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A Comprehensive Simulation Methodology for Fluid-Structure Interaction of Offshore Wind Turbines

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Abstract

This paper gives an overview of a comprehensive simulation methodology for fluid-structure interaction (FSI) of offshore wind turbines that is being developed at the Applied Mathematics Department of SINTEF ICT. The methodology will account for most of the scales ranging from mesoscale meteorology through microscale meteorology to the aerodynamics of wind turbine blades. The meso and micro scales are handled through a unidirectional coupling of a meso and micro scale atmospheric code while the fluid structure interaction part is dealt with an isogeometric finite element based fluid-structure simulation code IFEM. In the current work we have shown the potential of the coupled system which is actually meant to generate realistic boundary condition as a wind forecasting tool. Also we present a comparison of the IFEM computed drag, lift and moment coefficients against experimental data for flow around a 3-D oscillating airfoil.

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1. Introduction

The potential for wind energy extraction (both onshore and offshore) is large. However, at the current stage, the cost of wind power extraction from design to installation phase of wind turbines is quite high. Understanding of the wind generation mechanisms in atmosphere and the wind extraction by wind turbines has increased significantly in the last few decades. Many field measurement campaigns have been undertaken and wind tunnel experiments have been conducted in this regard and we have begun to develop a better understanding of the atmospheric boundary layer and flow characteristics around turbines. Although the understanding is not yet sufficient, it is still promising. However, in an offshore context the seemingly simple scenario is significantly complicated by non-linear wind-wave interactions, thermal stratification and development of internal boundary layers in marine atmospheric flow owing to land-sea discontinuity, significantly affecting both mean wind and turbulent conditions [1] and thereby the performance of the wind turbines.

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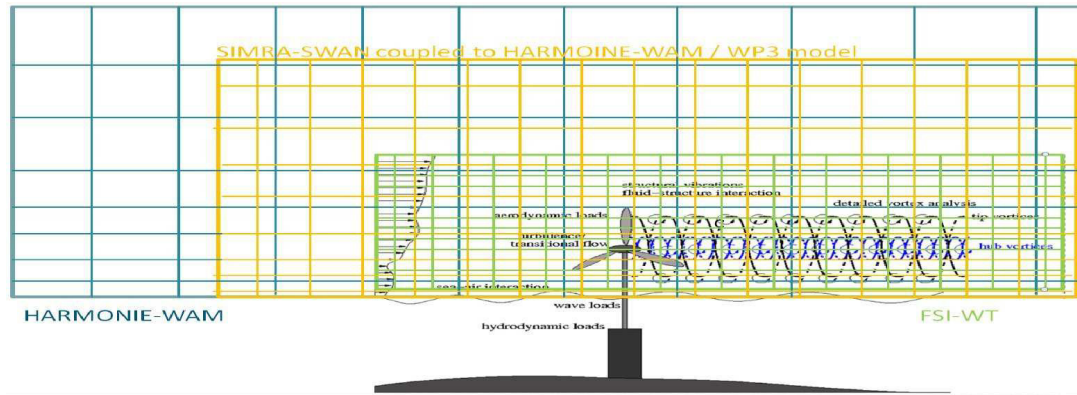


Fig. 1. Downscaling from meso through micro to FSI scales

In this paper, we present a multiscale approach to model the entire event from mesoscale meteorology, through microscale meteorology to the aerodynamics of wind turbine blades. The meteorological aspect of the problem is addressed via a unidirectional coupling of the mesoscale model HARMONIE (Hirlam Aladin Research on Mesoscale Operational Numerical weather prediction In Europe) ([2]) operated by the Norwegian Meteorological Institute and the microscale model SIMRA (Semi Implicit Reynolds Averaged) developed by SINTEF. In this project our ultimate focus is offshore so we are also coupling HARMONIE and SIMRA with the stochastic wave models WAM (Wave Modeling) and SWAN (Simulating Waves Nearshore) respectively. The wave-atmosphere coupled model will provide quantitative information about wind shear, stability and turbulence in the lower part of the boundary layer where the wind turbines would operate. Moreover, the current trend in wind turbine technology is towards larger turbines. This poses challenges related to torsional deformation, flutter of the rotor blades and wakes. Currently, widely used methods like actuator disc, actuator line and blade element models are significantly simplified and are not capable of capturing these effects accurately. To push the technology further, a robust and efficient method for fully coupled fluid-structure interaction (FSI) simulations using an isogeometric finite element methodology [3] is being developed. Some preliminary results from the new tool is presented in the paper. Also at the heart of wave-atmosphere coupling is the understanding of the assumptions made in the wave models, which according to the authors is in infancy. For example, it is common to account for the action of water waves on local meteorology by a simple pressure drag formula resulting in an added roughness length. We intend to employ a fully coupled Large Eddy Simulation (LES) of the Navier Stokes where the interface between the atmosphere and ocean is described using a Volume of Fluid (VOF) technique. This enables the study of wave growth and fine scale turbulent structures in the Atmospheric Boundary Layer (ABL). In additions to serving as a tool to improve wave models, the fully coupled LES can be used to provide input to detailed dynamic FSI simulations. Figure 1 gives a pictorial representation of the downscaling procedure.

2. Activities

2.1. Atmospheric Interaction

With the turbine blades getting larger and larger and already nearly a hundred meter long, the impact of atmospheric phenomena is gaining more attention. Because of a strong mass, momentum and energy exchange close to ground / sea surface and its effect being most significant in the lower part of the atmospheric boundary layer (or marine boundary layer), wind turbine performance and loading is expected to be significantly impacted. Strong wind shear and stability are the hallmark of the planetary boundary layer close to coasts as has been observed in the Plan Position Indicator (PPI) and Range Height Indicator (RHI) scan (conducted using lidar close to the Sola airport in Norway) shown in Figure 2 ([4]). It is thus evident that in the design stage of a wind turbine, prevailing wind, temperature and turbulence profiles should be taken into account. In this work we intend to achieve this using a downscaling process show in Figure 1 using different kinds of atmospheric (HARMONIE and SIMRA) and wave models (WAM and SWAN). The HARMONIE model is coupled to the wave model WAM while SIMRA model is being coupled to

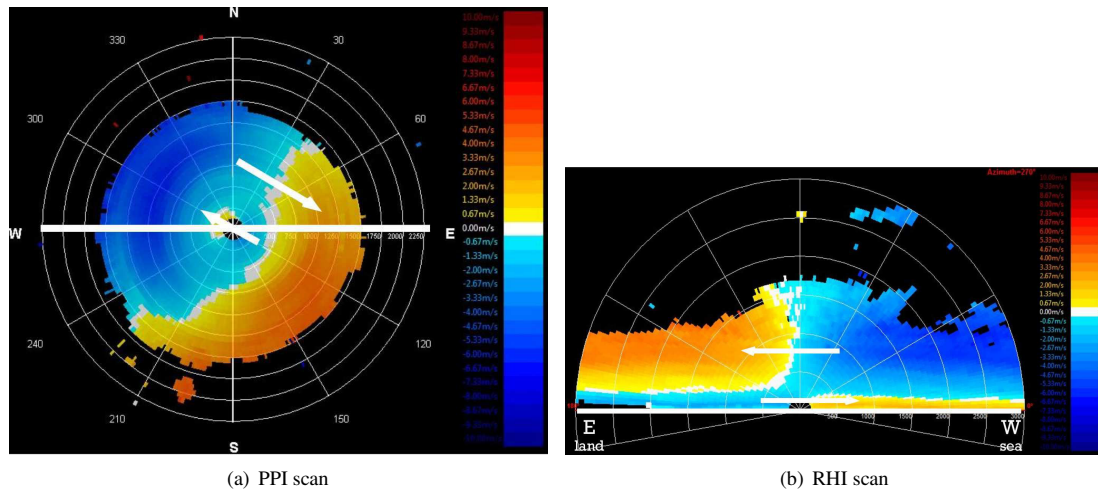
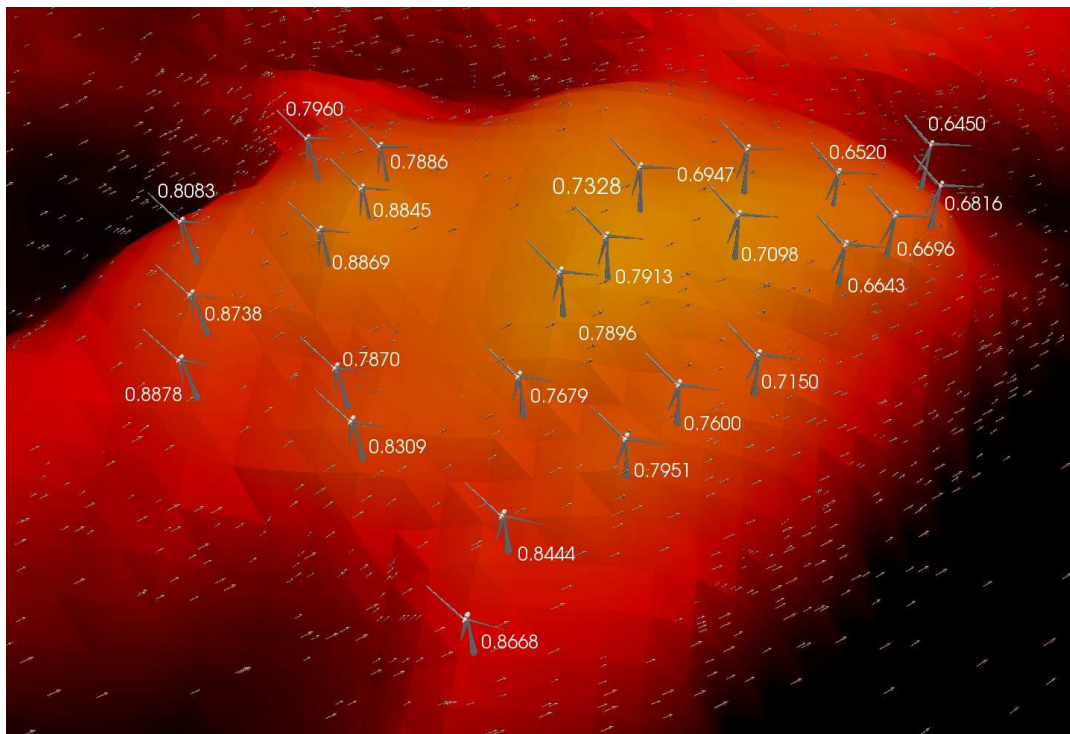


Fig. 2. Lidar data from Sola airport ([4])

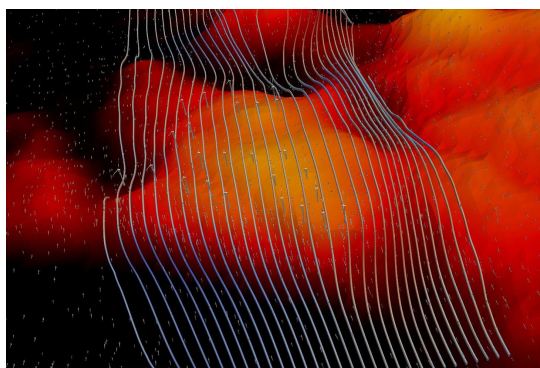
the wave model SWAN. The SIMRA-SWAN coupled model is unidirectionally nested into the HARMONIE-WAM model and is expected to provide realistic wind, temperature and turbulence fields at different scales. While the latter model has a horizontal resolution of $2.5\text{km} \times 2.5\text{km}$ the former can go as fine as $50\text{m} \times 50\text{m}$ resolution. The multiscale model is expected to play two roles: firstly to generate realistic boundary conditions for a detailed FSI simulation described in the Section 2.2 and secondly to forecast wind for power generation.

The multiscale model has been operational since 2009 and has been providing turbulence forecast for nineteen Norwegian airports located in highly complex terrain. The model has been extensively validated against wind tunnel / field data ([5], [6]) as well as against flight data ([7] and [8]). The presence of TrønderEnergi AS as one of our industrial partner and their willingness to share wind and production data (which is difficult to obtain at the moment from any offshore wind farm) from the Bessaker Wind Farm tempted us to test out the methodology for an onshore wind farm located in a complex terrain. The methodology although developed and tested for the onshore wind farm, can as such be applied to any offshore wind farm.

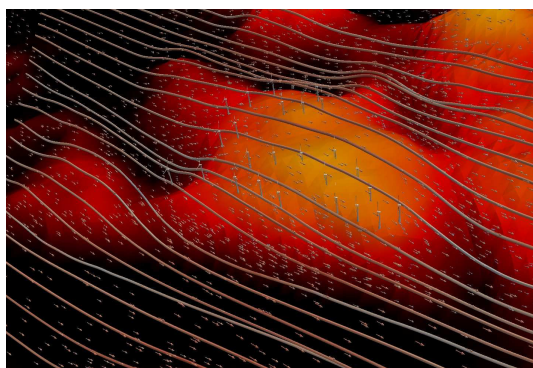
Analysis of wind farm data (10 minutes averaged wind magnitude and direction data from wind mast and production data from 25 wind turbines) showed that a few turbines are consistently underperforming (Figure 3(a)) relative to others in spite of the fact that the underperforming turbines lie in the first row facing the wind 60% of the time (thus wake effect could not be responsible for the inefficiency). Various offline simulations were conducted to understand the flow behavior in the region using the most prevalent wind, turbulence and stratification conditions experienced in the region. It was concluded that the strong stratification in the region resulted in a suppression of the vertical movement of the wind resulting in low wind availability to drive the underperforming turbines. Most of the air is channeled through the valleys surrounding the hill. Figures 3(c) and 3(b) show streamlines of the flow for two major wind directions (westerly and south easterly respectively) experienced in the region. The more the streamlines spread away from each other, the more the flow tends to avoid such areas. Clearly the underperforming turbines are located in less favorable wind conditions. Another reason could be the high turbulence and wind shear generated in the regions owing to their proximity to a valley resulting in frequent cutoffs. Furthermore, numerical wind power forecasting has been identified as a promising tool to address the increasing variability and uncertainty associated with wind power predictions and to more efficiently operate power systems with large wind power penetration. The data analysis showed that even when the wind magnitude and direction recorded at the wind mast at different instances were exactly the same, the corresponding energy production varied significantly, implying that a one point wind mast data is not a reliable source of information on which energy production forecast can be based upon. To resolve the mystery we analyzed the data from another site Titran located on the island of Frøya. The analysis is presented in the Section 2.4. The analysis suggests that even when the one point wind mast data were exactly the same at different times, the nature of horizontal and vertical wind shear could vary significantly resulting in very different power production. Since,



(a) Power production by each turbine



(b) Streamlines for Southerly Wind



(c) Streamlines for Westerly Wind

Fig. 3. Bessaker Wind Farm

field measurement is not always feasible, the use of numerical models achieves even more significance. In the current work we use the HARMONIE-SIMRA coupled model to forecast wind in real time and corrected the forecast using a Kalman filter. The forecasted wind can then be used to estimate power production using a power curve derived in operational conditions. The forecast results are shown in Figure 4. Currently, work is on to quantify the error associated with such forecasts by running 10 different ensembles of the model. A more detailed description of this activity is discussed in [9].

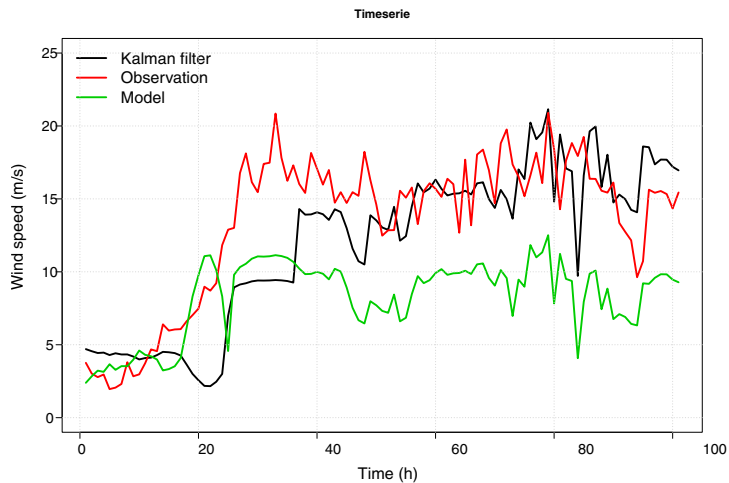


Fig. 4. Wind prediction using Kalman Filter

2.2. Fluid Structure Interaction

SINTEF ICT, Department of Applied Mathematics (SAM) has two decades of experience with developing FSI simulation tools. During the second half of the 1990s they initiated and coordinated an EU funded project denoted Fluid Structure Interaction for Structural Design (FSI-SD), see [10]. This FSI-SD project addressed wind induced motion of bridges by means of coupling a parallelized 3D Navier-Stokes solver based on Large Eddy Simulation (LES) turbulence model coupled with a flexible mounted 3D segment of the Storebæbridge, see [11], [12], and [13]. Furthermore, the FSI-SD project addressed vortex induced vibration of offshore risers and submerged pipelines using a strip theory approach, i.e. the CFD computations are done in 2D at a number of sections along the riser that was modelled using nonlinear beam elements, see [14] and [15]. Both of these approaches are going to be pursued in the ongoing research project denoted Fluid-Structure Interaction for Wind Turbines (FSI-WT), see www.fsi-wt.com.

More recently the research group at SAM has collaborated with Yuri Bazilevs (who is an associated research partner in FSI-WT) and addressed isogeometric fluid-structure interaction of blood flow in cerebral aneurysms, see [16] and [17].

Within the premise of this activity, a highly efficient FSI solver based on Isogeometric Finite Element Method is being developed partly inspired by our previous work on FSI as described above as well as the more recent isogeometric FSI-development done by our collaborator Yuri Bazilevs and co-workers, see [18], [19], [20]. The methodology is expected to bridge the gap between geometric modeling, mesh generation and numerical analysis leading to reduced modeling time. This new platform is now referred to as the IFEM (Isogeometric Finite Element) platform and consists of preprocessor, solver and a post processor. In this section we briefly describe the basic module of the tool followed by some quantitative results. An accurate fluid-structure interaction analysis relies on the following

1. a high quality mesh
2. an efficient elasticity solver
3. an efficient Computational Fluid Dynamics (CFD) solver

Hence, all three of these requirements have been addressed in the present work. Since there is a transfer of information from the elasticity solver to the CFD solver and vice versa, the resolution of boundary layer is of utmost importance. Two different kinds of mesh generators (C-mesh and O-mesh) were developed. Figure 5 shows a two dimensional C-mesh and an O-mesh generated for a NACA0012 profile. An advantage of the later over the former is that the mesh refinement in one direction does not propagate in the other direction resulting in an efficient mesh. The downside of the O-mesh is that it requires a rounding off of the trailing edge of the airfoil. However, even the O-mesh due to

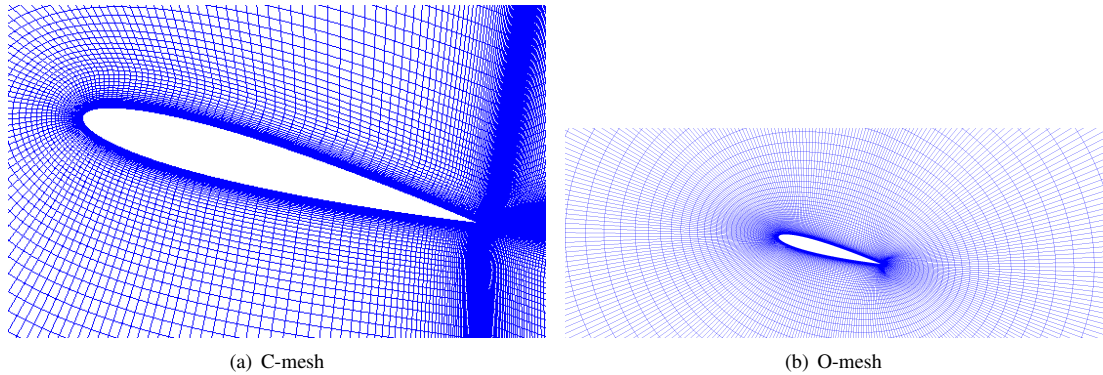


Fig. 5. Different kinds of mesh

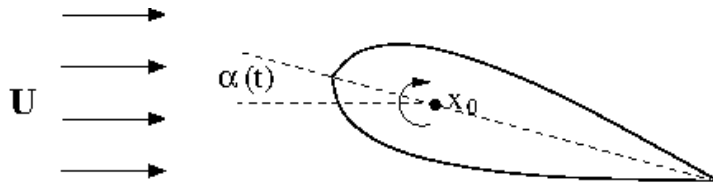


Fig. 6. Set up for the simulation

the high resolution requirements close to the wall surface results in highly stretched mesh impacting the numerical accuracy and stability resulting in longer simulation times. To deal with such stretched mesh an Algebraic Multigrid Solver (AMG) based on the software packages PETSc (Portable, Extensible Toolkit for Scientific Computation) and ML (Multilevel Preconditioning) has been developed. For the FSI solver an ALE (Arbitrary Lagrangian-Eulerian) formulation has been extended from using a rigid body motion for stiff wing sections to handle a general elastic structure and a general nodal force transfer module has been developed to transfer forces from fluid to structure. Linear and non-linear elasticity solvers have been developed further to include time integration schemes like Newmark, the generalized α -method and BDF (backward difference) methods needed to solve FSI problems. The method uses a combination of directional ILU (Incomplete Lower Upper) smoothers and semi-coarsening which seems to be very efficient in numerical tests. To model flexible wind turbine blades a beam model is currently being developed.

The research group at SAM and Department of Mathematical Sciences at NTNU (NTNU-IMF) have together more than two decades of experience with error estimation and adaptivity, see e.g. [21], [22] and [23]. In FSI-WT this expertise will be utilized to develop goal oriented adaptive simulation technologies in order to compute highly accurate interface forces (lift, drag and moments).

2.2.1. Validation

The FSI solver has been verified against experiments for a 3D NACA0012 profile in pitch motion during dynamic stall. The experimental setup shown in the Figure 6 consisted of a uniform flow (\vec{U}) incident on a 3-D airfoil oscillating in a rotatory motion governed by the equation $\alpha(t) = 14.85^\circ + 9.89^\circ \sin(\omega t)$ with rotation center located at $0.25c$ where c is the chord length. The objective of the validation exercise was to validate the model's performance for high angles of attack and to evaluate the performance / limitation for separated flows. The Reynolds number of the flow in accordance with the experiment was set at 980000. O-mesh with 19356×21 points (linear elements) with 194 points along the wing surface were used resulting in a wall normal mesh size of $\Delta_{min} = 5.10^{-5}c$. This is a very challenging case and the Spalart-Allmaras turbulence model with wall function $\tilde{\nu} = \kappa u_\tau y$ seems to perform well both against the experiments and other numerical simulations in the literature when it comes to aerodynamic coefficients like lift, drag and moment (Figure 7). Temporal evolution of the X-velocity contours is demonstrated in Figure 8. Moreover, it performs well compared to other RANS (Reynolds Averaged Navier Stokes) models like the $k - \omega$ SST model,

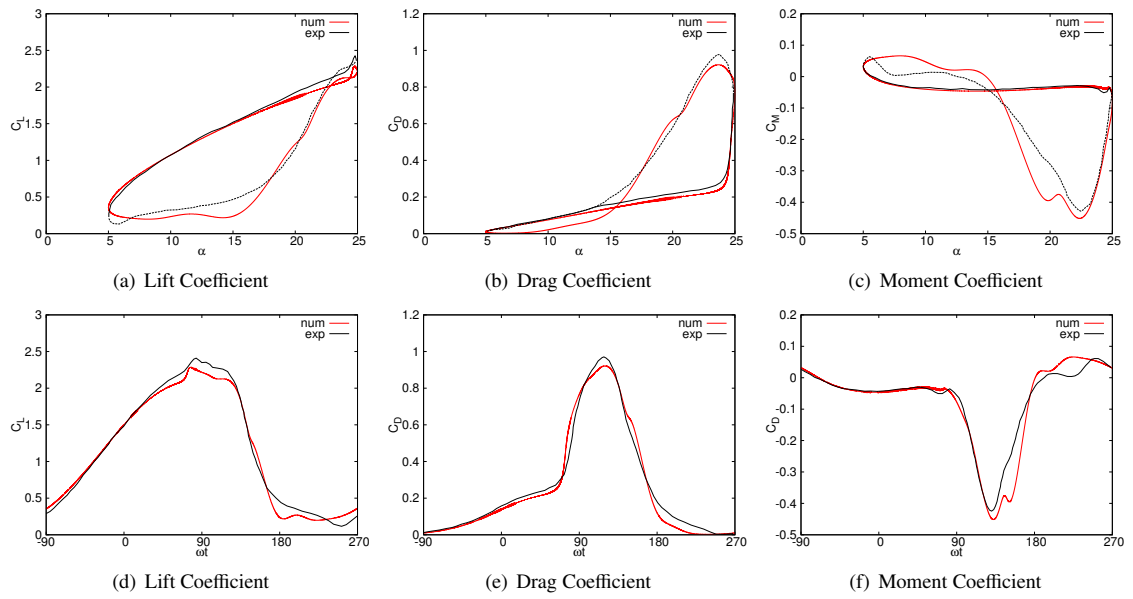


Fig. 7. Validation of lift, drag and moment coefficient against experimental data

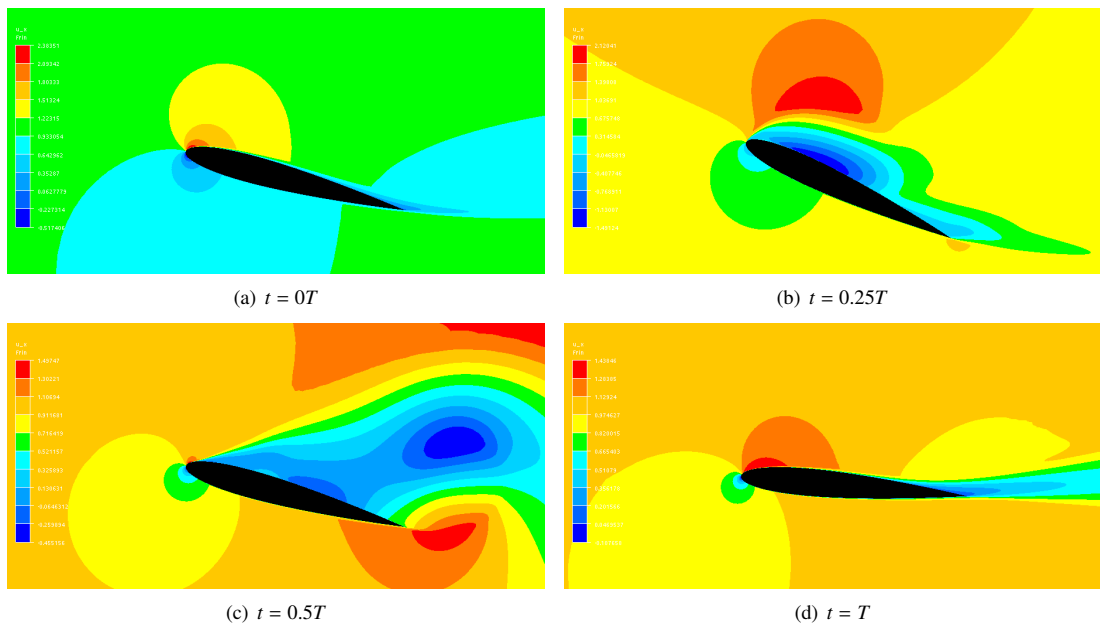


Fig. 8. Temporal evolution of X-velocity (U) contour

and further improvements would imply the use of a much more expensive computation using Large Eddy Simulation (LES).

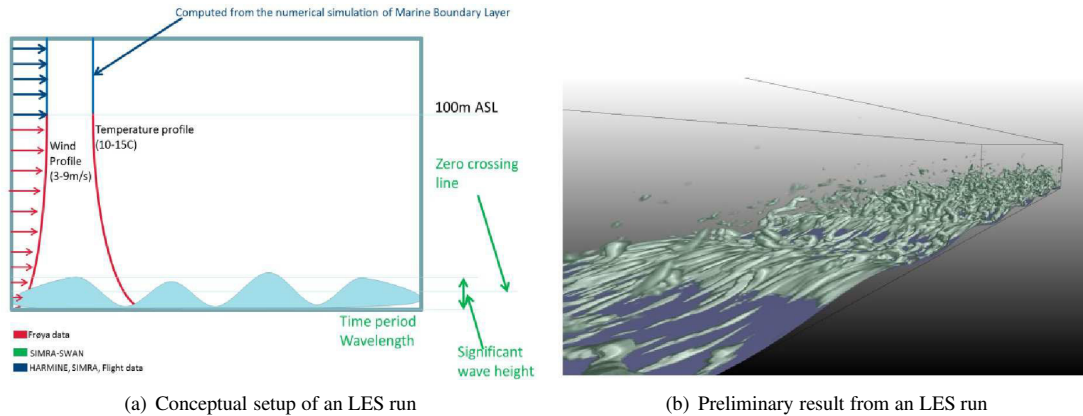


Fig. 9. Large Eddy Simulation of turbulent flow over wavy wall

2.3. Deterministic wave-atmospheric interaction

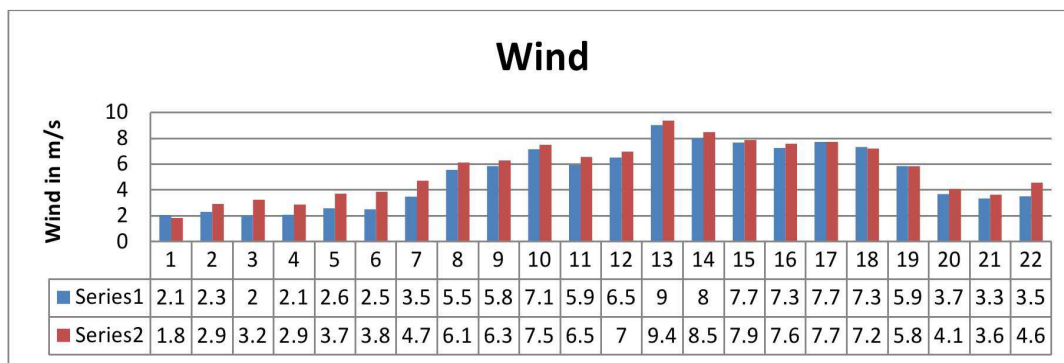
The wave-atmospheric interaction described in the Section 2.1 is based on a stochastic approach to modeling of sea waves. This approach is considered justifiable considering the highly chaotic nature of a sea surface. However, there are certain assumptions in the model which can be verified using a more deterministic approach. An example is the usage of a simple pressure drag formula resulting in an added roughness length which is used to account for the action of waves on local meteorology or the relationship between the shear stress at the wave-atmosphere interface and the wind at 10m above the sea surface. In this project we employ a fully coupled LES of the Navier-Stokes equations where the interface between the atmosphere and the ocean is described using a VOF technique. This enables the study of wave growth and fine scale turbulent structures in the ABL. In addition to serving as a tool to improve wave models, the fully coupled LES can be used to provide input to the FSI simulations. Since such simulations are computationally expensive, care is being taken to setup a case where we try to be as close to reality as possible in terms of relevant non-dimensional numbers. To set up the problem data from different sources are being processed and analyzed for creating realistic, yet computationally feasible simulations. Figure 9(a) gives an idea of how the simulation can be setup. Wind and temperature profiles, characteristic of an offshore / coastal region is being synthesized using the data from Frøya up to a height of 100m and numerical meteorological data above that. Significant wave height, time period and phase velocity of the waves in a coastal region is being derived from SWAN simulations compared against laboratory and field experimental data. A snapshot from a preliminary simulation is shown in Figure 9(b).

2.4. Data analysis from a coastal region

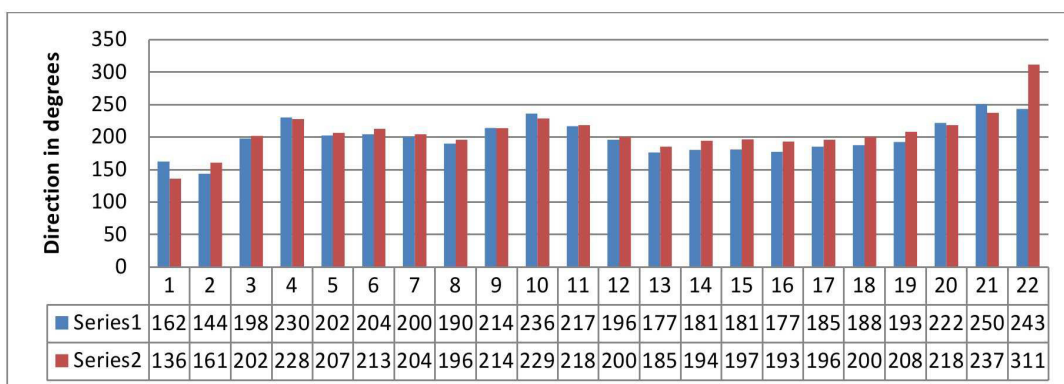
In order to understand the wind behavior in a coastal regions, data collected at the wind mast located in Titan on Frøya was analyzed. The data consisted of wind magnitude, wind direction and temperature measured at six different heights of 10, 16, 25, 40, 70, 100m above the ground surface. Here we present some interesting observations from the analysis of the data for a particular day. The data was hourly averaged and plotted in the form of a histogram for two different heights, 10m and 100m. A quick look at the Figure 10(a) shows that the wind magnitude can change by up to 25 – 30% while the wind direction can change by up to 70° (figure 10(b)) implying the existence of strong wind shear. This is a compelling evidence to question the use of one point mast data for power forecast.

3. Conclusion and Future Works

The paper describes a comprehensive design methodology for wind turbines. A unidirectional multiscale model consisting of models capable of resolving different scales and physics has been developed and employed for the synthesis of realistic wind, temperature and turbulence profile to be used in detailed FSI simulations of a wind turbine. The model's potential as a power forecasting tool is also demonstrated. The added advantage of using the observation



(a) Hourly averaged wind magnitudes at 10m and 100m heights



(b) Hourly averaged wind directions at 10m and 100m heights

Fig. 10. Hourly wind data from a wind mast located at Titran (Frøya). Series 1 corresponds to data at 10m height while Series 2 corresponds to 100m height.

data to improve a forecast was demonstrated. Various new algorithms were developed for conducting detailed FSI simulations. Drag, lift and moment coefficients computed using the tool was found to be in good agreement with experimental data. Various assumptions that are taken for granted in wave-atmospheric interactions are now being questioned and investigated. Data analysis from different sites highlights the weaknesses of using a one point data for wind magnitude and direction to make power forecasts. Having come so far, there is still a lot to be done. The next step consists of running the forecast model in real time with output being compared to the real production as well as predictions using traditional methods. Significant improvements are foreseen when the couplings between the stochastic wave models and atmospheric models become operational. The detailed LES simulation is expected to improve the understanding of wave-atmosphere interactions. The FSI solver will enable the conduction of a detailed simulations around a real full rotating wind turbine. It is hoped that results from such simulations will lead to an improvement of the existing simplified models.

Figure 11 shows the synergies between different activities very elegantly. It pictorially expresses what has already been achieved and what is expected out of the project once it commences.

Acknowledgements

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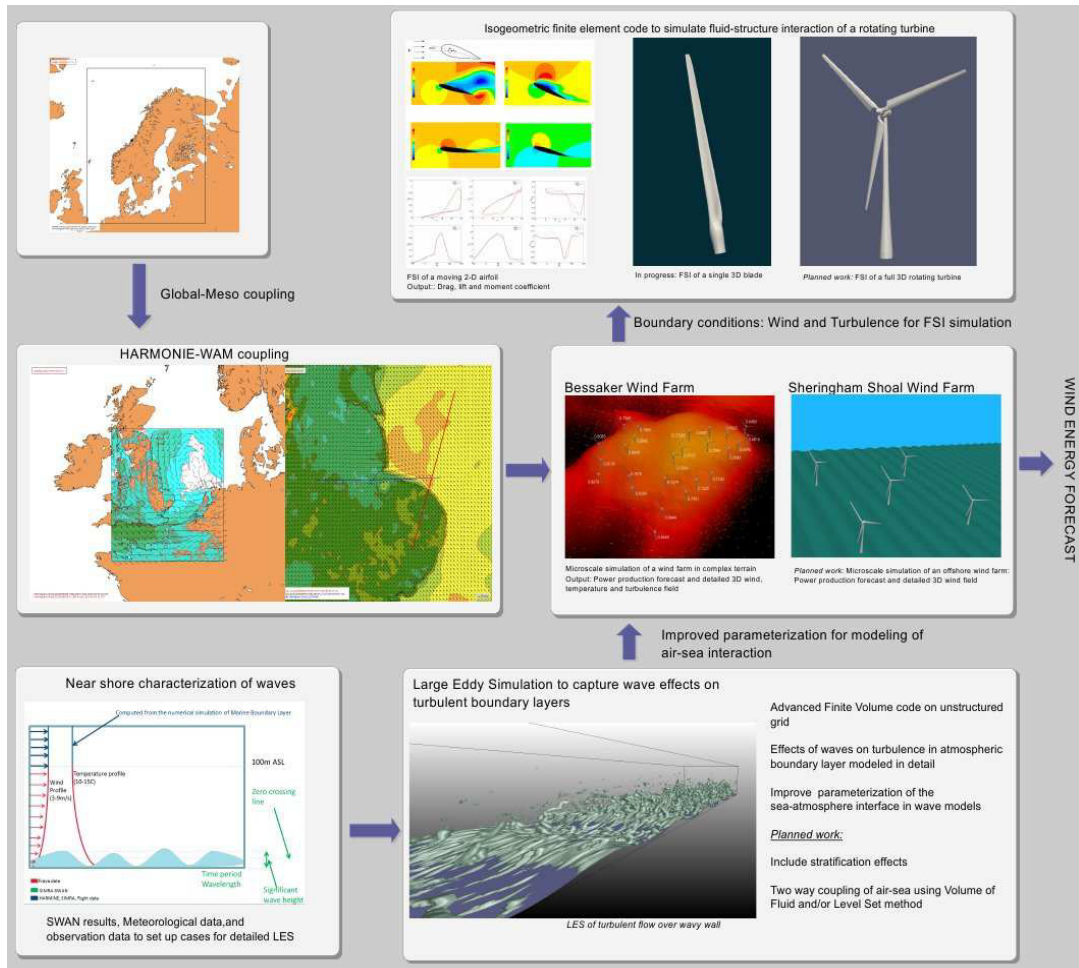


Fig. 11. Synergy between different activities

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