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DESIGN AND INSTALLATION OF A TENSION MOORED WIND TURBINE

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ABSTRACT

This paper describes the design of the floater and the mooring system for a small wind turbine. The engineering basis and the hydrodynamics calculations are described, as well as the installation and commissioning sequences.

KEYWORDS

Wind turbine, tension moored floating structure.

Figure 1. Land restrictions at buildings near the sea afford an opportunity for mooring a small wind turbine just a short distance offshore and supplying power back to the building via marine cable.

INTRODUCTION

There are opportunities for mooring a small wind turbine just a short distance at sea and supplying power back to the building via a marine cable.

This paper concerns whether it is possible to have a floating mooring designed so that above the water it appears like and acts like is it a single pole permanent pile. If a permanent piling can be avoided in favor of a floating design, the wind turbine could be towed to a boat slip of protective shelter for servicing, or when there are severe seas, following the same rules of safe practice in protecting small boats and yachts. This paper concerns the deign basis for a one kilowatt floater. We did not consider barges or spar buoys. Each may have cost advantages. They would not, however, appear or act as a single permanent piling.

Figure 2 is a rendering for the one-kilowatt tension moored wind turbine (TMWT). The wind turbine shown has a rotor diameter of two meters. For stability reasons the buoyancy part of the structure is moored to the sea bed using tensioned mooring lines. It is also kept low under the free surface to minimize the wave exciting forces.

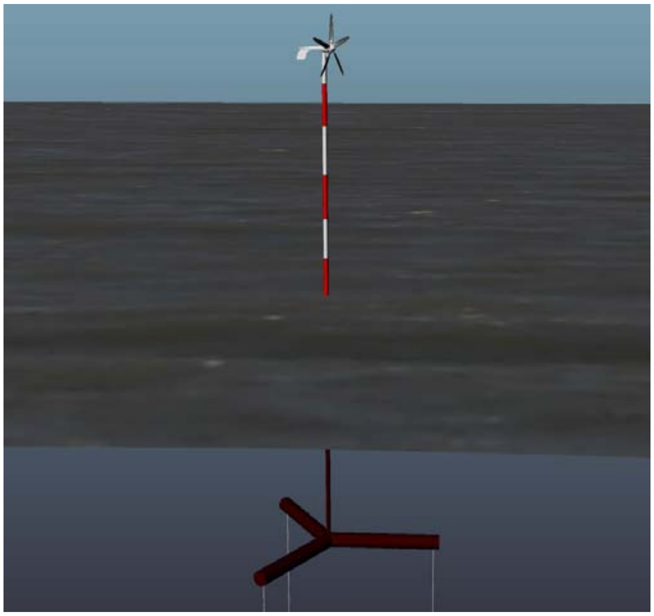

Figure 2. Tension Moored Wind Turbine (TMWT)

DESIGN BASIS

This prototype aims at proving the feasibility of placing a floating wind turbine in a semi-protected offshore environment. In the initial design phase a series of criteria were determined to be crucial to the safe operation of the system. The prototype was designed and sized to meet the following requirements:

1. The wind turbine blades should not touch the water.
2. The horizontal cylinder forming the hull should not come out of the water
3. The minimum tension in the tendons should be positive at all time to avoid slack events leading to snap loads.
4. When not tethered, the system should float with positive stability.
5. Available metocean data and sea bottom conditions for offshore Santa Catalina Island, CA were used.

Waves

The metocean conditions contributing to the design of the prototype at the site were wind, waves and tides. The NOAA national Data Buoy Center station 46025 offshore southern California near Santa Catalina Island provided 25 years of wave and wind data.

The wave data is summarized in Figure 3 (a and b) which shows, for each data-year a monthly breakdown of the highest significant wave height observed. The data is then combined in Figure 4 which shows both the highest and maximum 8-min average wave height and wind speed, again at the buoy site.

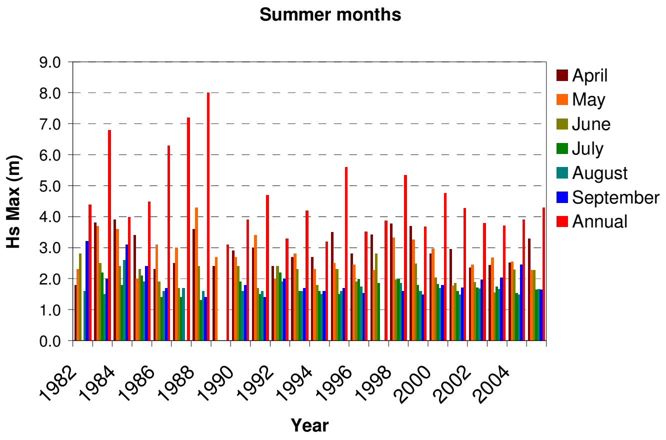

Figure 3a. Wave height monthly summary for the data available from Station 46025 – Summer.

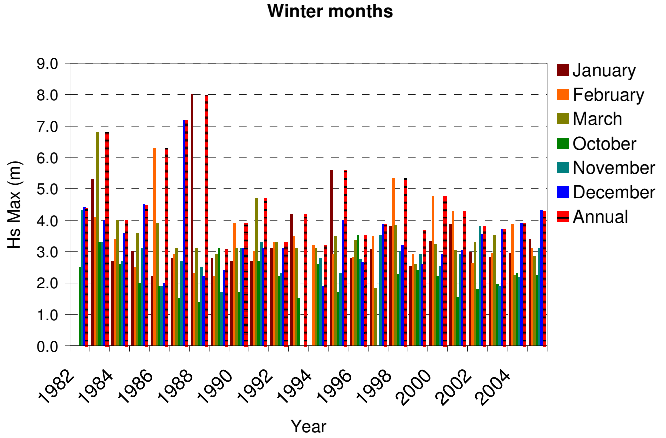

Figure 3b. Wave height monthly summary for the data available from Station 46025 – Winter.

Previous experience has shown that wind and wave observation at the site were very correlated with what station 46025 was recording.

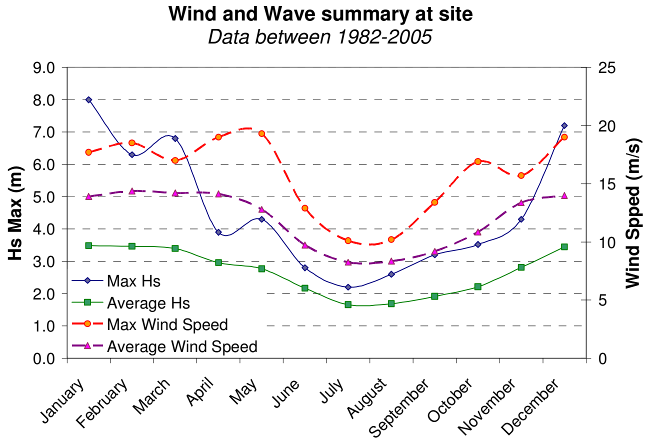

Figure 4. Wave height (solid) and Wind speed (dashed) monthly expected maximum and maximum 8 min average.

Tides

The online tide tables for Santa Catalina Island showed a maximum range for 2007 of 2.75 m (+2.2, - .55) [9 ft, + 7.2, -1.8]. Combining both the tides and the expected maximum wave height were used to determine the mast height and the hull draft.

Wind and turbine Performance.

The one-kilowatt 5-bladed turbine shown in Figure 5 will be placed on the prototype. The turbine diameter is 1.8 m (6ft) and weighs 45.4 kg (100 lbs).

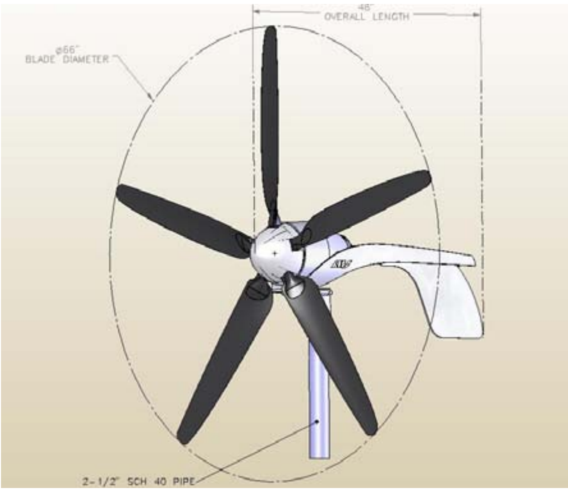

Figure 5. AeroVironment 1 KW wind turbine.

The horizontal force it applies on the mast is of the form:

$$F_T = \frac{1}{2}\rho_{air} C_d A V^2 \qquad (1)$$

Where Cd is a function of the wind speed V and is shown in Figure 6. A is the turbine swept area.

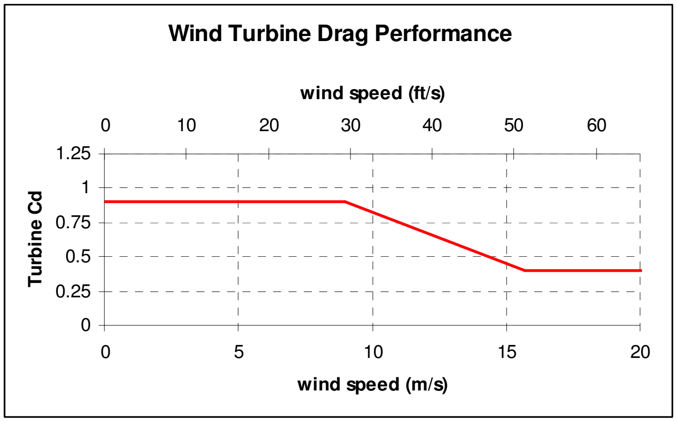

Figure 6. Turbine drag coefficient

From the previous wind and wave conditions the cases summarized in Table 1 form the design metocean conditions for the prototype.

Table 1: Prototype design metocean conditions

Case		Hs	Tp	Wind	Heading
	ref	*ft*	*sec*	*ft/sec*	*deg*
Swell	1a	8	10	--	0
Swell	1b	8	10	30	0
Swell	1c	8	10	30	60
Storm	2a	8	6	--	0
Storm	2b	8	6	50	0
Storm	2c	8	6	50	60

The two headings are shown in the sketch of figure 7. We expect case 1 to show the highest loads on tendon 1. In both cases the wave height is 8 ft, but the wave period is reduced from the swell case to the storm case. At 30 ft/sec, the turbine is designed to slow down and the drag coefficient drops. This is reflected in the calculations explained further.

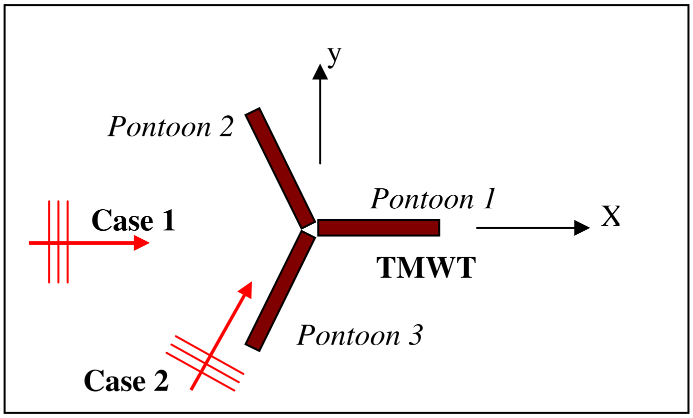

Figure 7: Sketch of design cases

TECHNICAL APPROACH

The initial sizing of the prototype was done using a simple spreadsheet, which calculated the displacement, weight and pretension in the mooring line. The mast height and hull draft were selected such that, knowing the expected max wave height and tidal range, the tip of the blade would stay out of the water, and the hull would not pierce the water surface. Initially, the hull displacement was such that the moment caused by the wind on the mast and turbine at the base of the mast would be less than the restoring moment from a single tendon assuming its pretension was 1/3 of the difference between the weight and the displacement. This was only a starting point. The dynamic analysis described in the next section was performed for multiple pontoon lengths and diameters, in the iteration cycles done to meet the no slack load and no pontoon out of the water requirements. This was done for the six metocean design conditions of table 1. The tendons are an integral part of the system. Some stretch is needed to avoid repeated slack and snap loads. MI&T's time domain code TIMEFLOAT was modified to model fiber ropes with non-linear stiffness.

These requirements were finally met and the prototype significant characteristics are shown in table 2. The turbines weight is 100 lbs. The total prototype weight is 1135 lbs. The initial pretension in each tendon is 560 lbs.

The tendons consist of 3 segments: a short chain segment at each extremity for installation and connection purposes and a 12-strand fiber rope in between. The target water depth is around 90 feet. The rope segments are 60 feet. Since the draft is 22 feet, there will be around 5' of chain on both sides. Changes in topography over the three anchoring points will be absorbed by a difference in chain length. The rope characteristics are shown in table 3.

Table 2. TMWT general dimensions.

GENERAL DIMENSIONS		
Clearance between MWL and bottom of blade	18	*ft*
Blade length (diam is twice the length)	3	*ft*
Mast height above MWL	21	*ft*
Mast height below MWL	22	*ft*
Total mast height	43	*ft*
Mast diameter	0.33	*ft*
Mast material	steel	
Mast thickness	0.12	*in*
Pontoon		
Length of one Pontoon from center to edge	10	*ft*
Diameter of Pontoon	1.33	*ft*
Pontoon material	steel	
Thickness of Pontoon	0.18	*in*

The system will be moored using large gravity anchors often used for mooring balls. The weight of the anchoring system is determined from the dynamic analysis since the maximum dynamic tension in the tendon is calculated. In this case 5000 lbs will be used. This gives a safety factor of about 2.

Table 3. TMWT tendon characteristics.

Water depth	90 *ft*
length of tendon	60 *ft*
Breaking strength	8600 *lbs*
Line diameter	5/8 *in*
Elastic elongation percentage	
% breaking strength	% elongation
10	1.31
20	2.27
30	3.27

ANALYSIS PROCEDURE

The response of the floater described in this paper is obtained in the time-domain, which includes nonlinear effects such as the non-linear stiffness of the fiber mooring system, and the viscous effects on the hull pontoons and cylindrical mast. A time-domain motion analysis solver is used to predict the platform motion in the sea-states of table 1. This solver (TIMEFLOAT) solves Newton's equations of motion. The vessel mooring and wind turbine responses are fully coupled through a time-marching scheme. Wave loads are modeled using WAMIT, a linear diffraction-radiation solver and viscous effects on the hull using a modified Morison equation model. More details on the numerical model have been presented in Cermelli et al. (2005) and Zambrano et al. (2006).

The added mass, damping, wave exciting and drift forces are obtained using the diffraction/radiation code WAMIT. The hull panel model is presented in Figure 8.

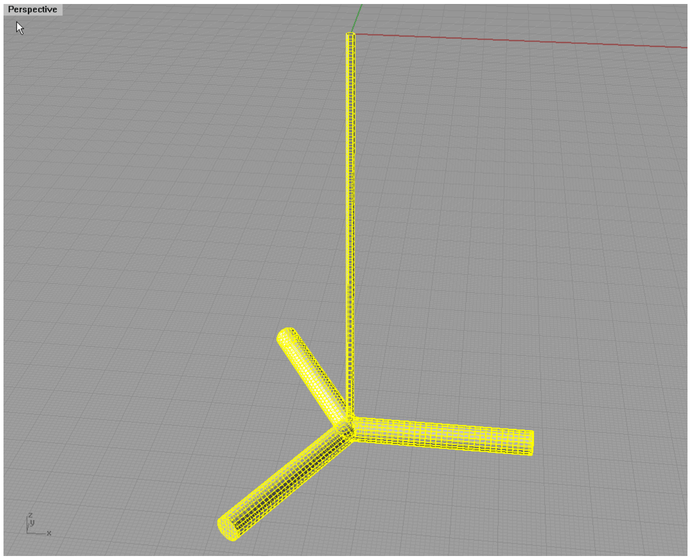

Figure 8: WAMIT Panel model of submerged section for hydrodynamic calculations

Time-domain simulations of the floater subjected to external forces are performed using the TimeFloat software, which was developed by Marine Innovation & Technology and used on a variety of floating systems projects (small and large ships, turret-and spread moored, semi-submersible, and buoys) and validated by comparison with published data and several model test campaigns.

TimeFloat solves the Newton's equations of motion of the floaters in the time-domain using a fourth order Runge-Kutta time-marching scheme. At each fractional time-step, the various external forces (due to wind, waves, and the mooring lines) are updated based on the motion of the ship. The mooring line configuration is determined using a finite-difference scheme described in Cermelli et al. (2005).

A detailed description of the methodology has been given in Zambrano et al. (2006).

FLOATER BEHAVIOR

Frequency response

WAMIT can output response amplitude operators (RAO) for the freely floating body but the coupling of the mooring system and the viscous effects around the tubulars are not accounted for. Therefore the RAO's presented in Figure 9 are obtained using time-domain simulations. Monochromatic sinusoidal waves of different frequencies are run, and the rms of the motion or tendon response is divided by the rms of the input signal. Therefore all the important force contributions are modeled. Figure 9a and 9b show the motion and tension RAO in direction 1, with pontoon 1 downstream of the incoming wave train. Figure 9c and 9d show the same RAOs, this time with pontoon 3 upstream of the incoming wave.

A numerical decay test was performed in the piston (vertical) mode. The heave natural frequency is 1.37 sec.

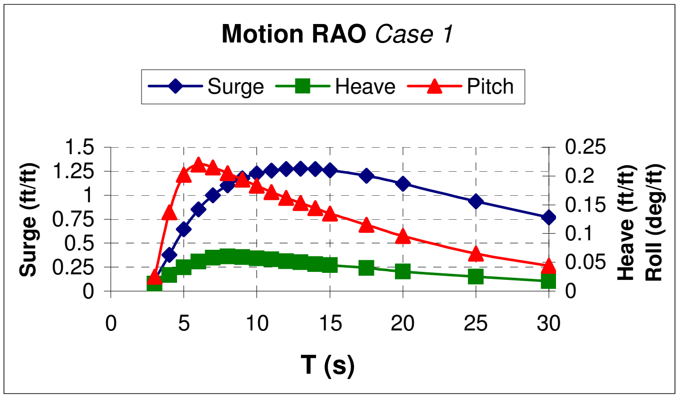

Figure 9a. Surge motion RAO – heading from case 1

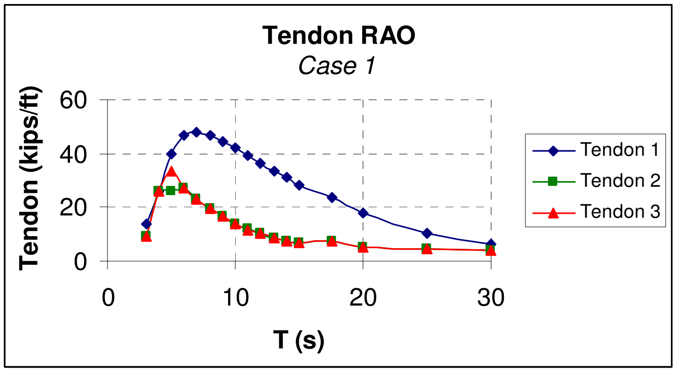

Figure 9b. Tendon RAO – heading from case 1

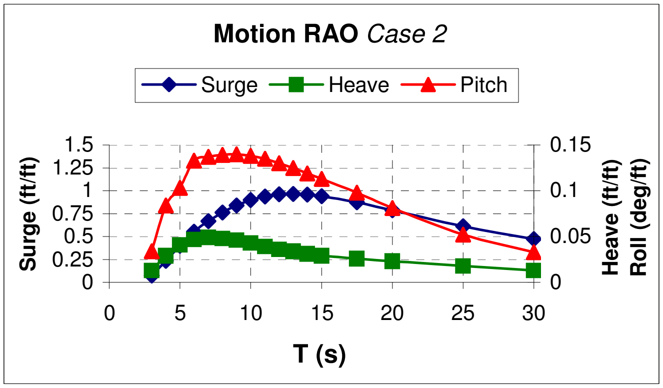

Figure 9c. Surge motion RAO – heading from case 2

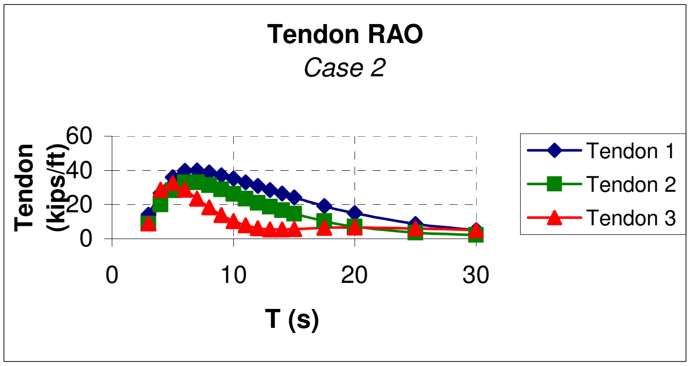

Figure 9dc. Tendon motion RAO – heading from case 2

Time domain simulation

Time domain simulations were performed for the cases defined in table 1. In all cases the following criteria were met.

- There were no slacking events. Minimum tension stayed positive in all tendons with a safety margin. As expected, the minimum tension observed was for case 1b, swell inline with pontoon 1 (downstream).

- The maximum tensions were well within the mooring line strength. The tension stayed within 10% of the ultimate strength so fatigue issues are avoided since the prototype will stay on site for only six months.

- From the sum of the maximum wave height, the highest tide level and the maximum heave observed, the mast was found to be high enough at 21 feet. Similarly, the sum of the minimum wave height, minimum tide and minimum heave observed, the draft is sufficient at 22 ft.

Table 4. Statistics summary of motions and tensions for all design cases.

case 1a			Swell - Pontoon 1 downstream - No wind						
Hs	8	ft	@	0	deg				
Tp	10	sec							
Ws	0	ft/sec	@	0	deg				
							tendon	tendon	tendon
	Surge	Sway	Heave	Roll	Pitch	Yaw	1	2	3
	ft	*ft*	*ft*	*deg*	*deg*	*deg*	*lbs*	*lbs*	*lbs*
Max:	6.22	0.00	0.11	0.00	0.63	0.00	910.2	650.2	650.2
Min:	-5.60	0.00	-0.49	0.00	-1.66	0.00	309.0	419.8	419.8
Mean:	0.03	0.00	-0.04	0.00	-0.47	0.00	612.5	528.1	528.1
Std	2.41	0.00	0.08	0.00	0.44	0.00	84.4	25.1	25.1

case 1b			Swell - Pontoon 1 downstream -						
Hs	8	ft	@	0	deg				
Tp	10	sec							
Ws	30	ft/sec	@	0	deg				
							tendon	tendon	tendon
	Surge	Sway	Heave	Roll	Pitch	Yaw	1	2	3
	ft	*ft*	*ft*	*deg*	*deg*	*deg*	*lbs*	*lbs*	*lbs*
Max:	7.08	0.00	0.12	0.00	1.23	0.00	836.3	684.6	684.6
Min:	-4.76	0.00	-0.56	0.00	-1.14	0.00	237.5	454.4	454.4
Mean:	0.81	0.00	-0.05	0.00	0.09	0.00	546.2	561.9	561.9
Std	2.41	0.00	0.10	0.00	0.44	0.00	85.0	25.1	25.1

case 1c			Swell - Pontoon 1 downstream -						
Hs	8	ft	@	60	deg				
Tp	10	sec							
Ws	30	ft/sec	@	60	deg				
							tendon	tendon	tendon
	Surge	Sway	Heave	Roll	Pitch	Yaw	1	2	3
	ft	*ft*	*ft*	*deg*	*deg*	*deg*	*lbs*	*lbs*	*lbs*
Max:	4.72	4.37	0.10	0.21	0.64	1.29	851.8	676.2	716.8
Min:	-4.03	-2.43	-0.44	-1.20	-1.20	-2.50	310.5	306.6	518.7
Mean:	0.30	0.80	-0.04	-0.42	-0.20	-0.20	580.8	499.9	590.5
Std	1.61	1.60	0.08	0.28	0.29	0.73	68.6	49.8	30.4

case 2a			Storm - Pontoon 3 upstream - No Wind						
Hs	8	ft	@	0	deg				
Tp	6	sec							
Ws	0	ft/sec	@	0	deg				
							tendon	tendon	tendon
	Surge	Sway	Heave	Roll	Pitch	Yaw	1	2	3
	ft	*ft*	*ft*	*deg*	*deg*	*deg*	*lbs*	*lbs*	*lbs*
Max:	2.61	0.00	0.05	0.00	0.11	0.00	709.2	578.8	578.8
Min:	-2.76	0.00	-0.11	0.00	-1.07	0.00	512.0	488.7	488.7
Mean:	-0.13	0.00	-0.01	0.00	-0.47	0.00	612.9	528.1	528.1
Std	1.20	0.00	0.03	0.00	0.26	0.00	39.9	19.6	19.6

case 2b			Storm - Pontoon 3 upstream -						
Hs	8	ft	@	0	deg				
Tp	6	sec							
Ws	50	ft/sec	@	0	deg				
							tendon	tendon	tendon
	Surge	Sway	Heave	Roll	Pitch	Yaw	1	2	3
	ft	*ft*	*ft*	*deg*	*deg*	*deg*	*lbs*	*lbs*	*lbs*
Max:	5.07	0.00	0.05	0.00	1.88	0.00	527.5	683.9	683.9
Min:	-0.43	0.00	-0.22	0.00	0.40	0.00	299.8	577.9	577.9
Mean:	2.10	0.00	-0.04	0.00	1.09	0.00	427.0	621.4	621.4
Std	1.21	0.00	0.05	0.00	0.28	0.00	42.2	20.3	20.3

case 2c			Storm - Pontoon 3 upstream -						
Hs	8	ft	@	60	deg				
Tp	6	sec							
Ws	50	ft/sec	@	60	deg				
							tendon	tendon	tendon
	Surge	Sway	Heave	Roll	Pitch	Yaw	1	2	3
	ft	*ft*	*ft*	*deg*	*deg*	*deg*	*lbs*	*lbs*	*lbs*
Max:	3.80	2.17	0.03	-0.90	0.92	3.30	612.1	489.5	775.2
Min:	-1.43	1.51	-0.17	-1.47	-0.27	-3.79	407.7	410.3	648.2
Mean:	0.98	1.83	-0.04	-1.12	0.30	-0.11	520.9	450.0	698.9
Std	1.19	0.14	0.04	0.10	0.25	1.62	41.6	15.8	23.0

Figure 10 shows, for case 1b, time series of the simulation. Fig 10a is the wave height, 10b the six DOF motions and 10c the tension in the lines. We see the direct correlation between the large waves and the increase in heave, surge and tension response.

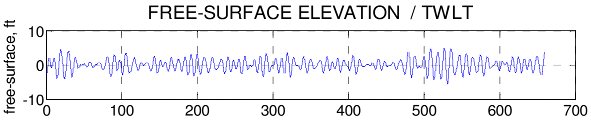

Figure10a: Surface elevation for case 1. Swell, Pontoon 1 downstream

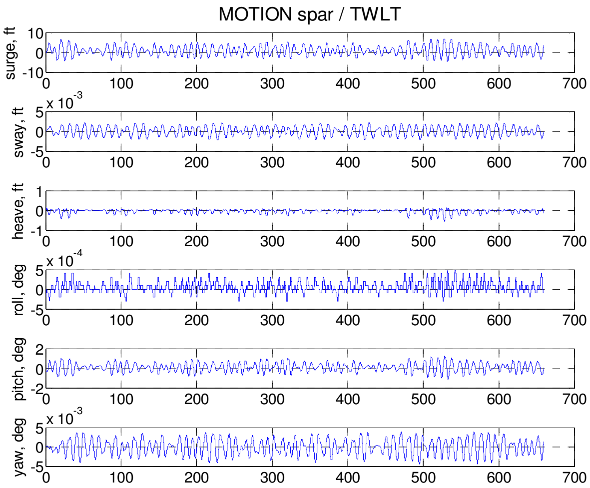

Figure 10b: Motions for case 1b. Swell, Pontoon 1 downstream

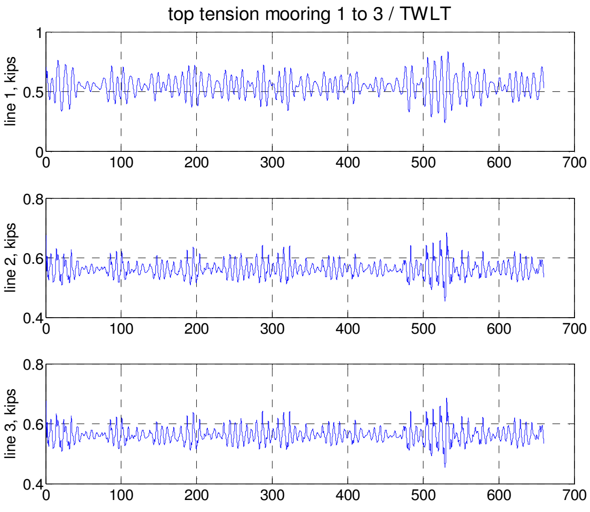

Figure 10c: Tension for case 1b. Swell, Pontoon 1 downstream

INSTALLATION AND COMMSIONING

The system is designed to be towed to the site and should have enough stability to float in calm water as seen in Figure 11. The freely floating draft is .59 feet and the GM 28 feet. The righting arm curve shown in figure 12 is obtained for heel angles in the y-z plane, with pontoon 1 along the x-axis. This is the worse case, as one pontoon is not contributing to the restoring moment. The prototype would have to heel more than 18 degrees before capsizing.

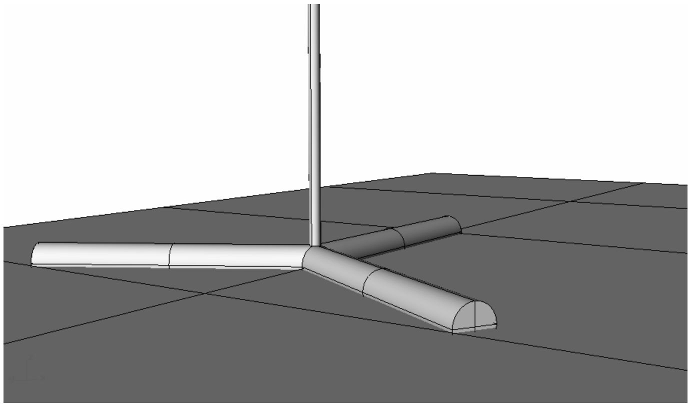

Figure 11 Sketch of freely floating hull

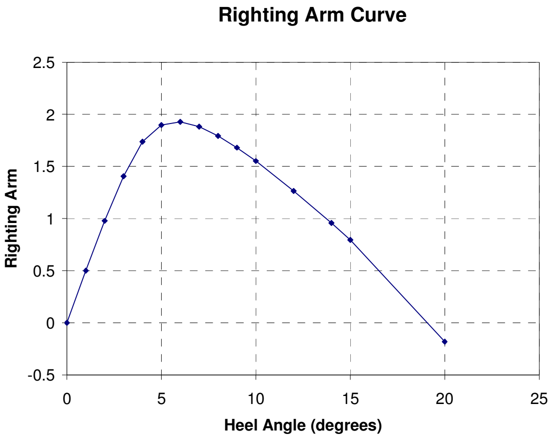

Figure 12. Right arm stability curve

Several installation methods have been considered. Since the prototype has, at the time of this writing, not been installed yet, the selected method may be different from the one that is currently planned and described here.

The planned installation sequence is as follow.

- The anchoring blocks will be preinstalled at the site and the water depth carefully measured. An I-Beam template with rings at the right spacing will secure the mooring blocks together. The tendons will be cut and spliced to the exact length.
- The prototype will be assembled on Santa Catalina Island. It will then be put in the water using a crane and towed to site using one of two-harbors mooring vessels, which are fitted with an A-frame and an independent external winch.
- The prototype will be towed to the site. A ballast weight of about 900 lbs will be attached to the bottom of the hull and lowered using the external winch. The mast will be held vertical using a sling and the boat A-frame. With the ballast in-place under the hull, the prototype should have about 100 lbs of excess buoyancy.
- The tendons will be connected sequentially using divers. The chains at the end of the tendons will be connected to the hull and the anchor using a pin and shackle. Additional ballast may be positioned on the pontoons to match exactly the submergence of the pontoon with the tendon length.

CONCLUSIONS

A tension-moored hull is clearly the most feasible solution because of the small size of the floater and the inherent significant motions in waves. In addition to the single pole visual requirement, engineering requirements were to keep the turbine blade out of the water, the hull in the water and the minimum tension smaller than the pretension to avoid slack and snap loads.

The following key points continue to be investigated.

- The mast and hull resonant frequency is not being excited by either the rotor thrust fluctuations and blade passing frequency and rotational frequency.
- The bending moment and fatigue of the mast hull weld is crucial. The hull tubulars are compartmented and the system can function properly in case the center region around the weld floods.

ACKNOWLEDGMENTS

We acknowledge the assistance of the Santa Catalina Island Company. Results from the experience of placing a one-kilowatt TMWT at sea will be submitted for presentation at OMAE 2008.

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