Wave driven wind and implications for offshore wind turbine performance

First Symposium on OpenFOAM in Wind Energy, 20-21 March Oldenburg, Germany

Siri Kalvig
StormGeo / University of Stavanger, Norway
Introduction

- Motivation
- Wave-wind interactions
- Method
- Results
- Turbine performance simulations
- Conclusions & comments

Acknowledgements
Eirik Manger, Acona Flow Technology
Richard Kverneland (masterstudent, UiS, 2012)
Anne Mette Nodeland (masterstudent, NTNU, 2013)
Tommy A. M. Fredriksen (masterstudent, HiT, 2013)
Motivation

Statoil’s Hywind Norway, Photo; Lene Eliassen

A typical offshore wind picture….  How does a ”non-flat” sea affect the wind fields?
Motivation

- Will wave induced wind at an offshore wind site result in different wind shear and turbulence levels than expected?

- And if so, how will this affect the turbines?
Wind sea and swell influences the atmosphere different!

Wind sea - waves generated by local wind
Swell - long period waves generated by distant storms

The wave age is the ratio between the phase speed of the peak of the wave spectrum ($c_p$) and the wind speed in 10 m ($U_{10}$).

Wave age <1,2 : wind driven wave regime
Wave age >1,2 : swell dominated

(Crawford et al., 2007)

Most common is a mixture of wind sea and swell, and this makes the picture even more complicated.
Wind wave interaction

• Sullivan et al. (2008) developed a large-eddy simulation (LES) with a two-dimensional sinusoidal wave and identified flow responses for three cases; wind opposing swell, wind following swell and wind over a swell surface with no movement.

• The flow responses in the different cases were very different and ‘fingerprints’ of the surface wave extended high up in the MABL.

Aim at develop a wave-wind simulation set up with open source CFD and with more computational effective methods.
Need to simulate wave movements!

Need a new boundary condition that take into account the sinusoidal movement of the “ground”.

Solution:
Transient OpenFOAM simulation with pimpleDyMFoam. New boundary condition implemented with mesh transformations.
Need to simulate wave movements!

Need a new boundary condition that take into account the sinusoidal movement of the “ground”.

Solution:
Transient OpenFOAM simulation with pimpleDyM Foam. New boundary condition implemented with mesh transformations.
Method

• The open source CFD toolbox OpenFOAM is used for both mesh generation and CFD computations.

• Wave speeds (c), wave amplitude (a), wave length (L) are input parameters to the model. The wave is “solid” so no wind-wave interactions.

• To start with a relatively small domain with length of 250 m and a height of 50 m was established. Various sensitivity analyses were performed where different wind velocities and sea states where studied in detail (Kverneland, master theses UiS 2012).

• Temperature and the Coriolis effect are not taking into account and only uniform wind is studied. The calculations use a URANS approach. The turbulence closure model used is the standard k-epsilon model.
In general:

The wind speed profile and the turbulent kinetic energy pattern far above the waves will be different depending on the wave state and wave direction.
Six cases:

Uniform wind of 5 m/s at the inlet and wave with $c=8$ m/s, $a=3$ m, $L=40$ m
Uniform wind of 5 m/s at the inlet and wave with $c=-8$ m/s, $a=3$ m, $L=40$ m  
→ wave age of 1,6

Uniform wind of 8 m/s at the inlet and wave with $c=8$ m/s, $a=3$ m, $L=40$ m
Uniform wind of 8 m/s at the inlet and wave with $c=-8$ m/s, $a=3$ m, $L=40$ m  
→ wave age of 1,0

Uniform wind of 10 m/s at the inlet and wave with $c=8$ m/s, $a=3$ m, $L=40$ m
Uniform wind of 10 m/s at the inlet and wave with $c=-8$ m/s, $a=3$ m, $L=40$ m  
→ wave age of 0,6
Wind speed and turbulent kinetic energy profiles in the case of wind aligned with the wave and wind opposed with the wave for simulations with $U=5$ m/s at inlet and wave age 1.6.
Wind speed and turbulent kinetic energy profiles in the case of wind aligned with the wave and wind opposed with the wave for simulations with $U = 8$ m/s at inlet and wave age 1.0.
Wind speed and turbulent kinetic energy profiles in the case of wind aligned with the wave and wind opposed with the wave for simulations with U = 10 m/s at inlet and wave age 0.8.
Results

Comparison with Sullivan et al. 2008:

An openFOAM URANS set-up with a wave with $a=1.6$ m, $L=100$ m and $c=12.5$ m/s on a domain of $1200 \times 100$ m is being compared with Sullivan et al.'s LES simulations. Preliminary results are promising and it looks like we are able to capture the same dynamics as Sullivan et al. But current simulations is too coarse and more refined simulations are needed.

Contours of the horizontal wind field for the situation of aligned (top) and opposed with wave propagation (middle), and stationary waves (bottom). The non-dimensional field shown is mean $\frac{U_x}{U_g}$.
Wind turbine simulations

- NORCOWE & NOWITECH organized a wind turbine blind test in 2011-2012, BT1 & BT2.

- BT1: Eight independent modelling groups submitted 11 sets of simulations. No obvious “winner” and large spread of results (Krogstad et.al. 2011).

Currently working with the Actuator disk and actuator line method.

Two master students of NTNU and TUC are working with the SOWFA set up.
Wind turbine simulations

ADM: openFOAM (simpleWindFoam)
Simple geometry and set up
$C_P$ and $C_t$ as input values (were obtained from paper of Krogstad et. al. 2010)

FRM: openFOAM and ANSYS/Fluent
By Eirik Manger, Acona Flow Technology
No input parameters
Drag and lift are calculated

ALM: openFOAM (Churchfield, 2011)
Several input values:
Airfoil look up tables, gaussian with parameter (epsilon),
number of actuator elements per blade, tip loss correction
Xfoil used to generate airfoil tables
Drag and lift are calculated
Wind wave interaction

- Field experiments and numerical simulations show that during swell conditions the wind profile will no longer exhibit a logarithmic shape and the surface drag relies on the sea state (i.e. Smedman et al. 2003 & 2009, Semedo et al. 2009).

- Swell can result in both higher and smaller effective surface drag and it is likely that swell can create different wind shear and turbulence characteristics so that a wind turbine site will be exposed to other external environmental condition than it was designed for.
Wind wave interaction

Wind following swell*

✓ The drag coefficients, $C_D$, will be significantly smaller than values reported in nonswell situations.
✓ There will be a low level jet near the sea surface; hence, the vertical wind profile will not exhibit a logarithmic shape.
✓ Over the jet, there will be less wind shear compared with a flat surface.
✓ The maximum wind speed in the low level jet could be higher than that of the geostrophic wind.
✓ The wind shear in the swept area of the rotor can be negative. The turbulent kinetic energy and the turbulence intensity will be smaller compared with those of wind opposing swell or compared with those of wind over a flat surface.
✓ The low level jet could represent unharvested wind energy.
✓ If light winds following swell incidents are frequently occurring, it is possible that the wind turbine will be exposed to larger mean wind and greater fatigue damage than it is designed for.
Wind wave interaction

Wind opposing swell*

✓ $C_D$ will increase, sometimes by more than a factor of four, compared with a flat surface.

✓ There will be a higher wind shear than the case with a flat surface.

✓ Less investigated that the situation of wind following swell.

✓ It is reasonable to think that stronger winds can develop opposite a fast moving swell in areas relevant for offshore wind energy. It is then likely that damaging forces on the rotor–nacelle assembly could occur, along with fatigue damage, potentially leading to damage and increased torque on gear boxes.

Wind wave interaction

• There is a gap between “best knowledge” (science) and “best practice” (codes, standards) in boundary layer meteorology for offshore wind energy!

• There is a need for improved guidance on the impact atmospheric stability and wave-wind interaction can have on the offshore wind industry

(Kalvig et al 2013, Wiley Wind Energy)

openFOAM is a great tool for contributing in this area!
References


E-mail: siri.m.kalvig@uis.no / siri.kalvig@stormgeo.com