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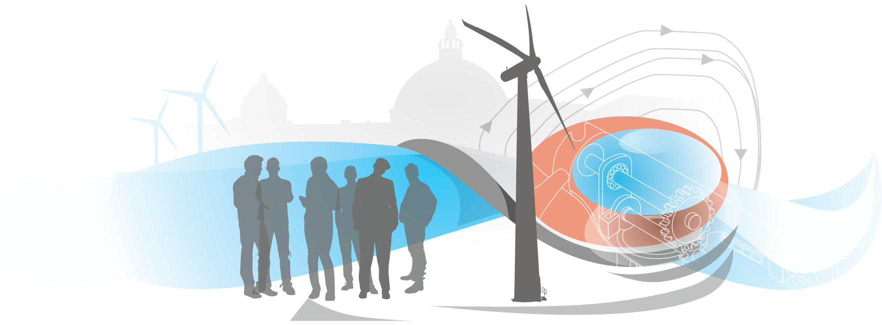

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Rotor & wake aerodynamics

Vortex Method Application for Aerodynamic Loads on Rotor Blades

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Keywords: rotor aerodynamics, vortex method, wake modeling, prescribed and free wake, lifting line and lifting surface.

INTRODUCTION

The aerodynamics of a wind turbine are dominated by aerodynamic flow around the rotor. There are different methods to model the aerodynamics of a wind turbine, such as blade element momentum (BEM) theory and solving the Navier-Stokes equations using computational fluid dynamics (CFD). Today, for design purposes, the use of engineering models based on the BEM method are prevailed. This method is fast and simple but it is acceptable only for a limited range of flow conditions and breaks-down in the turbulent wake state and the vortex ring state. There are some modifications based on empirical corrections to modify the BEM method in order to defeat this restriction. But, they are not relevant for all operating conditions and often go wrong at higher tip speed ratios. The vortex theory which is based on the potential, inviscid and irrotational flow can be a better choice to predict aerodynamic performance of wind turbine where its aim is to model a wind turbine consisting of finite number of blades (vs. BEM which assumes a wind turbine as an actuator disk) and wake geometry.

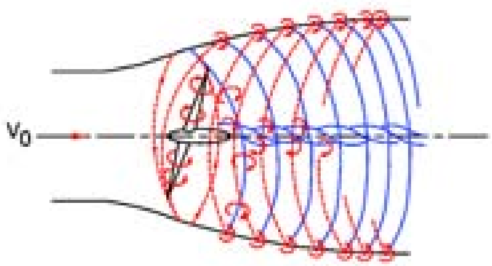

Figure **1**: Schematic of the vortex wake behind the rotor blades.

Compared to the BEM method,the vortex method is able to provide more physical solution and it is also valid over a wide range of turbine operating conditions.[1]

THEORY

Generally, the vortex flow properties can be categorized as an incompressible flow ($\nabla \cdot V = 0$) at every point and irrotational ($\nabla \times V = 0$) at every point except at the origin where the velocity is infinite.[2]

For an irrotational flow, a velocity potential (ϕ) can be defined as ($V = \nabla\phi$). Therefore, for a flow which is both incompressible and irrotational, the Laplace's equation ($\nabla^2\phi = 0$) is introduced. This means that one of the solutions to Laplace's equation can be based on the vortex flow.[2]

As stated above, the velocity field by a straight vortex line segment called induced velocity filed can be determined by the Biot-Savart law ($\vec{V}_{ind} = \frac{\Gamma}{4\pi}\frac{d\vec{l}\times\vec{r}}{|\vec{r}|^3}$) where Γ is the strength of the vortex flow and $\vec{r}$ is the distance vector from the vortex filament to an arbitrary point P [2].

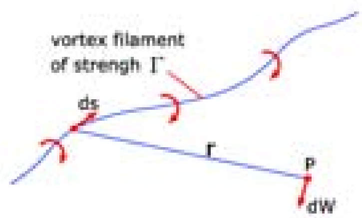

Figure **2**: Schematic for the Biot-Savart law.

According to the vortex theory, there are different approaches to model rotor blades and wake. Lifting line and lifting surface can be used to model the rotor blade while the wake can be simulated as prescribed wake or free wake where the wake elements are defined by vortex filaments.

In this paper, four different models are presented. In the prescribed wake model, the blade is modeled by lifting line and lifting surface while in the free wake, due to reducing the computational time (the computational cost of using a lifting surface model is higher than a simple lifting line model), it is modeled as lifting surface with one panel

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chord-wise known as Weissinger L-Type blade.

Also, in the prescribed wake model, the wake is modeled as either trailing vortices or vortex rings while in the free wake, the wake is divided into two regions, near wake which is modeled by trailing vortices and far wake by a single strong tip vortex.

BLADE MODEL

In the vortex theory, the blade can be introduced as lifting line or lifting surface. The rotor blade is divided into a number of spanwise sections where each section can be introduced as bound vortex with known circulation values. Here, their difference are described.

Lifting line

In this model, the blade is divided into one or more sections replaced with a straight vortex filament of constant strength (for each section) Γ called bound vortex which is located at $1/4$ of chord line (behind the leading edge) along the span [2]. The control points where the bound vortex circulation and also induced velocities by the wake are calculated are located at the bound vortices of each section. The trailed wake vortices extend downstream from the $1/4$ chord making a series of horseshoe vortex filaments.

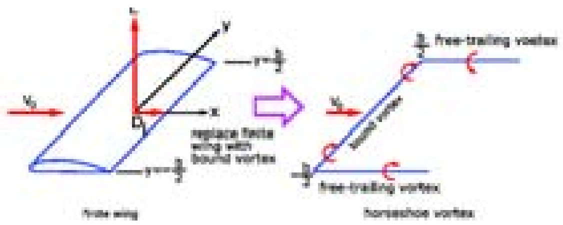

Figure **3**: Schematic of a lifting line model.

Lifting surface

Recall that vortex flow is an inviscid, irrotational and incompressible flow and its governing equation can be stated as the Laplace's equation. The proper boundary condition must be defined in order to solve this equation. The boundary condition which needs to be satisfied is the zero normal flow across the blade surface, $(\nabla(\Phi+\Phi_\infty)\cdot\mathbf{n}=0)$ [3]. In the lifting surface problem, this boundary condition means that the sum of the normal velocity component at each control point including the induced velocity by the bound vortices and wake as well as the free stream must be zero, $(V_{ind,bound}+V_{ind,wake}+V_\infty=0)$. Therefore, for each control point the normal vector is defined.

To solve the lifting surface problem, the blade is divided into a number of panels in chord-wise direction (or one panel chord-wise as a reduced model) and the wake can be presented as trailing horseshoe vortices or vortex rings.

For the lifting surface model with trailing horseshoe vortices, similar to lifting line, a straight bound vortex (for a twisted blade, it is not straight) is located along the blade and at each spanwise section where the leading edge is $1/4$ chord in front of it and the trailing edge of each section is $3/4$ chord behind it. The strength of the vortex Γ is assumed to be constant for the horseshoe vortex and a positive circulation is defined based on the right-hand rotation rule. The control points where the bound vortices circulation and the induced velocities due to the wake (trailing vortices) are evaluated, are placed at the $3/4$ chord behind the leading edge.[3]

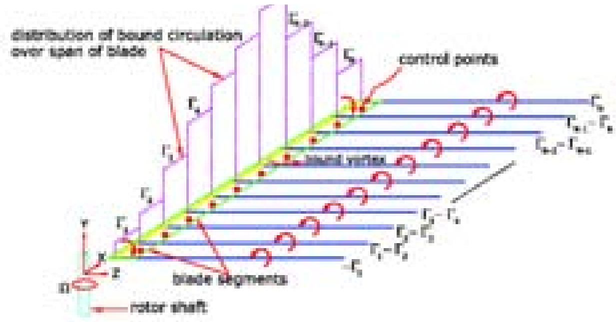

Figure **4**: Schematic of the Weissinger-L blade model.

DIFFERENT APPROACHES

Lifting Line Prescribed Vortex Wake

In this approach, the blade is modeled as lifting line and the trailed wake constructed by vortex filaments has a helical shape with constant diameter. Since the effect of the induced velocity field by far wake is small on the rotor blade, then we consider the wake length equal to $5D$ of the wind turbine rotor plane. Also the the wake are moving with a constant velocity equal to the inflow condition at rotor plane. [4]

Each blade section is considered as a $2D$ airfoil subjected to a local vector resultant velocity (V_{total}), including wind (V_∞), rotational (Ωr) and induced velocities (V_{ind}). According to the Kutta-Jukowski theory $(L' = \rho V_{total}\Gamma)$, the lift force per span L' of each blade element is related to the circulation Γ where ρ denotes the local air density.

The trailing vortices originating from the blade bound vortices emanate from all points along the blade and generates a helical vortex sheet behind of each rotor blade. These helical vortex sheets induce velocity field around the rotor blade reducing the angle of attack seen by each blade section. In that case the real angle of attack called effective angle of attack can be defined as $(\alpha_{eff}=\alpha_{geom}-\alpha_{ind})$.

Lifting Surface Prescribed Vortex Wake

Here, the blade is presented as lifting surface with only one panel chord-wise called Weissinger L-Type model [5] and the wake system is totally similar to the lifting line prescribed wake. The first step of the solution is to compute the unknown values of circulation (Γ) at each blade section by fulfilling the flow tangency (zero normal flow) as boundary condition at each control point located at the $3/4$ chord line of each blade element.

Panel Method Prescribed Vortex Wake

The panel method is based on the thin lifting surface theory by vortex ring elements where the blade surface is replaced by the panels which are constructed based on the camberline of each blade section. The blade is divided into number of panels both in chord-wise and spanwise directions which contains vortex rings with strength Γ_{ij} where i and j are panel indices in chord-wise and spanwise directions and a positive Γ is defined as the right-hand rotation. The leading segment of the vortex ring is located at the $1/4$ panel chord line and the trailing segment is located at the $3/4$ panel chord line. Therefore, the control point is placed at the center of the vortex ring. The normal vector at each control points is defined where the zero normal flow boundary condition across the blade must be satisfied.[3]

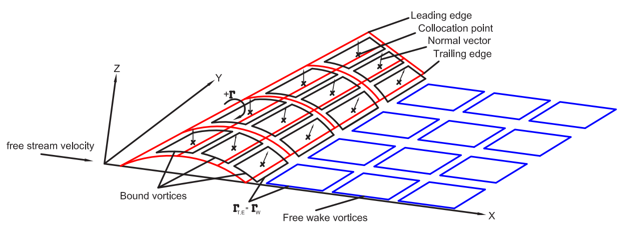

Figure **5**: Schematic of a blade and wake in panel method.

Free Vortex Wake

In this method, the blade is modeled as lifting surface with only one panel chordwise (Weissinger L-Type) and the wake is divided into two parts: near wake and far wake.

The near wake modeled as helical horseshoe trailing vortices extend only 30 degree of blade revolution where the far wake is presented as a single strong tip vortex.

To determine the radial position and the strength of the tip vortex, it is assumed that the trailing vortices outboard of the maximum lift are rolled-up into a one tip vortex with a strength equal to the maximum blade bound vortices while its radial release point is assumed to be at the physical blade tip.

In free vortex wake method, Lagrangian markers are placed on the vortex filaments trailing from the blades and it is assumed that each two consequent markers are connected to each other by a straight vortex filament. The governing equation for the movement of each Lagrangian marker can be written as $\frac{d\vec{r}}{dt} = \vec{V}(\vec{r},t), \vec{r}(0) = \vec{r}_0$ where $\vec{r}_0$ is the initial position vector of the marker. The velocity term in the right-hand side of the governing equation includes different terms such as free stream, rotational, induced velocities. The induced velocity term contains the

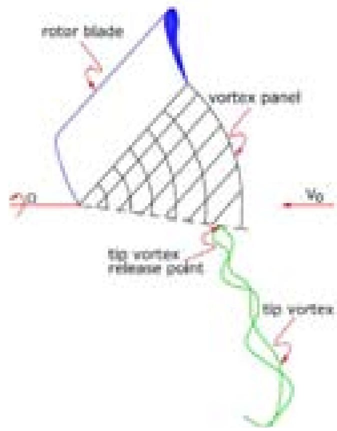

Figure **6**: Schematic of near and far wake of free wake model.

induced velocity produced by blades and wake. In free wake model against the prescribed wake, since the interaction between the wake elements by the Biot-Savart law are taken into account, then the computational time is much higher than the prescribed one.

RESULTS

Here is some preliminary results to compare different approaches. The $5MW$ reference wind turbine [6] has been used fir evaluation and the operating condition has defined as $V_\infty = 8.0[m/s]$ and $1.0032[rad/s]$ as wind velocity and rotational velocity, respectively. The results of each method have been compared with GENUVP. [1].

Figure 7 shows both geometric and effective angle of attack. As can be seen, in all cases, because of the Wake induced velocity field around the rotor blade, the effective angle of attack is less than the geometric one.

The distribution of circulation along the rotor blade is shown in Fig.8 where as we expected before, the maximum value occurs near the blade tip.

Figure

The tangential and normal forces generating torque and thrust, respectively on wind turbine are the most important forces acted on the blade. According to Fig.9,10, their maximum values are near the tip.

The normal force producing the thrust

CONCLUSIONS

Four different approaches of vortex theory application for wind turbine performance analysis has been applied. based on the results, it seems that the the panel method and free wake models give better prediction compared with

[1] GENUVP is an unsteady flow solver based on vortex blob approximations developed for rotor systems by National Technical University of Athens. (Courtesy of Prof. Spyros Voutsinas)

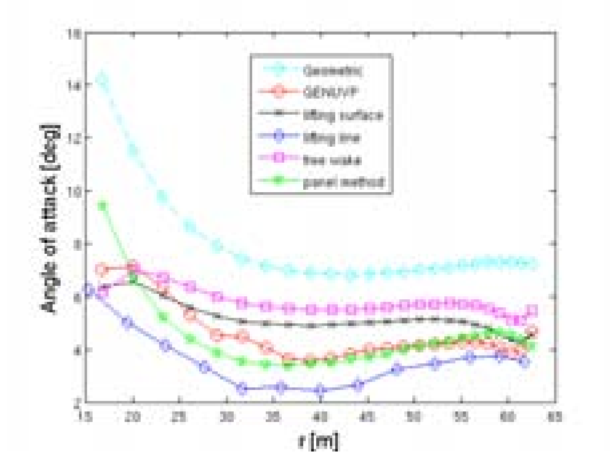

Figure **7**: Angle of attack, geometric vs. effective

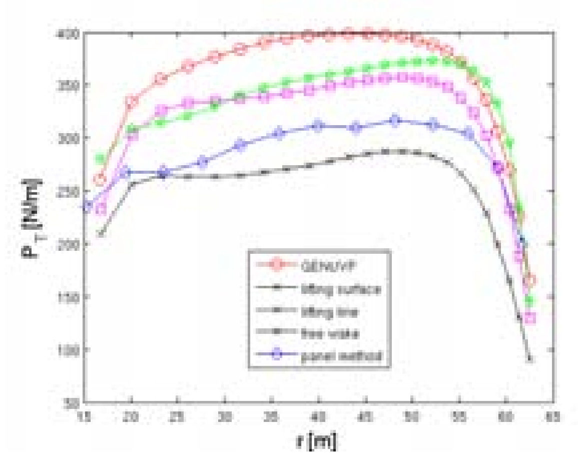

Figure **9**: Tangential force acting on the rotor plane

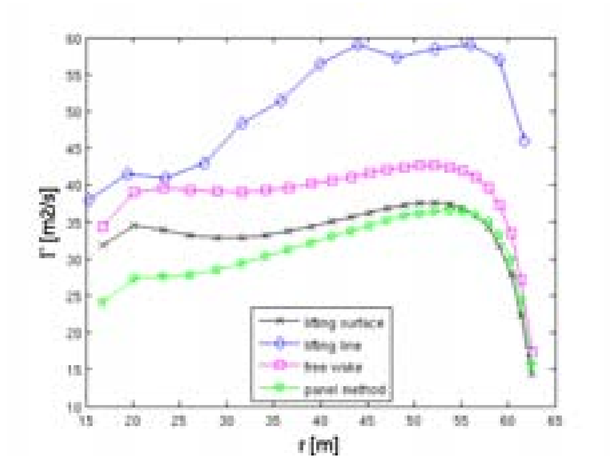

Figure **8**: Circulation distribution along the blade

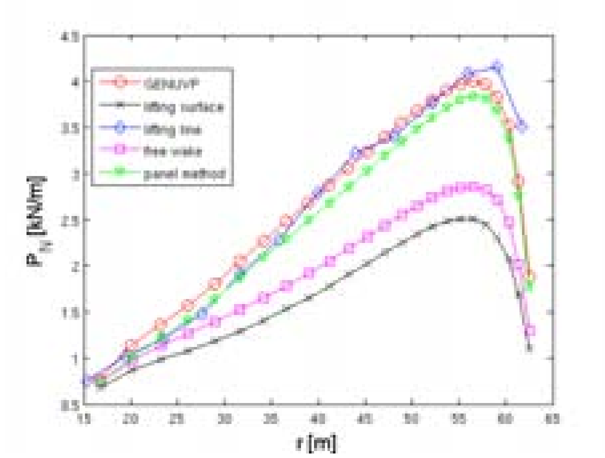

Figure **10**: Normal force acting on the rotor plane

other approaches. It seems that using lifting surface with only one panel chordwise is not a suitable choice for simulation because of lacking the effect of the blade surface curvature, but the its computational time can consider as the advantage of this method.

In lifting line method, dependency of the results to the aerodynamic tables such as C_L and C_D very obvious. To conclude, the vortex method for analysis of wind turbine aerodynamics can be a suitable way which still needs more comprehensive studies in order to get the more realistic solutions.

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Analytical and Numerical Study of a Constantly Loaded Actuator Disk using CFX

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Keywords: CFD, CFX, Actuator disk

Introduction

This study investigates a constantly loaded actuator disk model without rotation which is compared to previous theoretical and numerical modelling results; as well as previous experimental work. The aim of this study is to compare an actuator disk model without rotation to the literature.

Methodology

The work described used the commercially available computational simulation suite ANSYS-Workbench. The actuator disk was created as a thin cylinder using ANSYS DesignModeler with the computational fluid dynamics (CFD) calculations performed using ANSYS-CFX. The disc was modelled with an unstructured mesh and using symmetry conditions in the centre XY plane through the disc. The data produced were analyzed using both ANSYS and MATLAB and compared to the one-dimensional (1D) momentum theory [1] as well as previous studies featuring both numerical (of similar constantly loaded actuator disks without rotation [2]) and experimental data (of a small scale porous disk [3]). The actuator disk was modelled as a momumtum loss using aresistance loss coefficient related to the thrust coefficient (C_T).

Results

The model showed good agreement with the 1D momentum theory [1] in terms of the velocity and pressure profiles from a qualitative viewpoint. Similarly good agreement was shown when compared to previous numerical work [2] in terms of the quantitative velocity field. As expected this agreement deteriorated when compared to previously published empirical data [3] with respect to the velocity profile and particularly the turbulence intensity.

Conclusions

The study has shown how important the mesh reolution can be in capturing the flow charateritics and that the wake structure and recovery are affected principally by the thrust coefficient (C_T). Despite the lack of rotation and constant loading of the actuator disk model used in this study, good results were still obtained.

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Figures

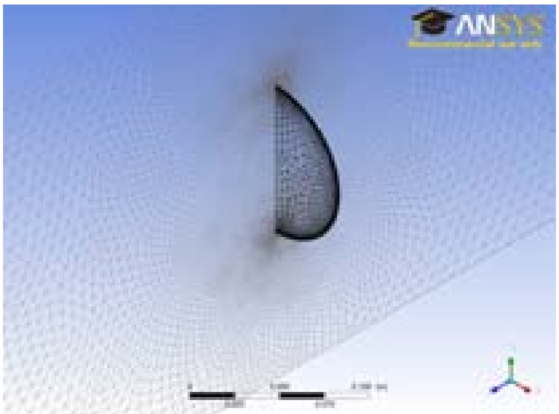

Figure 1: An unstructured mesh used as part of the study with the disc in the centre of the image in black.

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Measurements in Wakes of Multi-MW Wind Turbines

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Keywords: UAV, wind turbine, near wake

Introduction

A novel measurement approach [Kocer et al, 2011] has been developed to measure the flow field around full-scale wind turbines. The key enabler for this novel approach is the integration of fast response aerodynamic probe technology with miniaturized hardware & software for uninhabited aerial vehicles (UAV) that enable autonomous UAV operation. The measurements of the near wake of a 2 MW wind turbine that is located in a topography of complex terrain and varied vegetation are reported here. The measurements are conducted to support the development of ETH Zurich's advanced wind simulation tool [Jafari et al, 2012].

Measurement system

The unsteady, three-dimensional flowfield around the wind turbine is measured using the instrumented UAV shown in Fig. 1. This electric-powered, pusher-propeller-driven UAV has a wingspan of 800 mm, an overall length of 750 mm and a take-off mass of 900 g.

Figure 1: Instrumented UAV (wingspan, 800 mm) equipped with a seven-sensor fast response aerodynamic probe (diameter, 20 mm).

The UAV is instrumented with a seven-sensor fast response probe (7S-FRAP) for measurements of the wind flow [Mansour et al, 2011]. The sensing elements of the 7S-FRAP are miniature silicon piezo-resistive chips. These differential pressure sensors are embedded within a 20 mm hemispherical probe head; thus the 7S-FRAP yields measurements of the wind speed relative to the UAV. A GPS onboard the UAV yields the ground speed; therefore, the wind speed relative to the ground can be determined.

Results

The evolutions of the velocity deficit are measured in the wakes of the wind turbines that are located at two different sites. At both sites the wind turbines are operating under comparable conditions. The comparison of the wakes' evolution in terms of the measured velocity deficit at hub height, at three different span wise positions is given in Fig. 2. The comparison of the velocity deficits indicates a maximum difference of 15% at hub and mid span and 10% at rotor tip. There is generally good agreement in the measured evolutions of the wakes at two sites.

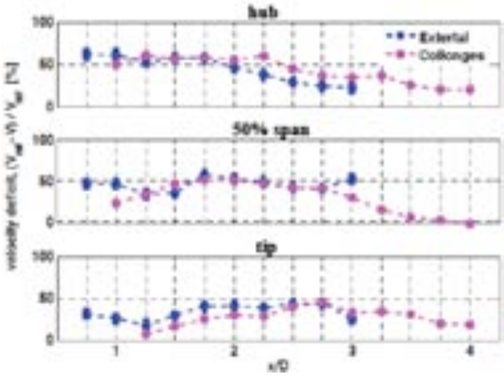

Figure 2 Comparison of stream wise evolutions of velocity deficit at hub, 50%span and tip measured at two sites.

Conclusions

Detailed measurements in the near-wake of two full-scale wind turbines are made using an instrumented UAV. These data are used to support the development of ETH Zurich's advanced wind simulation tool.

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Experimental and numerical analysis of horizontal axis wind turbine wake – Tip vortex evolution

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Keywords: Horizontal axis wind turbine wake, tip vortex decay, PIV experiment, Vortex-In-Cell method.

Introduction

The wind-produced kWh is still a rather costly good and, if its penetration in the world energy market shall be enhanced, as for any other energy resource the "fuel" must be used in a more efficient way and the O&M costs must be reduced. For the case of a wind farm, this is translated in smarter control and more strategic turbine layouts aimed at containing the power losses and the increased structural loads due to wake effects. This are matters to address in the early design phase by mean of efficient flow simulation tools. The current design codes find their basis in the 1980s, when they were developed to model the flow within small wind farms: they are mostly algebraic models [3,4,5] or simplified Navier-Stokes solvers [7], lacking of many of the required physical processes which are needed to predict wind turbine wake behaviour. This results in unpredicted wake losses by 10% in many operational wind farms. The present project is part of the general attempt to increase the knowledge on the physical behaviour of wind turbine wakes. This is addressed from both the numerical and experimental sides. The ultimate objective is to establish a relationship between near wake dynamics and far wake behaviour and to propose and quantify modifications to the current wake models, for decreasing uncertainties and enhancing the accuracy of power loss prediction within a reasonable amount of computational time.

PIV Measurements and Vortex code

A series of PIV measurements will be performed in the OJF tunnel of TUDelft with 0.5 m diameters two-bladed turbines. The tip vortex breakdown is considered as the sign of transition from near to far wake. This transition is assumed to be the onset of a more efficient re-energisation process of the wake and as such its localisation is very important for design and control purposes. The near wake extension will be measured for different inflow conditions. In a first campaign the relationship between the free stream turbulence intensity and the near wake length will be studied. The results will be compared to existing mathematical models [2]. In another experimental campaign, two rotors will be placed in a tandem set up, in order to determine the near wake extension with wake interaction, both in a full wake and in partial wake situations. The wake interaction will also be analysed in the case of two actuator discs in tandem and in the case of a rotor in the wake of an actuator disc. This will help to evaluate the error due to the actuator disc approximation in numerical simulations. During the experiments, the relation between the torque applied on the rotor and the rotation of the wake will also be studied.

A new wake simulation tool is being implemented. It is based on a 3-D Vortex-In-Cell (VIC) model. The model is characterised by a very low numerical diffusion, an indispensable features when the evolution of complex vortex structures needs to be captured .The novelty of this implementation is the generation of turbulence, which will be introduced in the inlet plane by a synthetic turbulence generator and not via costly precursor simulations of a turbulent ABL, as it is often done in LES and recently in a VIC code for the simulation of a HAWT [1]. The model of Mann [6] and Xie and Castro [8] will be evaluated.

Conclusions

The diffusion and breakdown of the near wake and the effect on the far wake will be studied, with special focus on the influence of ambient turbulence and of wake interaction. The outcome of the present project will constitute the backbone of the improvements which are to be made to the current simulation codes, as well as for their validation.

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Effect of Spinner Geometry and Rotation on the Flow near the Hub of Modern Wind Turbines

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Keywords: rotating body, spinner, NREL offshore 5-MW baseline wind turbine, CFD.

INTRODUCTION

Flow separation in the blade root region of modern wind turbines leads to a power loss. The blade root region consists of a rotating spinner, three rotating blades and a fixed nacelle. The flow in this region is inherently unsteady and three-dimensional. It is governed by effects of rotating spinner, drag interference between pairs of blades, flow separation and vortex formation at the blade root.

With a variety of spinner geometries of modern wind turbines (Figure 1), we are interested in the effects of spinner geometry on the flow in the blade root region. To investigate the effects of spinner variations, a simplified Computational Fluid Dynamics (CFD) model was proposed with a rotating spinner and a fixed nacelle without blades.

NUMERICAL SIMULATION

The CFD model included a real scale rotating spinner and a fixed nacelle. It was based on the NREL offshore 5-MW baseline wind turbine [1]. Reynolds Averaged Navier-Stokes equations (RANS) were used in this steady simulation.

Three different spinner geometries were investigated, including an elliptical spinner with spinner diameter D_S = 4.6 m, a blunt elliptical spinner with D_S = 4.6 m and a conical spinner with D_S = 5.2 m. The effect of rotation and spinner geometry were investigated in the rated condition of U_∞ =11.4 m/s.

RESULTS

The surface pressure distribution on the elliptical spinner in the flow direction shows a slight difference between the rotating and non-rotating spinners. The tangent force on the rotating spinner increases only about 1.5% with respect to the non-rotating spinner. This difference appears on the position of spinner with maximal radius (Figure 2).

The flow is accelerated when it passes the spinner, who induces a radial flow component. The region with accelerated and induced radial flow is depicted in Figure 3 for the three spinner geometries. For a real scale elliptical spinner of NREL offshore 5-MW baseline wind turbine, the accelerated flow region extents to maximal 8.6% of non-dimensional radial position $\mu = r / R$ and the induced radial flow region to μ = 0.093. For a conical spinner the accelerated flow region is shifted downstream along the nacelle and induced radial flow region covers the whole spinner.

CONCLUSIONS

Based on CFD simulations of the flow past different spinner geometries, the effect of rotation of the spinner with a fixed nacelle of modern wind turbine was investigated. The accelerated flow region past the conical spinner is shifted downstream along the nacelle and its induced radial flow region covers the whole spinner. Spinner geometry is a control factor on the flow in the blade root region.

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FIGURES

Figure1: Spinner geometries.

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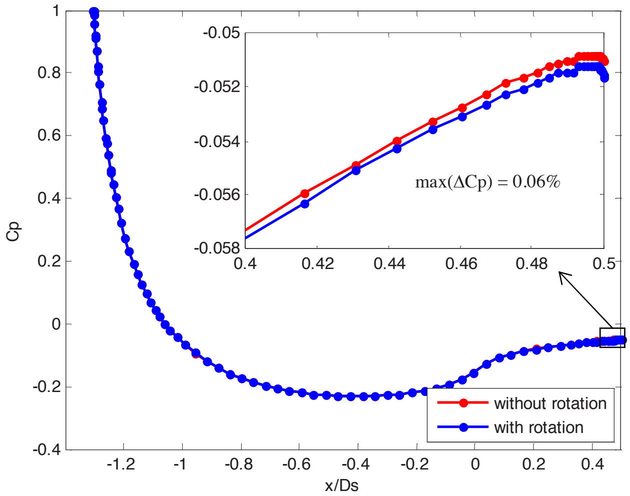

Figure 2: Surface pressure distribution on the elliptical spinner.

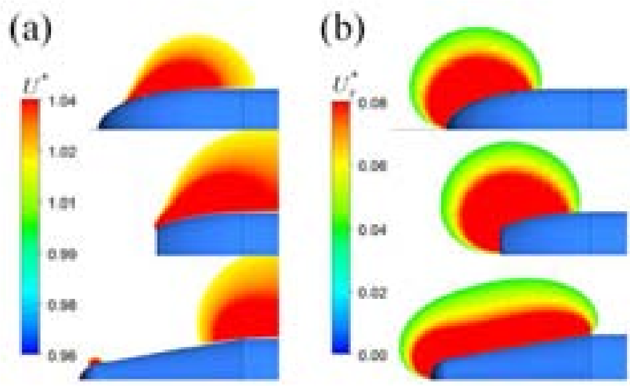

Figure 3: (a) Accelerated flow region; (b) induced radial flow region.

3D effects in the near wake of a VAWT

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Keywords: Rotor Aerodynamics, Wake Aerodynamics, Vertical Axis Wind Turbine, Vortex Particles Methods, GPGPU, CUDA

Introduction

Vertical Axis Wind Turbines (VAWTs) are currently experiencing a renewed interest, both in industry and in academia. This is going beyond the field of small rotors (< 100kW) for urban environment where they have commonly been applied. VAWTs represent an interesting alternative to the more popular Horizontal Axis Wind Turbines (HAWTs) for offshore (floating) multi-megawatt machines thanks to their higher scalability, greater simplicity of construction and of maintenance. There is, however, a lack of extensive and updated research on the physical phenomena characterizing VAWT aerodynamics.

The present research focuses on analyzing the wake aerodynamics of a VAWT by means of a GPU-accelerated Vortex Particle Method (VPM). 3D effects, in particular the tip vortex motion and its effect on the wake recovery, are mainly addressed.

The Hypothesis

The wake of a VAWT differs substantially from that of a HAWT, not only for the way it is created but also in its dynamics. VAWT's wake is inherently unsteady and three-dimensional with a high level of vorticity caused by the azimuthal variation of circulation around the blades. Multiple blade-wake interactions (BWI) cause elements of instability which then propagates downstream.

Experiments conducted with StereoPIV in the OJF of TUDelft [1] showed an inboard movement of the tip vortices, while the wake expands perpendicular to the wind direction and the axis of rotation. In the wake of a HAWT the expansion is radial and the tip vortices move outboard. The VAWT's inboard motion of the tip vortices is supposed to enhance the wake recover by increasing the mixing of the wake with the free stream.

This might have a positive consequence in a wind farm scenario where the distance between turbines could be decreased, optimizing the wind farm extension.

Numerical Analysis

A VPM model is used for the numerical analysis of the wake of VAWTs. The body is modeled with panels of source and doublets elements while the wake is model with vortex filaments, free to evolve under mutual induction. The model is able to catch the unsteady 3D aerodynamics of VAWTs. The code has been accelerated by running in parallel on Graphic Processing Units. The CUDA architecture has been used and the code runs on a 256-core NVIDIA GPU. This allows the use of direct integration for the calculation of the wake induction. The model is thus completely gridless, avoiding numerical diffusion, and doesn't introduce approximations in the velocity recover with multipole methods. A viscous sub-model is being implemented in the code to allow for simulation of viscous diffusion of the wake vorticity.

Experimental data are used to validate the numerical results. The numerical data then serves for a better understanding of the dynamics of the tip vortices, the influence that these have on the wake recover and the turbine's parameters which control the inboard motion.

Conclusions and Future Work

Preliminary results from the inviscid numerical model showed the inboard motion of the tip vortices, in agreement with experimental results. A parametric study on the space discretization of the body and the time discretization is being carried on to verify the convergence of the model. Next the diffusion sub/model will be implemented to account for viscous diffusion and allow the up-scaling of the turbine model from the wind tunnel size to the MW target size.

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Experimental methodology for the study of the far wake meandering of a modeled wind turbine

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Keywords: atmospheric boundary layer**,** far wake aerodynamics, wake meandering, hot wire anemometry, experimental methods

Introduction

Wind turbines long term power production prediction and maintenance planning has shown to be inaccurate. One reason is that unsteady wind turbine wake interaction in wind turbine fields is not taken into account in classical models used by the industry.

Far wake of wind turbines located in ABL flows is characterized by a non periodic trajectory variation called meandering. The objective of the experiments described here is to inquire whether the wake unsteady behaviour can actually be described as a passive tracer of the atmospheric boundary layer (ABL) large scale turbulence[1]. This behaviour would be analogous to the dispersion of pollutants in the atmosphere.

Section 1 : Methodology

One part of the work has been dedicated to the development of a methodology for horizontal wake tracking by mean of a static hot wire rake. Hot wire sampling rate is high enough to be useful for spectral analysis, as opposed to slow particle image velocimetry (PIV)[2].

Validation data is provided by simultaneous PIV measurements (Fig. 1), to ensure that the wake centre calculated from spatially sparse but temporally rich hot wire data is consistent with the wake center obtained from PIV data (high spatial resolution but low sampling rate, Fig. 2).

Section 2 : Data analysis

The wake centre position time series obtained via hot wire data are correlated with the transversal velocity measured in the upstream wind flow.

The inter-correlation figure (Fig. 3) shows a clear peak in the vicinity of the anticipated time interval, matching the main flow convection speed and longitudinal spacing of the measurement points.

Coherence and phase analysis (Fig. 4) reveal that the correlation is close to the maximum value in the low frequency region, and then progressively decreasing and reaching 0 at a cut-off frequency $\boldsymbol{f_c}$ that is possibly directly linked to the average longitudinal wind speed $\boldsymbol{U}$ and wake diameter $\boldsymbol{D_w}$ by a relationship such as $\boldsymbol{f_c = \frac{U}{2D_w}}$ [3].

Conclusions

This work demonstrates the opportunity of temporally resolved actuator disc wake tracking by mean of a hot wire rake in experimental conditions.

The data collected indicates a strong correlation between low frequency upstream turbulence and wake trajectory. This and previous work on the subject suggest the possibility of extrapolating from experimental and numerical results a realistic transfer function between the approach flow turbulence and wake meandering.

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Figures

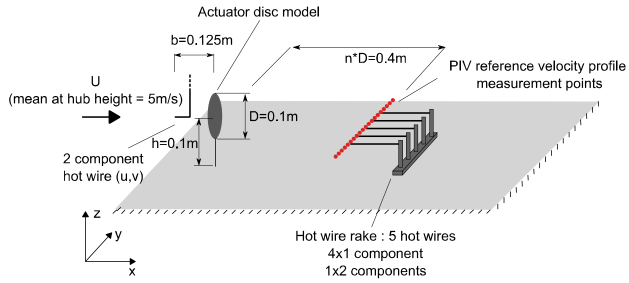

Figure 1: Experimental set-up

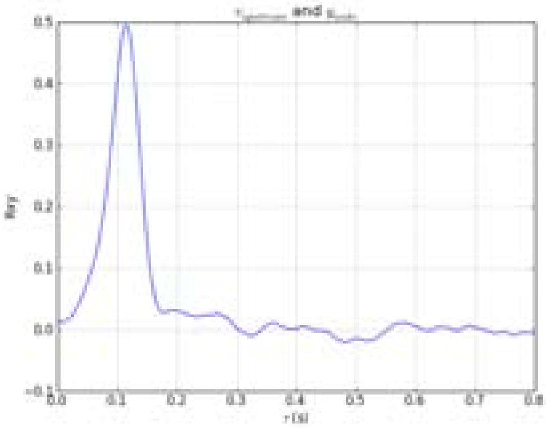

Figure 3: Cross-correlation between $v_{upstream}$ the transverse component of the upstream velocity and y_{wake} the horizontal position of the wake.

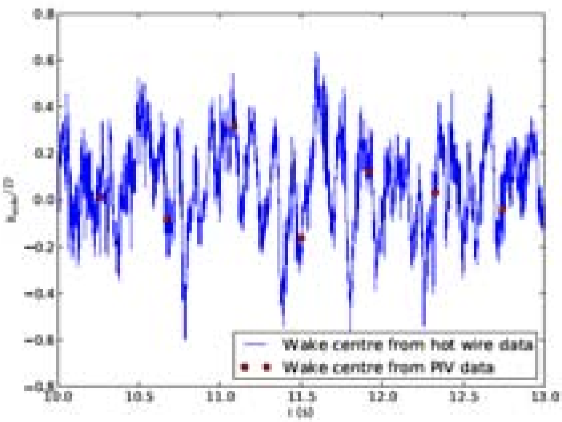

Figure 2: Sample of the wake centre time serie obtained by hot wire anemometry, along with PIV data for validation

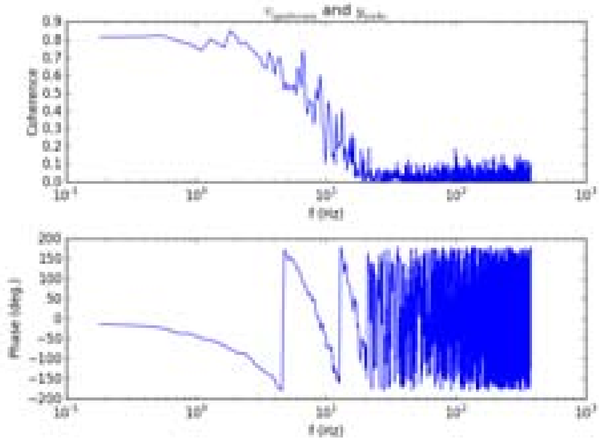

Figure 4: Coherence and phase diagrams between $v_{upstream}$ and y_{wake}

Application of a coupled near and far wake model for wind turbine rotor aerodynamics

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Keywords: rotor aerodynamics, near wake model, vortex model, indicial function

Introduction

A coupled model for unsteady wind turbine aerodynamics, based on the work by Beddoes, [1], Madsen and Rasmussen, [2], and Andersen, [3], has been further developed and applied to calculate the aerodynamic forces on vibrating wind turbine blades. The model consists of a near wake model to account for the aerodynamic coupling of different radial sections on the blade and the fast unsteady effects, and a BEM model, which provides the mean induction from the far wake and can handle slow dynamic inflow effects.

Model description

The near wake model only includes the induction from the trailed vorticity in approximately the first 90 degrees of rotation. The vortex filaments move along prescribed circular arcs, which allows for approximating their exact induction according to the Biot-Savart law by exponential indicial functions. Due to this approximation, an efficient trailing wake algorithm can be used to compute the effects of the trailed vorticity.

The shed vorticity is handled by an indicial function model based on Theodorsen theory. The far wake model is coupled to the near wake model through the thrust coefficient, which is reduced by a coupling factor that depends on the operating conditions of the turbine.

Results

Preliminary results of the coupled aerodynamic model are shown in Figure 1. The rotor of the NREL 5 MW reference turbine has been used in the computations. Prescribed flapwise blade vibrations with an amplitude of 0.25 meters at the blade tip and a frequency of 1 Hz are applied after the startup of the rotor. These vibrations are mostly accounted for by the near wake model. A pitch step of 4° in 0.5 seconds shows the capability of the coupled model to simulate both slow and fast unsteady effects.

Conclusions

A coupled wake model has been implemented that can be used to compute the aerodynamic forces in steady and unsteady conditions. Since the near wake model takes the radial coupling between blade sections and the radial dependency of the time constants into account, it is thought to be valuable for future investigations of aeroelastic stability.

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Figures

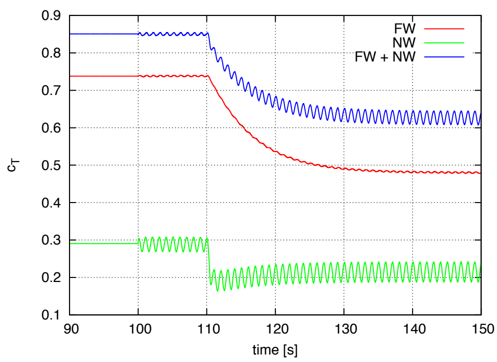

Figure 1: Thrust coefficient of the NREL 5 MW turbine due to the far wake, near wake and combined induction. The hub wind speed is 8 m/s. The simulation includes prescribed flapwise vibrations of the blades and a pitch step.

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Two Bladed Wind Turbines: Undetermined for more than 30 Years

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Keywords: two bladed turbines, design concepts, teeter, load reduction

Introduction

Two bladed wind turbines have been discussed since the beginning of modern wind energy. However, in contrast to three bladed turbines they have been quite unsuccessful due to diverse reasons. Partially these reasons came from onshore requirements, as the optical and acoustical behavior of a two bladed turbine is quite unfavourable in contrast to a three bladed one. Higher dynamic loads are a second reason why two bladed turbines were not regarded by most turbine manufacturers.

Today, the debate on two bladed turbines comes up again, as there might be advantages of those turbines in the offshore area.

This paper questions the suitable design of two bladed turbines. This will be done with a look back in history and a structured analysis of today's two bladed turbines.

The eighties and Nineties

A look back in history shows that quite an amount of former multi-megawatt research turbines was two bladed. Especially in the late seventies and eighties national research programmes on wind energy led to diverse two bladed turbine concepts. A second round of those programmes was done in the nineties.

Having a closer look on basic turbine design aspects (rotor position, power control, yaw system, load reduction) it can be seen that there was a wide diversity. Especially looking at load reduction a two bladed turbine offers different possibilities to teeter which is an opportunity that a three bladed turbine does not have.

It seems obvious that the first research turbines in the late seventies and early eighties showed diverse design concepts.

However, the interest in experiments does not seem to stop. Even in the time between 1990 and 2000, where a lot of experiences was gained with the first turbines, a common understanding of the "ideal" turbine concept did not seem to come up.

Today

This situation does not change if you have a look on today's two bladed wind turbines. From nine current turbines, each of them has its own unique design configuration. Especially the teeter mechanism still seems to have a certain attention as four of nine analysed concepts consider a teetered hub as passive load reduction. This is remarkable especially as methods for active load reduction (e.g. individual pitch control) offer opportunities which were not available on earlier wind turbines.

Conclusions

During more than 30 years of the dominant three bladed wind turbine development, two bladed turbines were developed at quite regular intervals.

Despite such a long time of experiences there seems to be no common understanding of a "state of the art" two bladed wind turbine. If two bladed wind turbines should be regarded for offshore use there is still a lot of research to be done as many questions especially about their most suitable load reduction principle must be answered.

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Fluid-Structure-Interaction on Tidal Current Turbines

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Keywords: Fluid-Structure-Interaction, Tidal Energy, Tidal Current Turbine, Hydrodynamics, Hydroelastics, Multibody-Simulation, Computational Fluid Dynamics

Introduction

The research area of Tidal Current Turbines is related to the research on Wind Turbines. Both are based on the physical approach of a lift-driven open rotor. But due to the difference in density of water and air, the behavior of the fluidelastic systems differ. This behavior is investigated for a Tidal Current Turbine in this research project. While the actual state of the art for tidal energies focuses on very conservative and simplified approaches, a deeper insight into the physics of the hydroelastics can lead to a major reduction of the cost of energy production.

Methodology

Hydroelastic Simulations

The known methods of coupled BEM- and Multibody-simulations used in wind energy research are problematic to use for Tidal Current Turbines. These problems arise due to the low aspect ratio and high hub to tip ratio compared to wind rotor blades and subsequent inaccurate fluid representation in BEM. Also the known methods of coupled CFD and FEM-simulations used for turbine blades do not lead to efficient results due to the fact that the stiffness of the blades and the rest of the mechanical system are of the same order. Based on these limitations, a new method of simulations is required.

In this research project CFD (Code: Ansys CFX) for the analysis of the fluid and Multibody-Methods (Code: Simpack) for the structural modelling are coupled. With this coupled method it will be possible to investigate the hydrodynamics and hydroelastics in detail. Also it will be possible to analyse the interaction of each mechanical system in the Tidal Current Turbine with the flow.

Numerical Water Tunnel

The fatigue loads on Tidal Current Turbines are mainly driven by three conditions. These are the turbulent inflow, the orbital velocities of waves and the rotor tower interaction. For each of these a model is implemented into the CFD-code to simulate the physical boundaries in a high enough resolution as an input for the Fluid-Structure-Interactions.

Results

The numerical water tunnel has been implemented, tested and is ready to be used with turbulence input files from the random phase methods, stochastic and deterministic waves based on the Airy- and Fenton-theories and rotor tower interactions based on the sliding mesh approach. The coupling of CFD and Multibody simulations is in progress and shows good results in the first simplified test cases.

Conclusions

Within this project a new method of simulation for Tidal Current Turbines to analyze the Fluid-Structure-Interactions will be developed. Ongoing research is required to improve the understanding of hydroelastics on Tidal Current Turbines.

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Figures

Figure 1: Tidal Current Turbine assembled in the workshop [Voith]

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Levels of Detail for Hydrodynamic Load Calculation Methods in Floating Offshore Wind Turbine Simulations

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Keywords: Floating Offshore Wind Turbines, Aero-Servo-Hydro-Elastic Simulation Code Development

Introduction

Most of the so far built offshore wind turbines are installed in shallow to intermediate water depths with bottom-fixed support structures. However, in deeper waters bottom-fixed support structures are not feasible anymore both from an economic and technological point of view [cf. 1, 2]. Accordingly, for countries with large water depths off their shore floating offshore wind turbines are the only solution in order to benefit from offshore wind energy.

This work presents the current state-of-the-art in hydrodynamics in aero-servo-hydro-elastic simulations for floating offshore wind turbines. Furthermore, an outlook is given on how this state-of-the-art will be enhanced in the future.

Levels of Detail for Hydrodynamics

The simulation of floating offshore wind turbines with an appropriate level of accuracy is crucial as it is closely tied to the realization of reliable and cost-effective designs. Although there are simulation codes that can be used to simulate floating offshore wind turbines, their possibility to account for hydrodynamics is usually rather limited. Currently, it is common to use modifications of Morison's equation [3] to calculate the hydrodynamic loads as this is suitable while considering slender structures.

However, as the structures grow larger (as they do for floating offshore wind turbines), effects from radiation and diffraction as well as second-order effects need to be accounted for. For the time being, these effects are mostly neglected in the simulation codes [1, 4]. However, sophisticated hydrodynamic methods should be available to the users of aero-servo-hydro-elastic simulation codes. At the same time, the user must be able to use the simple approaches as well when it is appropriate.

For this work, the calculation methods for the calculation of hydrodynamic loads are categorized according to their level of detail. That is, there are simple low-level approaches such the before-mentioned Morison's equation [3] and also high-level approaches like, e.g., approaches that use time-consuming computational fluid dynamics (CFD) calculations.

Conclusions and Outlook

The categorization of methods for calculating hydrodynamic loads according to their level of detail is motivated and introduced. The next step is the definition of transformations between the levels of detail. That is, the user can transform the input parameters from a high-level approach into input parameters for a low-level approach. This will allow the user to keep his models consistent in an easy way. Furthermore, it will be investigated how appropriate the different levels of detail in the hydrodynamic load calculation are for floating offshore wind turbines. This will be done through verification (code-to-code comparison) and validation (code-to-measurement comparison).

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CFD simulation of MEXICO Rotor Experiment

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Keywords: CFD simulation, MEXICO experiment, yaw, immersed wind turbine model

Introduction

As global wind power capacity increases, wind farm power density should be optimized with respect to wind turbine placement and operation. The development of wakes and their subsequent interactions can have a profound impact on the annual energy output of a wind farm, particularly in offshore wind farms, where wake effects dominate the flowfield due to the low level of ambient turbulence. The modeling of wind turbine wakes and their interactions is one focus of the wind energy program at ETH Zurich. One development of the ETH Zurich program is an immersed boundary model for the terrain [1] and more recently an immersed boundary model for the wind turbine [2]. In order to specify accurate boundary conditions for the immersed boundary model, dynamically-scaled experiments and numerical simulations are being undertaken at ETH Zurich to detail the characteristics of the near-wake under different inflows and operating conditions. The present work describes the numerical simulations.

Methodology

This work documents the results of numerical simulations of the turbulent flow in the near wake downstream of a three-bladed wind turbine. The simulations are performed by Reynolds-Averaged Navier-Stokes (RANS) modeling, using the commercial solver ANSYS CFX 12.1 and including the full rotor (D=4.5 m), nacelle and tower geometry. The simulations are based on the Model Experiments in Controlled Conditions (MEXICO), conducted by the Energy Research Center of the Netherlands (ECN) [3]. Steady-state and unsteady simulations are carried out for both uniform and non-uniform inflow conditions at three tip-speed ratios $\lambda = 4.17, 6.67$ and 10. The results are compared to experiments to confirm grid independence and the effects of increasing tip-speed ratio and of yawed inflow of 30° are studied. Flow properties are reported across the rotor and at different downstream distances.

Results

The results show good agreement with experimental data both for the uniform and yawed inflow. Available from the MEXICO experiments are: pressure distributions on the blades, PIV flowfield measurements upstream and downstream of the rotor and forces on rotor, and bending root moments. Flowfield measurements extend from one rotor diameter (x=1D) upstream to 1.3 rotor diameters (x=-1.3D) downstream. Representative results for the turbulence intensity, velocity deficit and flow angles are presented over a plane downstream of the rotor (up to x=-2D). Moreover, the evolution of the tip vortices is visualized and the vortex pitch at different tip-speed ratios is estimated. Results at 30° yaw and =6.28 show a 20% reduction of the estimated torque and some fluctuation of the mean extracted torque is observed. Furthermore, the wake is skewed by 6° and large non-uniformity is observed in the wake properties.

Conclusions

The results of RANS simulations of the flow in the near wake of a three-bladed horizontal-axis wind turbine are presented. The simulations, which are based on the MEXICO experiment, show good agreement with experimental data and the detailed flow properties in the near wake are documented. Therefore, a tool is developed to estimate the detailed near-wake flow under both uniform and non-uniform conditions. The numerically predicted data serve as boundary conditions in the ETH Zurich immersed boundary wind turbine model, helping to expand its capabilities for yawed inflow and achieve modeling of the wake evolution with reduced computational effort.

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Turbine structure & materials

Modal and Sensitivity Analysis of the support of an offshore wind turbine under scattered soil parameters

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Keywords: offshore support structure, natural frequencies, probabilistic analysis, sensitivity analysis

Introduction

Modal analyses of an offshore support structure with different boundary conditions for soil-structure interaction concepts are investigated. Using sensitivity analysis the influences of various soil parameters on the natural frequencies of the support structure are examined.

Methodology

The numerical model of the investigated support structure is taken from the ForWind project “Probabilistic Safety Assessment of Offshore Wind Turbines” [1] consisting of Rotor Nacelle Assembly, Tower, Transition Piece, Substructure and Foundation. The model concerns a monopile substructure following the DOWEC pre-design [2]. The chosen tower desires from the DOWEC pre-design, which is based on a tower definition by NEG Micon Holland [2]. The DOWEC tower was also utilized within the OC3 Project [3]. The design basis of the investigated support structure is slightly modified to project specific needs (see further [1]).

The soil is modelled in two different ways. In a first investigation (model S1) the soil is simplified as a clamped bearing at three times the monopile’s outer diameter below mudline (see also [1]) and a modal analysis is conducted. In a second step the soil is modelled with spring and damper elements for a single sand soil layer (model S2). The spring stiffness in dependence of the soil layer is calculated with a program developed at the Institute for Geotechnical Engineering using P-y-curves. Therein typical loading conditions and ranges of soil parameters for the North Sea are assumed.

Within the second model (S2) the soil parameters are scattered and modal analyses are conducted. A sensitivity analysis for the numerical model of the chosen support structure and the statistical input parameters is performed to identify the influence of each soil parameter on the natural frequencies. The probabilistic analyses are carried out with the optimizing structural language optiSLang® [4].

Results

The natural frequencies of the support structure could be compared with the results presented in [2].

Comparison of the natural frequencies resulting from the simplified soil model (S1) and the sophisticated soil model (S2) results to deviations of 3 to 5%. Sensitivity analysis of the soil parameters shows that the natural frequencies are mainly influenced by the internal friction angle φ', but the deviations in the natural frequencies are not significant at all.

Conclusions

The influence of typical soil parameters on the natural frequencies of an offshore support structure was studied. Thereby a dependency between the internal friction angle and the natural frequencies was detected. However, modal analyses showed that this influence is not significant.

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Aerodynamic Damping in Offshore Wind Turbine Support Structure Design

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Keywords: offshore wind turbines, integrated design, support structures, aerodynamic damping

Introduction

In offshore wind turbine design, the turbine and the support structure are often separated. Once separated, proper interface modeling is a requisite for decent design. A main interaction mechanism is aerodynamic damping, resulting from the structural response of the blades to oscillating loads.

Currently, the damping resulting from aerodynamic response is partly integrated in the loads on the tower top and partly processed as modal damping of the first structural mode. This simple and rather simplistic approach mainly facilitates engineering purposes, but does not properly represent the dynamic interaction between structure and loads.

Current Practice: Distributed Damping

The incorporation of aerodynamic damping in support structure design is twofold. To determine tower top loads, the rotor is modeled rigidly fixed at the hub. The resulting loads include the damping effect of the oscillating flexible blades.

The additional damping, resulting from the flexible tower, is determined by assuming rigid blades. Subsequently, this damping is added to the continuously distributed structural damping of the tower and support structure, in order to facilitate simple finite element modelling. Ultimately, the total damping is converted to modal damping coefficients, usually only taking the first structural fore-aft mode into account.

By assuming the aerodynamic damping component, resulting from tower motion, as continuously distributed over the tower height, the discrete action of the turbine rotor at the tower top is neglected. The question rises whether a more physically correct model would significantly alter the structural response.

Discrete Dashpot Method

In accordance with the current practice, the offshore wind turbine is modelled as a cantilever beam, representing the tower and support structure. The rotor nacelle assembly is implemented as a lumped mass at the tower top. The structural damping is incorporated as viscous damping.

Instead of continuously distributed damping, the aerodynamic damping is represented by a discrete dashpot at the tower top. The different models are depicted in Figure 1. The steady state response to an oscillating top load of both models is compared. The comparison is done in the frequency domain, where both top deflection and maximum bending moment are compared.

Conclusions

By modelling the aerodynamic damping as a discrete dashpot, the structural response is affected significantly. As this manner of modelling represents the actual physics best, this method is to be preferred.

Moreover, the proposed approach does not obstruct the application of simple finite element models and allows for distinguished aerodynamic damping properties in the fore-aft and side-to-side modes.

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FIGURES

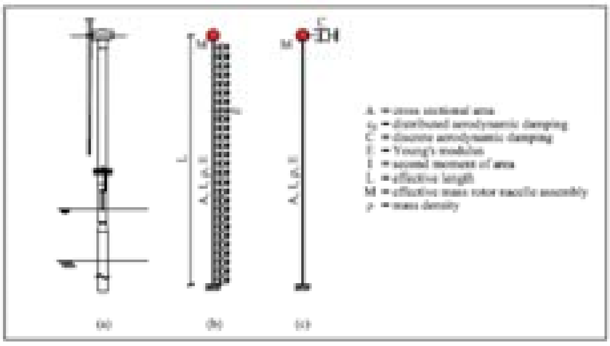

Figure 1: Schematic representation of (a) offshore wind turbine support structure, (b) cantilever beam model with discrete mass and distributed aerodynamic damping, and (c) cantilever beam model with discrete mass and discrete aerodynamic damping.

Cross-section analysis program for composite wind turbine blade

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Keywords: Cross-section analysis; Composite; Blade;CLT

Introduction

Most wind turbine blades are made of thin-walled shells with composite materials. Cross-sectional properties of the thin-walled shells, such as shear centre, mass centre and section stiffness, of the composite materials are essential information for the dynamic and aeroelastic analysis of wind turbine blade, in which the blade is often represented as one-dimensional beam instead of the three-dimensional shell. However, due to the complexity of composite material and blade structure topologies, it is not easy to obtain the cross-sectional properties of the blades.

Finite-element techniques, despite that they are accurate for stress and displacement analysis, cannot obtain cross-sectional properties directly. One has to rely on computationally complicated post-processing of force-displacement data. One of such post-processing tools is BPE(Blade Properties Extractor), which uses the displacements of the full finite element model of blade to a series of unit loads applied at the blade tip to obtain the stiffness matrices of the equivalent beam elements[1].

Comparing to finite-element techniques, classical lamination theory (CLT) is fast and reasonably accurate. Therefore, it has been widely used for analyzing composite materials. The CLT can be used to combine properties and the angle of each ply in a pre-specified stacking sequence to calculate the overall effective properties for a laminate. Based on several reasonable assumptions, the CLT enables us to transfer a complicated three-dimensional elasticity problem to a solvable two-dimensional problem[2]. One of the assumptions is that each ply is under the condition of plane stress, which is acceptable for composite blade due to the fact that most blades have thin-walled structure.

In this work, based on the CLT, a Matlab program is developed to calculate the cross-sectional properties of composite blade. The calculated results from the program are validated with experimental data which are available from reference [3].

Methodology

The cross-section of the blade is discretized into a number of area segments. The CLT[4] is applied on each area segment to obtain the effective material elastic parameters, which will be integrated to obtain the overall cross-sectional properties.

Results

The case study we used for the study is a two-cell composite wind turbine blade with elastic couplings[3]. Simulation results demonstrate a good agreement with the experimental data published in reference [3].

Conclusions

In this work, based on the CLT, a two dimensional cross-section analysis software code has been developed using Matlab. Comparison with published experimental data shows that the code provides adequate accuracy for calculating cross-sectional properties of composite wind turbine blade. It is believed that the code can be used as a useful pre-processor for blade dynamic and aeroelastic analysis.

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Monopile 2.0 for Offshore Wind Farm Princes Amalia

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Keywords: Support structure design, Offshore wind energy

Introduction

The support structure of an offshore wind turbine has a significant share(15-25%) in the costs [1][2]. In order to reduce the cost of energy(COE) in future wind farm, the support structures designs must be improved. In order to come to reduction of the cost of energy for future wind farms, the design of the support structures of the wind park Q7/Prinses Amalia are reviewed. The Prinses Amalia Wind Park(PAWP) is taken as a example for a desk study in order to illustrate the potential of reduction of COE. This wind farm started to produce power in March 2008 and consist of 60 Vestas V80 2.0MW turbines standing on 4.0m diameter monopiles just 20km off the coast of IJmuiden in the Netherlands. In figure 1 the layout of the support structure design of the Prinses Amalia wind park is given. This research is part of the FLOW [3] program, which strives to reduce cost and risk of offshore wind energy.

Approach

In order to make a review design of the support structures of the PAWP, the current monopile design is reviewed. The redesign is made with the current design limitation and regulations. This will point out whether the designs of the PAWP are conservative. Two methods of fatigue calculation are used to calculate the fatigue damage of the support structure designs. Subsequently, design constrictions, design choices, calculation considerations and design optimization are discussed in order to point out the potential of reduction of the COE by redesigning.

Conclusion

It is shown that a monopile of 3.5m in diameter could have been used. If scour would not be taken into account, as scour protection is applied, even a pile of 3.3m in diameter could have been used. These monopile designs of reduced diameter size are checked on the natural frequency requirements, yield ,local and global buckling, and fatigue. With the reduction of the diameter a reduction of the wave loads and the weight of the monopile is realized. With a more slender monopile a total weight reduction of the monopile of 26% could have been realized. Futhermore an outlook on future improvements of the design is given.

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Figures

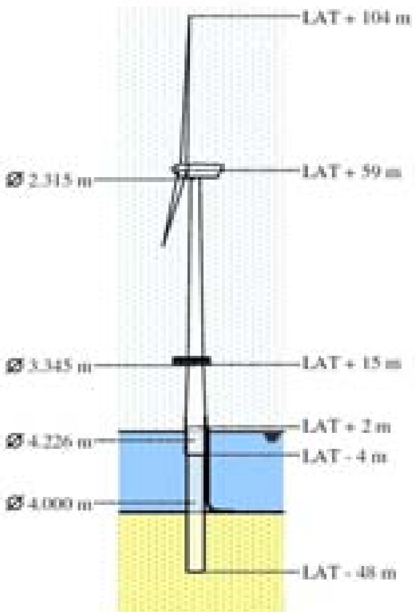

Figure 1: Layout of the monopile based support structure of the Prinses Amalia wind farm

Aerodynamic load & aeroelasticity

A New Aeroservoelastic Horizontal Axis Wind Turbine Analysis Tool: Code Validation

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As wind turbines are ever increasing in an effort to more efficiently harvest energy, non-linear structural effects start to play a more influential role. Traditional wind turbine analysis tools such as GH Bladed or NREL's FAST code are based on modal formulation of the structural model. By definition, these models cannot include geometric or material nonlinearities that may occur for very large wind turbines. Another short coming of these codes is that they only include traditional control methods such as pitch control. Neither code is designed for smart rotors, a research subject that attracts attention throughout the last decade. To overcome these limitations a new aeroservoelastic analysis tool for wind turbine with distributed trailing edge flaps. It was developed based on the experience gained from the first generation of aeroelastic codes of Delft University of Technology [1].

The code combines a dynamic inflow model with a Blade Element Momentum (BEM) approach. The two dimensional unsteady aerodynamic model that is used in the code is an implementation of the dynamic stall model of Andersen et al. [2] with the shape integrals developed by Gaunaa [3]. The model is an extension of the Beddoes-Leishman type dynamic stall model of Hansen et al. [4]. A Prandtl tip loss correction and root flow correction was used as described in [5]. This model was embedded in Simulink to make use of the SimMechanics package included in Matlab. A multi-body approach was used to simulate the structural dynamics. A multi-body code with a variable number of elements interconnected by 3 rotational degrees of freedom were used. The rotational degrees of freedom are modelled as discrete rotational springs. Flap dynamics have been modelled as force inputs to the structural model. Modal damping has been assigned in the spring-damper elements that connect the bodies. Both the aerodynamic module and the structural module can operate with a variable number of elements or aerodynamic sections. The aerodynamic loading is interpolated on the structural elements. The structural displacements, rotations and velocities are returned as input to the aerodynamic module.

The aerodynamic and structural model were created for this code. The input of the wind field has been significantly remodelled compared to previous codes of Delft University of Technology to decrease calculation time. The wind file generation is done in Turbsim, however the data is now pre-processed such that only part of the interpolation needs to be done during the execution of the code. The torque and pitch controller are implementations of [6], analogue to previous aeroelastic codes of Delft University of Technology.

In this paper the results of the benchmark of the new design code with traditional codes are presented for the 5MW reference turbine of NREL. Good agreement for a wide range of wind

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speeds has been found for power production, tip deflections, root bending moments and generator power. The dynamics of the wind turbine are compared as well. The natural frequencies for both edgewise and flapwise bending are in good agreement with the results obtained by FAST and Bladed. Finally, the unsteady load components have been investigated. The power spectral density of the root bending moment compares well with the load spectrum obtained by GH Bladed.

Keywords: Analysis Tool, Wind Turbine Aeroelasticity, Smart Rotor, Non-linear Structural Effects

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An Actively Controlled and Aeroelastically Scaled Wind Tunnel Wind Turbine Model

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Keywords: wind tunnel, aeroelasticity, control

INTRODUCTION

An aeroservoelastic model with individual blade pitch and torque control of the Vestas 3MW V90 wind turbine was developed at the POLI-Wind Laboratory of the Politecnico di Milano [1]. The model, shown in Figure 1, was designed for enabling a number of experimental investigations, including the testing of control laws, studies on the aeroelasticity and stability of wind turbines, and the calibration of simulation tools. In the present paper we describe the design and main characteristics of the experimental facility, and we present the results of some selected applications.

APPROACH AND METHODS

The model is operated in the boundary layer wind tunnel of the Politecnico di Milano (see Figure 2).

Aerodynamics

Among several stringent requirements, the rotor was designed so as to achieve good aerodynamic performance, notwithstanding the much lower Reynolds number of the scaled model with respect to the real one. To this end, the rotor was designed using special low Reynolds airfoils, equipped with transition strips of span-wise varying width and thickness that were optimized based on wind tunnel measurements.

Rotor thrust and torque values at different TSR and blade pitch were corrected for wind tunnel blockage effects using a RANS CFD approach on Chimera grids (see Figure 3). Using the corrected thrust and torque measures, a novel maximum likelihood identification procedure was used for estimating the lift and drag characteristics of the airfoils in operation. Such airfoil data was first used for the optimization of the transition strips, and then employed in the definition of a coupled LES/lifting-line model of the wind tunnel/wind turbine system developed at Vestas.

Structures and Systems

Tower and blades of the wind turbine model are flexible, and correctly represent the placement of the lowest natural frequencies with respect to the excitation harmonics. The machine is mounted on a six-component balance, and strain gages are used for the measuring of the shaft torsion and bending as well as of the root bending of the blades; other sensors include an accelerometer in the nacelle, and rotor and blade encoders.

Control

The experimental model is controlled by a hard-real-time module implementing a supervisor of the machine states and pitch-torque control laws (see Figure 4). Operations in open loop (as for example during shut-downs) and closed loop can be conducted on the system. An operator control station implements software for the management of the experiment, and for the data logging, post-processing and visualization of all measurements.

CONCLUSIONS

The model has been characterized from the structural and aerodynamic points of view. Furthermore, the system has been tested in a number of steady and unsteady operating conditions, in open and closed loop. These results have shown that the experimental apparatus is capable of supporting a variety of research activities in the area of aeroelasticity and control of wind turbines. A second wind turbine model is under advanced state of development, and it will be used for the study of wake-wind turbine interactions.

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FIGURES

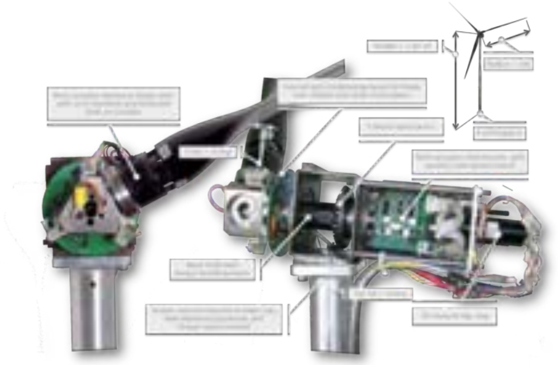

Figure 1: View of the hub and nacelle systems

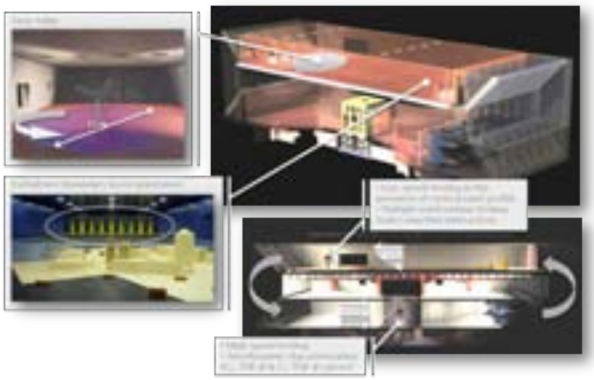

Figure 2: The boundary layer wind tunnel at the Politecnico di Milano

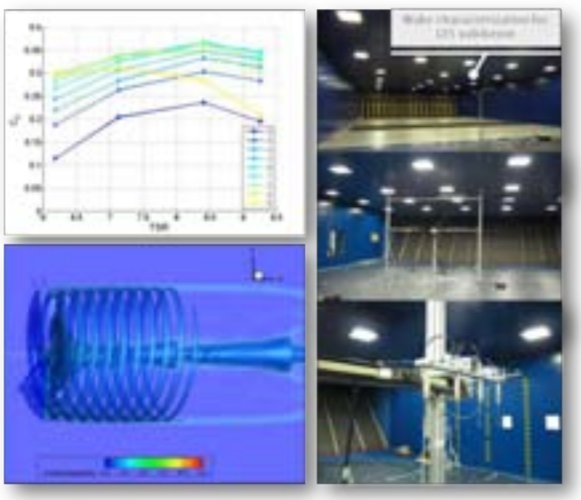

Figure 3: Aerodynamic characterization of the rotor

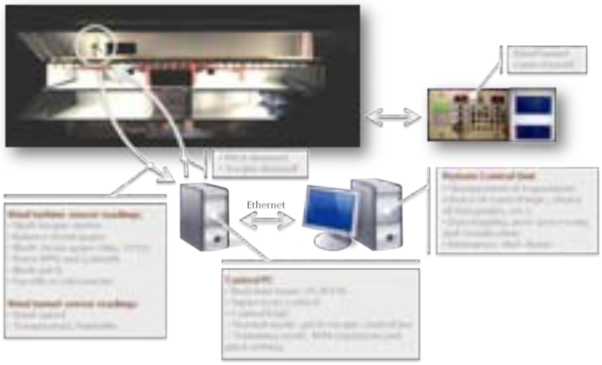

Figure 4: Data acquisition, control and model management system

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Aeroelastic panel code for airfoils with variable geometry

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Keywords: deformable airfoil, load control, flaps

Introduction

This paper discusses an on-going effort towards the development of unsteady aeroelastic models of airfoils with variable geometry. The investigation has been motivated by the expected change in future designs for wind turbine blades. Deformable airfoils in the blade are currently considered as an effective load control, allowing the increase of the aerodynamic efficiency or decreasing the cost of the blades.

Taking into account the good balance between accuracy and computational effort, the development of a panel code is proposed. The first attached flow version of the panel code is called AdaptFoil1. In addition, an analytical code based on thin airfoil theory, AdaptFoilAC1 was developed as a complementary tool.

Implementation

The panel code AdaptFoil1 is mainly based on the book by Katz (Ref. 1) and has the following characteristics:

- Closed body panel method for thick airfoils.
- The singularities used are a piecewise constant doublet and a piecewise constant source along each panel.
- The Neumann and Dirichlet conditions are combined to fulfill the non penetration condition.
- Tangential velocity between the upper and lower panels at the trailing edge is equal to the vorticity being shed.
- Free wake and a time-stepping method is used to calculate the wake roll-up.

RESULTS

Firstly, an extensive validation of the steady and unsteady aerodynamic part was carried out.

Figures 1 and 2 show respectively the Cl and Cd of a flat plate under a sudden acceleration. Results for a NACA 0003 have been compared with the results of AdaptFoilAC1, with results of a lumped vortex method, and, in the case of Cd, with a discrete vortex method (Ref. 1). The results, except the lumped vortex method, show a good agreement, and all the models converge together to the steady values.

Additional validation has been performed for changing geometries. Experimental data of a pitching NACA 0012 airfoil with an oscillating TE flap has been found in Ref. 2. Figures 3 and 5 show respectively the Cl and Cm of a combined pitching and TE flap motion. For the AdaptFoil1 computations, some corrections have been used for the pitching and oscillating flap, and for the Cl and Cm results. The corrections take into account deviations between the theoretical case and the real testing conditions due to the wind tunnel and the airfoil. The results show a good qualitative agreement with the experimental data.

To validate the aeroelastic modeling the simple stability analysis of Ref. 3 has been used. The case is a plunge-pitch airfoil and the objective is the estimation of the flutter speed in different conditions. Figure 5 shows the comparison of the normalized flutter speed for three different values of the centre of gravity of the airfoil χ_α, with varying ω_h / ω_α (ω_h is the frequency of plunge mode and ω_α is the frequency of pitch mode). First, there is a region of divergence in the curves $\chi_\alpha = 0$ and $\chi_\alpha = 0.05$ (flat region of the flutter speed), that is not calculated in the work by Zeiler. Apart from that, the agreement with Zeiler is very good, except in the case of $\chi_\alpha = 0.2$ at high values of ω_h / ω_α. The reason is that flutter is less sensitive to the wind speed in that region, and inaccuracies in the calculation could be varying the flutter speed estimation.

Conclusions

The development and validation of AdaptFoil1, a new panel code for deformable airfoils, is presented, covering steady aerodynamic validation, unsteady aerodynamics and aeroelastic validation. It provides a computational-efficient framework for investigating new blade actuation concepts.

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FIGURES

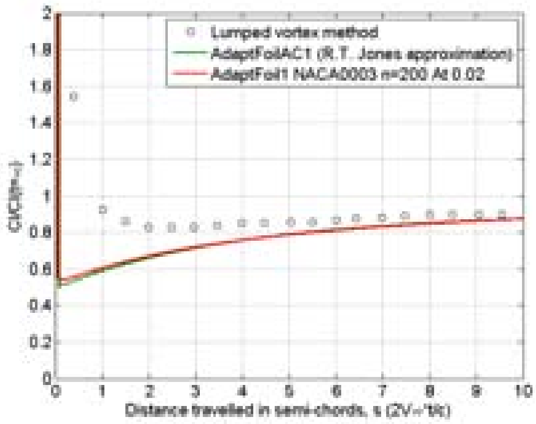

Figure 1: Sudden acceleration of a flat plate, Cl comparison between AdaptFoil1, AdaptFoilAC1 and results of Ref. 1.

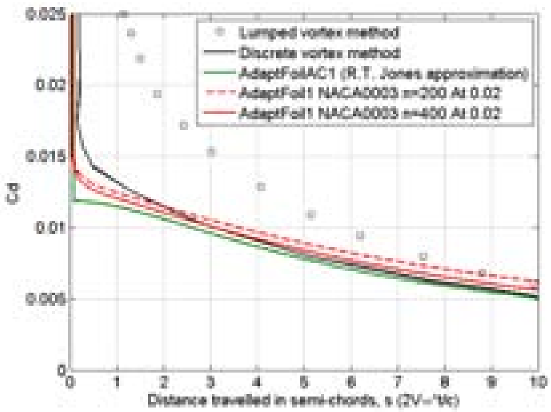

Figure 2: Sudden acceleration of a flat plate, Cd comparison between AdaptFoil1, AdaptFoilAC1 and results of Ref. 1.

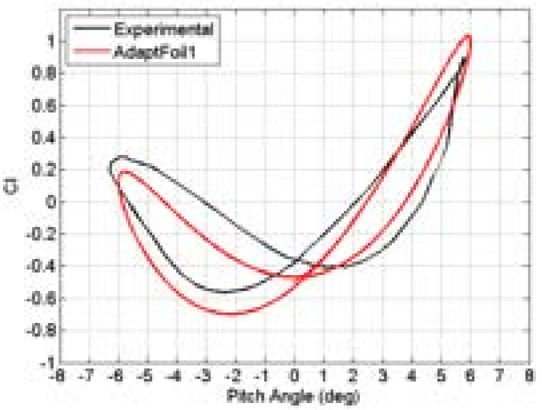

Figure 3: Combined pitching and TE flap oscillation for a NACA 0012, Cl comparison between AdaptFoil1 and experimental data (Ref. 2).

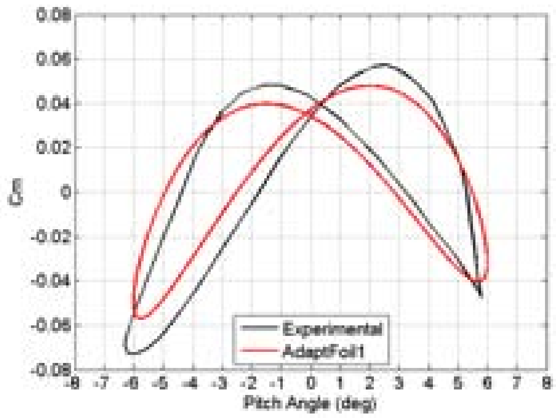

Figure 4: Combined pitching and TE flap oscillation for a NACA 0012, Cm comparison between AdaptFoil1 and experimental data (Ref. 2).

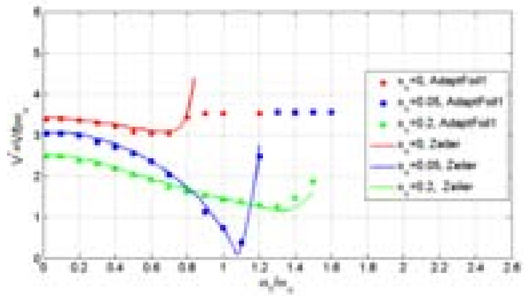

Figure 5: Flutter wind speed for a plung-pitch airfoil (airfoil radius of gyration $(r_\alpha)^2$=0.25, aerodynamic centre a=-0.3, inverse mass ratio κ=0.05), comparison with results of Ref. 3.

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Stochastic modeling of lift and drag dynamics for a rotor aerodynamic model considering turbulent inflows

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Keywords: Wind tunnel measurements, turbulent inflows, stochastic modelling, lift dynamics, drag dynamics, blade element momentum method, aerodynamic model.

INTRODUCTION

The design of a wind turbine is mainly focused on two parameters; the optimum power and longer life. The achievements of these targets lead to several challenging tasks to perform as the wind turbines operate in dynamic wind environment forever. One of these challenges is to understand and account for dynamic forces acting on the rotor blades stemming from volatile wind behavior.

This contribution provides the development of an aerodynamic model for a blade element based on a novel stochastic approach which brings further insight into high frequency lift and drag dynamics. The measurements have been performed at wind tunnel of Oldenburg University for an airfoil FX 79-W-151A. The turbulent flows were generated using different grids including a fractal grid. The modeled dynamic airfoil characteristics are then used to obtain the corresponding local dynamic forces acting on the rotating blade element in the context of Blade Element Momentum (BEM) theory. The model is being developed with the aim to integrate into a stochastic rotor model.

METHODOLOGY

The methodology is consisting of three steps. In first step measurements have been performed in wind tunnel to get the airfoil data. The lift and drag forces were measured directly on the airfoil using two strain gauge force sensors. Details of the measurement can be found in [1]. Then in the second step a stochastic approach is applied on the measurement time series of lift and drag coefficients that uses a first-order stochastic differential equation called the Langevin equation [2, 3]. The basic stochastic model has been extended to cover oscillation effects [4] observed in lift and drag time series. In addition, an optimization scheme [5] based on a χ^2-test [6] on the probability density functions of both the model and measurements has also been applied to achieve the best possible results. In the last step, BEM theory is applied on the modelled lift and drag coefficient dynamics, where an airfoil element is assumed to rotate at a certain local radius having a constant pitch to get the resulting local dynamic forces acting on the airfoil.

RESULTS

The lift and drag coefficient dynamics modelled with a novel stochastic approach and are compared with actual measurements which suggest good agreement. The modelled and measured airfoil characteristics are then imported into BEM theory to obtain the local aerodynamic forces acting on the rotating airfoil. The obtained normal and tangential force coefficient illustrations for both the model and measurement also show good matching.

CONCLUSIONS

An extended stochastic model of the lift and drag dynamics of an airfoil has been developed based on wind tunnel measurements. The model has been integrated to BEM method to get the local aerodynamic forces acting on the rotating airfoil. The forces are obtained on an annular assuming a constant local radius and constant pitch angle. The goal is to develop an aerodynamic model like AeroDyn [7] which is to be combined with a rotor model.

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European Academy of Wind Energy

LEC Laboratory for Energy Conversion

Concurrent aero-servo-elastic design of a wind turbine operating in partial load region

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Keywords: wind turbine; controller tuning; swept-back blade; aero-servo-elasticity;

Introduction

In this work we investigate the effects of combining a passive controller with a standard active controller for the regulation of a pitch-torque regulated wind turbine operating in the partial load region.

One of the most used strategy to control pitch-torque controlled wind turbines in the variable rotational speed region is to select the torque proportionally to the square of the rotational speed and to keep the pitch angle at a constant value. This approach allows to track of a specific tip speed ratio that is usually selected to obtain the maximum power coefficient. This strategy in practice is not always optimal because due to large rotor inertia the controller cannot adjust instantly the rotational speed to keep the tip speed ratio at the desired value when changes in the wind speed due to turbulence occur. When the tip speed ratio changes the wind turbine is not operating at the maximum power coefficient but the operational point continuously drops along both sides of the power coefficient-tip speed ratio curve [1], reducing the power extracted. Moreover a low tip speed ratio can lead to stall-induced vibrations and hence to high fatigue loads.

The aim of this work is to investigate the effect of a passive controller in order to reduce the oscillations of the rotational speed to help the controller to keep the tip speed ratio constant. The passive controller used in the investigation is obtained with a swept-back blade [2].

Methodology

In this work we perform a parametric analysis varying some design variables to identify the synergy effect of the active and the passive controllers. The design variables included in the investigation are the gain of the $k\Omega^2$ controller, the sweep of the blade and the blade pitch angle. To quantify the performances of the wind turbine, a cost function is selected so that it is possible, with a single parameter, to have a first idea on the goodness of the investigated configurations. The cost function is based on loads and on the annual energy production to take into account the effects on the main structural components and on the power production performances. The loads used in the cost function are obtained from a set of turbulent simulations computed with the aero-servo-elastic code *HAWC2*.

Conclusions

Preliminary results show that with a swept blade it is possible to improve the performances in the partial load region. Figure 1 shows a preliminary result where the cost function is computed varying two design parameters. The plot shows the increment in the cost function with respect to the cost of the reference configuration obtained with a unswept blade and a k coefficient to track the maximum power coefficient. The variables considered in this case are the sweep at the tip of the blade (x axis) and the k coefficient (y axis). From the figure it is possible to see that the cost function can be reduced when sweeping the blade and that for different sweep values the gain k that guarantees the minimum cost differs.

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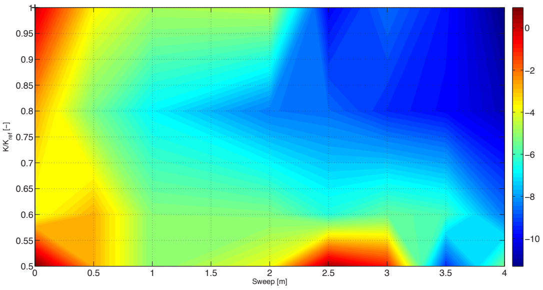

Figure 1: Percent cost function increase due to changes in the sweep of the blade (*x* axis) and in the *k* coefficient (*y* axis). The reference value, corresponding to the unswept blade with a *k* equals to the one to track the maximum power coefficient, is in the upper left corner.

New Test Bench for Optical Measurements of Rotor Blade Deformations on Wind Turbines

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Keywords: Rotor blade deformation, IPCT (Image Pattern Correlation Technique), DIC (Digital Image Correlation), construction, test bench, construction

INTRODUCTION

The rated power of a wind turbine correlates with the diameter of the rotor. Over the last 30 years commercial wind turbines have evolved from approximately 10 m rotor diameter and a rated power of 50 kW into today's multi-megawatt class with rotor diameters exceeding 150 m and rated powers of well above 6 MW. This development has produced light, slender and flexible structures where the aeroelastic response of the turbine becomes a constant concern with regard to fatigue strength and overall performance. In order to optimize energy production and to ensure a long-life cycle, low maintenance costs and operational safety, sophisticated design tools are needed which have been calibrated and validated against experimental data. However, experimental data from full scale wind turbines is still rare and quite hard to gather because of the larger scales involved. A current project at the Institute of Turbomaschinery and Fluid Dynamics (TFD) aims to apply an optical measurement technique for in field 3D deformations measurements of the rotor blades during operation [1],[2]. During the first phase of this project a new test bench was designed to sample the optical system under lab conditions.

TEST BENCH

The test bench features a two-bladed rotor with or without profiling and is propelled by an electric servo drive. It has a variable rotor diameter of up to 2 meters and each blade can be excited individually by a piezoelectric patch. Electrical power is supplied to the rotating system by a slip ring which also features 8 test points for measuring voltages inside the rotating system. The rotational speed of the rotor is constantly monitored by an incremental encoder on the rotor shaft. Each blade has a distinct random pattern to provide reference points for the optical measurement technique. The whole test bench has been designed with mobility in mind. Therefore, testing the sensitivity of the optical measurement technique with regard to environmental conditions like direct sun light is an option.

CONCLUSIONS

Construction of the new test bench has only been finished very recently. The first test run is currently planned for the beginning of august. Hopefully some preliminary results can be presented at the seminar in addition to the construction.

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FIGURES

Figure 1: Rendered CAD geometry of the test bench

Turbine design, operation & performance

Wind Turbine Pitch Fault Detection using ANFIS

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Keywords: Wind Turbine, SCADA System, Fault Detection, Fuzzy Inference System, ANFIS.

Introduction

In this paper we propose a new method for analysing wind turbine (WT) SCADA data by using Adaptive Neural Fuzzy Inference System (ANFIS) with the aim to achieve automated detection of significant pitch faults. Compared to other existing approaches [1], the proposed approach has greater transparency and the results show strong potential for wind turbine pitch fault prognosis.

Wind Turbine Pitch Fault Analysis

WT pitch faults are known to be significant importance. A statistical analysis of WT pitch faults, using typical variable-speed pitch-to-feather control strategy [2] and an approach from [3], have shown that the pitch fault symptom can be clearly identified from four scatter plots, as shown in Figure 1.

In addition, this study has also found that SCADA signals can show fault malfunction information much earlier than SCADA alarms. Therefore, a diagnosis procedure, based on the aforementioned statistical study and ANFIS, is proposed and described in next section.

ANFIS Diagnosis Procedure

As shown in Figure 2, the diagnosis procedure consists of the following 4 modules:

- *Data Acquisition:* get data from SCADA system and make sure the selected data subject to predefined conditions.
- *Feature Extraction:* data pre-processing and extract the 4 features as mentioned in Figure 1.
- *Multiple ANFIS Diagnosis:* overall ANFIS result is the aggregation of the 4 individual ANFIS.
- *Fault Diagnosis Result:* ANFIS result will be checked with alarm information to get the final result.

Training ANFIS

ANFIS is the fusion of neural networks and fuzzy logic, which provide learning as well as transparency [4]. In order to generate the training data for ANFIS, the degree of fault is measured as follows:

$$Degree\_of\_Fault = 1 - \frac{\|x - c\|}{D_{max}}$$

where x is the fault data, c is the centre of the fault and D_{max} is distance from the furthest data point x to the centre c. The training data with the degree of fault is shown in Figure 3 and the result of the corresponding ANFIS is shown in Figure 4.

Results

In order to demonstrate the feasibility of the proposed ANFIS diagnosis procedure, the trained system was tested against to another 4 WTs to identify similar pitch faults. Some results are shown in Figure 5.

Conclusions

This paper proposes a new approach to WT pitch fault detection using ANFIS. The feasibility study of this approach has been demonstrated. However, two critical problems still need to be resolved:

- ANFIS result is not consistent with domain knowledge. This is largely due to insufficient data, as shown in Figure 4.
- The training procedure for ANIFS needs to be optimised.

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FIGURES

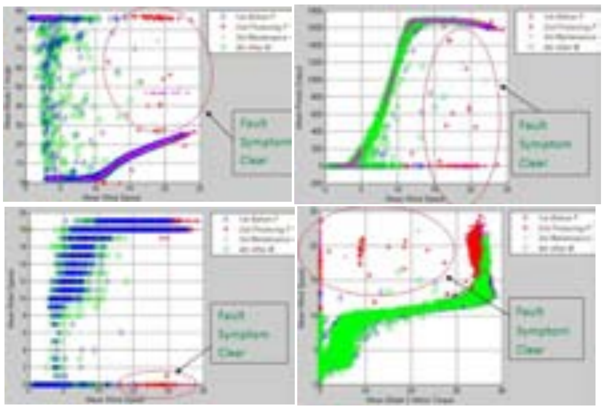


Figure 1: Pitch fault can be clearly identified from 4 scatter plots: *WindSpeed vs BladeAngle, WindSpeed vs PowerOutput, WindSpeed vs RotorSpeed, BladeMotorTorque vs Windspeed*.

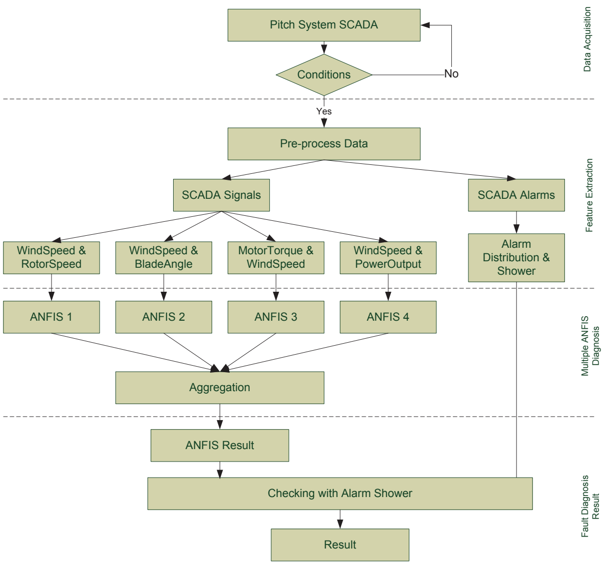


Figure 2: The ANFIS diagnosis procedure

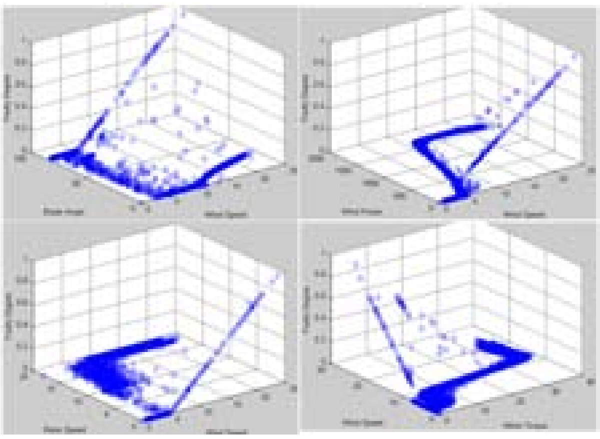


Figure 3: Training data with degree of fault.

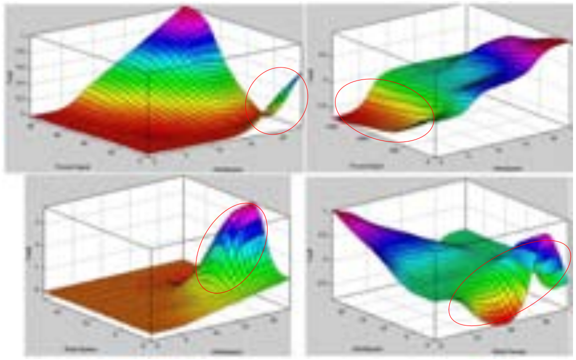
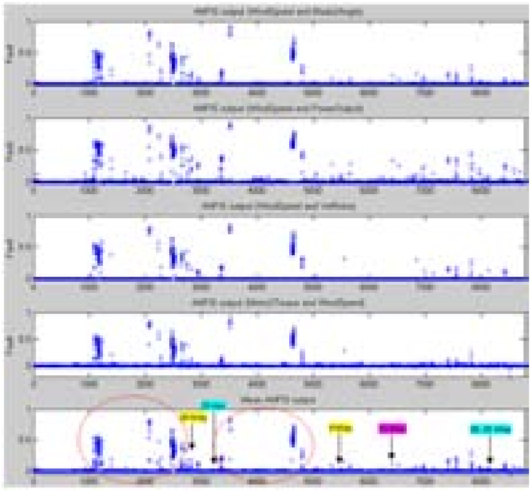
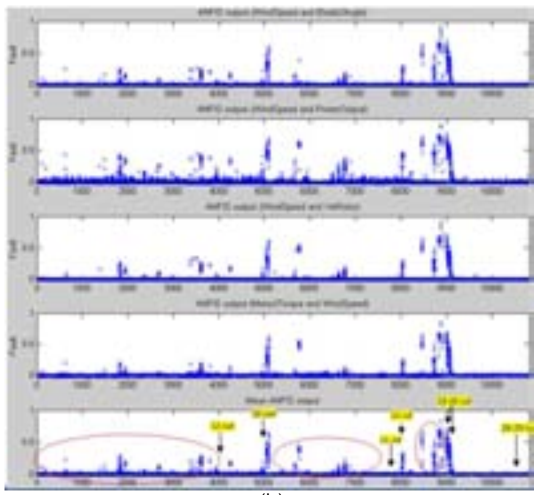


Figure 4: 4 ANFIS results. The encircled area is not consistent with domain knowledge; largely due to insufficient data.



(a)



(b)

Figure 5: Pitch fault testing in WT A (a) and WT B (b); (Labelled area is the day(s) of the corrective maintenance, encircled area demonstrated the feasibility of this approach.)

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Using conformal mapping for the design of VAWT airfoils

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Keywords: VAWT, 2D, aerodynamics, flow curvature, airfoil, conformal mapping

Introduction

In the effort of designing a complete Vertical Axis Wind Turbine, the airfoil design is an important task. When designing the airfoil for a certain Cl-Cd-Cm performance, it should be noted that there is a significant impact of the flow curvature experienced by the airfoil. This flow curvature changes the pressure distribution over the airfoil. In order to avoid having to simulate the real airfoil in a curved flow environment, Migliore [1] suggested to apply a conformal transformation on the airfoil geometry to obtain a virtual airfoil which has the same performance in a straight flow environment. This research evaluates the applicability of a conformal mapping in an inverse way, i.e. if we design an airfoil with desirable Cl-Cd-Cm-behavior in a straight flow, can we apply a conformal mapping to find an airfoil having the same characteristics in the real (curved) flow environment of a VAWT? The airfoil shown in Figure 1 is obtained through the optimization of an airfoil for a VAWT considering the aerodynamic airfoil performance in straight flow.

Conformal Mapping

By definition, a conformal mapping is a transformation between coordinate systems maintaining local angles. In other words, the distance between points may change, but the angles between lines are preserved. Conformal mapping functions are generally expressed in a complex plane, so let's take the complex number $z = x + iy$, where x and y represent the airfoil coordinates in the original Cartesian reference frame.

One of the simplest conformal mapping functions is the transformation from Cartesian to polar coordinates, described by the function $f(z) = {e^z}/{e}$ This transformation not only preserves the local angles, it also preserves the length of the chord line along the new circular path. The obtained airfoil is shown in figure 2 for a mapping with c/R = 1.

Pressure Distributions

The first step in the comparison of the mapped airfoil with its original is the pressure distribution. Figure 3 shows the pressure distributions of the airfoil in Figure 1 and a conformal mapped airfoil like the one in Figure 2, but now for a c/R = 0.1. These pressure distribution are obtained in inviscid potential flow from a 2D panel-vortex code. The pressure distribution of the mapped airfoil is the result of a curved flow field, assuming rotation without incoming wind. The original airfoil was subjected to a straight inflow case under zero angle of attack. The result in Figure 3 shows a near exact pressure distribution, except a positive and negative offset for the lower and upper surface respectively.

The cause for this offset can be found in the velocity magnitude. In the case of an airfoil rotating as part of a VAWT blade, the local flow velocity experienced varies linearly with the distance to the center of rotation. The conformal mapping preserves the angles between the flow and the airfoil surface, but it does not correct for the variation of the velocity magnitude. This can be illustrated when repeating the simulation with the mapped airfoil in the curved flow, now prescribing the flow field to have no variation of velocity magnitude with radial distance. As shown in Figure 3, the result of this adaptation matches that of the straight flow result.

Conclusions

It is possible with conformal mapping to transform an airfoil to have the same pressure distribution in curved flow as the original airfoil in straight flow. However, for the operation of a VAWT the curved flow pattern comes with a variation of the velocity magnitude with radius. The geometric transformation is not capable to incorporate the effect of this velocity variation.

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FIGURES

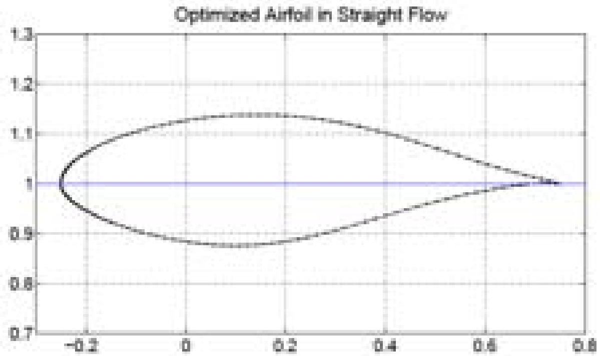

Figure 1: Airfoil optimized using the aerodynamic characteristics from straight flow simulations

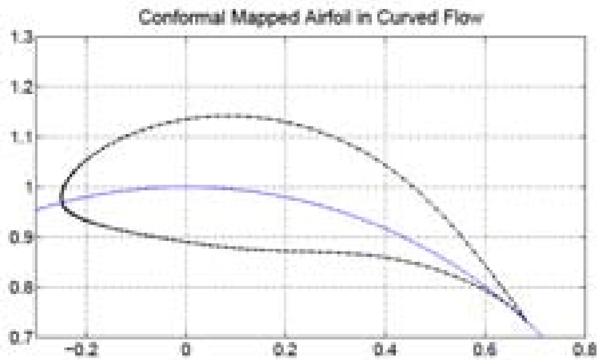

Figure 2: Airfoil obtained as a conformal mapping of the optimized airfoil in Figure 1, for c/R = 1

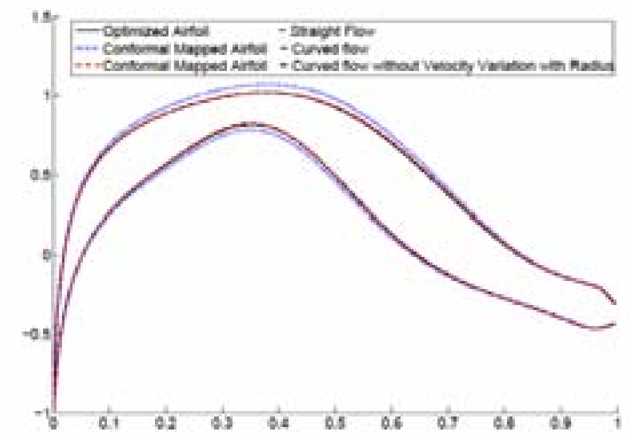

Figure 3: Distribution of negative pressure coefficient along the chord for the optimized airfoil (Figure 1) and a conformal mapped airfoil with c/R = 0.1 in curved flow with and without a variation of the velocity magnitude with radius

Cp-Max: A Blade Design Optimization Environment

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Keywords: blade design, aeroservoelasticity, multibody dynamics, FEM analysis, control

INTRODUCTION

In this work we describe software procedures under development at the POLI-Wind Laboratory of the Politecnico di Milano for the multi-disciplinary design optimization of wind turbine rotor blades [1,2]. These automated design tools integrate a parametric high-fidelity aeroservoelastic model of the wind turbine together with cross sectional and three-dimensional FEM models of the blade, which support all necessary analyses, including performance, loads, aeroelasticity and detailed structural verification. The software eases the complex task of designing wind turbine rotor blades, where multiple contrasting goals and design constraints need to be married together.

APPROACH AND METHODS

Figure 1 illustrates the multi-level constrained design optimization of wind turbine rotor blades, which is implemented in the wind turbine design code Cp-Max (Code for Performance Maximization). The code can perform the aerodynamic design of the blade (chord and twist distributions for maximum annual energy production), the structural design (sizing of skin, shear webs, spar caps, etc., for minimum blade weight), or the combined aerostructural design for a figure of merit accounting for the cost of energy.

At the coarse aeroelastic level, performance, extreme and fatigue loads, natural frequencies, blade deflections and all other quantities necessary for design (either for the evaluation of the cost function or appearing as design constraints) are computed using a parametric model implemented with the wind turbine simulation code Cp-Lambda (Code for Performance, Loads, Aeroelasticity by Multi-Body Dynamic Analysis). Cross sectional analysis, including the evaluation of sectional stiffness matrices accounting for all possible structural couplings and the evaluation of local stresses and strains, is performed using the code ANBA (Anistropic Beam Analysis).

The coarse constrained multi-disciplinary optimization is run until convergence using the sequential quadratic programming (SQP) algorithm.

From the computed blade geometry the code automatically generates a 3D CAD model, which precisely accounts for all components of the blade as well as their associated material properties and laminate characteristics. The meshing of the blade is performed in a fully automated way by using either shell or solid elements, and the FE model is exported in the form of input files compatible with various commercial FE solvers.

The 3D FE model provides the framework for a fine-level verification of the design constraint inequalities associated with admissible stresses, strains, deflections and fatigue damage, as the detailed FE model reveals effects that may have been overlooked at the coarse level. In case constraint violations are detected at the fine-level, the coarse optimization loop is repeated with constraint bounds that are tightened proportionally to the violation amount. Coarse and fine-level iterations, illustrated in Figure 1, are repeated until an optimal design that satisfies the constraint conditions at the finest description level is obtained.

CONCLUSIONS

The automated design procedures described in this work were applied to a number of research and industrial projects, including the design of bend-twist coupled blades with passive load alleviation capabilities (see Figure 2), as more fully illustrated in the full paper.

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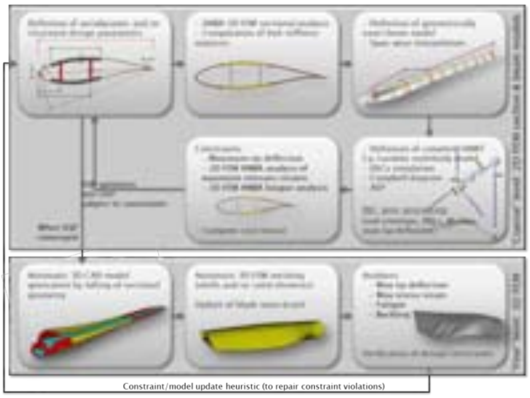

Figure 1: Multi-level structural design of a rotor blade

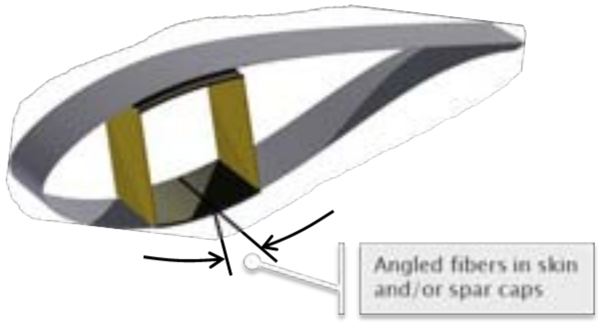

Figure 2: Twisting of fibers away from the pitch axis to induce bend-twist coupling and load alleviating behavior in rotor blades

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Discussions on the maintenance optimization of offshore wind turbine

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Abstract

Reliability and maintenance issues of offshore wind turbine (OWT) are complex and intricate. The main reason behind such complexity and intricacy is strongly linked with the factors related to weather, access, logistics and transportation in an offshore environment. It is of vital importance how to plan, optimize and implement the inspection and preventive replacement strategies given the weather, vessel, logistics and transportation constraints. In the present paper, a generic framework has been proposed how to identify important parameters which have significant influence on the reliability and maintenance of OWT. Afterwards the modeling framework has been developed to quantify the influence of the performance variables on the maintenance optimization. The combination of age and condition based maintenance approaches are considered in the current approach for finding the optimal inspection and maintenance interval. Necessary algorithms have been developed to search for the optimal inspection and maintenance intervals keeping in view the numbers of vessels, components and wind turbine. During the implementation of such process, different issues and challenges, which come in the way of its implementation, are highlighted for having the optimal operational and maintenance strategies. It has been highlighted how the adaptation of the proposed approach would reduce the frequency of visits to the wind farm, risks and hazards associated with the safety of the personnel.

Keywords: Maintenance, interval, condition, vessel, algorithm

Power Curve Measurements of Locally Manufactured Small Wind Turbines

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Keywords: small wind, power curve, data logging, local manufacture, rural electrification, Piggott

Introduction

Under the right conditions, the local manufacture of small wind turbines can provide a sustainable solution for rural electrification. The wind turbine designed by Hugh Piggott of Scoraig Wind Electric and described in the instructive manual, *A Wind Turbine Recipe Book* [1], is a rugged machine designed to be produced using only basic tools and techniques. The success of this manual has permitted the dissemination of the technology to the point at which over 1,000 machines have now been produced and can be found across the world in every single continent. Although estimates exist for the power and energy production of these machines, no accurate measurements of their performance has yet been made.

This research aims to measure the performance of a range of these machines, from 1.2-4m diameter (Ø) over the course of approximately 1 year. The testing is taking place in situ on the Scottish peninsular, Scoraig. Described in this paper is the measurement of the first two machines, 1.8m and 3m diameter wind turbines.

Methodology

The international standard for power curve testing of small wind turbines, as described in IEC-61400-12-1 [2] was used as a guide during the design of the measurement procedure to ensure the highest degree of accuracy possible given the available time and resources.

Characterisation of Variation from Local Manufacture

It is not expected that a generic power curve will be produced for each size of machine. On the contrary, this study recognizes the inherent variation in machines produced by local manufacture and seeks to investigate these further. For example, when a blade is carved by hand from wood, it is far more difficult to achieve the design geometry than if it were formed from fiberglass in a precision aluminium mold. Therefore, the first stage in the measurement process is to record the actual specifications of the wind turbines under test so that any deviation of the performance of the turbine can be traced back to a deviation from the design specification.

For example: Figure 1 shows the measurement of the aerofoil thickness, which could affect the onset of stall, whilst Figure 2 shows the measurement of the setting angle, which affects the relative flow angles along the blade. Other measured variables include air gap between stator and rotor; tail moment arm and weight; and yaw angle.

Technical Specifications of Data Logging Equipment

The data logging equipment installed at both the 1.8m and 3m Ø turbines are illustrated in Figures 3 and 4 respectively and detailed in Table 1.

Progress to Date

The data monitoring equipment was installed on both turbines in late April 2012, and is currently continuing to log data. Preliminary analysis of this data has already taken place and it is expected that during the summer months, both sites will receive sufficient periods of high winds in order to be able to reliably characterise performance in this region.

References

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[2] IEC Wind Turbines, in Part 12-1: Power Performance Measurements of Electricity Producing Wind Turbines. 2005.

Figures and Tables

	1.8m Piggott	*3m Piggott*
Wind speed	NRG Max40	Inspeed Vortex
Wind direction	Davis Pro-D	Inspeed E-vane
Anemometer & wind vane mounting	Hub height met-mast with 3 Øs separation	Boom at 1 Ø below hub height & 1 Ø separation
Temperature	Zener diode	Thermistor
Rotational speed	AC frequency	AC frequency
Current	Hall effect	Shunt
Voltage	Potential divider	Potential divider
Data logger	Logic Energy LeNet	Campbell Scientific CR10x
Sampling freq.	1Hz	1Hz
Averaging period	10min	1 & 10 min

Table 1: Technical specifications of the two sets of data logging equipment.

Figure 1: Measurement of the aerofoil thickness at the blade tip using digital callipers.

Figure 2: Measurement of the setting angle at the blade root using spirit level and ruler.

Figure 3: Data logging set up on the 1.8m diameter turbine.

Figure 4: Data logging set up on the 3m diameter turbine.

Stereo PIV to Validate IR Thermography as a Condition Monitoring Method for Rotor Blades on Operating Wind Turbines

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Keywords: stereoscopic particle image velocimetry, condition monitoring, maintenance, infrared thermography, rotor aerodynamics

Introduction

In harsh environmental conditions, such as offshore, particularly the rotor blades of wind turbines are exposed to heavy loads. Taking the resulting material requirements into account, there is a need for a reliable structural health monitoring method which is simple in application.

In this presentation, the BMU joint project *IR Vortex* will be described. The project is aimed at developing a condition monitoring method using passive infrared thermography by correlating thermograms with the flow field around rotor blades. The velocity field will be measured in a wind tunnel using stereoscopic particle image velocimetry (SPIV). This analysis, combined with numerical calculations and complemented by lift-drag measurements, enables an assessment of the power loss arising from damages or contamination of the rotor blades.

Passive Infrared Thermography

Passive infrared thermography is capable of visualising and resolving the differences in temperature naturally occurring on surfaces using a camera which is sensitive to radiation in the infrared spectrum [1]. Consequently, it is suitable for a thermographic investigation of inaccessible, distant or dynamic objects.

Stereoscopic Particle Image Velocimetry

Particle Image Velocimetry (PIV) is a technique to measure a 2D velocity field of a particle seeded flow in one plane. By comparing two temporally deferred images of the flow, it is possible to identify the shift vectors and the velocity of the particles. Applying a second camera to the PIV setup, this stereoscopic PIV (SPIV) configuration is capable to identify the 3D velocity field in one plane [2].

Numerical Analysis

Numerical simulations provide an insight of high temporal and spatial resolution into the state quantities of a flow. The DNS (direct numerical simulation) method is sufficient for Reynolds numbers $Re < 20.000$. Reynolds numbers above 20.000 usually occur with wind turbines and can be handled with URANS (unsteady Reynolds average Navier-Stokes) solvers [3].

Results

Thermograms of operating wind turbines reveal a wedge-shaped temperature pattern on both sides of the rotor blades (fig. 1). These patterns suggest vortex inducing damages or contamination on the rotor blades due to a higher heat transfer in turbulent flows. Furthermore, PIV measurements capturing the wind wake of a clean rotor blade (fig. 2) will be extended to a SPIV configuration to reveal the three-dimensional topology of a turbulent flow. Exemplarily, a result of a numerically solved flow around the blade root is shown in figure (3).

Conclusions

Within the project IR Vortex, the connection between damages, temperature distribution and flow formation on and around an operating rotor blade of a wind turbine is to be investigated. For this purpose, it is believed to combine the three methods, IR thermography, SPIV and numerical simulations, effectively to provide an on-site applicable condition monitoring method for rotor blades which estimates the power loss as well.

References

[1] X. Maldague and P. Rastogi. Applications of infrared thermography in nondestructive evaluation. *Trends in Optical Nondestructive Testing (invited chapter)*, pages 591–609, 2000.

[2] C. Willert. Stereoscopic digital particle image velocimetry for application in wind tunnel flows. *Measurement science and technology*, 8:1465, 1997.

[3] N. Kirrkamm. Simulation of a multimega watt wind turbine with opensource code OpenFOAM. In *Proceedings of EWEC*, 2010.

[4] P. Meinlschmidt. personal communication, 2012.

Figures

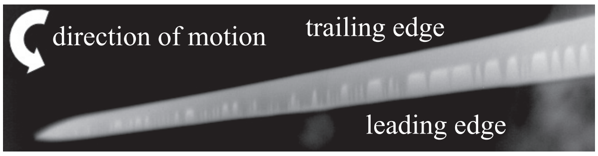

Figure 1: Thermogram of a turning rotor blade with a temperature pattern indicating a undesired turbulent flow (view on suction face) [4].

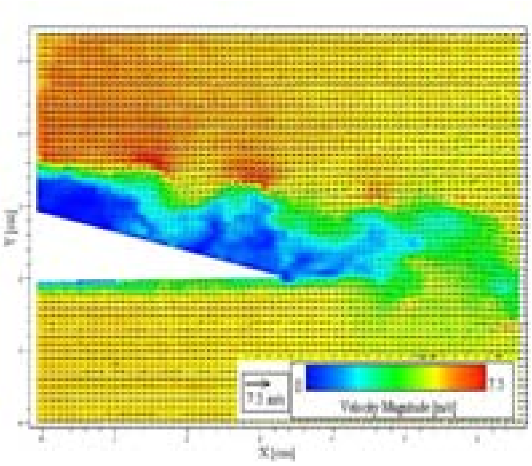

Figure 2: PIV measurement visualising a wind wake of a clean rotor blade.

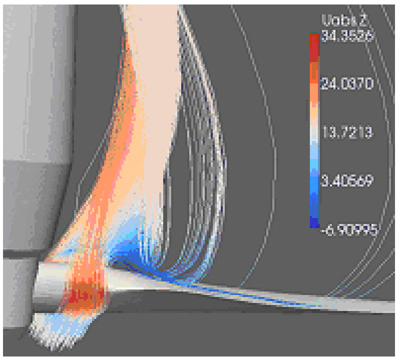

Figure 3: Streamlines around a blade root of a 40 m rotor blade simulated by OpenFOAM®.

Distributed optimization of a wind turbine blade

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Keywords: cost of energy, optimization, structural design, controller design, integrated design

Introduction

With a desired 20% integration level of sustainable energy in 2020 by the European Union, a desired capacity of 6000 MW offshore in The Netherlands by 2020 and the predicted lack of availability of fossil fuels, wind energy has a bright future. However, the largest bottleneck is still the cost of energy which is roughly twice the cost of their fossil alternative. For that reason, the Far and Large Offshore Wind (FLOW) innovation program was initiated. One of the targets of this program is to reduce the production costs with 20%, which would significantly strengthen the position of wind turbines. A key element in making turbines more cost effective is to optimize both the structure and the controllers in a single design.

Methodology

The main drawback of the current design procedure of wind turbines, i.e., first optimizing the structural dynamics and aerodynamical behavior, followed by the independent design of the different controllers, is that the combined dynamics do not yield optimal designs. One way to improve the design is by using an integrated design approach. This means simultaneously optimizing both the structural dynamics and the controllers, with the ultimate goal to minimize the cost of energy.

The central approach taken here is to parameterize the design parameters and formulate an objective function. This means that for the integrated design of wind turbines, the parametrization consists of structural and controller parameters. Constraints are introduced and imposed on to the objective function in order to guarantee feasible solutions. Finally, the integrated design is accomplished by iteratively optimizing the design and subjecting it to design loads to check whether the design is satisfactory. If the design specifications are not met, the optimization procedure is repeated.

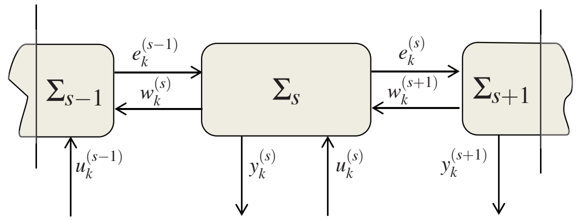

Figure 1: Interconnected string of systems.

Results

The first step in the research focuses on the structural part of a wind turbine blade. The blade is modeled by an Euler-Bernoulli beam (which can be extended later to a Timoshenko beam). The local mass and stiffness properties over the length of the beam are found by using the Finite-Element Method. This information is used to represent the local elements of the beam by local Linear-Time Invariant systems. Hence, the beam is represented as a string of local dynamical systems. Then, interconnecting these systems in an efficient way, by using Sequentially Semi-Separable matrices [1] (see Fig. 1), enables to apply efficient optimization algorithms to find optimal mass and stiffness distributions over the length of the beam. The latter is realized by parameterizing the local mass and stiffness parameters and optimizing with respect to some user-defined objective function.

Conclusions

The approach of representing a structure by a string of local interconnected subsystems allows to efficiently optimize structural properties. The techniques used are rather general and can therefore be applied to many more structures. Furthermore, the framework also allows to efficiently incorporate distributed controllers in to the design, making it very attractive for integrated design approaches.

References

[1] Justin K. Rice and Michel Verhaegen. Robust and distributed control of a smart blade. *Wind Energy*, 13(2-3):103–116, 2010.

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Automatic Wind Turbine Gear Fault Detection and Diagnosis

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Keywords: gearbox, condition monitoring, vibration analysis, gear tooth fault detection and diagnosis.

Introduction

Reducing the cost of energy becomes a critical issue in order to make wind power competitive to conventional sources. The current trend in wind turbine (WT) development is for larger, more complex machines located in remote offshore locations which present operation and maintenance challenges and higher capital and operational costs. Significant operational cost savings can be made by establishing technically and economically viable condition-based maintenance through the implementation of automated condition monitoring system (CMS) data interpretation [1]. Gearbox faults, with high replacement costs, complex repair procedures and revenue loss due to long downtime [2], are widely considered as the leading issue for WT drive train CM. The aim of this paper is to analyse and experimentally identify gearbox gear tooth damage by establishing pattern feature parameters from gearbox vibration signatures. The proposed frequency tracking algorithm may be incorporated into a commercial CMS for automatic gear fault detection and diagnosis.

Wind Turbine Condition Monitoring Test Rig

Figure 1 shows the Wind Turbine Condition Monitoring Test Rig (WTCMTR) used in this research. It has been designed to act as a model for a WT drive train and consists of a 30kW wound rotor induction generator driven through a 5:1 two-stage helical gears parallel shaft gearbox by a 54kW DC motor. A variety of drive shaft speed inputs can be applied to the WTCMTR via the DC motor controlled by a 2MW variable speed WT model. Vibration data from a single-axis, vertically mounted accelerometer located on the gearbox high speed end have been processed using an SKF WindCon 3.0 unit, a commercial CMS currently used on full size operational WTs. Experiments were conducted to investigate the progression of a high speed shaft (HSS) pinion tooth defect introduced into the WTCMTR. Three cases of experimental vibration signature were examined: (a) healthy HSS pinion, (b) faulty HSS pinion, with a damaged tooth on its leading contact edge and (c) faulty HSS pinion, with an entire tooth remove, as shown in Figure 2.

Sideband Power Factor (SBPF) algorithm

The experimental results show that the presence of meshing frequency harmonic sidebands and their amplitudes can prove to be very valuable when detecting and diagnosing gear defects. However, the manual analysis of the spectra requires significant time-consuming work due to the great number of frequency bands to be monitored. A gear fault diagnostic algorithm, named Sideband Power Factor (SBPF), has been proposed in order to reduce each vibration spectrum to only one parameter for each data acquisition. The SBPF sums the power spectral density spectrum amplitudes of the stage 2 gearbox meshing frequency second harmonic and its first 5 sideband peaks, spaced at the HSS rotational frequency on each side of the centre mesh harmonic. It tracks the overall power of the spectra associated with the sideband frequency window identified from the experimental results. Figure 3 shows the SPBF values for damaged and missing tooth cases normalised to the healthy case. The rise in the spectra power is clearly evident even in the case of low severity tooth damage.

Conclusions

Automatic detection and diagnosis of gearbox faults during early stages of fault development using a meshing frequency narrowband SBPF algorithm may be possible. The adoption of the SBPF algorithm enables the reduction of each spectrum to only one parameter for each data acquisition and avoids time consuming and costly manual analysis for spectra comparison.

References

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[2] S. Faulstich, B. Hahn, P.J. Tavner. Wind Turbine Downtime and its Importance for Offshore Deployment. Wind Energy, 14(3) pp. 327-337, April 2011.

FIGURES

Figure 1: SKF WindCon WTCMTR process overview.

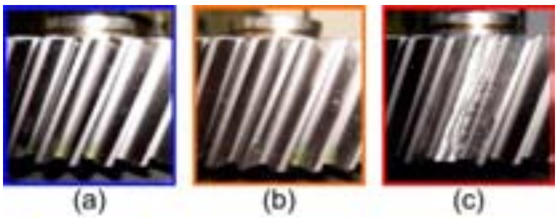

Figure 2: WTCMTR gearbox high speed pinion damage introduced for fault testing: (a) healthy, (b) damaged tooth and (c) missing tooth.

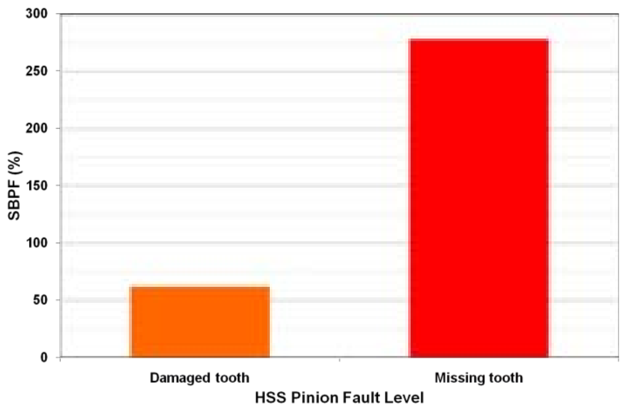

Figure 3: SBPF values for the two investigated gear tooth fault levels normalised to the healthy case.

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Reduction in Thermal Cycling of the Switching Devices in Wind Turbine Converters through Control of the Coolant Flow Rates

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Keywords: Reliability, Thermal Model, Wind Turbine, Power Converters, Thermal Cycling, Fatigue life, MATLAB, Simulink.

Introduction

Thermal cycling is a significant contributor to the degradation and eventual failure of switching devices, specifically IGBTs, in a power device. Large temperature changes, caused either by environmental conditions or power dissipated in the switching devices, stress solder bonds causing damage and the eventual failure of the device. By controlling the size of these temperature fluctuations using a coolant fluid the lifespan of the device maybe improved. Methods in which this can be achieved are investigated.

Method

A thermal equivalent circuit of an IGBT and its case mounting was constructed in MATLAB Simulink using the SimPower package. A wind profile is adjusted to show the relevant amount of power dissipated as heat in a 2 .3 MW turbine converter. A cooling system is added using water as the coolant. This complete model is used to investigate the apparent thermal cycling occurring in the IGBT and fatigue life.

The coolant system is modified to investigate the effects of various parameters has on device lifetime such as ambient temperature fluctuation and coolant temperature.

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An Overview of Maximum Power Point Tracking Techniques for Wind Energy Conversion Systems

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Abstract — **This paper presents on overview of maximum power point tracking (MPPT) techniques for different types of wind energy conversion systems (WECS). In order to obtain maximum power from the wind turbine (WT), variable speed wind energy conversion systems (VSWECSs) are preferred over constant speed wind energy conversion systems (CSWECSs). In VSWECS, the rotational speed of the turbine is varied by controlling the aerodynamic or electrical parameters of WECS to maintain a constant tip-speed ratio (TSR). This is called maximum power point tracking and different techniques are applied to different types of WECS namely Squirrel Cage Induction Generators (SCIGs) based WECS, Permanent Magnet Synchronous Generators (PMSGs) based WECS, and Double Fed Induction Generators (DFIGs) based WECS.**

***Keywords*— MPPT, TSR control, PSF control, and HCS control**

1. Introduction

Wind energy occupies the first position in power generation from renewable energy as it is abundant, in-exhaustive, environmentally friendly, and pollution free. The sun is the source of wind energy. The differential heating of earth's surface and atmosphere produces horizontal and vertical air currents. These air currents are affected by the earth's rotation and contours of land resulting in wind.

In earlier days, wind energy was used to sail ships, mill grains and pump water. Electricity was first realised from wind energy in the early 19th century. Wind energy has now emerged as one of the most promising renewable energy to meet electricity demand.

Since 19th century, several developments and researches were made to capture the maximum power from the WECS. Some of them are aero-dynamical improvements (improvements made in number of blades, diameter of blades, blade materials, and control system for pitching the blades), electrical improvements (like the use of DFIG and PMSG instead of SCIG and use of various power electronic switches), and mechanical improvement (like gearbox, tower, foundation and structure materials).

All these developments are used for efficiently capturing power from the WT. In order to capture maximum power from the WT either aerodynamic methods or MPPT methods or both are used.

Aerodynamic methods like pitch control, stall control and yaw control need careful design of blades and are considered less efficient when compared to MPPT techniques.

Conventional MPPT approaches (with or without wind speed measurement) are found to be efficient in tracking maximum power from the WT. Different types of MMPT techniques like Tip Speed Ratio (TSR) control, Power Signal Feedback (PSF) control and Hill Climbing Search (HCS) Control [1-2] which are briefly discussed in this paper. .

2. General Characteristics of WT

The WT is a device that converts the kinetic energy in the wind into mechanical energy [3]. The equation for output mechanical power of WT is given by Eqn. 1.

$$P_m = \frac{1}{2}\rho C_p A V_w^3 \tag{1}$$

Also,

$$C_p = f(\lambda, \beta) \tag{2}$$

$$\Lambda = R\frac{\omega_m}{V_w} \tag{3}$$

where ρ is the air density (kg/m^3) , C_p is the power coefficient that is a function of TSR (λ) and blade angle (β), A is the wind turbine rotor swept area (m^2), and ω_m is the mechanical angular speed (rad/s).

Eqn. 2 is usually provided by turbine manufacturers in the form of a of non-dimensional curve as shown in the Fig. 1.

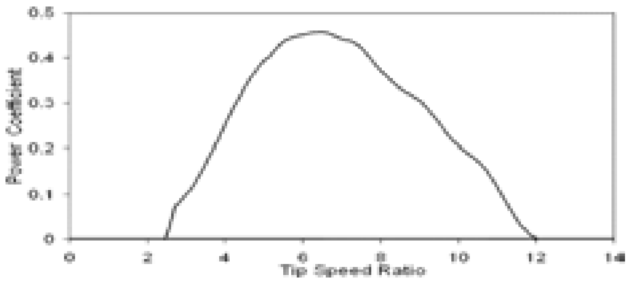

Fig. 1 Power coefficient (C_p) vs Tip Speed Ratio (λ) for β = 0

The output torque of the turbine is given in Eqn. 4

$$T = \frac{1}{2}\rho\pi R^3 C_p {V_w}^2 \tag{4}$$

The variation of torque with respect to turbine speed is shown in Fig. 2 and the variation of power with respect to turbine speed is shown in Fig. 3.

From Eqn. 1, it is clear that P_m is linearly proportional to C_p. So to get maximum power, the WT must be operated at the maximum value of C_p, which is obtained from the datasheet. In addition, from Eqn. 2, C_p is proportional to λ and β. However, as this paper discusses only MPPT techniques for variable speed constant pitch turbines, β is assumed to be 0. Hence, C_{pmax} is proportional to λ and to get maximum mechanical power output, the WT must be operated at C_{pmax} (i.e. at optimal λ).

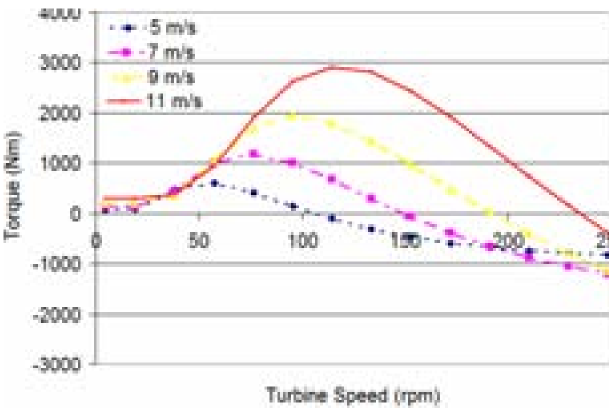

Fig. 2 Turbine Speed Vs Torque

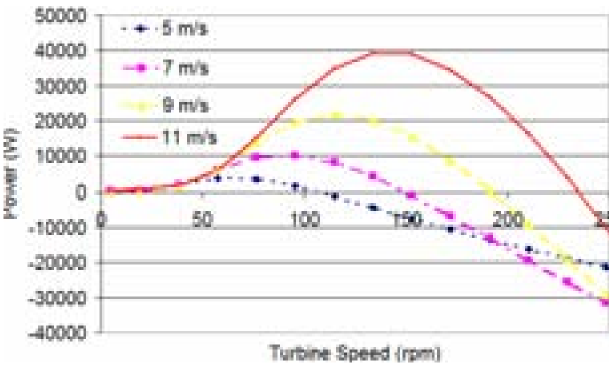

Fig. 3 Turbine Speed Vs Power

3. Simple Rule for MPPT

This paper discusses the tracking of maximum power of WT electrically and not aerodynamically (β = 0). In order to track the MPPT, C_p must be maintained at its optimal TSR. The optimal TSR is obtained by adjusting, in real-time, the rotating speed of the WT according to the variation in wind speed (as $\Lambda = R\frac{\omega_m}{V_w}$).

4. MPPT Techniques

MPPT techniques may be classified as follows.

1) Techniques those are dependent on turbine characteristics (TSR control, PSF control).

2) Techniques those are not dependent on turbine characteristics (HCS and AHCS).

Advantages of former techniques are that they are faster in determining the optimum point and easier to implement. However, they work well for selected WTs only.

Advantages of latter techniques are in using intelligent memory that does not require the knowledge of turbine characteristics. However, when used for large and medium inertia turbines, they fail to reach the maximum power point under rapid wind variations.

5. MPPT Techniques for PMSG based WECS

Fig. 4 shows the PMSG based WECS where only the grid side control is involved. The advantages of using PMSG in WECS are: i) non-requirement of gearbox, ii) high overall efficiency, iii) high reliability, iv) reduced weight, v) less maintenance requirements and vi) self-excitation feature. Three types of MPPT techniques namely TSR, PSF and HCS controls for PMSG based WECS are discussed in this section.

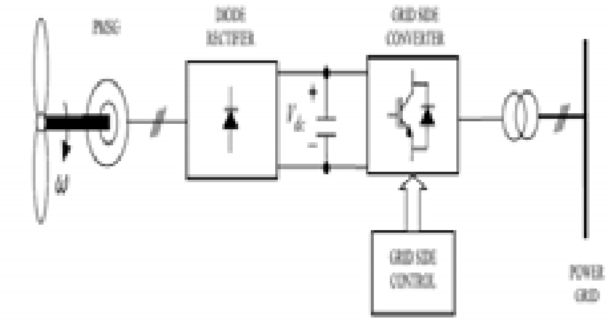

Fig 4 PMSG based WECS

5.1 TSR Control of PMSG based WECS

In TSR control of PMSG, the wind speed is estimated a-priori and is used with the TSR information from turbine characteristics to calculate the optimum rotor speed command for the WT. The optimal rotor speed command acts as the input to the PI controller and alters the switching ratio of the grid side converter, thereby adjusting the rotor speed to the wind speed, thus resulting in maximum power generation.

5.2 PSF Control of PMSG based WECS

In PSF control of PMSG, the turbine power is compared with the reference power. Depending on the error, a control signal is passed on to the grid side control system. Fig. 5 shows the reference power generation for PSF control.

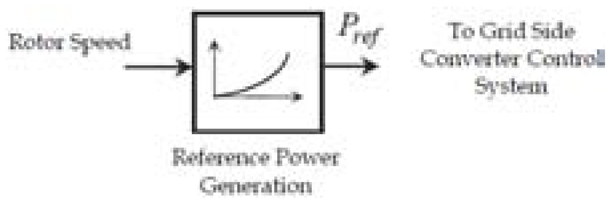

Fig.5 Reference Power Generation for PSF Control

5.3 HCS Control for PMSG based WECS

This control algorithm uses search-remember-reuse technique. Memory is used for storing the peak power points obtained during training process, which are used in future for tracking the MPP. The algorithm starts with an empty intelligent memory with a relatively poor initial performance. This method is based on the fact that at MPPT, $\frac{d_P}{d_\omega} = 0$. If the present value of power due to the increase in command speed

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is greater than the previous value of sampled power, the command speed is increased to reach MPPT. If the present value of power due to the decrease in command speed is greater than the previous value of power, the command speed is decreased to reach MPPT. Similar procedures are carried out for the other two cases namely the decrease of power when command speed is increased and increase of power when the command speed is increased. Fig. 6 shows the HCS control principle.

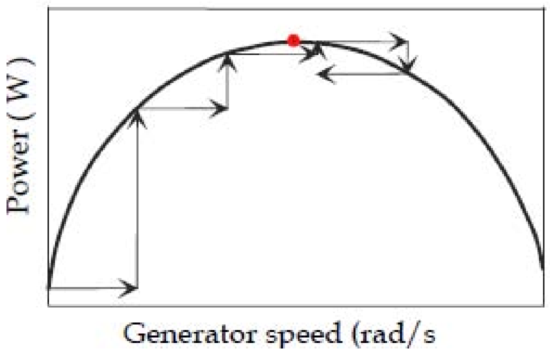

Fig. 6 HCS Control Principle

6. MPPT Methods for SCIG based WECS

Fig. 7 shows the SCIG based WECS in which machine side and grid side control are involved. SCIG based WECSs have the advantage of being robust; having less maintenance requirements and relatively inexpensive when compared to PMSG based WECSs. In addition, SCIG based WECSs require bidirectional power flow as they require reactive power from the grid. Therefore, power electronic switches are used in the machine side as well as in the grid side and MPPT control techniques are applied to the machine side converter.

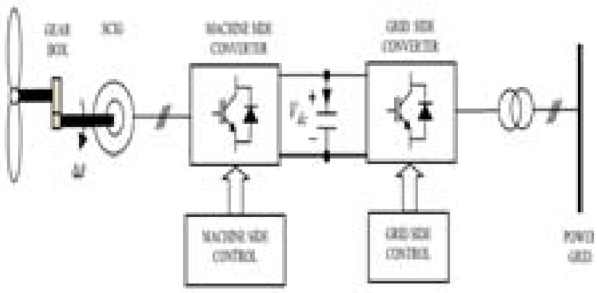

Fig. 7 SCIG based WECS

6.1 TSR Control for SCIG based WECS

TSR control of SCIG based WECS is similar to TSR control of PMSG based WEC, except that the reference speed command is sent to the machine side converter.

6.2 PSF Control for SCIG based WECS

PSF control of SCIG based WECS is similar to PSF control of PMSG based WECS, except that the reference power command is used to change the modulation index of the grid side converter

6.3 HCS Control for SCIG based WECS

In HCS control, if the output power increases with the last increment of speed, then the search process is continued in the same direction; otherwise the search direction is reversed to reach MPPT. This can be implemented using a fuzzy logic controller.

7. MPPT Techniques for DFIG based WECS

Fig. 8 shows the DFIG based WECS where the stator side is directly connected to the grid but the rotor is connected through a back to back PWM converter. The purpose of rotor side converter is to provide power at slip frequency.

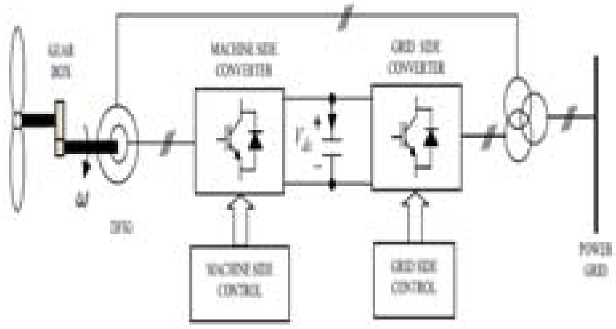

Fig 8 DFIG based WECS

7.1 TSR Control for DFIG based WECS

TSR control is possible with wind speed measurement or estimation. In TSR control, the actual speed is compared with the estimated wind speed and the optimal value of λ is calculated in order to obtain the generator speed for optimum power extraction from the WECS.

7.2 PSF Control for DFIG based WECS

In PSF control of DFIG, the generator output power and rotor speed are sensed and given as input to a fuzzy logic controller (FLC) whose output is the maximum power to be generated. The rotor speed is altered to capture maximum power. Fig. 9 shows the FLC based PSF control.

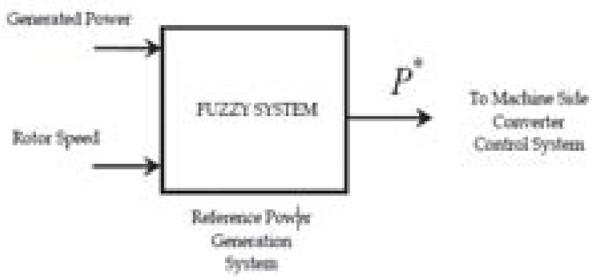

Fig.9 FLC based PSF Control

7.3 HCS Control for DFIG based MPPT

HCS control is implemented via perturb and observe algorithm. It is also implemented in DFIG based WECS similar to the above two methods.

8. Conclusion

The paper presents three MPPT techniques for controlling variable speed fixed pitch WECS for different types of generators. The first two techniques are used when the wind is above the rated speed while the third technique is used when the wind is below the rated speed. The HCS technique require high memory while the other two techniques namely PSF and TSR, require the prior knowledge of system characteristics. and more sensors. The HCS control is beneficial technique, as they do not require more number of sensors, control is simple and is independent of turbine characteristics.

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Eddy Current Losses Calculation for a 10MW Ironless-stator Axial Flux Permanent Magnet Synchronous Generator for Offshore Wind Power Plant

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Keywords: Axial Flux Permanent Magnet (AFPM) generator, continuously transposed conductors (CTC), eddy loss, Roebel.

INTRODUCTION

It is well-known that using expensive Litz wire is an effective solution to reduce eddy current loss in the high-speed low-power electrical machines. However, in our offshore wind power application where a direct-drive 10MW ironless-stator generator and full-scale converter are used, the use of Litz wire becomes also necessary. Meanwhile, the progress in manufacture of Roebel winding and CTC make these conventional cheap solutions promising to be employed for a cost-effective generator.

STATE OF THE ART

Even though the magnet load in ironless axial flux machine is quite low (<0.4T normally), there is significant tangential component, which also contribute to the eddy loss in winding [1]. The use of the full-scale converter injects much harmonics current into the stator windings and induces more eddy losses.

Litz wire has brought its advantages to reduce eddy loss considerably, therefore, is being used in the renewable energy market [2]. However, this multiple strand flexible solution is considerably more expensive. Meanwhile, the new technology in manufacturing of conventional cheap transposed winding has evolved so much that interesting levels of loss reduction can be obtained when subjected to more complex transposition.

MODELING AND TEST

Fig. 1 shows the 3D model used for eddy current losses calculation (section enclosing two poles of the machine). Although the main intention is to test at the active zone, transposition in the end winding zone will also be studied.

The bar has to be transposed so that the strands from the left (right) half at the beginning of the transposition move to the right (left) half by the end of the transposition. Eddy loss calculation requires skin-depth level mesh and massive computing. A computing server (48-core, 128RAM) is used in the calculation.

A pre-made 50kW ironless axial flux prototype is planned to be used for the validation purpose.

CONCLUSIONS

It is expected to gain some understanding about latest Roebel windings and CTC when applied to the low-speed ironless-stator AFPM machines, and cost-effective winding solution is expected to be found for such large-diameter machine.

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FIGURES

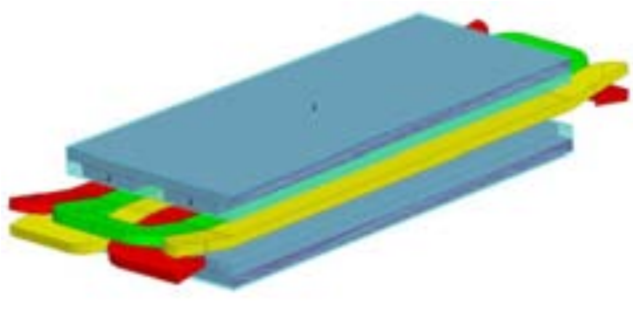

Figure 1: 3D model of the ironless machine. 1– rotor, 2 – PMs.

Deployment of Multi-Agent-Systems for Optimizing O&M of wind turbine

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Keywords: Maintenance, Reliability, Availability, Optimization, Modelling, Simulation, AI, Multi-Agent-Systems, MAS, Data Mining, O&M, Reliability-oriented.

Maintenance management for wind turbines (WT) aims on the one hand at reducing the overall maintenance cost and on the other hand at improving the availability. Although modern onshore WT attain high technical availability of up to 98 %, the evaluation of maintenance work in previous projects ([1], [2]) shows, that high WT availability requires additional maintenance work and costs. There is a considerable scope for optimizing the reliability and maintenance procedures. A possibility therefore is to systematically make use of available knowledge and past experience. The consideration of several conditions e.g. weather conditions, power prognostics, stock keeping etc. are also essential for optimal decisions.

Besides the statistical analyses, using RAMS/LCC-methods, an additional approach to explore possible options regarding the suitable WT O&M strategy (e.g. the optimal cost and interval to carry out preventive maintenance tasks), is the so called Multi-Agent-System (MAS) combined with Data Mining (DM). MAS which is a new discipline in the world of Artificial Intelligence (AI) and the DM, which is a high-performance computing methodology used to observe and deduce hidden knowledge and logical dependencies of a great amount of data using several appropriate algorithms, should be investigated in this paper. Thus, a methodology for the use of AI in WT maintenance is proposed.

The reliability-oriented maintenance of WTs relies particularly on management and evaluation of operating and maintenance data [1]. However, today's organization of data acquisition and data management used by wind farm operators (WFOs) doesn't permit the sophisticated use of experiences [3]. Additionally WFOs/service companies are missing tools and necessary information (e.g. failure statistics, weather forecasts, staff disposition, etc.), instructions and recommendations needed for their maintenance decisions. By estimation of failure probabilities, remaining useful life and early recognizing of possible damages and errors as well as by using wind and power prognosis, maintenance tasks and procuring of spare parts could be appropriately planned and unexpected stops could also be avoided. For an efficient maintenance planning the economic boundary conditions e.g. spare part and personnel costs or the temporal development of the fluctuating electricity tariff at the electricity market are to be considered. For the support of a foresighted maintenance strategy a MAS is to be developed, which uses reliability characteristics and cost information from WFO, and weighs the competitive interests of the different aspects for the studied case. It suggests therefore favored maintenance measures for the decision-maker.

A schematic representation of the research within the work is shown in figure 1. Different Agents manage different competitive tasks. Some of them have the task to analyse the failure rates, while others regard weather and power forecasting, and the third category considers the question of cost of the whole maintenance process. A main goal thereby is to submit the WFO with an arranged list of requirements and proposals, on how the next maintenance should look like. This goal will be achieved by suggesting optimal or alternative solutions for the decision-maker.

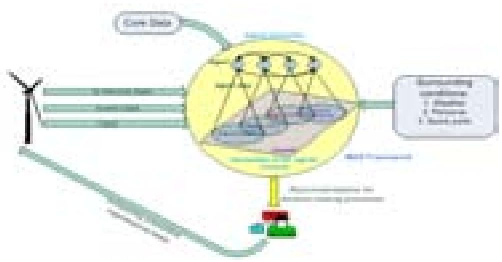

Fig 1: Use of MAS for improving the maintenance decisions

Within this contribution an approach combining MAS and DM will be described. It will show the ability to improve operating maintenance activities and help the wind farm operators managing their task planning, taking into account several surrounding conditions in the analysis.

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A case study of Python based programming architecture for TURBICE

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Keywords: Ice accretion, wind turbines, Python scripting

INTRODUCTION

Wind turbines operating in cold climates are prone to experience more loads due to icing of the turbine blades and high density of cold air. Ice accretion on wind turbine blades is undesirable due to change of the aerodynamic shape and properties of the blade, fatigue loading, load imbalance, and ice shedding, which may even lead to a turbine shutdown in addition to the performance degradation. Therefore, ice accretion simulation research which is coupled to a structural analysis simulation is of high importance in order to estimate and study the effects of ice loads on the wind turbine, which is the main purpose of this PhD research.

A NEW PROGRAMMING ARCHITECTURE FOR TURBICE

Current focus of this research is on further development and enhancement of TURBICE, which is the in-house two-dimensional wind turbine blades ice accretion simulation program of VTT written in Fortran. A new architecture of the program is going to be constructed in a Python interface for extended modularity, flexibility, and usability.

Python is a high-level general purpose object-oriented scripting language that is convenient for ease of code generation and maintainability, provides a programming environment suitable for scientific computing through incorporation of various specific libraries, as well as text processing and visualisation, and which is extendible via other kind of available libraries.

USING PYTHON AS A CODE GLUE

Additionally, using Python as code glue, therefore getting advantage of other programming languages' advantages is a beneficial and acknowledged approach [1-4]. Fortran or C enables fastest run-times as compared to high-level languages, however lacking many advantages that one could gain from object-oriented and dynamic languages. Therefore, in order to overcome the drawbacks of a number crunching language, while maintaining fast computation advantage, utilizing Python as a code glue is going to be the new implementation strategy for further development of the program.

CONCLUSIONS

Implementation of a prototype of the proposed programming architecture is initiated recently, and a case study of this implementation process is presented in this work.

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Dynamic Behavior of Offshore Floating Wind Turbines

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Keywords: offshore floating wind turbine, hydrodynamics modelling, multi-body system, computational fluid dynamics, scale model test

INTRODUCTION

Research about Floating Offshore Wind Turbines (FOWT) recently gained momentum and first prototypes have been deployed in European waters in 2007 (Blue H Technologies BV [1]). Offshore wind farms benefit from stronger, more consistent and more predictable winds compared to onshore. Floating support structures are favored if fixed-bottom foundations are economically unfeasible due to increasing water depths.

MOTIVATION

However, higher investment costs have to be faced and there is increased complexity in modelling and simulating FOWTs. Additional degrees-of-freedom (DOF) of floating systems result in aerodynamic and hydrodynamic effects that onshore or fixed-bottom offshore wind turbines are not exposed to.

APPROACH

The complex interaction between the aerodynamic and hydrodynamic forces on the floating structure and the dynamic response of the wind turbine and support platform need to be investigated further. In this research, the FOWT is modeled by means of a multi-body approach using the simulation tool SIMPACK. It is coupled to NREL's AeroDyn [2] and HydroDyn [3] modules providing sophistcated dynamic simulation capabilities.

A fluid-structure coupling using Computational Fluid Dynamic (CFD) methods will be used to gain more detailed insights into the complex dynamic effects. The hydrodynamics are of particular interest in this study and a focus will be on effects that have not yet been taken into account. Additional, design load cases that are specifically important for FOWT need to be specified for future developments in the industry. This research may contribute a better understanding.

Scale model tests of FOWTs, like UMaine/NREL's recent wave basin test at the MARIN [4], will be performed and used for validation of the findings. However, scaling a FOWT is very complex due to the combined wind and wave loads. Similitude of the dominant scaling relationships for hydrodynamics (Froude number) and aerodynamics (Reynolds number), respectively, between the model and a full-scale prototype is hard to obtain and impractical. Further investigation on inclusion of airfoils with low Reynolds number dependency and preservation of aeroelastic effects is needed.

CONCLUSIONS

The importance of FOWT in research and industry is increasing and the complex dynamic behavior needs to be modeled more accurately. The level of detail will be advanced using CFD methods for hydrodynamics. Scale model tests will help to validate the simulation results and capabilities.

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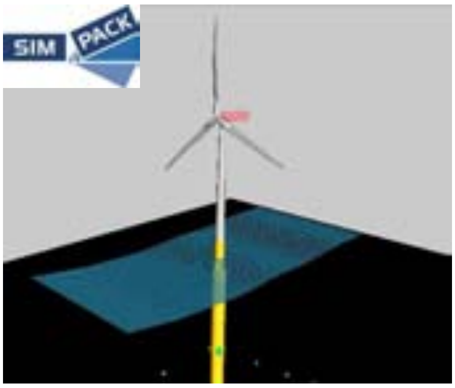

Figure 1: Floating Offshore Wind Turbine modeled in the multi-body simulation tool SIMPACK

On the influence of marine boundary layer characteristics on power curves of Multi-Mega Watt wind turbines

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Keywords: boundary layer meteorology, power curve, wind resource, offshore, stability, turbulence intensity, shear, alpha ventus

Introduction

Until the year 2030 the total wind energy capacity in Europe is expected to grow up to a total of 400 gigawatts (GW) of which more than one third (150 GW) is projected to be installed offshore. For this reason, wind farms of several 100 MW installed capacity are planned, concentrated in small regions, mainly in the Southern North Sea [1]. Thus, fluctuations in the wind field can pose a threat to the stability of the electrical grid.

Offshore wind turbines are subject to a varying wind profile within the marine boundary layer, which is mainly influence by atmospheric stability. The impact of atmospheric stability on the power production of offshore wind turbines has hardly been studied. Onshore studies have indicated a difference in power production of up to 20% between unstable and stable stratification [2].

Method

Within the framework of the RAVE-OWEA-project boundary layer characteristics such as shear and turbulence intensity from measurements at the FINO1 met mast have been investigated. The nearby offshore wind farm ‘alpha ventus’ allows studying the influence of these parameters on power curves of wind turbines within the wind farm.

One minute wind speed time series from the FINO1 met mast were combined with the power production from the SCADA data for the wind turbines within the wind farm. Power curves binned by shear and turbulence intensity groups were derived. For nondimensionalisation of the results one year mean power curves were taken.

Results

Non-Wake

The non-wake power curves show only a small dependency on shear, a 5% difference between power curves of low shear (unstable) and high shear (stable stratification) was found. In the non-wake case the turbulence intensity showed a higher influence (Fig. 1). In the region below rated power differences of up to 15% between low (stable stratification) and high turbulence intensity (unstable stratification) occurred.

Wake

In the wake case the influence of the stability on power curves is more pronounced. Differences of more than 20% between unstable and stable stratification (based on turbulence intensity measure) were identified (Fig. 2). Again, the area of strongest influence is the region below rated power. This wind speed range is of economically high interest as they are observed more than 30% of the year at the FINO1 met mast.

Conclusions

A clear influence of stability on the power output of wind turbines was found. The influence is higher on wake than on non-wake wind turbines. The profitability of a wind farm project is often restricted to an accuracy of less than 5% in the power output forecast. During most wind energy siting processes neutral stratifications are assumed. This way changing atmospheric properties can lead to severe financial problems.

In future work, the influence of stratification for other offshore wind farms in the North- and Baltic Sea will be investigated. Results from this research will lead to a better understanding of available power in different atmospheric conditions and improve wind farm control strategies for a better integration into the electrical grid. Not least results can support the improvement of engineering wind farm wake models.

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FIGURES

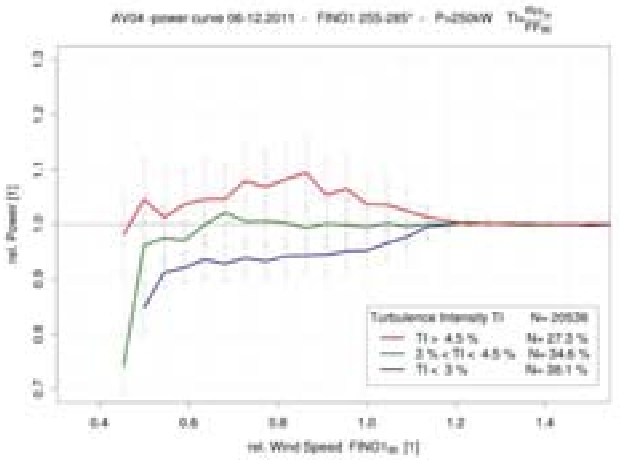

Figure 1: Influence of Turbulence Intensity (TI) on a non-wake wind turbine power curve

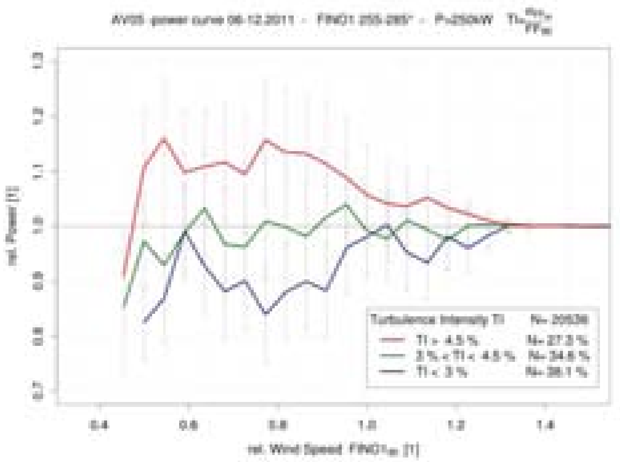

Figure 2: Influence of Turbulence Intensity on a wake wind turbine power curve.

Comparison of Geared and Direct-Drive Generator Concepts for Large Wind Turbines

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Keywords: Generator modelling, cost of energy, annual energy production, direct-drive generator, geared generator, gearboxes

Introduction

Over the past few decades, wind turbine manufacturers have been exploring various drive train topologies ranging from multistage gearbox and standard induction generators to gearless direct-drive systems. With high emphasis on turbine reliability for modern offshore developments, many manufacturers are beginning to use permanent magnet (PM) direct-drive systems into their turbines to eliminate excitation losses [1]. Permanent magnet machines do not require an additional power supply for the magnet field excitation and have higher efficiency and reliability [2] compared with electrically excited machines. Sizing and cost become more significant issues with this configuration as direct-drive PM generators may require very large diameters and so can be heavy and expensive which in turn can create transport and installation issues. The combined use of a permanent magnet generator and a gearbox (Multibrid [2]) is proving to be an effective compromise between geared and gearless systems.

It is therefore crucial for developers understand cost and reliability implications for each drive train configuration in order to effectively generate a high return on investment and overcome installation and maintenance issues associated with offshore development.

This study aims to develop the work presented in [1] and focuses on the comparison between permanent magnet direct-drive and geared (single, two and three staged) in terms of cost of energy.

The four configurations considered in this paper are:

- DDPM – direct-drive PM generator
- PMG1G – PM generator with single stage gearbox
- PMG2G – PM generator with 2-staged gearbox
- PMG3G – PM generator with 3-staged gearbox

Section 1

The comparison of the four generator systems was achieved through the simulation a theoretical 6 MW wind turbine with a rated speed of 12 rpm. Each configuration was modeled in Matlab to assess the performance in terms of voltage, current and losses, and the overall cost of energy. By considering factors such as the initial capital costs, operations and maintenance of each generator topology, a comparison of the total cost of energy over the lifetime of the turbine was drawn for each and the optimum design choices are discussed.

Section 2

Cost of Energy

Cost of energy (COE) per MWh is calculated using the following equation:

$$COE = \frac{(FCR * ICC + AOM)}{AEP}$$

FRC is Fixed Charge Rate, ICC is Initial Capital Cost, AOM is Annual Operation and Maintenance and AEP is Annual Energy Production [5].

Conclusions

Initial results imply that despite having high capital costs, direct-drive systems may have improved reliability which will reduce maintenance costs over the lifetime of the turbine. In this paper we highlight the sensitivity to assumptions of availability and AOM costs for the COE.

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European Academy of Wind Energy

LEC Laboratory for Energy Conversion

Wind Turbine Drivetrain Test Facility

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Keywords: drivetrain, testing facility, nacelle test bench, robust control, turbine modeling

Introduction

The development of new wind turbines is primarily based on simulations and static hardware tests of individual components or minor parts of the overall system [1]. Only when the first prototype is built, the interaction of all components under real conditions regarding e.g. dynamic loads and grid states are investigated.
Against that background it seems appropriate to undergo an intermediate step and test the overall system on a test bench which applies dynamic mechanical loads on the rotor side and different transient grid states on the electrical side of the system.
This also provides research and development departments the opportunity to test new components and experimental control concepts under real, but safe and repeatable conditions.
Such a test bench in the typical power class of onshore wind turbines 1..4 MW, is currently been developed and installed at RWTH Aachen University, in cooperation with Vestas and other industrial partners to establish the Center for Wind Power Drives (CWD)[2].

Test Bench Concept

The test bench is carried out as hardware-in-the-loop (HIL) system. The nacelle with dismantled rotor but all its inside components (gearbox, generator, ...) is in a loop with software that simulates the natural environment of the wind turbine.
On the mechanical side, the rotor shaft is mounted to an electrical machine for creating the rotor torque while all other torques and forces are transferred to the hub via hydraulic actuators (Figure 1). A real-time aerodynamic model calculates these torques and forces for given wind speed, turbulence intensity and rotation speed. Wind events according to [3], such as extreme wind direction changes (EDC), are also implemented and can be triggered in real-time. The actuators can transfer load changes within the spectrum of the blades first eigenfrequency.
The wind turbines power link is connected to a converter-based grid. A real-time grid simulation provides the converters reference and is capable of simulating grid failures [4] to determine e.g. the turbines fault-ride-through (FRT) behavior.
To use the original controller of a wind turbine, yet another simulation is necessary to detect controller commands for actuators not present any more (e.g. yaw motor) and simulate the corresponding measurement signals.

Opportunities

Since a fully equipped Vestas V52 wind turbine nacelle is available throughout the project and beyond, one aim is to establish a research platform for testing new developments on a real wind turbine. Therefore a generic wind turbine controller on rapid control prototyping hardware is set up to be able to easily integrate any desired control law. With this open interface provided, developed models and advanced control laws can be evaluated and tested directly on the wind turbine under real conditions. After implementing state of the art controls to investigate current wind turbine behavior and assess possible improvements, modern control strategies will be investigated. The focus will be on robust multiple-input-multiple-output (MIMO) controllers. Apart from the power maximization objective, fatigue load reduction in the drive train and the overall system is to be considered as well as output power quality and grid stability (network services). Resulting effects on the mechanical components can be observed exactly since gearbox, shaft and generator are equipped with additional measurements.
Other research activities will focus on new drivetrain concepts, condition monitoring systems and fault prediction.

Conclusion

For independent research, the overall wind turbine test facility can compensate the lack of research turbines in the field. Hence scientific findings can be validated more quickly and the knowledge can faster be transferred into industrial applications.
For OEM's and component suppliers, the test facility also provides a common reference to evaluate their products.
Experience gained with the test facility might also lead to a change of the certification procedure stated in DIN EN-61400, partly replacing long term prototype tests by defined procedures on such test facilities.

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Figures

Figure 1: The nacelle test bench at RWTH Aachen University

Investigation into the causes, impacts and mitigations of reduced power system inertia.

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Keywords: Power System Inertia, Frequency Response, Synthetic Inertia, Wind Energy Penetration, DFIG.

INTRODUCTION

THE PROBLEM

Electrical power systems have traditionally been reliant on large, predominantly synchronous generators to provide the requisite power to satisfy instantaneous consumer electricity demand; however this scenario is unlikely to continue as the penetration of variable-speed wind energy generation increases in the coming years.

Traditional synchronous power systems have within them an inherent property – inertia (resistance to change of speed) – which is caused by the combined rotational mass of the generators connected to the system. This useful physical property of the system contributes to overall network stability by reducing the rate of change of rotational speed (acceleration) of all connected synchronous machines and therefore reducing the rate of change of system frequency in the event of a fault (i.e. loss of generation/load).

In contrast to conventional synchronous generators and fixed-speed wind turbines the increasingly popular doubly-fed induction generator topology for MW-scale wind turbines effectively provides no inertial response to the power system [1].

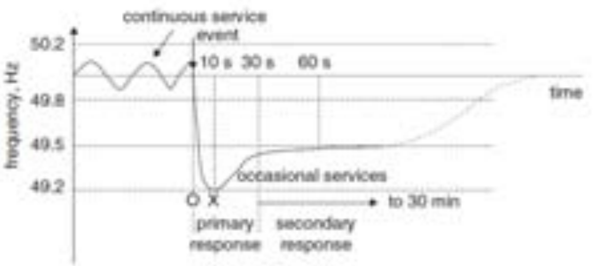

Figure 1: Frequency Service Quality Control

An emerging problem for power system operators is that of reduced total system inertia as a result of the increased penetration of variable-speed, converter-interfaced wind energy generation on the power system and the associated alterations to frequency control and system stability [2].

OBJECTIVES OF THE PAPER

The paper examines the causes, impacts and mitigations of reduced power system inertia and brief descriptions of the fundamental concepts regarding system inertia are given. Illustrative simulations and investigations are carried out using a Simulink model to highlight the effects of reduced inertia, focusing particularly on the instantaneous system response following a fault (i.e. before controller action). Finally, future work and potential mitigations to the reduced inertia and frequency response problems are discussed.

CONCLUSIONS

It is shown through simulation that a reduction in power system inertia results in increased rates of change of frequency (ROCOF). At the present moment there is a wide range of potential mitigations to the problem of reduced inertia, including synthetic inertia, flywheels and demand-side management – all of which have a part to play in the development of future power networks incorporating large amounts of high-efficiency, variable-speed wind energy generation.

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FRT and protection assessment for offshore network

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Abstract

Significant numbers of countries are investing in offshore wind energy. Despite of the economic crisis, the wind energy sector is growing wealthy. Governments think that renewable energies and concretely the offshore wind energy could possibly be part of the EU economy engine.

The increasing energy production for a singular wind turbine and installation of large scale of offshore wind farms combine together with large scale onshore wind farms will probably soon replace high scale of conventional power stations. Hence, wind energy should have an important role in the electrical network behaviour. This future electrical offshore network and its onshore connection had been planned but not yet installed. Therefore, potential problems should be studied and identified, and finally solutions should be applied. These solutions should mitigate possible electrical network damages.

The offshore to onshore connection will depend of the distance between the transmission platforms and shorelines and finally the total power transmitted.

Although, the electrical array and the control system for the offshore power is not yet decided, it seems that VSC-HVDC could be the best solution to transfer high quantity of power. This control and its transmission technique has proven its reliability to transfer short amount of power in long distances and it has also show a high performance in term of mix power from different energy sources, i.e: wind energy and gas&oil power station.

The objective of this paper is to develop a control system which could mix different type of energies and then transmitted this power without significant hazards. The control system should increase the reliability during the steady state and large transients,

reducing lose and minimising its control system complexity. This assessment will evaluate different scenarios in which is represent possible North Sea offshore projects. The dynamic performance of these scenarios would be simulated through computer modelling using Matlab-Simulink. It focuses on the performance of the control system during large transient. The possibility of multi-terminal connection HVDC (MTDC) has been taken under consideration and several scenarios should be implemented.

Title of poster

Probabilistic security constrained reserve scheduling for systems with high wind power penetration

Abstract

The expected increase in the installed wind power capacity highlights the necessity of revisiting basic operational concepts like reserve scheduling and N-1 security, so as to take into account the intermittent nature of the wind. To achieve this, we propose a probabilistic framework to design an N-1 secure day-ahead dispatch and determine the minimum cost reserves. We formulate a stochastic optimization program with chance constraints, which encode the probability of satisfying the transmission capacity constraints of the lines. To incorporate a reserve decision scheme, we take into account the steady state behavior of the secondary frequency controller, and hence consider the deployed reserves to be a linear function of the total generation-load mismatch. The overall problem results in a chance constrained bilinear program; to achieve tractability, the issues arising due to the bilinear terms and the presence of the chance constraint need to be resolved. To alleviate the former, we propose two convex reformulations of the initial problem, whereas to deal with the chance constraint we use a constraint sampling technique, namely scenario approach. To quantify the effectiveness of the proposed methodologies we carry out Monte Carlo simulations corresponding to different wind power realizations generated by a Markov chain based model.

Floating Multi-Rotor Systems

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Keywords: Floating, offshore, multi-rotor systems, static stability, cost effectiveness, CAPEX

Introduction

Research into the development of Multi-Rotor Systems as a viable alternative to single rotor turbines has been widely acknowledged for many years. The Multi-Rotor system can provide a reduced overall mass and cost compared with one turbine of equivalent power. This is due to the fact that energy converted from the wind is proportional to the square of the rotor diameter whilst the CAPEX is proportional to the diameter cubed [1].

Prior investigation has been carried out by Upwind into the applicability of an offshore 20MW turbine [2]. The research proposed hopes to extend the investigation into the possibility of designing an offshore 20MW multi-rotor system comprising of a number of much lower rated turbines (400kW). However up until now very little work has been done to consider how a multi-rotor machine of this size will float in a stable manner out at sea. This project aims to compare the principles of floating offshore platform design of a multi-rotor system with its equivalently rated single turbine. The overall stability of the platform is considered, as well as the sizing constraints that are introduced with using a Spar Buoy. Conclusions as to the feasibility of such a design will be presented.

Sizing and Stability

The aim of this project was to design an offshore floating platform for a 20MW multi-rotor System. However to quantify the design a comparison was made between the multi-rotor system and an equivalently rated single rotor turbine. This provided a strong indication of the benefits that a multi-rotor system could have over that of a single turbine. Sizing of the floating platform was conducted using MATLAB by taking into consideration the weight distribution, wind loading and current loading on each structure. The floating platform used for comparison between the two structures was a floating spar buoy. Hydrostatic stability analysis was then performed on each structure. This looked at the maximum static heel angle that the structure would experience during a period of maximum wind loading and current loading.

Finally an alternative design of the floating structure was considered. This design considered the floating platform as a continuation of the truss structure of the multi-rotor system itself. This was to establish whether or not overall stability would be compromised using a floating spar buoy compared with a semi-submersible structure. The result would help inform the overall design process and allow conclusions to be made as to the most optimum design of an offshore platform for use on a multi-rotor system.

Construction and Installation

Little research has been done into the feasibility and cost-effectiveness of constructing such large structures. Part of this research project was concerned with providing a detailed discussion of the practicalities involved and an initial overall cost estimate of carrying such a process out.

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Turbine modeling & control

Cyclic control optimization for a smart rotor

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Keywords: Adaptive Trailing Edge Flaps (ATEF), Cyclic Pitch Control, active load alleviation, periodic control, Smart Rotor.

INTRODUCTION

The paper presents a study of the performances of a smart rotor in a deterministic wind field, where individual pitch variations, and flap actuators follow cyclic control signals. The control signals are obtained by solving an optimization problem, where the cost function matches the control objective, e.g. blade root load variation or power output. The method does not depend on additional sensors, neither on feedback control; thus, it can provide a reference setup that would facilitate performance comparison between different types of actuators. Furthermore, the results from the cyclic control optimization would give a useful term of comparison for future implementation of a feedback controller.

An attempt is made to use the proposed cyclic optimization method to optimize the power capture of a smart rotor below rated conditions. The investigation will include results from both individual pitch and trailing edge flap control strategies.

METHOD

The study is carried out on the NREL 5 MW reference wind turbine [1]. The standard baseline controller provides the generator torque, and the reference collective pitch signal. The aeroelastic response of the turbine is simulated using the code HAWC2 [2]. The aerodynamic effects of the flap are accounted for by using the dynamic stall model described in [3]. The flap actuators extend from 77% to 97% of the blade span, and their deflection is limited to ±10 deg.

The problem of finding a suitable cyclic control action is formulated as a constrained optimization problem. The optimization tries to minimize the cost function by looking for an optimal trajectory for the control signal. To reduce the dimension of the problem, the continuous control signal is represented by a finite number of values at fixed azimuthal locations; the signal is then reconstructed using piecewise cubic interpolation between the fixed points.

The objective function is evaluated through aeroelastic simulations, at each iteration of the optimization algorithm. To limit the simulation time, stochastic variations of the wind field, as from atmospheric turbulence, are omitted. Deterministic variations of the flow field, originate from wind shear (Normal Wind Profile, as in [4]), tower shadow, and structural tilt and cone angle.

(PRELIMINARY) RESULTS

A preliminary investigation is carried out to determine the potential of increasing power capture below rated conditions by cyclic control of the flap actuators. Figure 1 reports power coefficient (*Cp*) curves versus tip speed ratio (*lambda*), resulting from a steady BEM model of the NREL 5 MW rotor. By optimizing the collective pitch angle (blue line), the maximum *Cp* is increased. By including also an optimal flap deflection (red line), the maximum *Cp* is unchanged, but the curve becomes flatter around the maximum. The result suggests that using flap actuators below rated condition might increase the energy capture; upcoming simulations will allow to quantify the potential for the power capture increase.

(EXPECTED) RESULTS

Below rated conditions, cyclic control optimization will be carried out to optimize power capture. The investigated cases will include: collective pitch angle (CPA), CPA and collective flap, CPA and cyclic pitch, CPA and cyclic flap. Above rated conditions, the optimization will focus on reducing the blade root flapwise load variation.

(EXPECTED) CONCLUSION

The optimization procedures will return optimal cyclic control signals for the investigated turbine. The smart rotor performances will be then assessed in terms of increased power capture below rated conditions, and reduced load variation above rated, for both individual pitch, and flap control strategies.

The final results will also indicate whether the cyclic control optimization method provides a suitable setup for comparing the potential of different types of smart rotor actuators. The method is however limited to cyclic repetitive control actions, and, as such, can only address periodic (deterministic) disturbances, and it cannot evaluate smart rotor performances in alleviating the effects of stochastic disturbances, originating for instance from wind turbulence.

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FIGURES

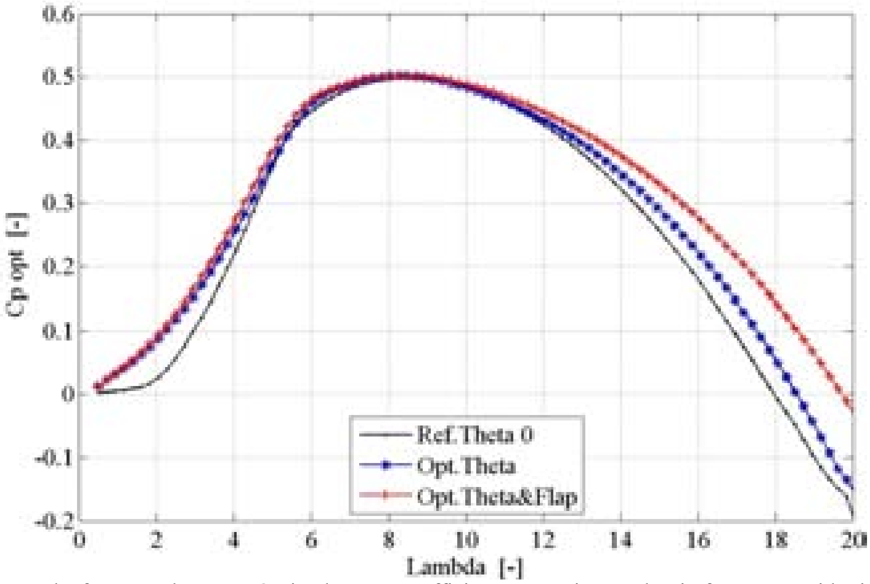

Figure 1: Preliminary results from steady BEM. Optimal Power coefficient versus tip speed ratio for a rotor with pitch fixed to zero (baseline, black line), optimized collective pitch (blue line), optimized collective pitch and flap deflection (red line).

European Academy of Wind Energy

LEC Laboratory for Energy Conversion

Active Power Control in Wind Turbines for Grid Stabilization and Primary Control

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Keywords: active power control, wind turbine control, grid stability, voltage angle stability, primary control, virtual inertia

Introduction

As the share of electrical power generated by wind turbines is increasing, grid stability must be maintained and primary control has to be provided by wind turbine generators. To improve voltage angle stability in the grid, the current phasor of the grid-side inverter of doubly-fed induction generators (DFIG) or synchronous machines with full inverter (SM) may be controlled depending on the measured voltage phasor. This causes short-term power deviations at the grid side converter, thus requiring a certain amount of stored energy in the turbine and converter system. For participation in primary control, the power infeed has to be adjusted on a short-term scale up to about 10 seconds, which also requires storage of energy. This storage may be provided by a separate unit in the dc-link of the inverter system or by the rotor inertia.

In this paper, the rotor inertia approach will be discussed and a suitable control system is introduced.

Control Design

The controller was designed to follow the turbulent power output, while a defined power offset can be added to the turbulent power output. This is supported by wind speed estimation based on the operational conditions of the turbine. The estimated wind speed also allows for an estimation of the possible additional energy delivery and to estimate the deviation of the rotor speed from the optimal rotor speed. In below-rated wind speeds the rotor slows down if additional power is demanded. In that case a recovery phase is necessary to return to normal operation. With the new control system, the recovery phase can be triggered at the desired time and the time course of the power reduction can be shaped as desired. This scheduled recovery allows for coordination with secondary control, so that the primary control power delivered by the wind turbine is not causing disturbances to the power system at a later time.

The controller has been designed around a 1-DOF model of the turbine with $C_p - \lambda$ aerodynamics. A power feed forward control, which is based on estimated wind speed has been added to the standard turbine controller.

For validation, the nonlinear IWES WTsim 2.0 code has been used.

Results

The active power controller was tested under step power offset conditions, to ensure the functionality in the whole operational range of the turbine. Exemplary time series are provided in Figure 1, showing a power offset for partial load and full load condition with constant wind speed. From t = 300 s to t = 310 s, an additional power ΔP = 0.05 p.u. is requested. In below-rated operation, the rotor speed decreases during this phase. Afterwards, the turbine waits for the recovery trigger from the central controller until t = 315 s, when the transition to standard control mode is initiated.

In further simulations, the ability to provide power offset steps of $\pm 0.1\, p.u.$ for 10 seconds at any wind speed (in the range of 4 to$25\ \frac{m}{s}$) has been showed.

Conclusions

The presented control scheme for Active Power Offset control in wind turbines has been successfully tested in nonlinear time-domain simulations. Even at cut-in wind speed, an additional power of 0.1 p.u. can be supplied for 10 seconds. This implies that wind turbines are able to supply primary control, if a suitable interface to secondary control is established. Grid stability can be enhanced by frequency or phasor feedback loops.

This work has been funded within the project *Wind farm control for grid integration (0325170B)* by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety.

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FIGURES

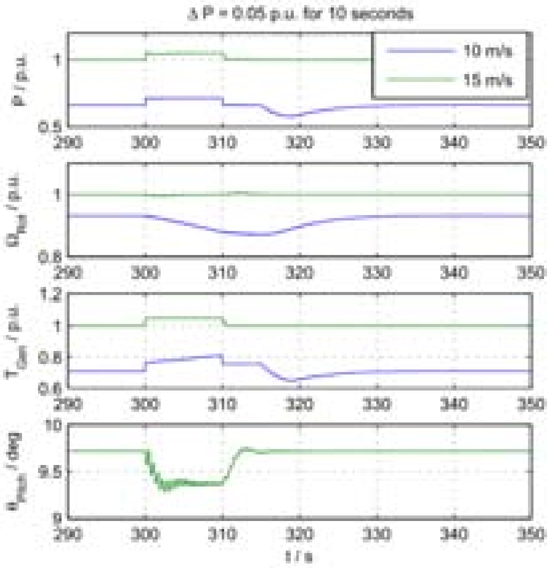

Figure 1: Active Power Control under constant wind conditions

High level control and optimization of kite power systems

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Keywords: Airborne Wind Energy, AWE, kite power, pumping operation, distributed control, optimization

Introduction

Airborne Wind Energy (AWE) systems are a novel way to harvest wind energy without the need for a heavy tower and foundation. During the last decade the number of companies and research groups involved in the development of AWE systems increased from three to sixty. AWE systems are expected to work with a very high capacity factor, because the wind-speed at increasing altitudes is higher and steadier. In many applications they also promise a substantial decrease of costs per kWh. The principle of operation of the AWE demonstrator of TU Delft will be explained. Current concepts of high-level control and optimization will be explained. First test results will be presented.

Principle of operation

Kite power systems combine one or more computer-controlled inflatable membrane wings with a motor-generator unit on ground using a strong and lightweight cable[1]. Each pumping cycle consists of an energy generating reel-out phase, in which the kites are operated in figure-eight flight manoeuvres to maximize the pulling force, and a reel-in phase in which the kites are depowered and pulled back towards the ground station using a small fraction of the generated energy (see Fig. 1).

Figure 1: Pumping Kite

To reach a high efficiency of the wind harvesting mechanism, a high reel-out and a low reel-in force are required. A high reel-out force is achieved by flying crosswind, a low reel-in force is realized by de-powering the kite. The current demonstrator needs less than 20% of the reel-out energy for reeling in.

Automated control

In Fig. 2 the high-level structure of the control system is shown: On the top left the user interface. Currently it allows to switch between manual operation, power production and parking. In yellow the sensor blocks are shown, in green the actuators. For the control of the flight path one planner and one controller component are used, for the the control of the motor/ generator (tether force and speed) a separate winch controller.

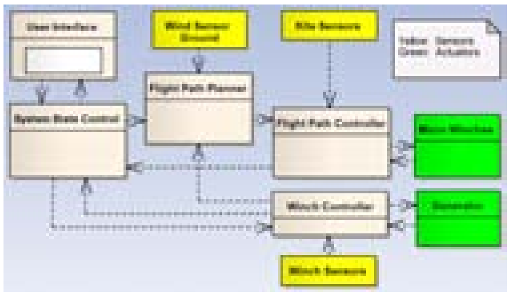

Figure 2: High level design of the control system

High level control and optimization

Kite power systems have more degrees of freedom than traditional wind turbines: Not only the trajectory of the kite during the reel-out phase can be optimized, but also the reel-out speed of the tether. For reel-in the optimization must be handled slightly different. For obtaining a low reel-in force the kite shall not fly crosswind. The maximum that the kite can be depowered and the minimal reel-in force depend on the safe flight envelope of a specific kite. Using a model based flight envelope as boundary condition the relationship between reel-in speed and force has to be optimized with respect to the total efficiency of the kite power system.

Conclusions

Since 2012 the low-level controllers of the winch and the kite are able to operate the system fully automatically for more than one hour. To achieve fully automated operation even under heavily changing wind conditions the flight path, the elevation angle and the set points of the winch controller have be adjusted automatically. Algorithms that are beeing developed for this automated optimization will be presented.

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Distributed Approaches to Wind Plant Control

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Keywords: Control Systems, Wind Plants

Introduction

This abstract presents two different methods for controlling wind plants in a decentralized framework, where each turbine controller is exchanging information with neighboring turbines in order to optimize the overall wind plant performance.

Data-driven control of wind plant power

Consider a row of n wind turbines with indices i, standing in the wake of each other, with power productions P_i and axial induction factors a_i. Due to wake interaction, changing a_i influences $\{P_j\}_{j=i}^{n}$, the power productions of turbine i and the turbines behind it. To maximize the total power, we can iteratively update set-points for a_i using a model-free Gradient-Descent Maximum Power Point Tracking (GD-MPPT) scheme:

$$a_i(k+1) = a_i(k) + \lambda \sum_{j=i}^{i+1} \frac{dP_j}{da_i}(k),$$

with iterations k, and a step-size scaling factor λ. The gradients are found using backwards differencing. Note that we only take into account the influence on the turbine i itself, and the turbine $i+1$ behind it, to come to a more time-efficient update scheme. Figure 1 gives the results of applying GD-MPPT on a wind plant simulation, showing an improvement of time-efficiency compared to the Game-Theoretic (GT) method presented in [1].

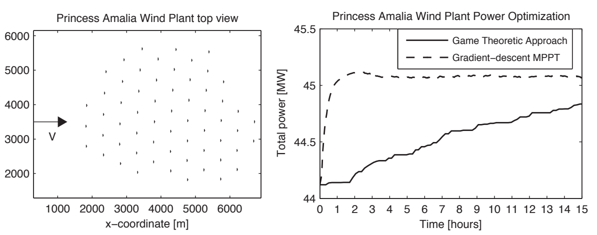

Figure 1: Results of power optimization with GD-MPPT and the GT approach of [1] on a simulation of the Princess Amalia wind plant, with incoming wind speed $V = 8\text{ms}^{-1}$.

*This PhD project is part of the Far and Large Offshore Wind (FLOW) innovation program, see also http://www.flow-offshore.nl.

Model-based control of wind plants

To control plant power more effectively, and reduce loads on each turbine, we may use a control design based on a model of the wind flow through the plant. The flow can be described by the Navier-Stokes equations:

$$\begin{cases} \rho\left(\frac{\partial \vec{v}}{\partial t} + \vec{v}\cdot\nabla\vec{v}\right) = -p + \mu\nabla^2\vec{v} + \vec{F}, & (momentum) \\ \nabla\vec{v} = 0, & (continuity) \end{cases}$$

with flow velocity vector $\vec{v}$ and pressure p varying over the spatial domain and over time t. Constants ρ and μ represent density and viscosity. The body forces on the flow $\vec{F}$, include forces exerted by the turbines on the flow, which can be seen as a control inputs, as they can be changed using the control degrees of freedom of each turbine. To use these equations for optimal control synthesis, spatial discretization and linearization steps need to be performed. Further, a Leray-type projection is needed which solves for the pressure such that the continuity equation is satisfied, to obtain the input-output relation between the control inputs and the wind speed profile.
In order to perform abovementioned operations efficiently, the distributed structure of discretized Navier-Stokes is to be exploited, by using the computationally efficient matrix operations for distributed systems given in [2]. Turbine controllers generated using these operations, work in a decentralized manner, exchanging information with directly neighboring turbines, just like in the GD-MPPT method.

Conclusions

This abstract presents a data-driven, and a model-based approach to distributed wind plant control. Subject of future research is to combine the approaches to obtain a computationally efficient control scheme for both power and loads, that is adaptive to changing operating conditions.

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Active Power Control with Undead-Band Voltage & Frequency Droop for HVDC Converters in Large Meshed DC Grids

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Abstract:

A new control method for large meshed HVDC grids has been developed, which helps to keep the active power balance at the AC and the DC side. The method definition is kept wide, leaving the possibility for control parameter optimisation. Other known control methods can be seen as specific examples of the proposed method. It can serve as a framework for the control of large DC grids, defining a common standard for the control scheme, but still leaving a lot of freedom for individual adjustments.

The proposed method is based on a so called “undead”-band, meaning that control activity is reduced within the band, but not set to zero as with a regular dead-band. It operates with a minimum of required communication. New converters can be added to the system without changing the control of the other individual converters. It is well suited to achieve high reliability standards due to the distributed control approach.

Keywords:

HVDC, Power Converter, Control, Droop, Meshed DC Grids, Dead-Band

Improvement on Controller Design for a Small Scale VAWT Model

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Keywords: controller design, VAWT, small scale, variable speed, stall regulated

Introduction

A model is developed in Simulink for a small, variable speed, stall regulated vertical axis wind turbine (VAWT) and controller, based on an initial design from a paper published in 2010 [1]. The effectiveness of the controller is explored by analysing the impact of various wind models, adjusting the level and structure of turbulence. The controller design is adapted and improved to incorporate the turbine's dynamic behaviour, with particular attention to drive train loading.

1. Analysing the Existing Controller

The below-rated performance of the controller is evaluated for the Maximum Power Point Tracking regime, as outlined in the original work by Ahmed & Ran [1]. The behaviour is also investigated in the above rated, constant power stalling regime, considering the impact on the drive train of mechanical torque transients due to turbulent winds. Closed-loop stability analysis is carried out, and implications of the adaptive control method are discussed.

In this initial analysis, turbine dynamics used in the model are simplified to ignore rotor modes. The controller design is adjusted to take into consideration drive train modes and minimise the extent of structural stresses on the modelled wind turbine system.

2. Improving the Design

Extending the VAWT model

The aerodynamic model previously used, based on a second order polynomial Cp-λ curve fit up to Cp_{max}, is not considered accurate for a vertical axis turbine. Alternative system models are investigated and discussed, although it is recognised that an accurate description of any specific vertical axis machine would merit extensive further work.

Implementing an Improved Controller

The Soft Stall Controller proposed is tested and improved, by the incorporating the modelled system dynamics. Another (feed-forward) controller is then implemented, and comparisons drawn. This work highlights some of the technical issues presented by variable speed stall regulated wind turbines, and strategies to overcome these.

Conclusion

For reasons presented, variable speed stall regulated wind turbines have not been developed commercially. However if they do emerge, machines will be small scale (a few kW) to minimise financial risk. Controller designs investigated here are likely to be relevant to future small wind systems.

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Robust control synthesis for gust load alleviation of large aeroelastic wind turbine models

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Keywords: Gust load alleviation, vortex panel, flexible body dynamics, discretization, PID, robust control.

Introduction

As the size of wind turbines is increased for larger energy capture, they are subject to greater risks of fatigue failure and extreme loading events. Further complications arise as they are gradually moved offshore and placed on floating structures, resulting in a coupling of loads from both wind and wave motion. This can be partially mitigated by pitch control but the response is slow and limited by the inertia of the blades. Innovative blade designs with active aeroelastic control techniques developed for aeronautics applications could be used to maintain steady loading on the blades, thereby reducing higher frequency vibrations and localised loads. This increases fatigue life and brings down cost of energy which is the main driver for continued wind energy research today.

Methodology

The paper will present a convenient formulation for the unsteady vortex panel method such that a state-space representation can be directly obtained. This allows us to fully understand the dynamics of the linearized aeroelastic model instead of relying on system identification to extract suitable state space forms for control system design. This will initially be coupled with a simple plunge-pitch aerofoil structural model for proof of concept. The modelling is then extended to 3D using a composite beam model for the structural formulation. This formulation combined with the Unsteady Vortex Lattice Method (UVLM) is currently being used in a framework for the Simulation of High Aspect Ratio Planes (SHARP) [1], and will be adapted in this paper for large and flexible wind turbine blades. Parameters for simulation will be based on the NREL 5-MW offshore reference wind turbine model. Both classical and robust controllers such as LQG and H_∞ are then implemented to obtain load reduction on the blades. Conventional flaps are chosen for the actuators but the model is sufficiently flexible to accommodate other active flow control methods.

Results

Under simulated turbulent gust conditions with von Kármán spectrum and 10% intensity, results showed that both classical and robust controllers were capable of load reductions of at least 80% using the 2D model for response at a section, as shown in Figure 1. In the 3D formulation, peak flap root bending moment could be reduced by 35% for a step gust. The flap deflection angles were all kept within ±5°. Comparing energy efficiency, PD controllers expended 70% more control energy than LQG and H_∞ controllers.

Since models developed using the vortex panel method are generally large, and given that the order of LQG and H_∞ controllers are at least equal to the size of the model, a straightforward method to save computation effort is to develop controllers from lower order models through relaxation of spatial discretisation. Although the results of the vortex panel method deteriorates exponentially as spatial discretization is relaxed (shown in Figure 2), controllers developed from these spatially coarse models are still effective in disturbance rejection on the fully converged model. This is shown in Figure 3, in which we can synthesise controllers using spatially coarse models that are an order of magnitude smaller in size, and still achieve comparable performance when placed in closed loop with fully converged models.

Conclusions

The aeroelastic formulation presented allows large turbine blades to be modeled in great detail, using conveniently structured vortex models for the unsteady aerodynamics with geometrically-exact composite beams. Our results demonstrate the huge potential of using active aeroelastic controls for load alleviation of large wind turbine blades and explore the use of spatial discretization to identify the optimum size of the controller for an effective synthesis.

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Figures

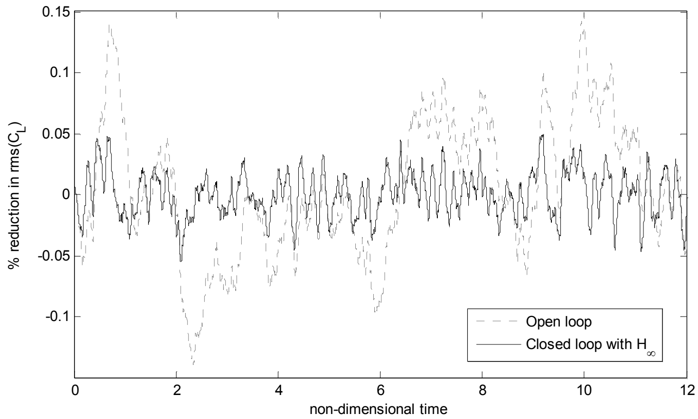

Figure 1: Comparing open and closed loop responses (similar trends are observed for PID, LQG and H_∞ controller)

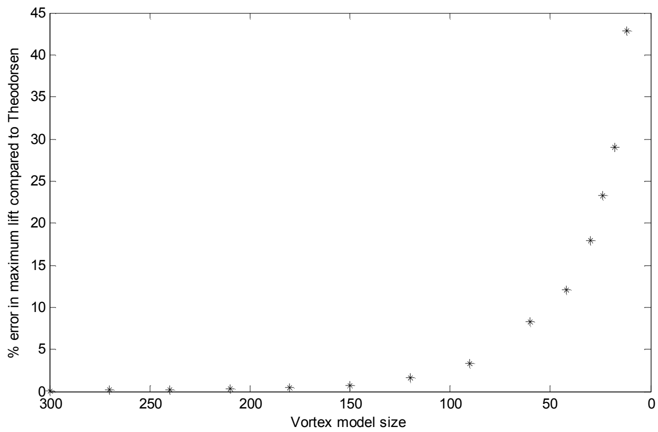

Figure 2: Effect of spatial discretisation on the convergence of vortex panel method towards the results of Theodorsen

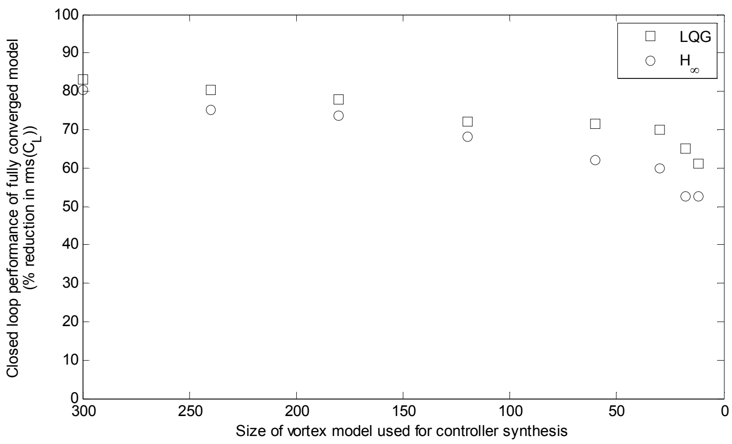

Figure 3: Closed loop performance of fully converged vortex model using controllers developed from coarse vortex models

Power control system of a simulated wind turbine

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Keywords: wind turbine controller, blade element momementum method, large eddy simulations

Introduction

When running simulations of variable speed turbines, a power controller needs to be implemented in order to ensure that the turbines are running at desired conditions. The power controller consists of two different parts; the generator torque controller (GTC) and the pitch controller (PC). Generally speaking, the GTC is used below rated power to allow the turbine to operate at its optimum tip speed ratio and the PC is used above rated power to keep the power output constant. This study focuses on the GTC part of the controller. The aim is to develop a power controller adopted for an in-house made blade element momentum (BEM) code. This controller, together with a PC, will in a later stage be included in a CFD code that can model several turbines. This part is outside the scope of this study.

Methodology

The controller used in this study makes use of the aerodynamic torque, T_{aero}, which is experienced by the turbine and determined in the simulation, which is put in relation with the generator torque, T_{gen}. The generator torque is a function of the rotational velocity. If these two torques at a given point in time are different, the rotor will undergo a rotational acceleration following $T_{aero} - T_{gen} = I_D \Delta\dot{\Omega}$ which is expressing Newtons second law of motion for rotating bodies. I_D is the moment of inertia of the drivetrain which in this case is the sum of the moments of inertia of the rotor and the generator. I_D is calculated for a 2.3 MW turbine which is a downscaled version of the NREL 5 MW turbine, [1]. The equation above is used to find the angular acceleration, $\Delta\dot{\Omega}$, which is integrated in time in order to find the perturbation of the angular velocity, $\Delta\Omega$. $\Delta\Omega$ is then added to the angular velocity. This procedure is used to find the angular velocity for every new time step. The simulation is carried out using an in-house made code, based on the BEM method, [2]. As input to the simulation, a time series of velocity is used, shown in Fig 1. This time series is created by running large eddy simulations with the EllipSys3D code, [3], with pre-generated turbulence and a prescribed boundary layer in order to represent atmospheric conditions. The time series is extracted behind a turbine modeled with the actuator disc method, [4]. Another input to the BEM simulation is the generator torque curve, as shown in Fig. 2. The generator torque curve is created using the method described by Jonkman, [1].

Results

The results show that the controller works as desired. It makes the turbine to run close to optimal C_P as the incoming wind speed varies due to the turbulent fluctuations, as depicted in Fig. 3. The rotor RPM curve is depicted in Fig. 4 and it can be seen that it has the same shape as the velocity curve. It is however more ”smeared out” which is due to the moment of inertia of the drivetrain. The response rate of the GTC is thus found to be dependent on the chosen value of I_D. A high value gives a low response rate which in turn makes the RPM curve more smeared out in comparison with the velocity curve. The C_P curve will in this case show peaks where the turbine operates at conditions far from optimum. For low values of I_D opposite results are obtained.

Conclusions

A power controller adopted for an in-house made BEM code for wind turbine simulations has been developed. As the results are satisfactory, the work will continue with the development of a pitch controller and the implementation in the CFD code.

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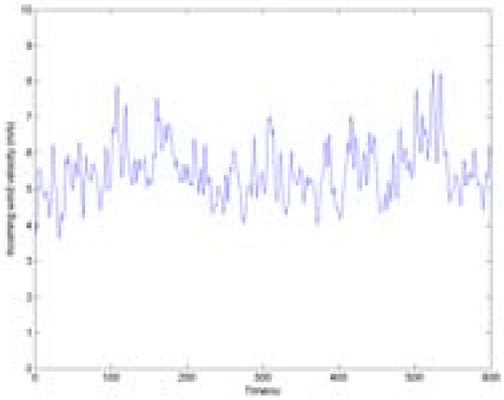

Figure 1: Incoming wind velocity located at 10R downstream from the first turbine.

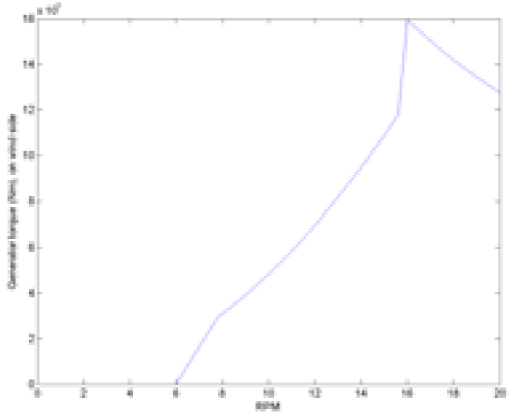

Figure 2: The generator torque curve as a function of the rotor RPM.

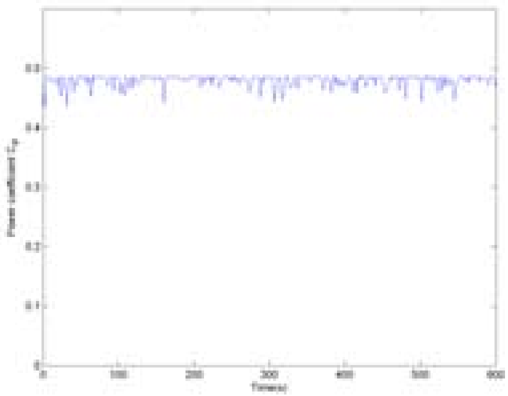

Figure 3: Power coefficient as a function of time resulting from the use of the control strategy implemented in an in-house made BEM code for a turbine that would be located 10R downstream from the first turbine.

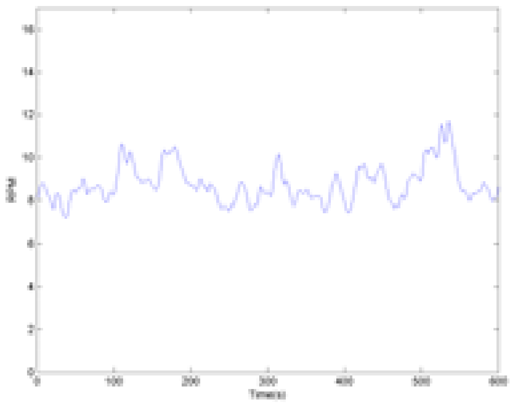

Figure 4: Rotor RPM as a function of time resulting from the use of the control strategy implemented in an in-house made BEM code for a turbine that would be located 10R downstream from the first turbine.

Active stall control for large offshore horizontal axis wind turbines; a conceptual study considering different actuation possibilities

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The tendency to increase the size of Horizontal Axis Wind Turbines(HAWT), together with the trend of installing wind farms further offshore, drives the search for more robust designs. Modern HAWT's deployed offshore are all variable speed and pitch-controlled. However if the pitch system can be eliminated the maintenance costs are expected to reduce and the availability will increase, leading to a lower cost of energy. This paper aims at assessing the feasibility of using active stall control rotors as an alternative for pitch controlled rotor blades. Active stall control in the context of the present research means the application of add-ons that actively provoke stall. The National Renewable Energy Laboratory (NREL) 5MW machine [1] is used as a benchmark. The Blade Element Momentum (BEM) code with the tip correction of Shen et al [2] is used to evaluate three different actuation technologies for active stall control: Boundary Layer Transpiration (BLT), Trailing Edge Jets (TEJ), and Dielectric Barrier Discharges (DBD).

How much actuator authority is necessary to keep the power output constant at wind speeds above rated? To answer this question the actuated section is considered to start from the tip of the blades, since outboard sections provide greater control over the blade loads and also because in sections near the root the magnitude of the Coriolis force postpones flow separation. Three different actuated lengths of the blade were considered, namely L=21, 29 and 37 m, measured from the tip of the blade. These lengths match the transition of the airfoils in the NREL 5 MW blade, as shown in figure 1. Different values of Cl over the actuated portion of the blades are imposed and the total aerodynamic power is computed for each combination of sectional Cl and actuated length of the blade. Results show it is necessary to have actuators over a significant part of the blade. For example if approximately half of the blade (29 m) is actuated, the local Cl must be decreased to about 0.8. This is illustrated in figure 2.

The aerodynamic code RFOIL_suc_V2 is used to simulate an airfoil with transpiration. This program is an adaptation of Drela's XFOIL [3], accounting for rotational effects and allowing for different porous regions and transpiration velocities to be imposed. The code is described and validated in [4]. Simulations are performed, at Re= 10 million, for different airfoils, for different porous regions and for various transpiration velocities. Results show that when blowing is applied in the leading edge (LE) area considerable changes in the aerodynamic loading are obtained, and the Cl remains practically constant for high angles of attack. This characteristic is interesting if one has the intention of using blowing to make the airfoil loads 'insensitive' to the AOA. Results are shown in figure 3.

There is interest in TE devices since they produce a significant change in lift. Trailing edge jets (TEJ) change the circulation associated with an airfoil section, and thus the aerodynamic loading. When compared to other TE devices such as flaps, TEJ have fewer moving parts and should thus be more robust. According to [5],[6], it is possible to obtain a change in Cl in the order of 0.4 over the entire linear region of the lift polar by imposing a jet momentum coefficient of 0.017. However, the authority of TEJ is reduced for large AOA since flow separation naturally occurs, which may happen when HAWT experience very large wind speeds.

The principle of operation of plasma actuators, including DBD, consists in applying a large electro potential difference over a small distance, which ionizes the air and transfers momentum to the air. DBDs have no moving parts, becoming attractive in applications where robustness is important, such as offshore wind turbines. The main issue associated with using the present DBD state of the art is that at large Re there is not sufficient authority. However, by optimizing the electric signal and geometry of the actuator it is possible to produce a body force that is one order of magnitude larger [7] than previous studies indicate, of up to 0.2 N/m for a single DBD actuator. Considering that more than one DBD device may be employed, it should thus be possible to provoke separation by carefully choosing the location of the actuator. Nevertheless, CFD simulations should be performed to verify this because the force field spatial distribution is complex and its effect is not accurately expressed solely through the net body force produced by the actuator.

A preliminary study on the feasibility of active stall control for HAWT was performed. Results show a large portion of the blades must be actuated, but this area may be reduced if the blade is originally designed to be controlled by active stall. Different actuation technologies have advantages and drawbacks. LE blowing is able to produce LE stall, and thus has a large authority. TEJs can yield significant changes in the lift coefficient, but only on the linear region of the lift polar. DBD have no moving parts, and even though they transfer a limited amount of momentum to the air, it should be possible to provoke separation by careful placing the actuator. All things considered, active stall control of HAWT appears to be feasible.

Figure 1 - Actuated regions of the blade

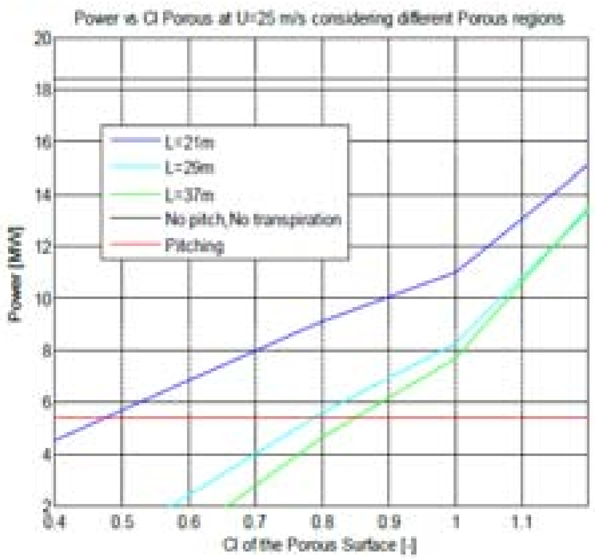

Figure 2 - Power vs Actuation Cl for different actuated blade regions

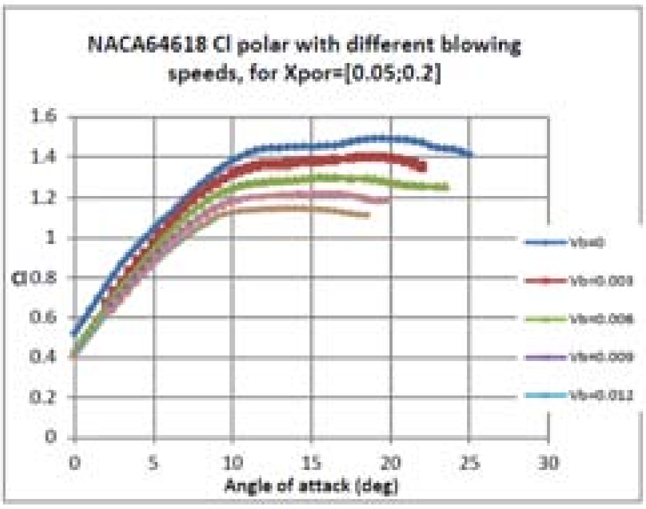

Figure 3 - NACA 64618 Cl vs aoa for different LE blowing speeds

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Application of coordinated control and power coordinated control to a 5MW Supergen Wind Turbine

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Keywords: Coordinated controller, Power coordinated controller, pitch demand, tower load, global gain scheduling.

Introduction

Wind energy is the key solution to the future clean and secure energy demand. New generation of wind turbines are required to provide greater installed capacity with better power quality. Inevitably the bigger the capacity output the larger the Turbines become in size and more difficult to control. Controllers are playing a key role in the wind turbine system and manufacturers are in competition for designing more accurate controllers. The main issue to design a controller is to satisfy the stability margin which becomes lower as wind turbines getting bigger.

This project aims to use a controller design which is done by Supergen for a 2MW wind turbine [1] and modify it for a 5MW Supergen machine. The CCD and PCC controllers are coordinate the pitch demand and torque demand simultaneously to reduce the tower load and pitch actuator activity in order to reduce the tower fatigue loads and increase the turbine's life time. The operation of CCD and PCC controllers are discussed and a controller is designed and tested on a 5MW Supergen model in Simulink and the GLGarrad-Hassan Bladed. The results of these simulations are provided and discussed.

Coordinated controller design

Tower feedback loop is used to adjust the collective pitch demand in respect to the tower acceleration. A better approach is used in this project to control the rotor speed and generator power through two separate feedback loops. The dynamic interaction between these loops is coordinated taking into account the tower load reduction objective of the controller while designing the feedback loops. The block diagram of CCD controller is depicted in Figure 1. Due to the nature of tower modes two non-minimum phase zeros appears at the tower frequency which are reducing the phase margin and consequently stability of the system, the effect of these two non-minimum phase zeros are removed by introducing a notch filter in Coordinated control design at the tower frequency. The depth and width of the notch filter must be chosen correctly to reduce pitch activity in vicinity of the tower frequency to reduce the tower fatigue load and also must not result in degradation of the speed loop performance. Too widely design will cause the generator speed to vary.

Power coordinated controller

Power coordinated controller is designed as an extension to the coordinated controller. The PCC design allows the controller to control the output power instead of generator speed. Controlling rotor speed through generator reaction torque loop instead of pitch demand loop at tower frequency will cause the power output fluctuations.

Figure 2 shows the block diagram of the PCC controller. CCD controller is modified in which power output is fed back and adjustment made on the torque demand in respect to this error.

Conclusions

A novel approach to alleviate tower fatigue load was discussed and simulated to increase wind turbine life time and generate power with better quality.

References

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Figures

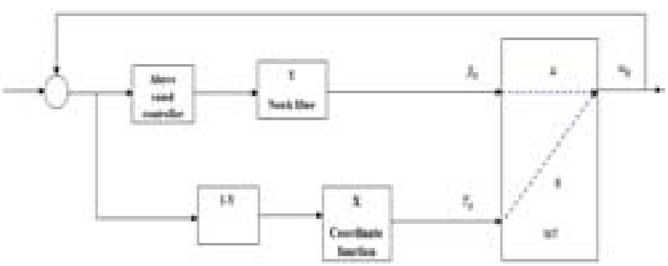

Figure 1, CCD controller

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Identification and distributed control of large scale systems: an application to wind farm

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Keywords: system identification, distributed control, aerodynamic interconnection, wind farm

Introduction

With the increasing capacity of wind farms, distributed control and optimization is of great importance to make wind farm operate in an economical state. However, interconnections between wind turbines caused by aerodynamics are very complicated and difficult to model and modify by first principle. Therefore, algorithms for identifying aerodynamic interconnections between wind turbines are necessarily required. The biggest challenge of distributed control and identification of spatially interconnected systems is the complexity of the control algorithms. The system matrix that describes the input-state-output behavior of N interconnected subsystems, with subsystems of order n, will be of size $nN \times nN$ matrix. Therefore most conventional solution algorithms will require $O(n^3N^3)$ floating point operations (flops), which makes traditional controller synthesis expensive for fine discretization of PDEs or large number of distributed subsystems.

Methodology

Sequentially Semi-Separable (SSS) matrices [1] provide an effective approach, which has linear computational complexity. State space model of 1-dimensional spatially interconnected system which is shown by figure 1 has SSS matrix structure. The extension of the 1D system to a 2-dimensional spatially interconnected system (2D) is shown in figure 2. The latter structure can be used to describe a wind farm and leads to a higher-level SSS structure, called multi-level SSS matrix structure. Our research focuses on developing a fast solver for multi-level SSS matrices of linear computational complexity for 2D system, which can be applied for identification of aerodynamics and distributed control of wind farms.

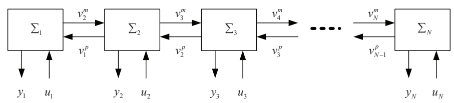

Figure 1: 1-dimensional spatially interconnected system

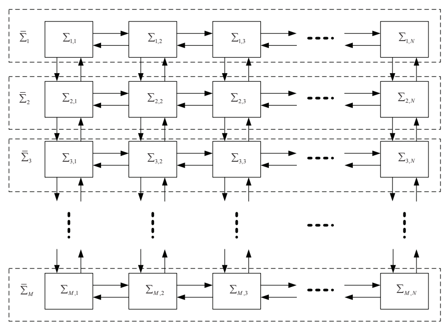

Figure 2: 2-dimensional spatially interconnected system

Conclusions

Our work consists of three steps, the first step is to implement the algorithms based on SSS matrices to do fast identification of a 2D system. The second step is to exploit the multi-level structure of the 2D system model to accelerate the computation speed via structure preserving model reduction for multi-level SSS matrix. The third step is to apply the previous mentioned algorithms to identify aerodynamic interconnections between wind turbines. Our ongoing research shows that algorithms based on SSS matrix structure for 2D system have linear computational complexity, which is very efficient for wind farm control and identification.

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Investigating the impact on control of soft support structure dynamics

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Keywords: control system, parallel path modification, floating wind turbines

Introduction

Nowadays, wind turbines are moving into deeper offshore waters where it is not feasible to use a traditional support structure. As a result, a preferred option for many cases is a floating wind turbine.

A floated wind turbine has significant reduction in the rigidity of the support structure compared to a tower mounted machine. The reduction of rigidity causes significant changes in the dynamics of the whole systems. These changes may result in instability of the entire system, hence this needs to be accounted for when designing the control system.

A simple way of modeling these changes is to reduce the stiffness of the tower in a standard wind turbine model. Moreover, the technique of alleviating tower loads is introduced to tackle instability of system.

Models and Dynamics

All variable speed wind turbine dynamics suffer from non minimum phase zeros (NMPZ), which are result of the interaction of the drive train with tower. The NMPZ are presented in a transfer function from pitch demand to generator speed.

The NMPZ demonstrate drawbacks of the control system to adjust the generator speed through blade pitch control, where the blade pitch control increases the generated speed instead of reducing it. In the case of a floating wind turbine, the NMPZ can be a source of negative damping for the platform of the floating wind turbine which has low natural frequency.

Parallel path modification

The idea of parallel path modification is to overcome the problem with the NMPZs by sending back the signal of nacelle velocity to the generator torque control. As result of it, the large phase loss due to NMPZ vanishes from the transfer function from pitch demand to generator speed.

Analysis

Two techniques coordinated controller design (CCD) and power coordinate controller (CCP) of parallel path modification with a simple input simple output (SISO) control loops for reduction of the displacement of entire systems are compared (see figure 1). Also the generator speed of SISO is compared with the generator speed of CCD and CCP

Conclusions

The CCD controller designed for the fixed support structure can be suitable for floating wind turbines, as CCD with tower feedback loop (TFL) alleviates the tower loads and reduces generator speed variations of a floating wind turbine.

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FIGURES

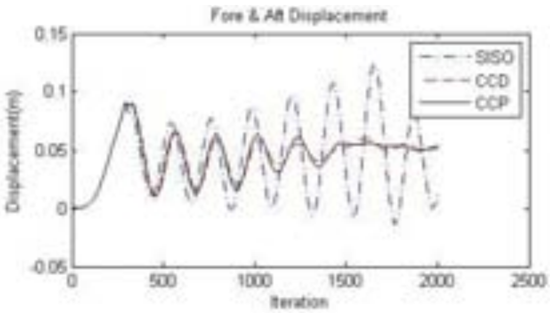

Figure : Provide displacement curves for different control techniques when natural frequency of a floating wind turbine is 0.62 rad/s.

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European Academy of Wind Energy

Laboratory for Energy Conversion

Investigating the Effectiveness of Implementation of Power Adjusting Controller on Different Wind Turbines

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Keywords: Wind turbine modelling and control, Aerodynamic separability

INTRODUCTION

The UK government has set a target 20% of electricity generation from renewable sources by 2020. Among various renewable technologies, the environmental benefits and cost-competitiveness have driven the rapid expansion of wind power as a significant green source in recent decades. However, there are certain characteristics of the wind energy challenges today's power system operation. If a large amount of wind turbines replace the synchronous generator, the low inertia of the grid could be troublesome. [1] Therefore, along with the increasing use of wind energy, the effects of wind turbine on power system have got more and more attentions. The high penetration makes it's more essential to operate the wind power in a similar manner to conventional plant. [2] In this paper, a controller for 2MW wind turbine which gives more flexible operation is used to generate boosted power in order to contribute the grid frequency drop. Also this method will help to correct the power unbalance, load reduction and synthetic inertia. Moreover, the novel control technology could make wind power to participate a more active role in power system. Furthermore, the comparison of the effectiveness of the power adjusting controller on 2MW and 5 MW variable speed wind turbine model is investigated.

CONTROLLER DESIGN

The idea of Power Adjusting Control (PAC) is brought by Adam Stock [2]. It is an additional outer feedback loop around the wind turbine central controller. The Power Adjusting Control (PAC) allows altering the power output of wind turbine. In particular, no changes of full envelope controller are needed. The boosted power output is gained by converting the kinetic energy of the rotor into electricity output through the increased torque. [2]The above function is achieved by additional torque demand ΔT_d and generator speed $\Delta\omega_g$ of PAC. The layout of PAC is shown in Figure 1.

CT controller

The addition torque demand ΔT_d consists of two parts: the instantaneously increase T_{ad} is given by the addition power demand ΔP divided by the rotational speed ω and the second torque component T_+ which is used to compensate for the power lost caused by the Power Adjusting Controller due to the reduction of rotor speed.

Cω controller

The Cω controller is designed to produce a dummy speed $\Delta\omega$ to compensate the reduction of generator speed due to the increase of the torque when operating below rated wind speed.

MODIFICATION

The PAC is firstly designed for 5MW wind turbine. The different operation strategy and turbine design between the 2MW and 5 MW wind turbine cause the different effectiveness. In particular, the operating strategy closes to the aerodynamic stall region for 2MW machine at high wind speed. Therefore, some modifications of the PAC are required to improve the effectiveness. In this study, aerodynamic separability in tip speed ratio and separability in wind speed is applied in this model to eliminate the effect of low inertia mechanism.

CONCLUSIONS

Simulations are conducted at many different wind speeds as shown in Figure 2. The results show that the design is suitable over the whole operating range and the design of operational limits ensures continuous safety operation. With some modifications, the PAC is capable of achieving same performances as 5MW wind turbine.

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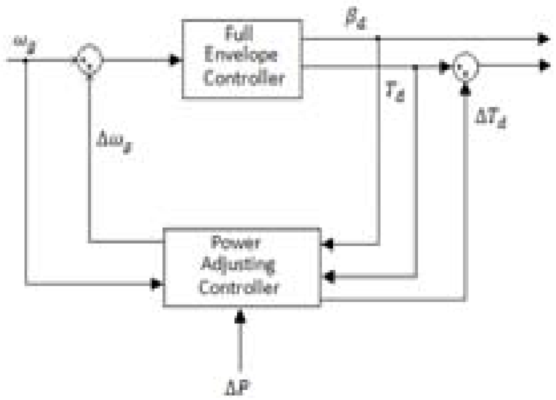

Figure 1: Power Adjusting Controller Layout

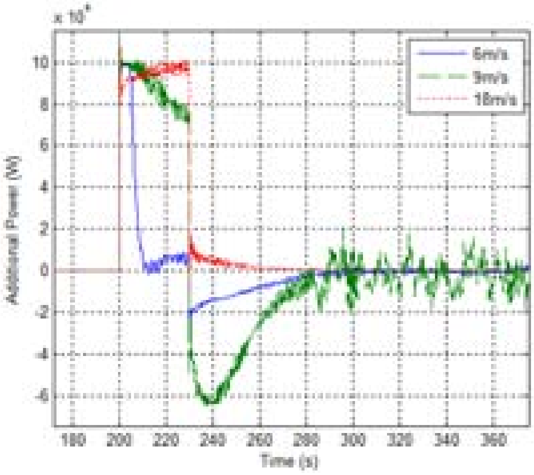

Figure 2: Additional power of different wind speed

Feed-forward pitch control of HAWT using LIDAR

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Keywords: Feed-forward, control, LIDAR, energy capture improvement, extreme loads reduction, and fatigue loads reduction.

INTRODUCTION

This abstract indicates a research work of design of a feed-forward control system using data collected from a LIDAR device mounted on a wind turbine.

METHODOLOGY

The prediction of wind flow has recently been increasingly important to wind energy production in terms of adjusting the control system. LIDAR system as a recent data collecting device provides advanced wind turbine performances. [1] The improved performances include a better energy capture due to better pitching, yaw and Cp tracking; reduced fatigue and extreme loads due to accurate wind speed, turbulence, direction and extreme gusts prediction. The LIDAR system, fully named Light Detection And Ranging system, makes it possible to remotely measure wind characterises. [1] The recent improvement of LIDAR size, cost and reliability provides the possibility to build the LIDAR system mounted on a wind turbine.

Feed-forward control is an addiction to the traditional feedback control and improves the control system performance by process a major disturbance before it enters the main control loop. [2] In ideal situation, the feed-forward process can cancel out the effect of measured disturbance. The block diagram is shown below in figure 1.

RESULTS

This research has used a wind turbulence produced from Bladed software to simulate the LIDAR data collecting system. A power spectral density function has been plotted to compare the wind speed frequency of different LIDAR measurement distances. The feed-forward control system will be added in a 5MW upwind feedback control system.

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FIGURE

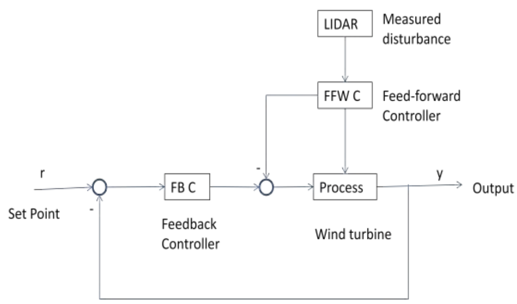

Figure 1: Feed-forward control system using LIDAR information block diagram

Micro & mesoscale wind

Large-eddy simulation of the neutral planetary boundary layer with a capping inversion over a very large wind farm

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Abstract

In this study, large-eddy simulation (LES) is used to simulate the neutrally stratified planetary boundary layer (PBL) under the stably stratified free atmosphere through a very large wind farm. In this type of flow the stable stratification aloft puts a constraint on the growth of the largest turbulent eddies in the vertical direction and leads to lower boundary layer depth compared with the standard Ekman layer. To do this, tuning-free Lagrangian scale-dependent dynamic models (Stoll and Porte-Agel 2006) are used to model the subgrid-scale fluxes and the turbine-induced forces are parameterized using the actuator disk model (Wu and Porte-Agel 2011). Considering the effects of earth's rotation and static stability in the free atmosphere has two important advantages with respect to using a constant pressure gradient forcing and no capping inversion. First, considering the Coriolis forces in the governing equations allows to investigate how the direction of the wind changes inside and above the farm due to the presence of the turbines, which is not possible in the unidirectional boundary layer flow resulting from an imposed pressure gradient. Second, the important effect of the wind farm on the boundary-layer height growth can be explicitly resolved and studied. The simulation results show that the extracted power by the wind turbines decreases when there is a capping inversion immediately above the PBL, compared with truly neutral PBL with no capping inversion. This can be due to the fact that the stably stratified free flow above the PBL limits the growth of the boundary layer and consequently the entrainment of kinetic energy from the flow above decreases.

Numerical simulation of a forest edge

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Keywords: Wind resource assessment, Computational fluid dynamics (CFD), Forest canopy flow.

Introduction

A numerical methodology to quantify the wind resource in forested environments is presented. The method is based on a Reynolds-averaged Navier-Stokes (RANS) approach using the $k-\varepsilon$ turbulence model with a corresponding canopy model. The example site investigated is a forest edge located on the Falster island in Denmark where a measurement campaign was conducted. The raw data of the LiDAR scans of the site were processed in order to obtain the forest characteristics which served as input to the flow model. A sensitivity analysis with regards to the resolution of the proposed digital surface model (DSM) was carried out. The numerical results of the complete method are finally briefly compared to the experimental measurements with regards to the wind field and turbulence characteristics.

Methodology

The standard $k-\varepsilon$ turbulence model with modified constants implemented in the flow solver EllipSys3D [1] was used. The model was further complemented with a canopy model [2] in order to account for the plant drag effect. The Leaf Area Density (LAD) serving as input to the canopy model was approximated as constant and was based on the Leaf Area Index (LAI) observations. The description of the boundary conditions used in the flow solver can be found in [1] where a constant shear stress flow is reproduced. Neutral stratification and the neglect of the Coriolis force were considered. The representation of the forest can be obtained from a scanning laser as a point cloud, i.e. a distribution of points having a set of xyz spatial coordinates. The large volume of data obtained from the scans however requires interpolation prior to the CFD input and a method is therefore presented in what follows. The classification as vegetation and ground points of the LiDAR returns was first processed with the open source code MCC-LIDAR which is based on a multiscale curvature algorithm [3]. The two sets of classified points were further interpolated onto two different grids using a local binning algorithm [4] in order to reconstruct the forest and terrain characteristics. The obtained grids were subtracted from each other so that the horizontal spatial tree height distribution could be retrieved. For the calculations presented here, the terrain was approximated as flat and solely the surface tree height distribution was retained as a CFD input.

Results

The Tromnæs beech forest edge experiment was located on the Falster island at 54°45′ N, 12°2′ E. From March-September 2008, a measurement campaign was conducted where both the foliated and the bare canopy period were covered. For this site, different interpolation methods for obtaining the tree height distribution using the local binning algorithm are analysed. The obtained grids are compared to forest inventory and a best interpolation method was determined. A grid independence analysis was thereafter conducted based on the chosen best interpolation method. Numerical calculations of the complete methodology are finally presented and results are compared to the mast measurements.

Conclusion

A numerical investigation at a forest edge was conducted. The LiDAR scans of the site were used as input to the numerical model. The results indicate that the methodology show promises for further developments and refinements.

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Near-Surface Small Scale Turbulence and Stability of Shear Flows Based on a Richardson Number Analysis

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Keywords: Multifractality, intermittency, stability and turbulence.

Introduction

We analyse near-surface atmospheric turbulence in the context of intermittency. To statistically characterise the stability, we used the probability distributions of the gradient Richardson number — large negative values indicate unstable conditions, large positive values indicate stable conditions and values close to zero are indicative of neutral conditions — this implies therefore anti-symmetric distributions correspond to either stable or unstable conditions. Since the empirical probability distributions follow power law behaviour the departure from neutral to (un)stable conditions is quantified with the ratio of the corresponding power law exponents.

Section 1: Data Description

The atmospheric measurements came from the GROWIAN field experiment that took place in Germany. It consisted of an array of propeller anemometers measuring wind speed inflow data at 2.5Hz over flat terrain. The propeller anemometers were positioned vertically at 10, 50, 75, 100, 125 and 150m with four horizontal measurements taken at 75, 100 and 125m. The spatial measurements meant we could calculate the horizontal and vertical shear structure functions of the horizontal wind allowing us to test Taylor's hypothesis over a wide range of scales.

Section 2: UM Analysis of Richardson Number

Under the universal multifractal (UM) framework, we study and compare the scaling properties of Richardson number time series at different heights. We found the amse type of multifractality as for the wind velocity increments but with a lower mean intermittency. The scaling non-conservativeness parameter, H, of the vertical shears of the horizontal wind varied from Kolmogorov to Bolgiano-Obukhov depending on the condition of stability. These results give new insights into the 23/9-dimensional model of stratified turbulence (Schertzer and Lovejoy, 1985, Lilley et al., 2006, Fitton et al. 2011).

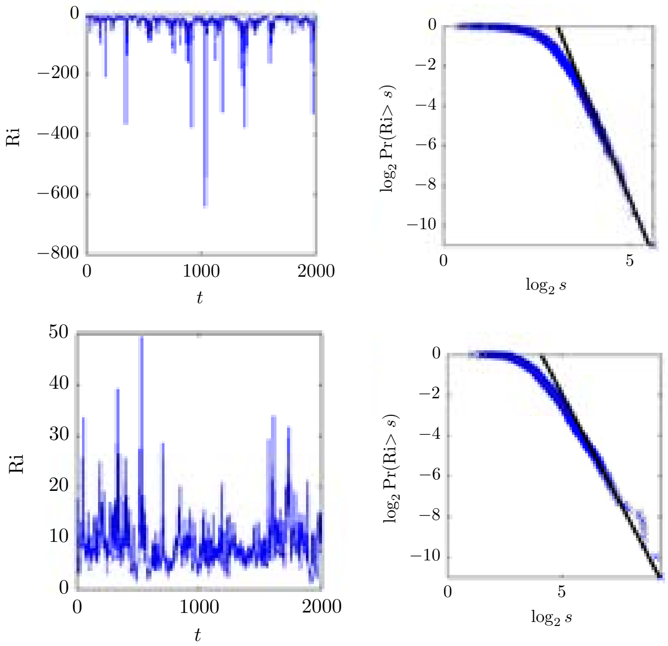

Figure 1: Left Column: Intermittency of Richardson Number time-series for stable (bottom) and unstable (top) conditions; Right Column: Corresponding probabilities of exceedence with tail exponents 2.1 (bottom) and 4.5 (top).

Atmospheric Stability and complex terrain: Comparing measurements and CFD

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Keywords: atmospheric stability, complex terrain, wind resource assessment, CFD, atmospheric boundary layer

Introduction

For wind resource assessment, the wind industry is increasingly relying on Computational Fluid Dynamics (CFD) models that focus primarily on modeling the airflow in a neutrally stratified surface layer. So far, physical processes that are peculiar to the atmospheric boundary layer (ABL), for example the Coriolis force, buoyancy forces and heat transport, are mostly ignored in state-of-the-art CFD models. In order to decrease the uncertainty of wind resource assessment, especially in complex terrain, the effect of thermal stratification on the ABL should be included in such models.

Methodology

The starting point for the present study is the existing in-house CFD code EllipSys3D [5]. This general purpose CFD solver has been initially developed for flow over terrain and is used for a wide range of wind energy applications. To model the flow within the ABL more appropriately, the finite-volume code is modified.

The focus of the present study is on flow over complex terrain, subjected to temporally varying surface temperatures. The aim of this work is to study the combined effects of temperature and complex terrain on the resulting wind field, and to validate it's representation in the model. To model the ABL more appropriately the effect of the Coriolis forcing and buoyancy are included in the CFD code EllipSys3D. Therefore an equation for the energy in terms of the potential temperature is solved in addition to the RANS equations. To close the given set of equations a modified version of the k-ε turbulence model is used: we use a length-scale limiter [1,2], and additional buoyancy terms [4]. Also ambient floor values for the turbulence variables are imposed in order to avoid numerical issues [6].

Results

With the modifications mentioned above the model is capable of representing non-neutral conditions. The resulting surface winds, temperature stratifications and TKE values are compared against observations taken during a field experiment in 2010 in India. Five 80m masts were erected near and on a 120m natural ridge equipped with sonic anemometers and temperature sensors. The motivation of this campaign was to study the combined effects of complex terrain and atmospheric stability. Comparison of non-neutral simulation runs against observations shows promising improvement towards neutral simulations (see fig. 3). However, the present study raises the issue of initial and boundary conditions of numerical experiments, because perfect test cases do not occur in reality.

Conclusions

The combined effects of atmospheric stability and complex terrain are analyzed based on observations and compared against non-neutral simulations. Furthermore the sensitivity of the numerical results on the forcing and the initial conditions are examined.

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FIGURES

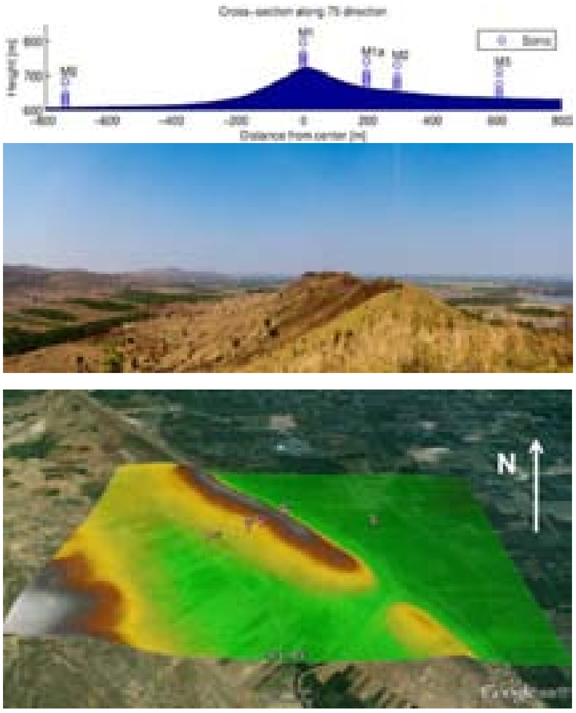

Figure 1: Almost two-dimensional 120m natural ridge with slopes around 35 degrees close to the village of Benakanahalli, India. Five 80m masts were erected that are equipped with sonic anemometers in five different heights and resolve both mean flow and turbulence.

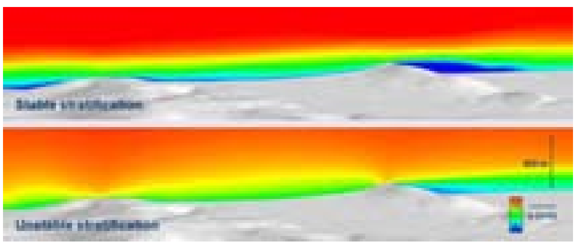

Figure 2: Non-neutral simulation over complex terrain: horizontal wind speed for (top) stable and (bottom) unstable conditions over the Benakanahalli site in India.

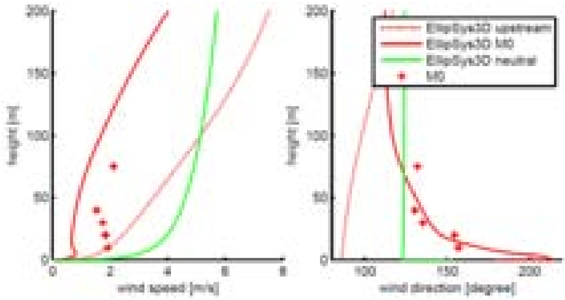

Figure 3: mast M0, 150° direction, stable stratification: comparison of measurements (+), and simulations (dashed: 12km upstream). This figure indicates that for stable conditions, the measurements at mast M0 are significantly influenced by terrain effects upstream of the site (terrain effect is difference between red lines). The modified model seems to capture these upstream effects partially (solid red line), whereas they are not present for the neutral model run (solid green line).

Software implementations in the long-range windscanner system

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Keywords: windscanner, lidar, wind energy

INTRODUCTION

The long-range windscanner (or just the windscanner) is a device that has two parts, a pulsed wind lidar and fully steerable scanner head (Figure 1). The joint group of three spatially separated windscanners represents the long-range windscanner system. Each windscanner has the range from 50 up to 10000 meters.

One of the aims with the system is to steer three laser beams to meet at a point (Figure 2) and to measure the 3D wind velocity vector by combining these three independent radial wind speeds. Thus, the assumption of horizontal homogeneity of the flow, required for a single wind lidar, is unnecessary. Furthermore, by moving the beam intersection over an area of interest, a complete 3D flow field can be measured.

Therefore the vision is to have three windscanners synchronized in both measurements and motions of the scanner head.

APPROACH

The start of the measurements on all windscanners should happen at the same time. To do this a good approach is to implement a GPS clock on each windscanner. In this way all windscanners will have the same time base.

After the start on the GPS time the time of move of the scanner heads between two intersectional points in space for all windscanners within the system should be the same. This will preserve the synchronization of the measurements and motions in the system after the start.

Hence it is important to have a monitoring system that can execute re-synchronization among the windscanners if the synchronization is lost.

RESULTS

The windscanner software (Agape®) was made based on the previously described approach. The heart of the software is the module called TeslaBlackBox® that is controlling the scanner head and furthermore calculates its trajectory based on user configuration. Also, it consists of a kinematic model of the scanner head that uses positions of windscanners and measuring points in 3D space and calculates optimized trajectories for all windscanners taking into account the synchronisation. The monitoring and controlling was achieved using a separate computer with specially made software (MC Wind ®) and a connection via any network interface (WiFi, 3G…) with the long-range windscanner system.

CONCLUSIONS

The software implementations that were made are taking all the advantages of the system's hardware components. Furthermore, they create vast possibilities for different measurement scenarios and above all they fulfill the initial vision.

FIGURES

Figure 1: The long-range windscanner – left a single unit, right a fully steerable scanner head

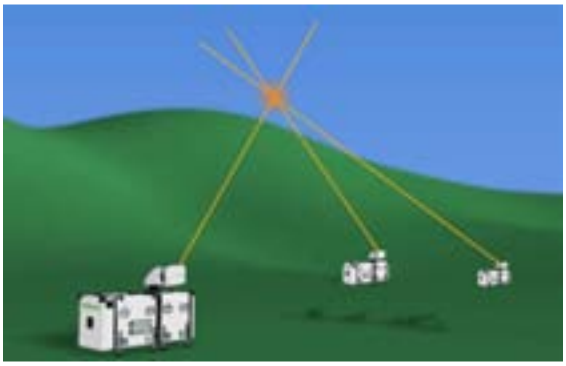

Figure 2: The long-range windscanner system – an intersection of the three beams

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Improved Spatial Modelling of Wind Fields

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Keywords: Wind Model, Forecasting, Adaptive Filter, Signal Processing.

INTRODUCTION

As the penetration of power systems by wind increases, accurate estimation of wind farm power production is vital for efficient system operation. Current wind models and aggregate power curves for wind farms use only wind speed to forecast power output for a given number of hours ahead. Using directional wind data, the precision of both aggregate power curves and wind profile prediction can be improved; this paper is concerned with the latter.

ADAPTIVE FILTERS FOR PREDICTION

There are many models for prediction of the wind profile; the most frequently used are auto-regressive (AR) in nature. This paper employs a liner adaptive filter for prediction and is mathematically similar to AR models.

The wind vector is treated as phasor in order to capture both wind speed and direction, the adaptive filter must therefore be complex valued [1]. As in vector auto-regressive (VAR) models [2], simultaneously modelling multiple sites increases accuracy by capitalising on the correlation between wind signals at sites separated by significant distance, we therefor employ a multi-channel filter to facilitate multiple inputs and output - this allows prediction of the wind profile at all sites if desired. A block diagram of a two-channel filter is shown in figure 1.

The filters $\boldsymbol{w}_{11}$ and $\boldsymbol{w}_{22}$ contain the autocorrelation coefficients of past time points of the signals x_1 and x_2 respectively and the filters $\boldsymbol{w}_{12}$ and $\boldsymbol{w}_{21}$ contain the cross-correlation between coefficients between past time points of x_1 and x_2, and x_2 and x_1, respectively. N past time points of x_i are stored in the filter input vector $\boldsymbol{x}_i(n) = (x_i(n), \ldots, x_i(n-N)$. The output, $y_i(n)$, is the predicted value of $x_i(n+1)$ and prediction error $e_i(n)$ can be calculated when $x_i(n+1)$ is known. The aim of the filter is to minimise the prediction error for each site.

The adaptive nature of the filter comes from the constant updating of the filter coefficients which captures the non-stationary behaviour of the wind signal - the filter is essentially time dependent.

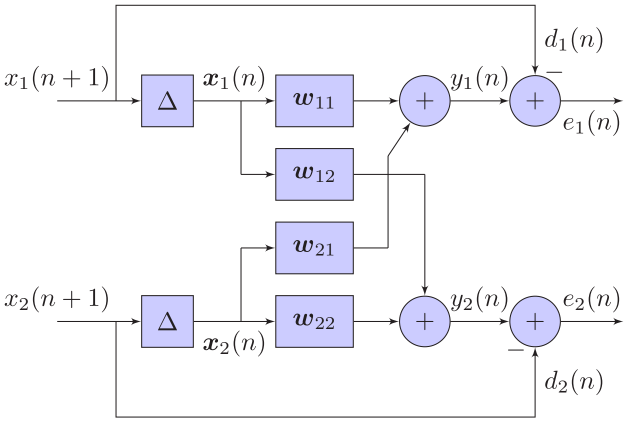

Figure 1: Two-channel Predictive Filter

Determining the Filter Coefficients

The filter coefficients can be determined in two ways, both of which require a known set of data. The first is an iterative gradient decent method which reduces the error by updating the filter coefficients as each error is calculated. The second is a direct calculation, which is computationally expensive, using the *Wiener-Hopf* equations.

RESULTS AND CONCLUSIONS

The process described above has been applied to data provided by the Brithish Atmospheric Data Centre and shows that a complex-valued adaptive filter can produce wind speed predictions to the same, if not a greater, degree of accuracy than many other approaches while also providing directional information.

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LEC Laboratory for Energy Conversion

Development of wind power forecast quality for new offshore wind farms: “alpha ventus ” experience

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Keywords: Wind power forecasting, wind energy artificial neural networks, physical modelling, offshore, MOS

INTRODUCTION

The accuracy of wind power forecasting plays an important role on grid consistency, need for balancing energy and hence reducing the cost of wind power integration.

This study investigates development of the offshore wind power forecast quality from beginning of operation up to one year of operational experience and it facilitates to decide the length of needed time series and selection of forecast method to get a reliable wind power forecast on a weekly time axis, so that represents a roadmap to develop wind power forecasting model for new offshore wind farms, for which no or limited power data are available. This paper represents a case study using data of the first German offshore wind farm “alpha ventus”.

METHODOLOGY

In this work, the weekly development of wind power forecast quality for day-ahead and shortest-term wind power forecast is investigated. The used models are physical model; physical model extended with a statistical correction (MOS) and artificial neural network (ANN) as a pure statistical model.

The physical model is based on the power curve of installed wind turbines and forecasts the power output of each wind turbine. Considering wake effects, the wind power of the whole wind farm is calculated. Physical model does not need historical data but leads often to systematical overestimations of the power output. In praxis, generally physical models are extended with a statistical correction. This extended model needs adequate data to model different weather situations to correct bias between measured and predicted wind speed or wind power. The ANN needs to be trained with NWP and measured power values from the past. ANN needs to have enough data to learn the relationship between power output and meteorological data. The advantage of artificial neural networks compared with other methods is the learning of complex relationships without knowing the physical background.

One of the effective ways of improving forecast quality is ensemble approach. A Multi-NWP physical forecasting model is investigated via merging different NWPs.

RESULTS

The day-ahead forecast results show that the prediction error of the physical model are more stable and fluctuating not so much. And also it has lower prediction error than ANN in first half of the complete time period. The statistical correction method MOS improves the forecast quality of the physical with removing systematical error. After an half year the results of ANN are being smoother and with the increasing availability of dataset the ANN learns the relationship between NWP data and power production better and as a result of this, it makes better predictions. Multi-NWP approach improves the quality of wind power forecast.

CONCLUSIONS

Both the shortest-term and day-ahead forecasts show that ANN does not predict good and not enough stable with poor data, but if there is enough data to feed-in the ANN, ANN delivers better and more stable results.

The physical does not need any historical data for the purpose of learning the relationship between meteorological data and wind farm power output. The results are showing that if there is not enough data existed, this model can be used to predict wind power. MOS extended model removes the systematical errors and improves the forecast quality of the physical model. Ensemble approach improves the forecast quality compared with single NWP forecasts.

The results show the importance of historical data for the increase in forecast quality. The storage of historical data is essential for a good prognosis.

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Data Quality of Wind Speed Measured using Buoy-mounted LiDAR

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Keywords: wind speed measurement, LiDAR, floating LiDAR, mean wind speed, turbulent wind speed.

INTRODUCTION

Accurate wind field measurements at sea are currently conducted using met masts installed on marine structures. Considerable cost and time savings can be made if wind fields were to be measured using buoy-mounted LiDAR systems [1]. This paper investigates the effect of wind speed when measured from a LiDAR system mounted upon a buoy. The velocity and acceleration of the buoy is not considered, only the displacement.

MODEL DESCRIPTION

In order to quantify the effect of buoy motion on wind speed measurement from a LiDAR system, a model was created which emulated a pulsed LiDAR system. From a wind field described by a mean wind speed, Guassian turbulent component and the logarithmic shear law two wind speeds are determined. The wind speeds are calculated from the data which a pulsed LiDAR system would measure, one for a the system tilting around a central pivot, emulating the motion of the system as a result of the sea state in one dimension, and the second, a reference value where the system is at rest. The LiDAR system takes one measurement of the wind speed every second. The tilt of the system is assumed to have the same frequency as the sea state, and as a result, measurements are taken at different increments of the tilt over the wave period.

The model assumes the buoy tilt, wave period and wind field are independent from one another. This is a simplification of reality, however the buoy tilt and wave period amplification decoupling is valid as the buoy itself will have a resistance to the wave motion, and there would likely be some mechanical motion compensation of the LiDAR system mounted on the buoy.

RESULTS

There are two different results to consider; the difference in the point wind speed measured and the resulting calculated mean wind speed. The mean wind speed determined from the tilting and reference LiDAR systems are very similar; there was less than a 1% difference in the two values.

Whereas the difference in the mean wind speed can be easily quantified by comparing the two values, a similar simple analysis cannot be applied to the measured point wind speed. The power spectral density functions of the two signals are determined to allow for comparison. This shows that at low tilt levels for a full range of wave periods and wind speeds, there is no change in the power of the wind speed signal determined from the tilting and reference system. As the tilt is increased a greater difference is noted in the power of the two signals, particularly at long wave periods. However, the degree of tilt required to produce this was large; greater than could be assumed achievable for a buoy-mounted system with mechanical motion compensation.

CONCLUSIONS

The results of this investigation show that the motion of a buoy-mounted LiDAR system with motion compensation will not affect the quality of the wind data collected. However, this result was achieved using a very simple model which only considers the system displacement and as a result should be considered as preliminary. Further work will have to be conducted in order to incorporate a more detailed wind and wave model, six dimensional buoy motion and system velocity and acceleration into the calculations. Without this, any result will not be conclusive.

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Wind farms

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A survey of available data and studies of Farm-Farm interaction

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Keywords: wake aerodynamics, farm to farm interaction, long distance wakes

INTRODUCTION

More and larger wind farms are planned offshore [1]. The most suitable sites for wind farms are limited by, for example, a certain range of water depth and distance from shore. Especially in countries with high goals for wind energy integration and combined with short coast line this will lead to more wind farms that will be build in the vicinity to other wind farms. Some examples are in the North Sea coast of Germany and in the Netherlands [2]

FARM WAKES

For wakes behind wind turbines and interaction inside wind farms one can find a wide range of studies [3],[4]. Fewer studies are published on farm wake or long distance wake that occurs behind the whole wind farms. With the coming development better knowledge will be needed to ensure better production estimations, especially when other wind farms are close and will interact with each other.

Available studies

The survey presents the available studies on farm wakes. Earlier studies have been made of the wakes behind Horns rev [5]. A survey was also done 2009 by Brand focusing more on the MESO scale effects [6]. Farm wake effects are also presented in some more articles [7].

VALIDATION DATA FOR SIMULATIONS

The survey will be used as a first step towards future LES simulations for studies of the farm wake. Therefore, available data is discussed and to what extent it can be used for validation of simulations.

Wake measurements

Satellite data is one source and it has from for example Horns rev been shown a farm wake on long distances [8]. The major source of information is otherwise measurements in met towers [9]. SAR [10] is also used and in some coming projects also horizontal LIDAR measurements will be available.

Wind farm data

Apart from wake measurements available input data needed for simulations of large wind farms are also discussed, such as: wind turbine types, meteorological conditions and energy production.

The survey is restricted to primary look at farm-farm interaction offshore and wind farms in European water.

CONCLUSIONS

The paper finally discuss which existing wind farms that can be of interest for farm-farm studies, including parameters such as available data, distance between farms and other data needed for validation of wake simulations.

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Simulation of turbulent flow inside and above wind farms: Model validation and layout effects

Yu-Ting Wu and Fernando Porté-Agel

A recently-developed large-eddy simulation (LES) framework is validated and used to investigate turbulent flow within and above wind farms under neutral conditions. Two different layouts are considered, consisting of thirty wind turbines occupying the same total area and arranged in aligned and staggered configurations, respectively. The subgrid-scale (SGS) turbulent stress is parametrized using a tuning-free Lagrangian scale-dependent dynamic SGS model. The turbine-induced forces are modelled using two types of actuator-disk models: (a) the `standard' actuator-disk model (ADM-NR), which calculates only the thrust force based on one-dimensional momentum theory and distributes it uniformly over the rotor area; and (b) the actuator-disk model with rotation (ADM-R), which uses blade-element momentum (BEM) theory to calculate the lift and drag forces (that produce both thrust and rotation), and distributes them over the rotor disk based on the local blade and flow characteristics. Validation is performed by comparing simulation results with turbulence measurements collected with hot-wire anemometry inside and above an aligned model wind farm placed in a boundary-layer wind tunnel. In general, the ADM-R model yields improved predictions compared with the ADM-NR in the wakes of all the wind turbines, where including turbine-induced flow rotation and accounting for the non-uniformity of the turbine-induced forces in the ADM-R appear to be important. Another advantage of the ADM-R model is that, unlike the ADM-NR, it does not require a priori specification of the thrust coefficient (which varies within a wind farm). Finally, comparison of simulations of flow through both aligned and staggered wind farms shows important effects of farm layout on the flow structure and wind-turbine performance. For the limited-size wind farms considered in this study, the lateral interaction between cumulated wakes is stronger in the staggered case, which results in a farm wake that is more homogeneous in the spanwise direction, thus resembling more an internal boundary layer. Inside the staggered farm, the relatively longer separation between consecutive downwind turbines allows the wakes to recover more, exposing the turbines to higher local wind speeds (leading to higher turbine efficiency) and lower turbulence intensity levels (leading to lower fatigue loads), compared with the aligned farm. Above the wind farms, the area-averaged velocity profile is found to be logarithmic, with an effective wind-farm aerodynamic roughness that is larger for the staggered case.

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Offshore Wind Farm simulations using Large Eddy Simulation

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Abstract

Large eddy simulation (LES) of flow in a wind farm is studied in neutral as well as thermally stratified atmospheric boundary layer (ABL). An approach has been practiced to simulate the flow in a fully developed wind farm boundary layer. The approach is based on the Immersed Boundary Method (IBM) and involves implementation of an arbitrary prescribed initial boundary layer (See [1]). A prescribed initial boundary layer profile is enforced through the computational domain using body forces to maintain a desired flow field. The body forces are then stored and applied on the domain through the simulation and the boundary layer shape will be modified due to the interaction of the turbine wakes and buoyancy contributions. The implemented method is capable of capturing the most important features of wakes of wind farms [1] while having the advantage of resolving the wall layer with a coarser grid than typically required for such problems.

Introduction

A set of continuity, momentum and energy conservation equations needs to be solved using LES technique. This is performed by applying a spatial filter over the fluctuating variables and modeling the small turbulence scales using sub-grid scale stress (SGS) models. The small scales refer to those that contain a small fraction of the total flow energy and are computationally expensive to resolve. In this study, the commonly used grid spacing δ is implied as the filter width and basically the effects of structures that are smaller than the grid size are obtained using the SGS modeling. The governing equations read

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial \tilde{u}_i}{\partial t} + \tilde{u}_j \left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} \right) = -\frac{1}{\rho}\frac{\partial \tilde{p}^*}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \nu \frac{\partial^2 \tilde{u}_i}{\partial x_j^2} + \delta_{i3} g \frac{\tilde{\theta} - \langle \tilde{\theta} \rangle}{\theta_0} + f_c \varepsilon i j 3 \tilde{u}_i - \frac{f_i}{\rho} + \tag{2}$$

$$\frac{\partial \tilde{\theta}}{\partial t} + \tilde{u}_j \frac{\partial \tilde{\theta}}{\partial x_j} = -\frac{\partial q_j}{\partial x_j} + \alpha \frac{\partial^2 \tilde{\theta}}{\partial x_j^2} \tag{3}$$

Where $\tilde{\phi}$ represents the filtering operation on the variable ϕ, $\tau_{ij} = \widetilde{u_i u_j} - \tilde{u}_i \tilde{u}_j$ and $q_i = \widetilde{u_j \theta} - \tilde{u}_j \tilde{\theta}$ are the SGS momentum and heat flux, $\tilde{p}^* = \tilde{p} + \rho \tilde{u}_i \tilde{u}_i / 2$ is the modified pressure, f_c, f_i, F_i are the Coriolis parameter, wind turbine loading, and external forcing such as wind force. $\tilde{\theta}, \alpha$ are the potential temperature (the temperature that the parcel of fluid at pressure p would acquire if adiabatically brought to a standard reference pressure of usually 1 bar. see [2]) and air thermal diffusivity. In the current version, a mixsed scale eddy viscosity LES model based on the scale similarity of the filter cut-out length region is used. The model is based on [3] and reads

$$\nu_{sgs}(\alpha, x, y, z, t) = C_m \delta^{1+\alpha} k_{sgs}^{\frac{1-\alpha}{2}}(x, y, z, t) |\Gamma(\bar{u}(x, y, z, t))|^{\alpha} \tag{4}$$

with δ being the grid size, $\Gamma(\bar{u}(x,y,z,t)) = \bar{S}_{ij}(x,y,z,t)$ or $\nabla \times \bar{u}(x,y,z,t)$ (strain rate or vorticity) depending on the nature of the flow and $\alpha \in [0,1]$ and serving C_m as the constant of the model which is chosen to be 0.01 in the current implementation. (See [4] for more details aboutimplementation of the model).

For the simulation of wind turbine, the actuator disc (AD) model of Mikkelsen [5] is used. The idea behind the AD is to represent the turbine loads on the flow with a virtual disc that exerts body forces through the simulation domain. The model requires table look up for the drag and lift coefficients of the specific turbine based on the calculated Reynolds number and the angle of attack. This method reduces the computational costs significantly (because there is bo need to resolve the boundary layer around the blades) while giving accurate prediction of wakes and statistical quantities behind the turbine.

The simulations of the ABL start with imposing the prescribed boundary layer (PBL) that follows a logarithmic profile with the velocity of 8 m/s at the turbine hub height. Then the forced PBL is relaxed and the wind turbine model is activated. The interaction of wakes occurs as soon as the wakes of the upwind turbine reach the downwind turbines.

Results

Simulations are performed usind the in-house CFD code Ellipsys3D. In the simulations, the domain size is 1.5 km by 0.7 km by 3 km in spanwise, vertical and streamwise directions, respectively and a uniform grid (collocated arrangement) consisting of 144 cells in each direction.

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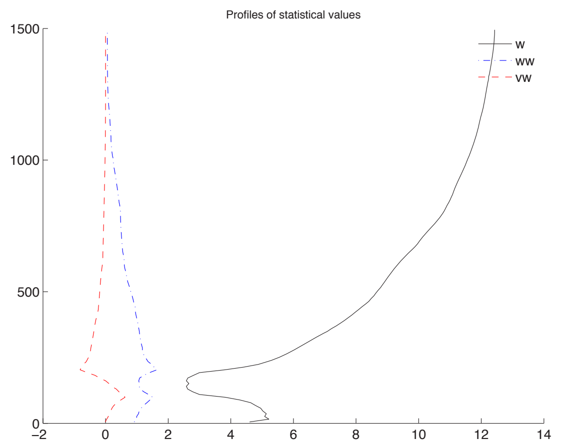

Figur 1: Profile of velocity deficit (solid line), fluctuating streamwise (blue dashed line) and normal (red dashed line) velocity stresses

A total number of 8 in-line turbines of 50 [m] radius with tower heights of 150 m are placed in the flow with streamwise spacings of 3.5 rotor diameters. A slip-free wall boundary condition is used at the bottom consistent with the use of the prescribed boundary layer approach, a symmetry boundary on the top and periodic boundaries on the vertical walls.

For the temperature initialization in stable stratification, a fixed value of 285 K is applied from the ground up to a height of 1 km which increases then linearly with the rate of 3.5 K/km. For the case of unstable ABL, the temperature is initialized with it's maximum on the bottom surface. It decreases to 285 K at a height of 600 m where it is then fixed at 285 K up to the top of the domain. To have the same basis for analysis of the results the same prescribed boundary layer profile is used for all simulations (neutral, stable and unstable (convective) ABL).

Figure (1) shows the velocity deficit as well as averaged Reynolds stress components of fluctuating streamwise and normal velocities.

Conclusions

LES simulations of wind farm wake interactions with the ABL was studied using PBL method that stems from the immersed boundary technique. The horizontally averaged values of mean horizontal velocity show a clear pattern of wake deficit.

From the figures, some of the statistics might be arguable especially close to the wall since the effects of roughness are not modelled in a physically consistent way. The so called low-level jet cannot be seen in SBL as well; however, besides significant computational cost improvement that is achieved using PBL approach, such a method is very useful in evaluating the wind turbine wake structures in shear flows. Nevertheless, more detailed aanalysis and further development of the current model including modifications for the stable and unstable ABLs is then being performed by the authors.

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