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AERODYNAMIC PERFORMANCE EVALUATION OF A WIND TURBINE ROTOR

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ABSTRACT

The analysis methods with varying fidelities are evaluated for prediction of aerodynamics performance of horizontal axis wind turbines, HAWT, for varying flow conditions. Reynolds Averaged Navier Stokes, RANS, equations are solved in higher fidelity analyses whereas lower fidelity tools are based on the blade element and momentum theories. The prediction capability of the tools is assessed for airfoil analysis at the flow regimes commonly encountered on horizontal axis wind turbines blades. Wind tunnel test results of DU91-W2-250 and NACA0015 airfoils are used as reference for 2D sectional analysis validations. HAWT aerodynamic performance prediction competence of the analysis tools are examined with validation studies applied for Risoe and Nord Tank wind turbines which have 100kW and 500kW capacities respectively. Gathering the required infrastructure and validated methodologies for HAWT aerodynamics analysis, the performance of the newly designed turbine rotor that outputs 820kW nominal energy is evaluated for varying pitch angles.

INTRODUCTION

The aerodynamic characteristics of the rotor directly affect the power generation efficiency of the horizontal axis wind turbines thus the investment put on those renewable energy systems. Although the design features of the mechanical and electrical systems also have considerable influence on the final amount of electrical energy extracted from the wind, the aerodynamic properties of the rotor blades play the major role on characterizing the total efficiency of wind turbines. Hence proper infrastructure for aerodynamic analysis is crucial and necessitated in the design phase of wind turbine rotor to be able to accurately evaluate the design choices that will influence the power generation performance.

Horizontal axis wind turbines have high aspect ratio blades which makes aerodynamic characteristics of blade sections to have major effect on cumulative performance [Bak and Fuglsang ,1999]. Therefore, properties of the utilized airfoils on turbine blade design affect the energy extraction process from the wind significantly. Low fidelity aerodynamic analysis tools, which are based on blade element & momentum theory using the aerodynamic database of airfoils in table lookup format, can perform efficiently in predicting the HAWT rotor performance [Sorensen and Shen 2002]. In such methods, the cumulative aerodynamic forces and torque on the rotor plane are calculated by integration of lift and drag force on each prescribed blade element. The aerodynamic force coefficients on each element is acquired from the aerodynamic database of airfoils which mainly consist of lift and drag coefficients between angle of attacks of -180° and 180° for varying Reynolds numbers. This database can be generated either by wind tunnel tests or predictions by analyses. Advanced competence for prediction of airfoil aerodynamics is an utter must for the accurate predictions with BEMT type analysis tools. Moreover the capability of accurate aerodynamic database generation for an airfoil is a crucial asset for a designer since the spanwise variation of airfoils along the blade is one of the most crucial design parameters on total performance.

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The analysis methods based on detailed three dimensional computational fluid dynamics solutions are capable of computing the flow field around the HAWT rotor without any empiricism except for those featuring in turbulence models. In last decade full three dimensional analyses employing the Reynolds Averaged Navier Stokes Equations gathered intense attraction of researchers aiming to enhance their capabilities for overall performance and loads prediction [Kang and Hirsch 2001] [Sorensen 2002] [Carcangiu 2008]. However, results evaluated by these methods are very sensitive to the variation of turbulence models, grid resolution, near wall modeling, boundary condition parameters etc. [Benjanirat and Sankar 2003] Systematic validation studies are needed to attain a reliable solution scheme, mesh topology and discretization methods that can be utilized in aerodynamic analysis of a HAWT rotor confidently. In addition, detailed CFD solutions require significantly greater amount of time and resources compared to lower fidelity tools [Sumner et. al. 2010]. Hence RANS/URANS analyses shall be conducted at the final phases of the design process for a limited number of conditions which are chosen for analysis after evaluating results with BEM theory based tools.

In this study, TRE203p wind turbine with a power capacity of 820 kW is evaluated with the aerodynamic analysis tools that have varying fidelities. Prior to TRE203p evaluation effort, analysis tools for airfoil and rotor aerodynamic performance are validated with existing test data. Aerodynamic analyses of airfoils are performed with a panel method coupled boundary layer solver and a commercial Reynolds averaged Navier-Stokes solver, Fluent. The lower fidelity aerodynamic performance analyses of wind turbine rotors are performed with a blade element solver, WTperf [Platt A., 2012], whereas higher fidelity analyses are performed with solution of 3D RANS equations by Fluent. The CFD analyses of the flow field around the three dimensional rotating blades are carried out by employing the moving reference frame method hence flow equations are solved in steady form. Throughout the study, the wind turbine rotor is treated with the isolated rotor assumption; hence the interaction of the rotor with tower, ground and other turbines is out of scope of this work. Each tool that is utilized for total performance prediction of the wind turbine rotors was validated by carrying out analyses for test case turbines that have varying sizes.

VALIDATION OF AIRFOIL AERODYNAMIC ANALYSES

Aerodynamic analyses of airfoils are performed with a panel method coupled boundary layer solver Xfoil [Drela,1989] and a commercial RANS solver, Fluent. Both flow solvers are utilized to predict the aerodynamic characteristics of the DU91-W2-250 and NACA0015 airfoils. The evaluations are compared against available test data [Bertagnolio and Sorensen,2001][Abbott,1959][Sheldahl and Klimas,1981] for validation purposes.

A typical mesh used in the analyses and the computed pressure contours together with streamlines around DU-93 family airfoil at high angle of attack are presented in Figure 1. The comparison of evaluated lift and drag coefficients from the XFOIL and RANS analyses are compared against the test results for the DU91-W2-250 airfoil in Figure 2. CFD results presented in the following figures are evaluated by using Fluent and utilizing two different turbulent modeling approaches. While in first approach the Spalart Allmaras turbulence model with wall function method is applied, as a second approach k-w SST model is coupled with the γ-Re_θ transition modeling. The depicted comparison shows that the analysis results are fairly consistent with the test data, especially up to the stall region.

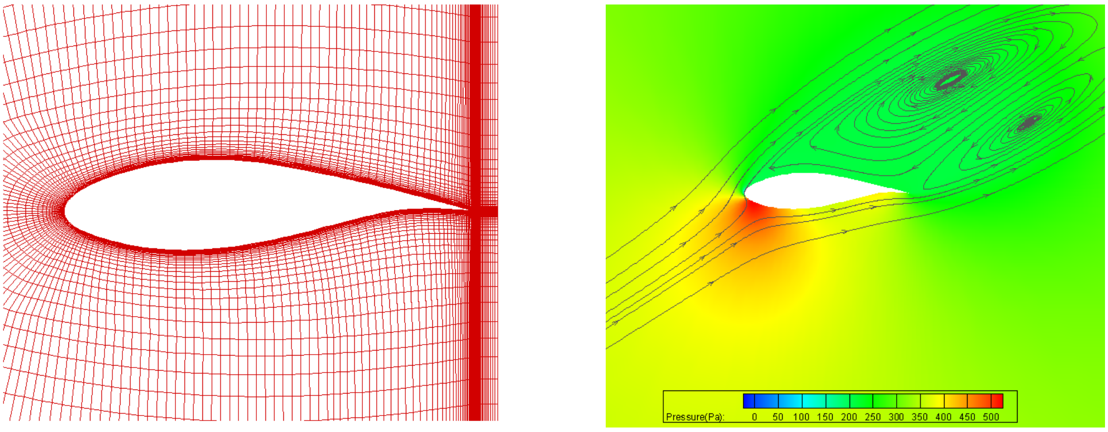


Figure 1 Typical Mesh utilized for airfoil CFD analyses and computed flow field around DU 93 family airfoil at high angle of attack condition

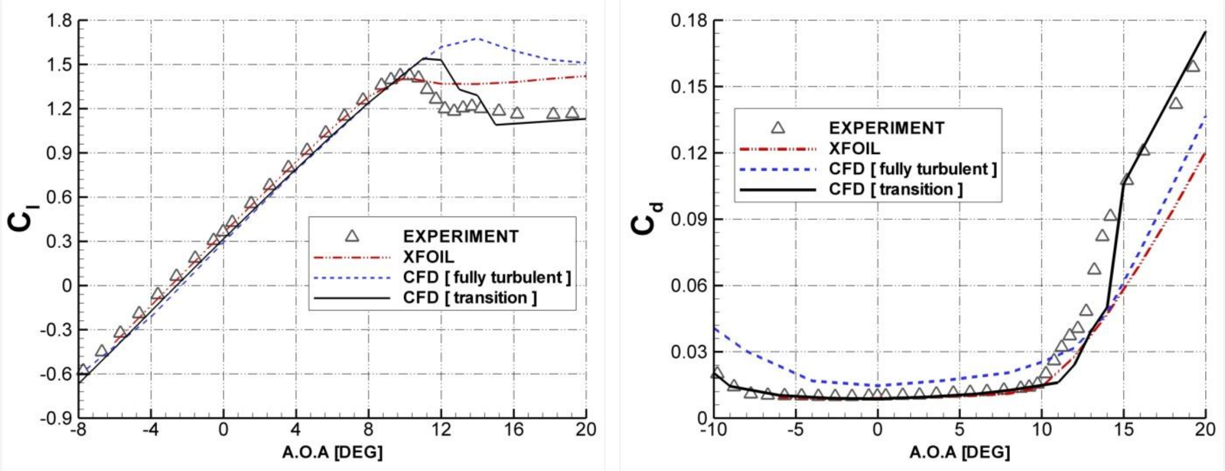
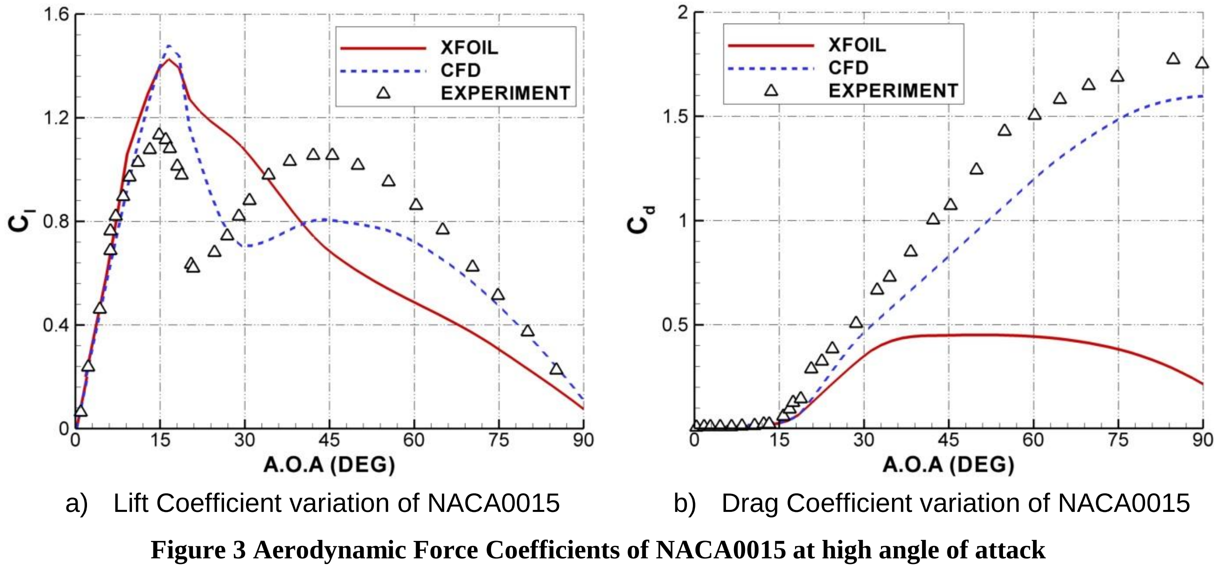


Figure 2Aerodynamic Coefficients of DU91-W2-250

The airfoil aerodynamic database not only consists of force coefficients corresponding to flow conditions up to stall region, but also of data corresponding to high angle of attack cases. Figure 3 depicts the predicted characteristics of NACA0015 airfoil for a wide range of angle of attack conditions and comparison of those computations against the test data. Transition modeling in CFD calculations did not introduce a significant improvement for the post stall regime predictions. The presented results show that at high angle of attack cases, XFOIL and FLUENT predict the lift at comparable accuracy whereas the drag prediction capability of XFOIL is poor.

Based on the validation studies applied for airfoil aerodynamics predictions, it is concluded that the generation of an aerodynamic database should be performed by XFOIL for the angle of attacks ranging between the negative and the positive stall regions considering its low cost and satisfying results. However, the high angle of attack conditions in the database shall be computed by a RANS solver due to the better performance in drag prediction.



a) Lift Coefficient variation of NACA0015 b) Drag Coefficient variation of NACA0015

Figure 3 Aerodynamic Force Coefficients of NACA0015 at high angle of attack

VALIDATION OF WIND TURBINE AERODYNAMIC PERFORMANCE ANALYSES

BEM and CFD type tools are validated for the performance prediction of a HAWT rotor by analyzing the Risoe [Schepers and Brand, 2002] and NordTank [Hansen 2000] wind turbines, whose blade geometries are depicted in Figure 4 and Figure 5 respectively. The turbines are stall-controlled, thus, the pitch angle of the blades are kept constant throughout the operation. The power control mechanism of the turbines relies on stall phenomenon. As the wind velocity increases, stall phenomena begins to take place, consequently the power generation performance diminishes due to the reducing lift force.

The surface and volume meshes required for CFD analyses are generated by using GAMBIT and Tgrid commercial tools. A typical surface mesh which is composed of mapped quad elements is depicted in Figure 6. 30 layers of body conforming prismatic cells are constructed on blade surface to resolve the boundary layer over the blade. The farfield mesh is generated by utilization of cartesian grid type hexahedral elements. In the vortical downwind region of the rotor, cells are refined by hanging node technique. Figure 7 depicts a typical volume mesh that is utilized in the analyses, by axial and tangential planes extracted from the flow domain.

The flow equations are solved in incompressible form employing a fully implicit pressure based solver. RANS solutions with moving reference frame located on rotor center are computed by utilizing the Spalart Allmaras turbulence model with curvature correction option. The velocity inlet boundary condition is applied to the far field boundaries located at upwind of the rotor and at the boundary circumferentially surrounding the flow domain. Pressure outlet type boundary condition is defined at the farfield boundary located at downwind. In order to reduce the computational burden the flow domain is simplified by the definition of the periodic boundary conditions and one third of the flow domain is analyzed with single blade geometry.

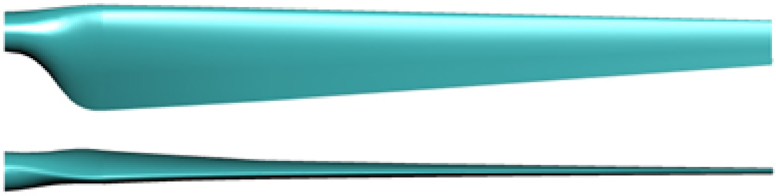


Figure 4 Blade Geometry of Risoe

Figure 5 Blade Geometry of NordTank

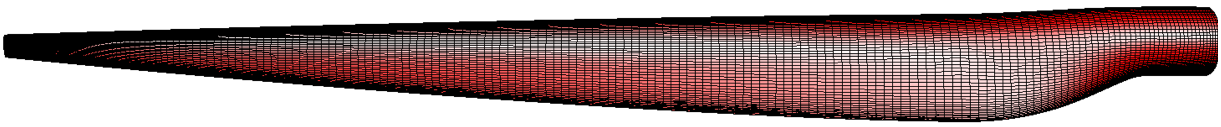
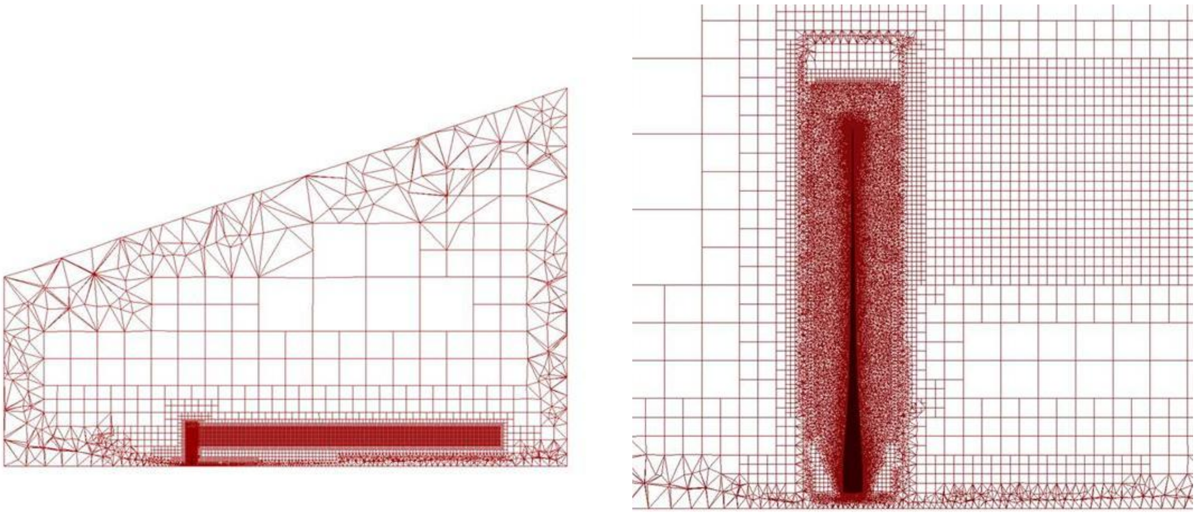


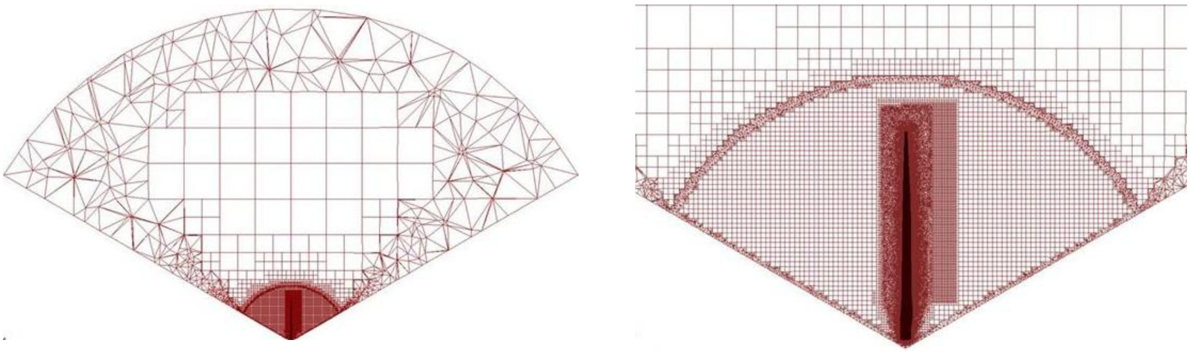
Figure 6 Surface mesh around HAWT blade

The power generation curves of Risoe and NordTank HAWT rotors are predicted for varying wind speeds and results are compared against the test data as shown in Figure 8 and Figure 9. According to the validation results presented, predictions by both methods are well matched with the test data.

Achieving the satisfactory level of accuracy from validation efforts, analysis tools are employed in the analyses required in the blade design of a new HAWT rotors.



Isoclip of constant tangential plane



Isoclip of constant axial plane

Figure 7 Isoclips taken from the volume mesh around the HAWT rotor

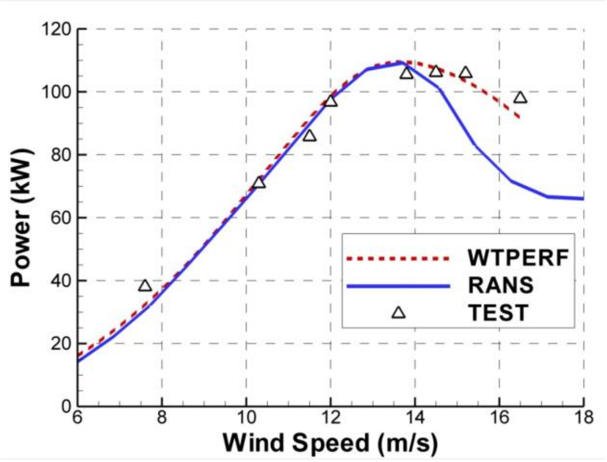


Figure 8 Power Curve of Risoe turbine

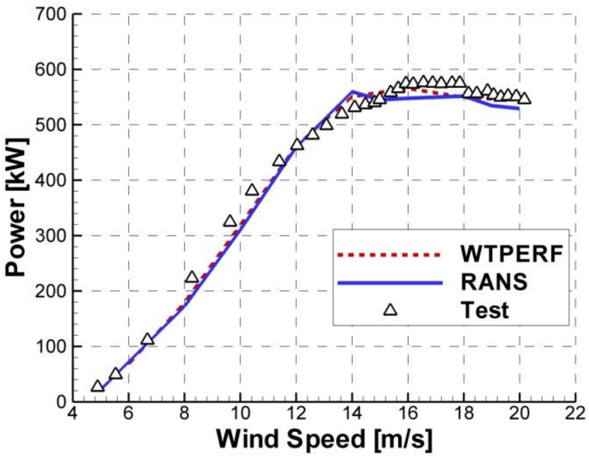


Figure 9 Power Curve of NordTank turbine

AERODYNAMIC PERFORMANCE EVALUTION OF TRE203

The wind turbine having mechanical power capacity of 820 kW is designed by utilizing aerodynamic analyses methods which are aforementioned in previous sections with their validation results. A loss of about 20% on mechanical and electrical systems is predicted and net output of electrical power is evaluated to be 650 kW. In Figure 10, the designed blade geometry is depicted and the technical specifications are given in Table 1. The designed turbine would be operating with pitch controller whose details are out of the scope of this study.

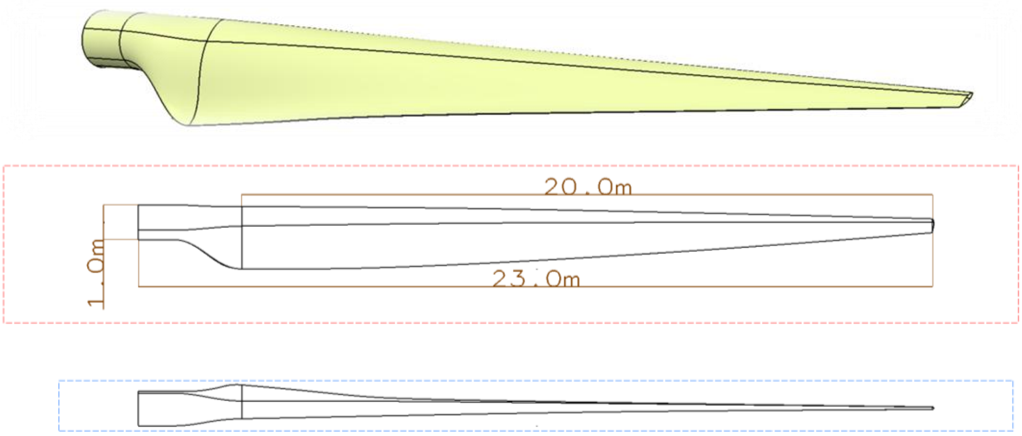


Figure 10 Blade Geometry of TRE203_v2

Table 1 Technical Specifications of TRE203_v2

Rated Mechanical Power (kW)	820
Rotor Diameter (m)	48
Blade Length (m)	23
Swept Area (m^2)	1809
Rotor Speed (rpm)	27.8
Number of Blades	3
Blade Tip Speed (m/s)	70
Power Control	Pitch control
Rotor Orientation	Up wind

The power generation performance of the final turbine design is evaluated by using both BEM theory based tools and RANS analyses. Figure 11 presents the power generation curves of the designed rotor which are evaluated by WTperf and Fluent analyses. Both analyses methods predict similar performance characteristics for the designed wind turbine rotor. Figure 12 presents post process examples evaluated with RANS analyses performed for 10 m/s wind speed condition.

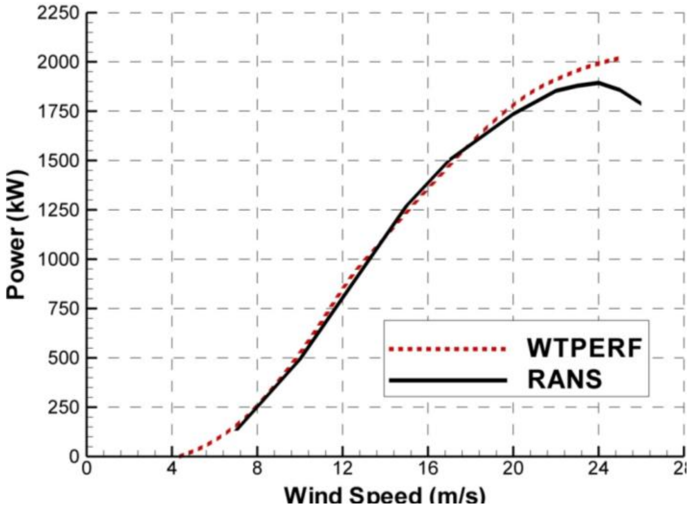
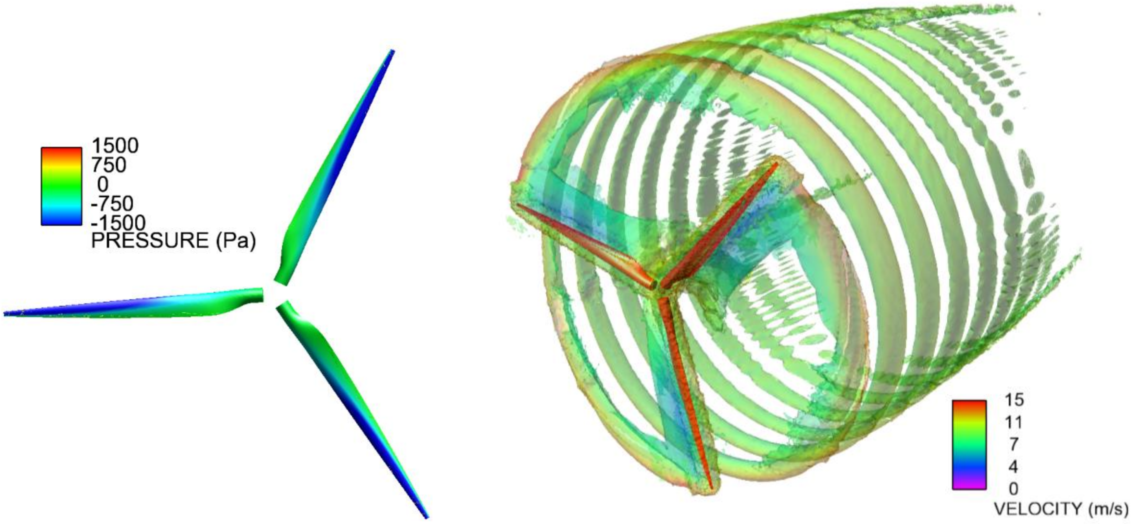


Figure 11 Power curve of TRE203_v2 HAWT rotor.

A competitor study is conducted for the designed turbine rotor and critical design parameters such as rotor diameter, rotational speed and rated wind speed are compared to existing HAWT designs. Figure 13 presents the variation of design characteristics of existing rotors and the designed wind turbine TRE203p having an electrical power capacity of 650 kW depicted on Figure 13. From the comparisons, it is seen that the designed turbine has a rotor diameter and rotor speed which is close to the average trend. For the rated wind speed, it has the advantage of reaching its rated power at a lower wind speed compared to the competitors.



Surface pressure contours computed for 10 m/s wind condition

Isosurface of vorticity magnitude colored with velocity magnitude for 10 m/s wind

Figure 12 Post process figures obtained from blade surface and flow field

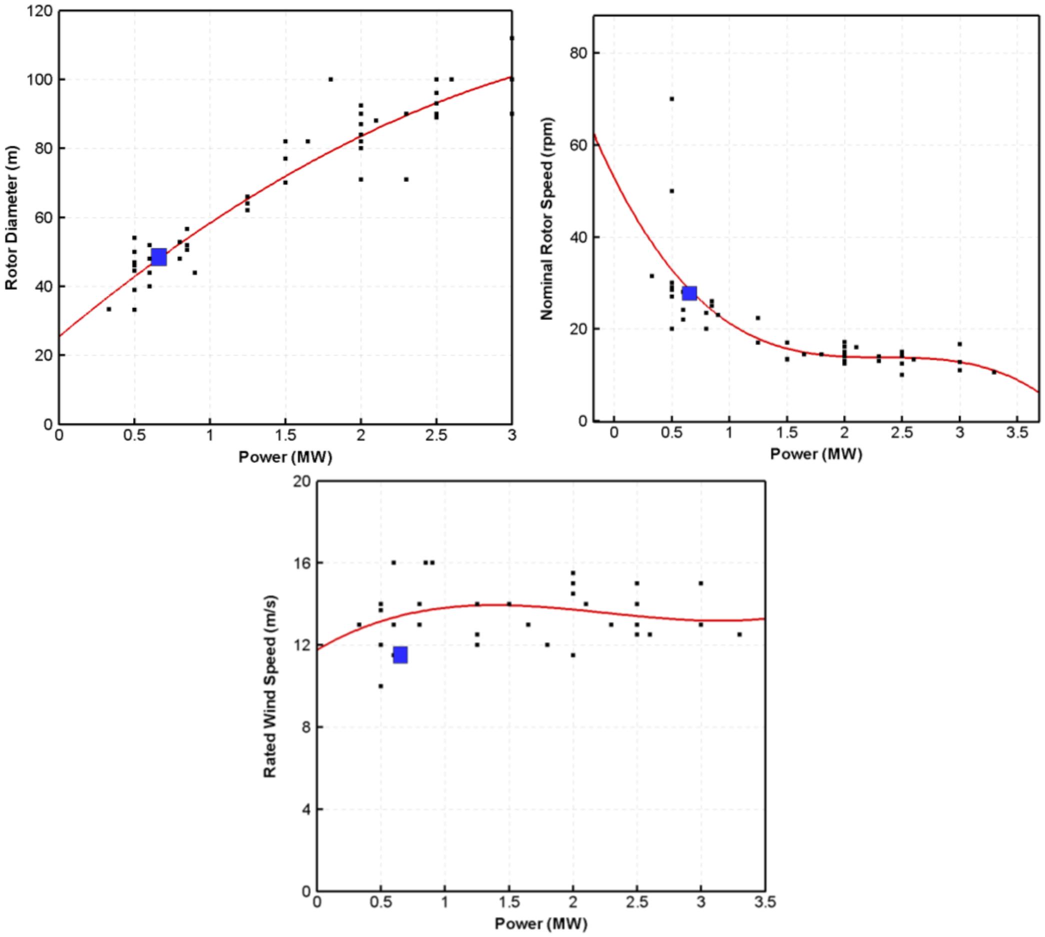


Figure 13 The Competitor Study along existing HAWT rotors

The blade geometry design is completed by the extraction of sections along blade radial stations and the creation of aerodynamic database for each section. Using this sectional data, rotor performance is examined. Variation of power curves for different pitch angles are formed using the BEM based tool and evaluated characteristics are presented in Figure 14. For the sign convention, turning the blade into the wind direction is defined as positive pitching. Sweeping different angle of attacks and wind speeds, analyses are redone and the designed envelope for the wind turbine is generated. The design envelope, which presents the conditions that turbine can produce power, is depicted in Figure 15. The operating conditions in which the wind turbine reaches its rated mechanical power are also depicted here.

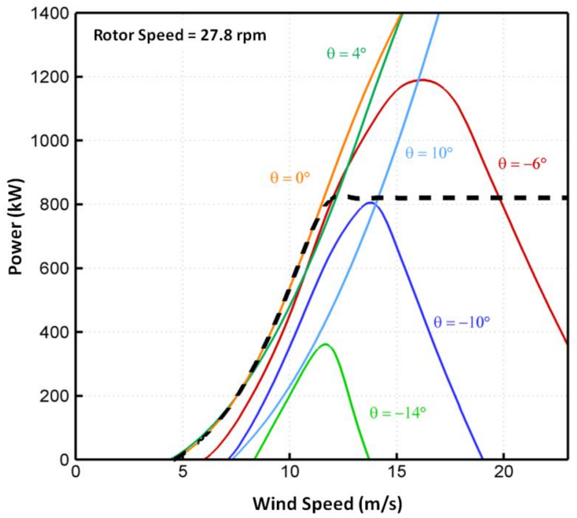


Figure 14 Power Curves for Different Pitch Angles

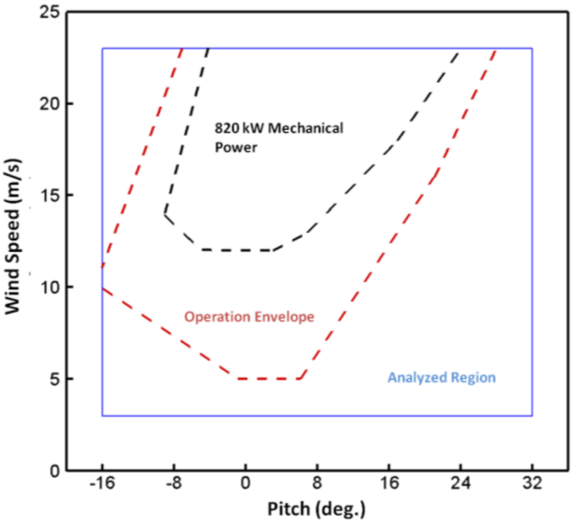


Figure 15 The Operation Envelope

CONCLUSION

The engineering analysis methodologies required through the design of a horizontal axis wind turbine rotor is studied comprehensively. The aerodynamic analysis tools with varying fidelities are examined against proper test cases and systematic validation studies are conducted. The analyses methods based on blade element momentum theory are prevailing in the conceptual design phase of the turbine rotors since they require significantly small amount of time and computational resources compared to the detailed 3D Navier Stokes solutions. On the other hand CFD solutions with validated methodology brings the designer the chance for validating the design concept and fine tuning for enhanced performance. Validating the analyses tools, the newly designed horizontal axis wind turbine, TRE203p is evaluated for its aerodynamic performance. Analyses results show that designed rotor promises similar performance compared to existing turbine designs. Examining the various pitch angles and wind speed conditions the operation envelope for the designed turbine is defined.

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