping
logging.
accel(idx) = 0;
accel = filtfilt(b,a,accel);


force = filtfilt(b,a,force);
force = force-180;  %Correct for weight of ram.




fh = figure('Position',[6 38 1267 690]);
ah1 = subplot(3,1,1)
plot(pos)
ylabel('pos (in)');
ah2 = subplot(3,1,2)
plot(vel);
ylabel('vel (in/s)');
ah3 = subplot(3,1,3)
plot(force)
ylabel('force(lbs)');
xlabel('time (s)');
linkaxes([ah1 ah2 ah3],'x');

start = [243 4100 9204 12480];
stop  = [2867 6005 10160 13960];
```

```
idx = [];
for i = 1:length(start)
    idx = [idx start(i):stop(i)];
end


pos = pos*.0254;  %Convert to meters.
vel = vel*.0254;
accel = accel*.0254;

m = 2250/2.2;  %Mass in kg
g = 9.81;

Area = 14.34;  %plate area in m^2
rho = 1025;  %water density
V = .142; %volume of plate in m^3

F = force(idx)*4.45;  %newtons
A = [accel(idx) .5*rho*Area*vel(idx).*abs(vel(idx))];
B = F + rho*V*g - m*(accel(idx)+g);

x = A\B;
mu = x(1);
Cd = x(2);


Force = (m+mu)*accel(idx) + Cd*.5*rho*Area*vel(idx).*abs(vel(idx)) +
m*g - rho*V*g;
fh = figure('Position',[6 38 1267 690]);

subplot(2,1,1)
[ah1,h11,h12] = plotyy(t,pos/.0254,t,vel/.0254);
%set(ah1(1),'YLim',[-1 1]);
%set(ah1(1),'YTick',-1:2/8:1);
set(ah1(2),'YLim',[-25 25]);
set(ah1(2),'YTick',-25:50/10:25);
set(get(ah1(1),'Ylabel'),'String','Position (in)');
set(get(ah1(2),'Ylabel'),'String','Vel (in/s)');

ah2 = subplot(2,1,2)
plot(t(idx),force(idx),t(idx),Force/4.45);
xlabel('seconds');
ylabel('force (lbs)');
legend('Measured Force',['Estimated Force: mu = ' num2str(mu,4) 'kg, Cd
= ' num2str(Cd,2)],'Location','NorthWest');

      linkaxes([ah1(1) ah1(2) ah2],'x');
```



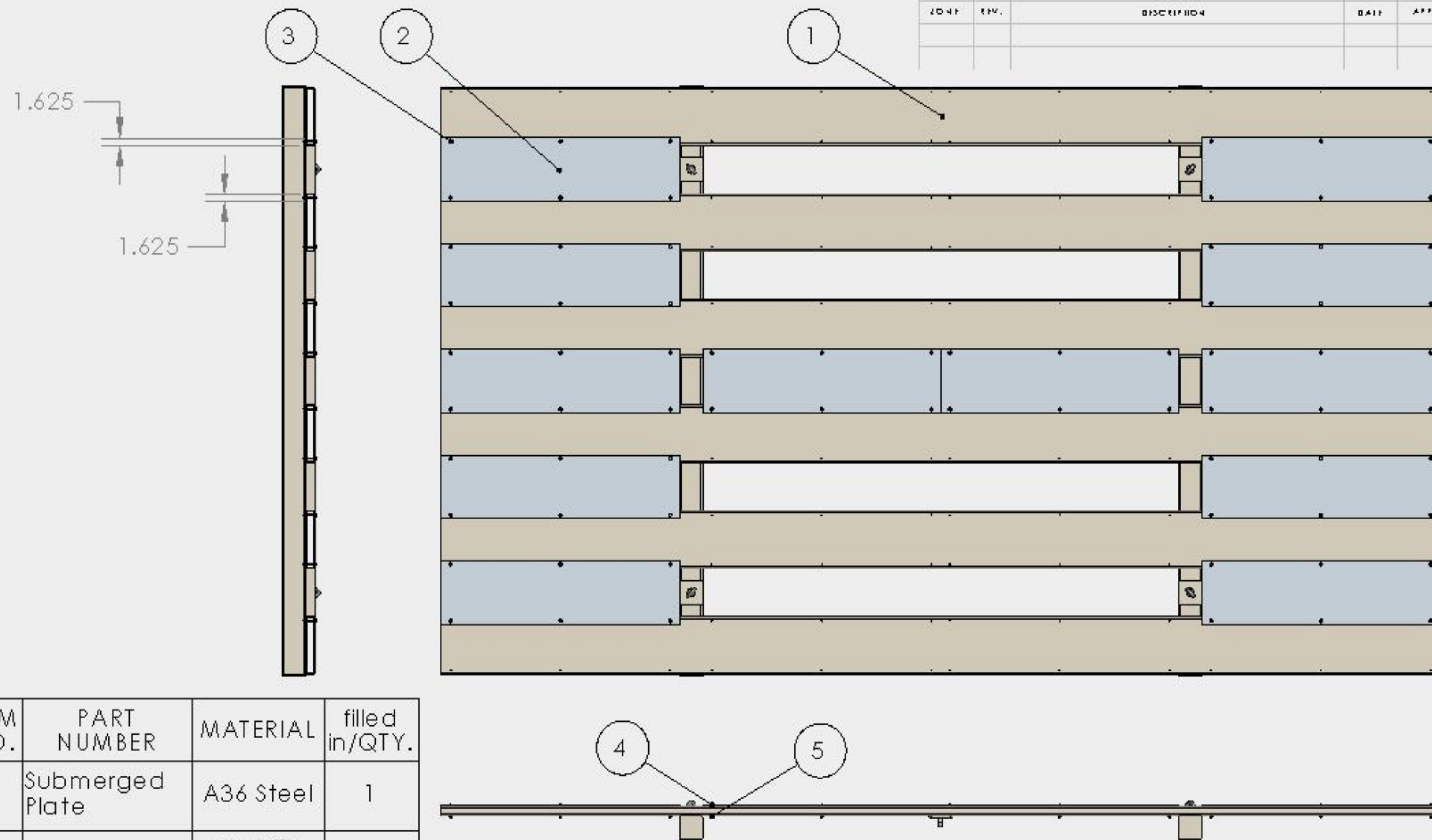
Monterey Bay Aquarium Research Institute

MBARI
7700 Sandholdt RD.
Moss Landing, Ca. 95039
PH: (831) 775-1700

Name: Fill in Plate

A FC-11-

Status:



ITEM NO.	PART NUMBER	MATERIAL	filled in/QTY.
1	Submerged Plate	A36 Steel	1
2	Fill in plate	6061-T6 Aluminum	12
3	RHBOLT 0.25-20x2.75x.75-N	18-8 S.S.	72
4	Regular FW 0.25	18-8 S.S.	144
5	HNUT 0.25-20-D-N	18-8 S.S.	72

Status:

REVISIONS				
ZONE	REV.	DESCRIPTION	DATE	APPROVED

UNLESS OTHERWISE SPECIFIED TOLERANCES ARE:

1 PLACE DEC	2 PLACE DEC	3 PLACE DEC	ANGLE
±0.1	±.02	±.005	±.5°

1. DIMENSIONS ARE IN INCHES
2. DIMENSION LIMITS APPLY AFTER PLATING.
3. REMOVE BURRS AND SHARP EDGES .015 MAX.
4. MACHINED FILLET RADII .0150-.050.
5. MACHINED DIAMETERS ON A COMMON CENTERLINE CONCENTRIC WITHIN .005
6. PERPENDICULARITY & PARALLELISM OF MACHINED SURFACES .002 PER INCH. MAX .012 INCHES FOR SINGLE SURFACE.

Material: See BOM

APPROVALS		DATE
DRAWN	7/20/2012	
CHECKED		
ENGINEER	Peter Carr-Barbery	

PROJECT NO. 207976

PROJECT
Power Buoy

WEIGHT lbs

Monterey Bay Aquarium Research Institute

MBARI
7700 Sandholdt RD.
Moss Landing, CA 95039
PH: (831) 775-1700

Name: Submerged Plate filled in

SIZE A | DWG. NO. FC-11- | REV.

SCALE: 1:32 | WEIGHT: 2136 | SHEET 1 OF 1