development of blade element momentum theory for unsteady flow with regard to the dynamic stall phenomenon

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ABSTRACT

The first step in turbine blade design is to select tip speed ratio. In this research the optimum speed ratio is calculated with regard to the dynamic stall phenomenon. The dynamic stall imposes large amplitude loading on airfoil sections and since it occurs in turbine operating envelope in unsteady flow. The purpose of this study was to investigate the effect of unsteady flow with periodic oscillation on the performance of horizontal axis wind turbines. A Dynamic stall model is implanted to analyze the static data obtained. Then, using this model and blade element momentum theory, the optimal tip speed ratio is calculated. Also, thrust and power coefficients are plotted in several different Tip speed ratios. In addition to dynamic results, static results are plotted in power and thrust graphs. Comparison of these results shows how the dynamic stall causes the deviations of responses to static state. This phenomenon affects the efficiency by -3% as compared to the static stall. Also the optimum tip speed Ratio increases in dynamic mode. In addition, time average diagrams of the drag coefficient show that the delay in separation starts approximately from the midpoints of the blade and reaches the maximum value at the root.

KEYWORDS

Dynamic Stall, Blade Element Momentum, Tip Speed Ratio, horizontal axis turbines, Unsteady flow

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1. Introduction

The use of blade element momentum theory for the design and analysis of horizontal axis wind turbines is of particular importance in academic research and industry. Blade element momentum theory (BEM) was first introduced by Glauert [1]. The reason for this widespread acceptance is the simplicity of the code and the good accuracy of the results. In BEM theory, the blades are divided into small elements. To obtain the aerodynamic forces of each element, the experimental data and look-up tables for drag and lift Coefficients are used. Using experimental data increases the accuracy of the predicted results [2]. For each segment eight unknown parameters namely, axial induction factor, rotational induction factor, tip loss correction factor, inflow angle and lift, drag and thrust coefficients must be calculated. These parameters can be found using a system of six algebraic equations and two lookup tables for lift and drag coefficients [3].

The most important problem that reduces the accuracy of the results in using BEM theory is the oscillatory behavior of the induction factor in each iteration loop [4]. In such cases, BEMs usually use code written on the basis of the AeroDyn module [5]. This reduces the accuracy of the results. This problem is compounded in cases where the problem is unstable. In these cases, the effects of dynamic coefficients are ignored. For example, the phenomenon of dynamic stall which has a significant effect on the amount of aerodynamic coefficients is ignored [5].

Considering the dynamic stall phenomenon can greatly improve the accuracy of the results. This phenomenon has been modeled by several researchers. One of the successful models is the Beddoes-Leishman method. This method performs dynamic stall modeling by dividing the model into three related parts.

The B-L model is the most widely used and extensively tested dynamic stall model in the literature. B-L model primarily tries to simulate the physical mechanisms governing the phenomenon of dynamic stall. These flow mechanisms are simulated by mathematically delaying the lift coefficient of attached flow, delaying the development of flow separation, and augmenting the lift coefficient through a convecting leading edge vortex [6].

2. Methodology

The purpose of this paper is to develop the BEM theory with regard to the phenomenon of dynamic stall. In the present study, at first the BEM method and its governing equations will be described, then this method is verified. The blade-element momentum implementation has been validated using AeroDyn an open-source software from the National Renewable Energy Laboratory. then, the phenomenon of dynamic stall and its governing equations is explained and the code for predicting the aerodynamic coefficients of dynamic stall is verified. The dynamic stall module has been validated against experimental data. Once the dynamic results are obtained, they can be used in BEM theory.

In fact, by modeling the dynamic stall, the look-up table used in BEM theory will be updated and the obtained results will have good accuracy in studying the unstable states. The aim of this work is to answer the following research question: How significant are the unsteady effects on the flow around and the loads on a HAWT blade? This topic investigated by developing a model which couples blade element momentum (BEM) and DS model.

The numerical model is split into two components: blade element momentum theory and dynamic stall model, which are coupled as detailed in this section. The flowchart shown in Fig. 1 describes how the Ds and BEM combined.

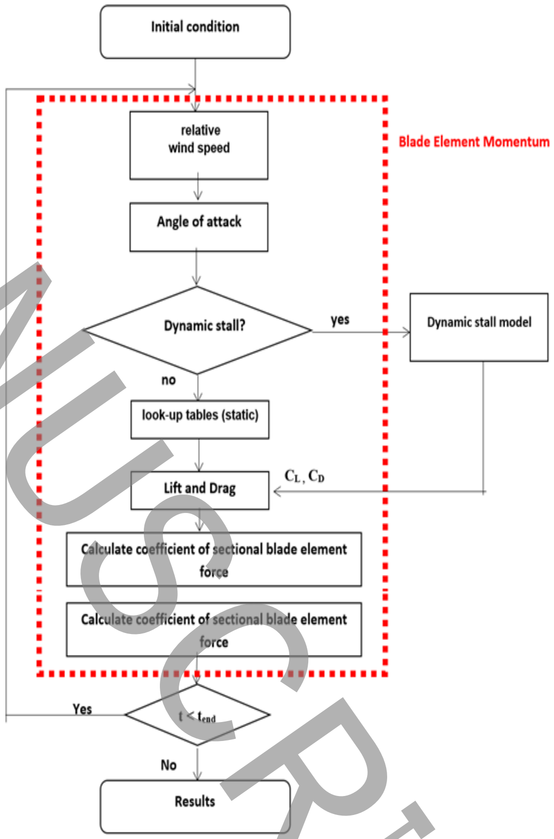

Figure 1. Flow Chart of Phases of the Study

In this study The turbine has uniform thickness NREL S814 profiles at each section, the flow is steady with a current velocity of 2.77 ms^{-1}, the rotor is normal to the flow and $\beta_p = 0$. The oscillation of the flow is a pitching motion of $a_t = 13.8^{\circ} + 10.75^{\circ} \sin wt$, the reduced frequency, defined $k_t = \frac{2\pi\omega}{w} = 0.001$, w is 0.091.

3. Results and Discussion

In this simulation, the values of power and thrust coefficient of turbine are calculated at over the time (in unsteady state). These values are plotted in Figure 2 and Figure 3 in term of dimensionless time. Also, the average values of these parameters is plotted on the same graph and compared with the static results. Although in some time steps, the thrust and power coefficients locally exceed the steady coefficient, but the overall and average results indicate that the turbine power and thrust are approximately reduced by about three percent compared to static mode.

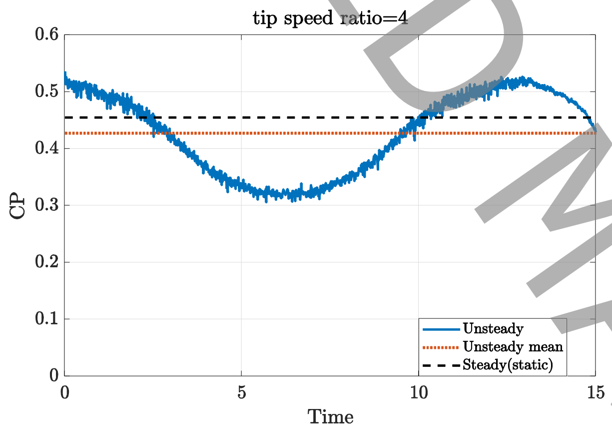

Figure 2. Comparison of power coefficient over 15 blade rotations, showing the predicted unsteady time history, and corresponding mean value alongside steady-state response

In Figure 3, the graph of the power coefficient of turbine is given in terms of tip speed ratio. In this figure, the mean power coefficient in the unsteady state and the static mode (steady state) are compared. As in the previous figure, it can be seen from the comparison of the steady and unsteady flow results that the reduction of the power coefficient and the thrust coefficient in all tip velocity ratios is noticeable. The reason for this is the dynamic stall phenomenon described in detail. Another important point is to increase the value of λ_{opt}. λ_{opt} is the tip speed ratio of the optimum speed of the turbine. The turbines in this λ produce the highest amount of power possible and have the highest efficiency. As can be seen in the figure 4, in unstable mode, the peak point of the graph is moved to the right.

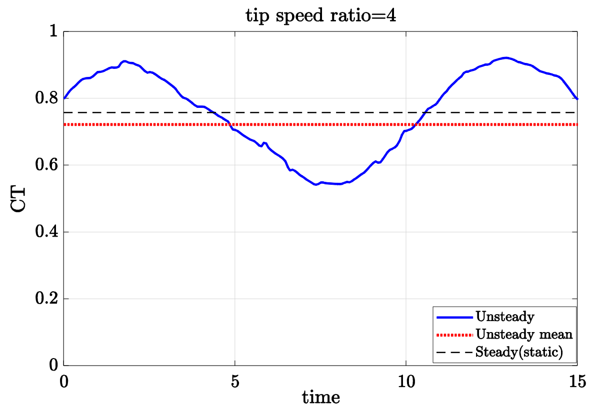

Figure 3. Comparison of thrust coefficient over 15 blade rotations, showing the predicted unsteady time history, and corresponding mean value alongside steady-state response

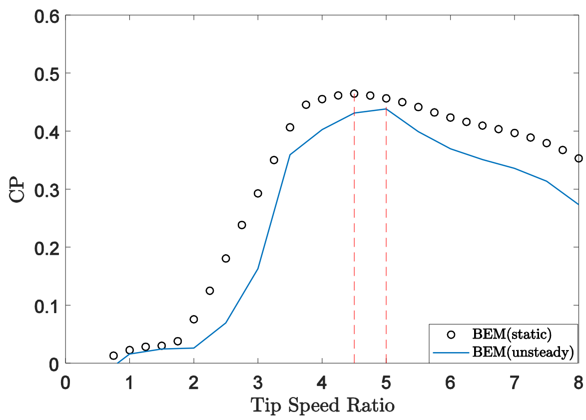

Figure 3. Comparison of power coefficient over different tip speed ratios, showing the corresponding mean value alongside steady-state response.

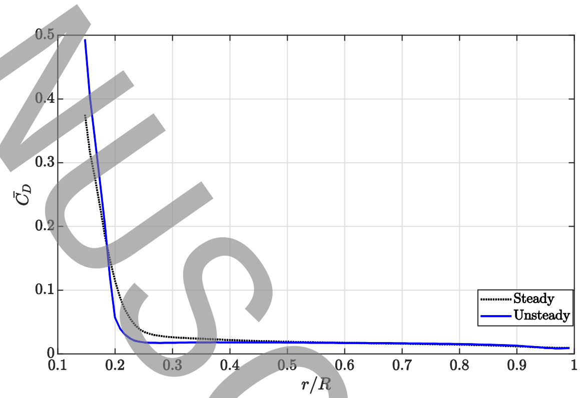

Figure 4. Comparison of mean drag coefficient along the blade span for steady and unsteady conditions.

In Figure 4, the average time value of the drag force coefficient at each blade cross section is shown. As can be seen, the unstable values of the drag coefficient increase sharply near the root of the blade. This phenomenon occurs because the intensity of flow separation on the surface of the blade increases due to dynamic stall. The two static and dynamic curves of the drag coefficient overlap from about 0.9r to the end of the tip. The reason for their overlap is that, at the end of the blade, the angle of attack is small, so dynamic stall phenomenon does not occur, and the static and dynamic results are similar.

4. Conclusions

In this study, the theory of blade element momentum was developed for unsteady problems (flow with periodic oscillating). also the performance of a horizontal axis wind turbine for finding the optimum tip speed was investigated. The main difference between such flows, with the uniform flow, is the phenomenon called dynamic stall. This phenomenon occurs when the blade or flow oscillate. This phenomenon delays the point of stall and causes drastic changes in the lift and drag coefficients. Unsteady-state power and thrust coefficient diagrams were obtained using the modified Beddoes-Leishman dynamic model. also The power coefficient diagram was also calculated against tip speed ratio. The results of the present study show that in unsteady turbines, the power and thrust coefficients decrease about 3% and the λ_{opt} ratio of the optimum speed of the turbine design increases. Therefore, using dynamic models and aerodynamic data based on these models can have a significant effect on the change in λ_{opt}.

5. References

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