Numerical Study on Flexible Horizontal Axis Wind Turbine Rotors and Active Flow Control

アムル モハメッド アブドウエルハミッド モハメッド ハラワ

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氏　　名　：アムル　モハメッド　アブドウエルハミッド　モハメッド　ハラワ

Name　　　AMR MOHAMED ABDELHAMID MOHAMED HALAWA

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（水平軸風車弾性ロータとアクティブフローコントロールに関する数値的研究）

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論 文 内 容 の 要 旨

Thesis Summary

The development of reliable Fluid-Structure Interaction (FSI) simulation tools and models for the wind turbines is a critical step in the design procedure towards achieving optimized large wind turbine structures. Such approach will mitigate the aeroelastic instabilities like: torsional flutter, stall flutter and edgewise instability that introduce extra stresses to the turbine structure leading to reduced life time and substantial failures.

The aim of this work was to study and achieve a better understanding of the aerodynamics of wind turbine blades and their related challenges, using various CFD simulations. Several issues were addressed, mainly the fluid-structure interaction (aeroelastic) effects on the wind turbine blades as well as the stall phenomenon with promising solutions to it using active flow control. The computations results were quite satisfactory and could represent a good foundation for future work in this area.

In this study, CFD simulations were carried out in order to calculate the stall characteristics and choose a suitable turbulence model for the DU96-W180 airfoil, developed by Delft University of Technology (TUDelft) and dedicated to wind turbines. The results were validated with the experimental wind tunnel results of TUDelft. The computations were carried out till the complete unsteady Kármán vortex shedding is formed in the airfoil's downstream wake. The results showed a successful capture of the stall phenomenon with an acceptable error margin. OpenFOAM's *pisoFOAM* solver alongside k–ω SST turbulence model showed reliability in matching the physics of the problem.

In addition, FSI simulations were held to the full-scale rotor blades of the NREL 5MW reference horizontal axis wind turbine. They were implemented using the vortex-based, MIRAS-FLEX of the Technical University of Denmark (DTU), as well as the CFD-based Ansys FLUENT. The aerodynamic loads and structural responses computations were carried out using a steady-state FSI analysis. Finally,

the results were compared and validated against another widely used BEM-based aeroelastic codes as FLEX5-Q^3UIC and FAST codes in different cases showing reasonable agreement.

Furthermore, in order to solve some associated stall-problems near the blade tips, a novel active flow control technique was tested on a wind turbine airfoil to investigate on the improvement of its aerodynamic performance. Numerical simulations were done for incompressible unsteady low Reynolds Number flow at high angle of attack. The flow control was achieved using an "Active Slat" where the periodic blowing effect was achieved by periodically opening and closing the slat passage. The merit of this concept is being flexible and activated only based on the requirements from a desired operating condition. A OpenFOAM® solver was developed in this study from the existing *pisoFoam* solver to simulate the active slat flow control technique. Various approaches were used to achieve the optimum excitation frequency for the active slat operation so that the best aerodynamic performance is guaranteed. Finally, good improvements were achieved in the lift coefficient and aerodynamic efficiency. Hence, that dictates a promising application on any blade surface experiencing stall issues or separated flows at higher angle of attack.

This thesis consists of 5 main chapters. Chapter 1 gives a short introduction on where wind energy stands today along with potential and challenges. Besides, it shows a brief history on wind power, the nature of wind energy, and an outlook on the global wind power utilization. Moreover, the capabilities of CFD applications in wind energy as well as the objective and motivation are included. In Chapter 2, some basic background theory on the aerodynamics of wind turbines is presented. Besides, more focus on the wind turbine Computational Fluid Dynamics is shown alongside the turbulence modeling and the discretization technique used in this work. Chapter 3 shows the Fluid-Structure Interaction study where it starts with a pre-computational study on the wind turbine airfoil DU96-W-180. That study yielded some important parameters to consider in the following simulations like the turbulence model and the appropriate mesh sizing to capture the physical behavior of the flow at near-stall angles of attack. Next, a vortex-based method for FSI simulations is discussed showing some sample results on the NREL 5MW HAWT rotor. Afterwards, CFD-based method is introduced for FSI simulations showing various aerodynamic and structural properties of the NREL 5MW HAWT rotor. Finally, for the sake of validation, a comparison between various codes were carried out showing a good agreement and useful suggestions for future extension of this work. In Chapter 4, the Active Flow Control flow control approach is presented with the active slat technique. Open-loop simulations using different excitation frequencies are investigated to show the impact on aerodynamic properties. Furthermore, the numerical analysis of the base case including frequency analysis technique as well as the slatted airfoil results are shown. Finally, the results were recorded and compared showing promising application of this technique for future similar applications. Last but not the least, Chapter 5 summarizes the thesis main conclusions besides showing some recommendations for future work.