The Vortex Ring State of Floating Offshore Wind Turbine

Background

In order to seek more high quality wind energy resource, the wind energy technology experienced a change from onshore to offshore and from shallow water to deep water. The floating wind turbines are confirmed to be more economically effective than the bottom fixed ones when settling in the water deeper than 50m. However, new engineering problems can be arisen due to the changes of both the environmental condition and the structural style. It is wise to recognise the problems and tackle the problems before they cause large economic losses. According to my research, the vortex-ring state of the floating offshore wind turbines can be one of the problems that needs to be faced by both researchers and industry.

What is the vortex-ring state?

The concept of vortex-ring state (VRS) was first introduced in the area of aviation. It is a dangerous condition that may arise in helicopter flight. When the helicopter descends into its own downwash, the vortex ring system engulfs the rotor causing severe loss of lift [1]. Essentially speaking, the vortex is the pressure difference on the windward and leeward sides of the blades during the rotation of any rotor.

It can be expected that the similar phenomenon can also happen to the rotor of floating offshore wind turbines. Due to the combined effects of wind and wave, the floating wind turbine often has large amplitude motions. The rotor of the turbine goes back and force in the air and interacts with the vortices its own wake.

The influence of VRS

According to Leishman’s book [2], at least the flowing phenomena will occur in the rotor in VRS:

- The tip vortices come very close to the rotor plane and considerable unsteadiness (aperiodicity) becomes apparent.
- Concurrent upward and downward velocities. It can lead to significant blade flapping and a loss of rotor control.
- The assumptions of momentum theory which is often applied to the aerodynamic analysis of wind turbine is no longer available.

Modified Wolkovitch’s criterion

In 1972, Wolkovitch [3] developed a method on the bases of momentum theory and actuator disk concept to predict the boundaries of the vortex-ring state which can occur in the powered helicoper during its descent. In the original theory, he assumed that a protective tube of vorticity separates the slipstream (inside the tube) from the relative wind (outside the tube). The vortex-ring state would occur when the relative velocity of the vortex cores normal to the rotor disc falls to zero.

Wolkovitch’s Flow model

Based on these assumptions, Wolkovitch built up the criterion to predict VRS boundaries on two sides – the boundary from propeller state to VRS which is called the upper boundary and the boundary from VRS to inflow state, which is called the lower boundary. In 1982, Peters [4] re-evaluated Wolkovitch’s theory and made some modifications. Here adopted in my work involves two items of the modifications. First, I abandoned the lower boundary prediction criterion which was proved to be not satisfied with experiments. Second, the upper boundary criterion was used as the prediction of the center of VRS rather than the boundary prediction.

Results of the prediction

The VRS center prediction was based on the modified Wolkovitch’s criterion and the data of SMW offshore floating wind turbine (with OC3 Hywind configuration) getting from fully-coupled analysis using the NREL open source codes FAST. The center of the VRS is predicted in time domain. A typical load case is shown here. (Load case: Hs=10m,Tp=10s, Wind=6m/s) The result shows that the rotor switches between different working states. When the ‘relative wind velocity’ across the ‘critical wind velocity’, the blade section is considered to be in the center of VRS.

The pictures below show the VRS prediction result of one section on a blade in time domain, and the VRS distribution of the rotor disc with azimuth angle.

Modified Wolkovitch’s criterion

Conclusion

The most important discovery in this research is that the VRS phenomenon happens to a descending helicopter also happens to the floating offshore wind turbine. The prediction indicated that the VRS often occurred to the outboard of the blades. The VRS region increased with the increase of the wave height and decreased with the increase of wind speed; it also related to the wave frequency, but not with the linear relationship. During VRS, the momentum theory breaks down, the existing calculation methods only plays a role of keeping the program run rather than calculate accurately.

Next step...

As the pioneer of VRS prediction criterion with momentum theory, Wolkovitch’s criterion is selected initially to do this cross-discipline subject. Other finer criterions developed after it will be explore later to obtain more accurate VRS boundaries. After that, a numerical method (more likely to be a vortex method) with both accuracy and effectiveness will be adopt to develop a program for the VRS part aerodynamic calculation of the coupled analysis of floating offshore wind turbine. This is the overall scenario of my research.

References