Some Hydrodynamic issues related to offshore wind turbines.

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Introduction

Power generation by wind turbines is a rapidly expanding business. EU is aiming at 22% the electricity production from renewables by 2010. Wind power will be the largest contribution to achieve this goal. Until now most of the wind parks are located on land. However, due to conflicts related to use of land, noise, visual impacts etc. major developments are now taking place offshore. Offshore locations have generally better wind conditions than onshore, i.e. higher mean wind velocity and less turbulence. However, offshore development involves extra costs related to foundation, installation and operation.

Fixed offshore wind turbines

Presently Horns Rev at the Danish west cost is the largest offshore wind park. It consists of 80 2MW turbines installed at 6 –14m water depth. It was installed in 2002. As for most fixed offshore wind turbines the foundation of turbine is a monopole, Figure 1. The cost of fixed foundations, including installation increases with water depth.
Further the first natural period of the system must not come close to the rotational frequency of the turbine or three times this frequency (for a three bladed turbine). These requirements are increasingly difficult to fulfil as the water depth increases, in particular as modern wind turbines are constructed for variable rotational speed. At the same time the cost must be kept at an acceptable level. State of art offshore wind turbines has power capacity of 3 – 5MW. The weight of the nacelle for and rotor is typically in the range 100 – 400tonnes. The hub height is 70 –90m above sea level. Depending upon the wind conditions the diameter of the rotor may range from 70 to 120m. The tip speed is typically 80m/sec.
Steep shallow water waves will frequently impact on the tower that may have a diameter in the order of 6 meters. Thus wave impact loads and ringing like response is to be expected. Present design practise use a Morison type load formulation for the wave loads and a simplistic slamming approach. I.e. the high frequency ringing load effects that may contribute significantly to fatigue are not always properly accounted for.

Floating offshore wind turbines.

Floating offshore wind turbines have been investigated by e.g. Henderson et al. (2002), Musial et al. (2004) and Bulder et al. (2003). Bulder et al. summarize a Dutch study during 2001 – 2002 on the feasibility of floating offshore wind turbines. They are comparing some of the floating support structures proposed for moderate water depths, i.e. water depths of approximately 50 meters. Disk-like floating supports and various tethered structures are considered. Further large supports structures with multiple turbines as e.g. in Figure 3 are reviewed. Key issues in the evaluations are: Stability, dynamic response, extreme loads, fatigue and economy. The study reported by Bulder et al. concludes that for their applications the tethered tri-floater is the most promising structure, Figure 2. Accepting larger water depth, deep draft solutions can be considered, as the tethered SWAY- structure, Figure 4 or spar-like foundations with catenary or taut mooring, Figure 5. The design of such concepts is almost independent of water depth and bottom conditions. A deep and slender structure will be an effective support of the tower and turbine, easy to manufacture and to install. It will also attract a minimum of wave forces. The weight distribution can easily be arranged so that the rigid body natural periods in heave and pitch and roll are outside the wave excitation range as well as the turbine frequencies. However, still fatigue of the tower will be a major concern. For a fixed structure the wind loads govern the fatigue loads. For a floating support structure the motions and gravity load components add on.

Interaction between wind loads and motions.

The wind thrust, F_t and power, P from the turbine are usually written as:

$$F_t = C_T \frac{1}{2} \rho_a \pi R^2 U^2 \quad [1]$$

$$P = C_P \frac{1}{2} \rho_a \pi R^2 U^3 \quad [2]$$

Here C_T and C_P are the thrust and power coefficients respectively. ρ_a is the density of air, R is the radius of the turbine and U the incident wind velocity. By momentum considerations we obtain a maximum C_P=16/27. The corresponding C_T is 8/9. Most turbines have a power curve as illustrated in Figure 6. As the wind velocity is increasing the power increases until the "rated power" is reached (about 12 m/sec). The relations above are valid below the "rated" wind velocity. Above the rated velocity multi-megawatt turbines adjust the blade pitch to keep the power output constant. I.e. the thrust is reduced as the wind velocity increases beyond the rated value. The blade pitch regulation may be performed based upon the average wind velocity. In Figure 7 the thrust/U^2 is plotted for a turbine working just above rated power. A linear fit to the data is performed and the thrust coefficient approximated by:

$$C_T(U,\omega) = C_{T0}\left[1 + k_{CT}(\omega)\frac{U_d}{U_w}\right] \quad [3]$$

Here U_d is the dynamic part of the wind velocity and U_w is the mean wind velocity. If we observe the relative wind velocity at turbine level and use an averaging time that is small compared to the wave period, the wind thrust may contribute with negative damping to the global pitch motion, in particular for low frequencies, i.e. standard state of art regulation algorithms for regulation of blade pitch should not be used for floating wind turbines.

If the wind velocity is below the rated velocity and we assume a constant C_T, the wind force contributes with positive damping of the wave induced motions. That means we are able to extract wave energy from the wind turbine. As an illustration we assume pure resonant wave induced pitch motion in steady wind and that the only contributions to damping are wave radiation and the wind turbine. By invoking Haskind relation we obtain the following average power extraction of wave energy in a regular wave with frequency ω and amplitude ζ_A:

$$\overline{P}_{ex} = 3\frac{\rho g^3 \zeta_A^2}{\omega^3} \frac{B_{55}^{(r)} B_t^{(r)}}{\left(B_{55}^{(r)} + B_t^{(r)}\right)^2} \frac{C_P}{C_T} \quad [4]$$

Deep-water waves are assumed. $B_{55}^{(r)}$ and $B_t^{(r)}$ are the pitch wave radiation damping at resonance and turbine damping respectively. The maximum possible wave power extraction is obtained for $B_{55}^{(r)} = B_t^{(r)}$. The maximum capture width of the waves is obtained as:

$$L_{cap} = \frac{3}{2\pi}\lambda \frac{C_P}{C_T} \quad [5]$$

Here λ is the wave length corresponding to the response frequency ω. In Figure 8 the power extraction with and without the effect of wave power extraction is illustrated. The case considered is a wind turbine with rotor diameter 40m and a foundation consisting of a vertical cylinder with radius 6 meters and draft 60m. If the effects of wave energy extraction can be utilized in practise remains to investigate. However, the effect provides a substantial damping at pitch resonance as illustrated in Figure 9. (Here the thrust effect is not tuned for optimum power extraction)

As for other spar-like platforms care should be taken to avoid Mathieu- instability. This can be excited by direct heave – pitch coupling or via the coupling to the difference frequency of the waves as illustrated by Haslum and Faltinsen, 1999. Other important dynamic issues are related vortex induced motions and slow drift motion responses. As for the fixed structures, care must be taken to avoid ringing loads and the corresponding fatigue damage. For most of these issues the coupled effect of wind loads and wave loads must be accounted for.

References

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Haslum, H.A. and Faltinsen, O.M. (1999). Alternative shape of spar platforms for use in hostile areas. In proc. Of Offshore Techn conference, Paper OTC 10953, Houston.

Henderson, A.R., 2003. Support structures for floating offshore windfarms, NREL /DOE seminar, Washington, October, 2003.

Musial, W., Butterfield, S. and Boone, A., 2004: Feasibility of floating platform systems for wind turbines. National Renewable Energy Laboratory, Golden, CO 80401.

Figure 1 Monopile foundation for offshore wind turbine.

Figure 2. The "Tri-floater" concept, from Bulder et al., 2003

Figure 3. Multi-turbine floater, Hendrikson, 2003

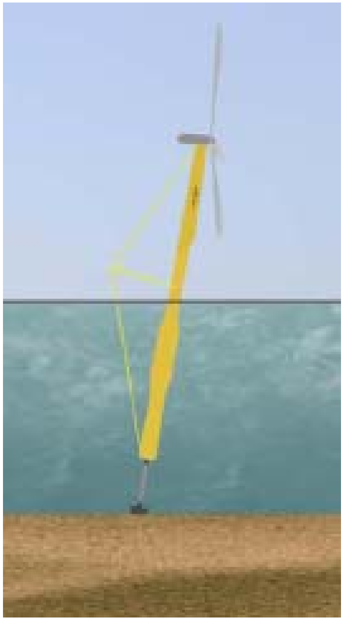

Figure 4. The SWAY ® concept by Inocean.

Figure 5. Spar foundation, Henderson, 2003

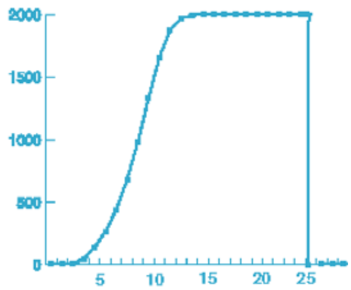

Figure 6. Power production versus wind velocity, 2MW turbine.

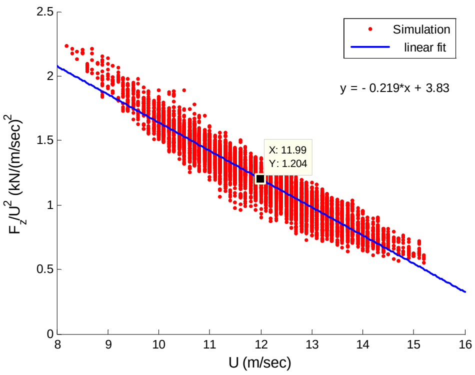

Figure 7. Simulated turbine thrust versus wind velocity.

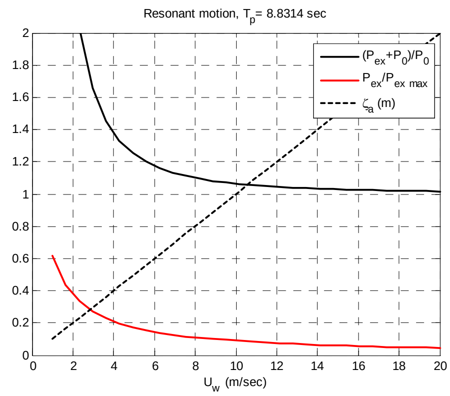

Figure 8. Additional power production due to wave effects. Dashed line: Assumed wave amplitude, Black line: Relative increase in power output. Red line: Wave power extraction relative to theoretical maximum.

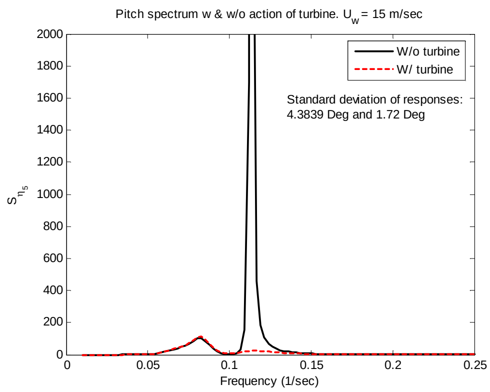

Figure 9. Example of reduced pitch motion due to wind turbine damping.