# FLOATING WIND TURBINES

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*In honor of Professor J. Nicholas Newman on the occasion of his 70th birthday*

## 1. Summary

The emerging need for renewable and environmentally friendly sources of energy has led to a recent and growing interest towards the development of floating offshore wind turbine technologies which may be deployed in water depths of up to 300 m for the cost-effective generation of electricity. Some advantages of operating in the offshore environment include higher and steadier wind speeds, less-restrictive acoustic requirements, and fewer space constraints. This research draws upon the experience of the oil/gas and wind industries respectively and studies the coupled dynamics of tethered and moored floating wind turbine technologies.

## 2. Fully Coupled Time-Domain Dynamics of a Wind Turbine: TLP Floater System

The coupled dynamics of a wind turbine mounted on a tethered Tension Leg Platform (TLP) has been studied in wind and waves by coupling the simulation tool MSC Adams with the aerodynamics and structural dynamics code FAST developed at the National Renewable Energy Laboratory (NREL) [Buhl, Jonkman, and Wright (2003)]. Time-domain simulations of the system responses and the turbine blade structural loads were reported by Withee and Sclavounos (2004) for a 1.5 MW wind turbine mounted on the TLP floater shown in Figure 1. The height of the rotor hub above the free surface is 84 m, the blade radius is 35 m, the turbine rotational speed is 20 rpm, the buoy diameter is 10 m, its draft is 12 m, the length of the radial arms is 20 m, and the water depths studied are 100 and 200 m. Figure 2 shows the results of simulations of surge free decay tests (plotted on a logarithmic scale) carried out to estimate the damping arising from the turbine rotor and the wave and viscous damping arising from the buoy. The two damping mechanisms were found to be of comparable magnitude, with the damping arising from the turbine rotor seen to obey a distinctly linear law. Representative simulations of the system responses and rotor blade root bending moments for a wind speed of 15 m/s in Sea State 6 are presented in Figure 3 for a TLP with one and three tethers on each radial arm, confirming the very favorable system dynamic attributes in a severe wind and wave environment. More details are presented in Withee (2004).

## 3. Frequency-Domain Response Analysis of Two Floater Concepts: TLP and Spar Buoy

During the next phase of this research, a comparative analysis was carried out of two alternative wind turbine floater concepts: a TLP, called Concept 1, and a spread-moored Spar Buoy, called Concept 2 (see Figure 4). A linear dynamic analysis was carried out in the frequency-domain by the SML (SWIM-MOTIONS-LINES) suite of programs, extended to account for the tower, nacelle, and rotor mass properties and the linear wind damping of the turbine rotor. The analysis found Concept 1 to be relatively soft in surge and sway but extremely stiff in the rotational modes. In contrast, Concept 2 was found to be stiff in surge and sway but softer than Concept 1 in the rotational modes. Furthermore, the natural frequencies of Concept 1 tend to be in the very low frequency region (0.2 ~ 0.3 rad/s) or high frequency region (~ 4 rad/s), for which there is little energy in typical ocean spectra. The natural frequencies of Concept 2 are in the region for which there is significant energy in typical ocean spectra; nevertheless, its RMS roll and pitch response does not exceed one degree even in the severest sea state. A summary of the performances of both concepts is given in Table 1 and a description of each environmental state is given in Table 2. It may be concluded from these results that the system responses are quite small, underscoring the promise of both concepts as realistic candidates for floating wind turbine systems in severe offshore environments. More details are presented in Lee (2004). Research underway is studying a Spar Buoy concept equipped with a conventional mooring configuration.

## 4. Nonlinear Wave Excitation by Steep Random Waves

The deployment of floating wind farms in shallow coastal waters and in offshore environments requires a design that will withstand aerodynamic forces due to extreme wind gusts and forces and moments exerted by steep ambient waves. The model developed by Sclavounos (2005) for the nonlinear Lagrangian particle kinematics of steep ocean waves may be implemented for the evaluation of the nonlinear excitation forces on slender vertical cylinders. This model allows the accurate modeling of the extreme unsteady loads by steep random waves by circumventing the need to use approximate extrapolation techniques for the wave kinematics above the calm water surface.

## 5. Future Work: Optimal Control of Floating Wind Turbine Responses by Blade Pitch Regulation

Onshore wind turbines are often equipped with blade pitch control mechanisms in order to maximize the wind power absorbed and to regulate the wind loads on the rotor blades. For large scale floating wind turbines, collective or individual blade pitch control mechanisms may be used to also control the system responses in wind and waves by optimally altering the unsteady aerodynamic forces exerted on each blade. This is a topic of active current research by the wind industry.

## 6. Acknowledgements

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## 7. References

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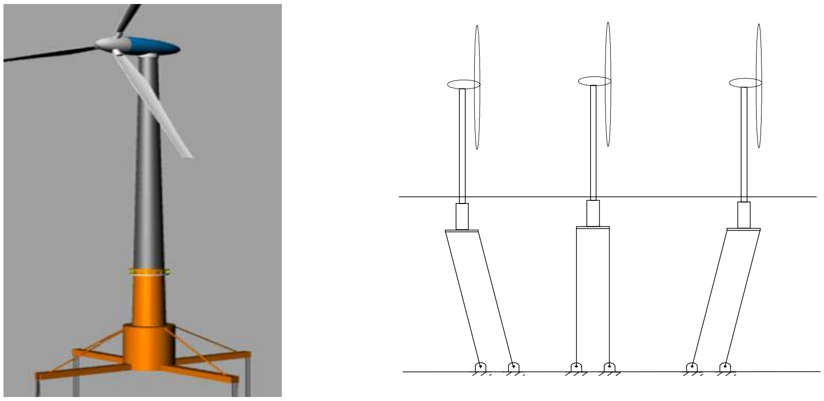


Figure 1: TLP Floater System

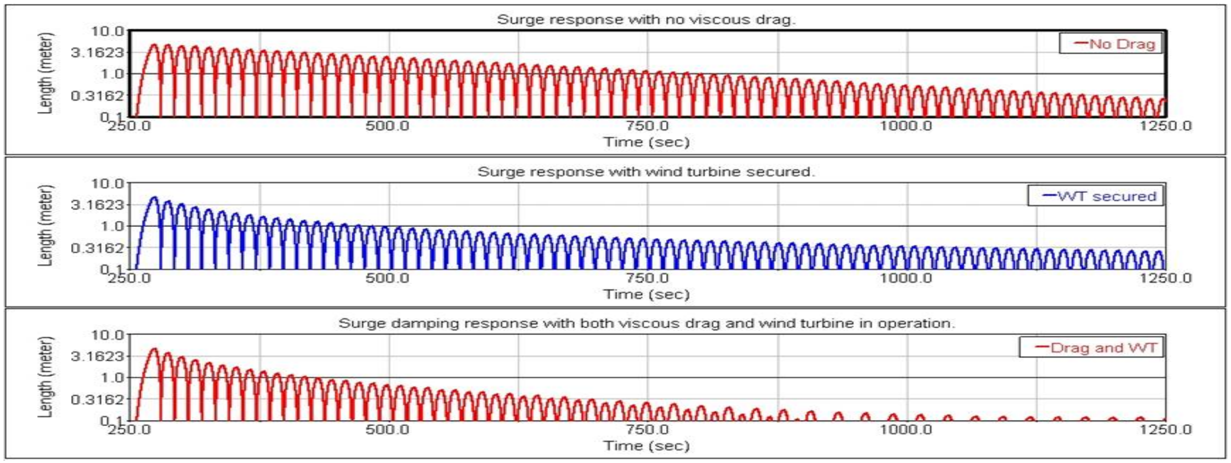


Figure 2: Results of TLP Floater damping test (Withee, 2004)

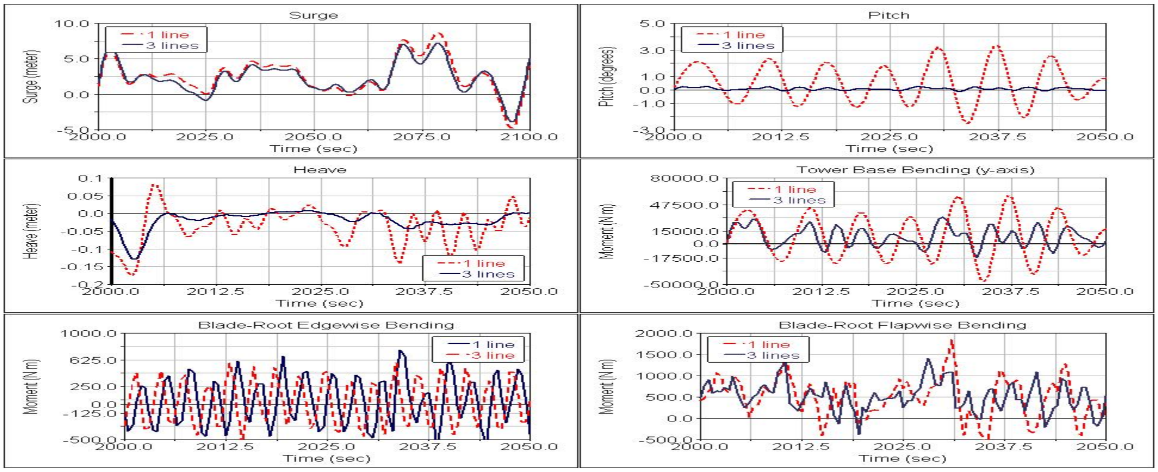
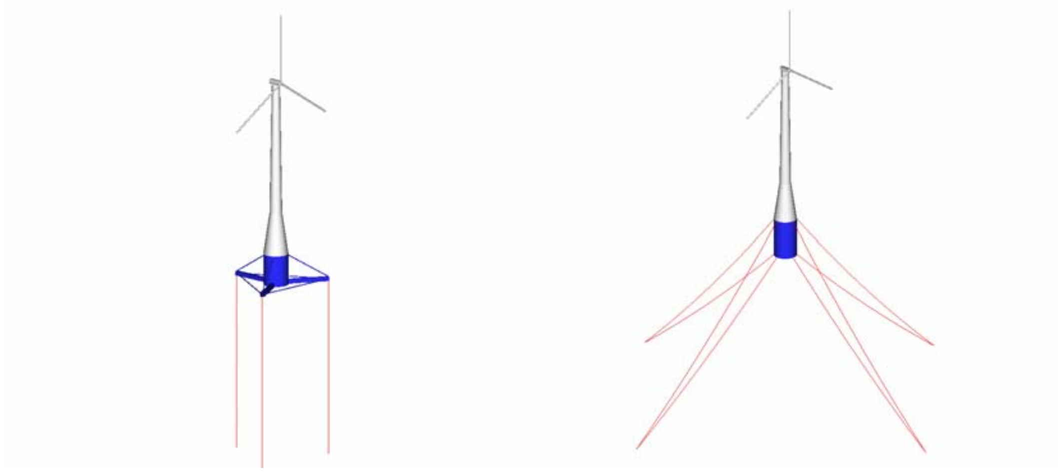


Figure 3: TLP Floater system responses and bending moments evaluated at a wind speed of 15 m/s and at Sea State 6 (Withee, 2004)



(a): Concept 1 (b): Concept 2

**Figure 4(a)-(b): Two alternative floater concepts**

| Concept 1 | Env. State 1 | Env. State 2 | Env. State 3 | Env. State 4 | Env. State 5 |
|---|---|---|---|---|---|
| $\sigma_1$ (m) | 1.08E-04 | 3.00E-02 | 0.257 | 0.770 | 2.53 |
| $\sigma_2$ (m) | 1.09E-04 | 3.02E-02 | 0.264 | 0.770 | 2.53 |
| $\sigma_3$ (m) | 1.39E-07 | 9.04E-05 | 1.15E-02 | 1.05E-02 | 4.29E-02 |
| $\sigma_4$ (deg) | 3.00E-04 | 8.00E-04 | 5.77E-03 | 9.00E-03 | 2.37E-02 |
| $\sigma_5$ (deg) | 2.73E-04 | 9.15E-04 | 3.23E-03 | 9.37E-03 | 2.42E-02 |
| $\sigma_6$ (deg) | 2.63E-06 | 1.18E-02 | 9.87E-02 | 0.159 | 0.328 |
| | | | | | |
| Concept 2 | Env. State 1 | Env. State 2 | Env. State 3 | Env. State 4 | Env. State 5 |
| $\sigma_1$ (m) | 1.23E-04 | 6.64E-02 | 0.253 | 0.402 | 0.562 |
| $\sigma_2$ (m) | 1.23E-04 | 6.38E-02 | 0.270 | 0.402 | 0.562 |
| $\sigma_3$ (m) | 3.47E-05 | 2.60E-02 | 0.158 | 6.42E-02 | 0.252 |
| $\sigma_4$ (deg) | 1.11E-04 | 2.92E-02 | 0.102 | 0.381 | 0.637 |
| $\sigma_5$ (deg) | 1.11E-04 | 3.28E-02 | 0.213 | 0.381 | 0.637 |
| $\sigma_6$ (deg) | 3.35E-08 | 2.99E-02 | 0.475 | 0.000 | 0.000 |

**Table 1: Summary of performance of two concepts in different environmental states**

| | Mean wind speed (knots) | Significant wave height (m) | Peak period (s) |
|---|---|---|---|
| Env. State 1 | 5 | 0.09 | 2.0 |
| Env. State 2 | 12 | 0.67 | 4.8 |
| Env. State 3 | 20 | 2.44 | 8.1 |
| Env. State 4 | 28 | 5.49 | 11.3 |
| Env. State 5 | 40 | 13.72 | 16.1 |

**Table 2: Description of environmental states**