11th World Congress on Computational Mechanics (WCCM XI)
5th European Conference on Computational Mechanics (ECCM V)
6th European Conference on Computational Fluid Dynamics (ECFD VI)
July 20 - 25, 2014, Barcelona, Spain

Coupled Wind LES and Ocean Wave Simulation with Actuator Disk or Line Models for Offshore Wind Farm Study

Di Yang[1], Lin Liu[2], and Lian Shen[2,*]

[1]Department of Mechanical Engineering, Johns Hopkins University, Baltimore, MD 21218, USA

[2]Department of Mechanical Engineering and St. Anthony Falls Laboratory, University of Minnesota, Minneapolis, MN 55414, USA

[*]Email address for correspondence: shen@umn.edu

Key Words: *Large-eddy simulation, Turbulent wind, Wind turbines, Ocean waves, Floating offshore wind farm.*

INTRODUCTION

Wind power at sea has many advantages over wind power on land, such as larger available space, faster winds, and relatively less visual and noise pollution. The presence of ocean waves introduces complexities to the design and operation of wind turbines. Scientific and technical challenges include the wind-and-wave coupling dynamics, the wave load on wind turbine platforms, the response of turbine power system to the wave-induced, periodically fluctuating air and water flow fields, etc. Therefore, for the success of wind energy harvesting at sea, there is a critical need to study the wind-wave-turbine interaction dynamics. In this study, we perform a CFD-based study of wind turbines in winds over waves.

NUMERICAL METHODS

We develop a hybrid numerical capability for the interactions among wind, wave, and turbines. The numerical framework consists of: (i) a large-eddy simulation of wind turbulence on a curvilinear coordinate system that follows the wave motion; (ii) a spectral simulation of nonlinear sea-surface waves with high resolution; and (iii) an actuator line model or an actuator disk model for the wind turbines. Our numerical method has been tested extensively for wind-wave interaction and for the simulation of winds past either a single wind turbine or a very large wind farm. Validation is done through the comparisons of the current simulation results with experimental and numerical results reported in the literatura.

RESULTS

Figures *a* and *b* show examples of our simulation results of the instantaneous flow field. The simulation in Fig. *a* uses an actuator line model for the rotating turbine blades. The tip vortices are seen. An interesting phenomenon is that the helical vortices become unstably more quickly than in the case of a wind turbine on land (result not plotted here). This enhanced instability is due to the disturbance by the swell below. This result is of significant importance to the load and safety of turbine structure and the efficiency of turbine power output.

The simulation in Fig. *b* uses an actuator disk model, which is suitable for studying the overall behavior of the wind farm. We have considered a variety of fully developed and fetch-limited windsea conditions. Statistical analyses are performed for the simulation results, with a focus on the mean wind profile, kinetic energy budget in the wind field, and the wind turbine power extraction rate. The results indicate that the stages of windsea development have appreciable effect on the wind farm performance. The wind turbines obtain a higher wind power extraction rate under the fully-developed wind-sea condition (described by the Pierson-Moskowitz spectrum) compared with that under the fetch-limited condition (described by the JONSWAP spectrum). This higher extraction rate is caused by the faster propagating waves and the lower sea-surface resistance on the wind when the windseas are fully developed. We found that the wave-induced difference can be as high as 8%.

CONCLUSIONS

In this study, we have developed a novel simulation approach for a comprehensive study of wind energy harvesting at sea to take the interactions among wind, waves, and turbines into full consideration. The simulations in this study are the first of their kind. Our results reveal that the difference in developing stage of windseas has appreciable impact on the wind turbine power output, mainly through the effect of sea-surface resistance to the wind field. The presence of swells can further have profound effect on the turbine performance, through the modulation of the wind field by the swells and through the swell-induced floating turbine motions. Our study quantifies the wave effects on wind turbines for the first time. The physical insights obtained from and the numerical tools developed in this study will be valuable to future study and development of wind power at sea.

REFERENCES

[1] Liu, Y., Yang, D., Guo, X. & Shen, L. (2010), "Numerical study of pressure forcing of wind on dynamically evolving water waves," *Phys. Fluids*, **22**, 041704.

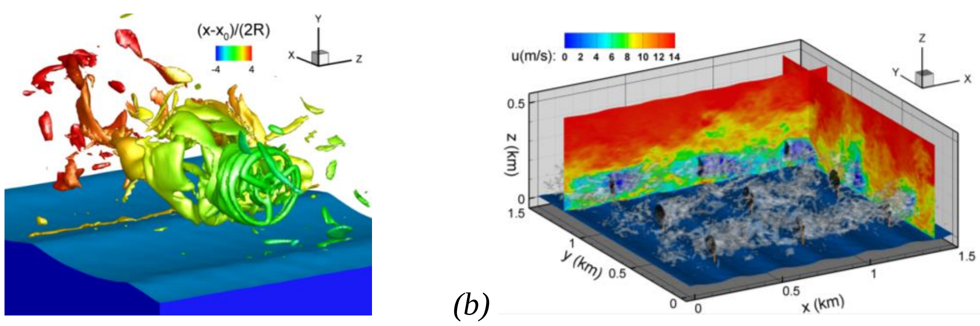
[2] Yang, D., Meneveau, C. & Shen, L. (2014a), "Large-eddy simulation of offshore wind farm," *Phys. Fluids*, in press.

[3] Yang, D., Meneveau, C. & Shen, L. (2014b), "Effects of swells on offshore wind energy harvesting – A large-eddy simulation based study," Renewable Energy, in review.

[4] Yang, D. & Shen, L. (2010), "Direct-simulation-based study of turbulent flow over various waving boundaries," *J. Fluid Mech.* **650**, 131-180.

[5] Yang, D. & Shen, L. (2011a), "Simulation of viscous flows with undulatory boundaries: Part I. Basic solver," *J. Comput. Phys.* **230**, 5488-5509.

[6] Yang, D. & Shen, L. (2011b), "Simulation of viscous flows with undulatory boundaries: Part II. Coupling with other solvers for multi-fluids computation," *J. Comput. Phys.* **230**, 5510-5531.



(a) *(b)*

Figures. Instantaneous turbulence vortical structures in the wake of wind turbines above waves, obtained from (a) actuator line model, and (b) actuator disk model.