SURROGATE MODELS FOR STALL REGULATED WIND TURBINES FOR IMPROVED PERFORMANCE PREDICTIONS

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ABSTRACT

Nowadays the Blade Element Momentum theory is used to determine a given element's airfoil section performance coefficient. The objective of this work is to improve the current method of determining the airfoil section performance coefficients and to determine these coefficients where little or no experimental data exists such as angles of attack of stall, post stall and at very low Reynolds numbers. Kriging method is used to develop surrogate models that can supply high quality airfoil sectional lift and drag coefficients over a wide range of angle of attacks and Reynolds numbers. One wind turbine blade (FX63137) is analyzed using BEM theory and the surrogate models. It is found that the predicted performance from the BEM theory and the Kriging method is very sensitive to the angle of attack and Reynolds number of the elemental airfoil sections and the performance predictions can be improved by using the developed surrogate models.

Keywords: Wind Turbine, Surrogate Model, Kriging Method, Airfoils.

1. INTRODUCTION

Amidst rising oil prices, it is very important to reduce the US crude oil import by one-third by 2025 through expanded exploration of crude oil and natural gas and investment in alternative energy sources including nuclear energy, biofuels and wind energy. The volatility in crude oil prices has led to renewed drive for renewable energy sources. Wind power is a renewable energy source that is clean, environmentally friendly and helps the US meet its energy needs and also provide economic benefits.

Currently, wind power accounts for 3% of electricity generated in the US with individual turbine capacity of around 4MW. In spite of these developments, it is still expensive to analyze the aerodynamic characteristics and performance parameters of wind turbine rotors through wind tunnel experiments or practical site experiments to improve the design and efficiency of wind turbine rotors. It is imperative that less costly means be devised to analyze the aerodynamic and performance parameters of the wind turbine blades.

Wind tunnel experiments have limitations on getting data on minimum Reynolds numbers (Re) and angle of attacks (\(\alpha\)). Figure-1 shows necessary angle, forces and torque that works in an airfoil. The objective of this work is to use surrogate models of blades to analyze performance characteristics at untried angle of attacks and Reynolds number for wind turbine blade designs. There are various types of surrogate models such as data fit type (single data, multiple data, and global data), model hierarchy type, and reduced order modeling. The current work uses global data fit type. The Kriging model is used to approximate the lift and drag coefficients of the wind turbine blades (FX63137) from wind tunnel experimental data.
2. LITERATURE REVIEW

The Blade Element Momentum (BEM) theory is a mathematical model and also one of the most commonly used models in engineering for the fluid dynamics design of rotor blades and evaluation of wind turbine performances. In designing the wind turbine blade this model enables the choosing of geometric characteristics of the turbine such as the aerodynamic airfoils, rotor radius, chord length, pitch and twist angles. This also includes the evaluation of the forces acting on the blade, the torque and power at the rotor shaft. The mathematical model also enables turbine performance evaluation at wide ranges of wind speeds.

The experimental data used by this paper has a small range of angle of attack from-11° to 20° because of wind tunnel limitations. The flat plate theory enables the calculation of the peak post-stall data using the Viterna and Corrigan method [2]. The combined experimental and flat plate theory data when modeled using the Kriging method could be used to simulate the blade design parameters and thus, the power coefficient (C_p), torque and normal and tangential forces acting on the blade. The peak rotor power and post peak-power is important in the predictive design of constant-speed and variable speed stall-regulated rotors.

Coefficient of power (C_p) is calculated using the equation:

\[ C_p = \frac{P}{\frac{1}{2} \rho_a AU_a^2} \]  

(1)

Here, \( P \) =Power, \( \rho_a \) =Free stream flow density, \( A \) =Cross-sectional area of the blade, \( U_a \) =Free stream velocity.

Experimental studies lack a method for determining the blade’s angle of attack (\( \alpha \)) distribution so that normal and tangential force coefficients (C_n and C_t) acquired from chord-wise pressure measurements can be converted into lift and drag coefficients (C_l and C_d) for engineering calculations.

By definition, ‘stall’ means a particular angle of attack when the blade does not produce any lift force, therefore we do not get any power from wind turbine. The region just after stall condition is known as 'post-stall’.

References [3-5] have concentrated on the determination of the angle of attack distribution from experimental data. Under the sponsorship of the National Renewable Energy Laboratory (NREL) the Lifting-Surface Wind Turbine (LSWT) performance-prediction methodology [6], provided a unique capability for deriving angle of attack. From Unsteady Aerodynamic Experiment (UAE) data of C_n and C_t could then be converted into values of C_l and C_d using angle of attack distributions derived from LSWT. Through an iterative process, agreement was achieved between UAE measured and LSWT-predicted C_n and C_t radial distributions [2].

This agreement yielded angle of attack distributions compatible with the measured post-stall 3D aerodynamic characteristics. Unlike blade-element momentum (BEM) theory, the LSWT methodology accounts for the induced effects of the blade configuration and those from the span-wise distribution of trailing vorticity in calculating the angle of attack distribution [3].

After an angle of attack of 20° the lift/drag ratio for the five radial locations at which pressure measurements were acquired essentially followed simple flat plate theory [7]. The difficulty of relating BEM-predicted angle of attack distributions to the post-stall 3-D aerodynamics and measured power are demonstrated in [3-5]. This finding pointed to the need for a global post-stall approach, as for instance, previously developed by Viterna [8] and [9] for generating post-stall C_l and C_d based on both airfoil and blade specific stall characteristics.

These generated post-stall data are combined with the experimental data to create surrogate models that are used to predict the lift and drag coefficients at untried location of the Reynolds number and angle of attack (untried sites) to predict peak power and other rotor performance characteristics.

The Kriging method is a good tool to provide good predictive values. The programs used are from the “Design Analysis of Computer Experiments (DACE) a Matlab Kriging Toolbox” for constructing Kriging approximation models based on data from computer experiments and to use this approximation model as a computer model [10].

3. GENERATING GLOBAL DATA

Since the experimental data of lift coefficient (C_l) and drag coefficient (C_d) are available for mainly pre-stall angle of attacks, flat plate theory was used to calculate the post-stall C_l and C_d from the given experimental data according to Viterna and Corrigan method [2,8]. Following are the set of equations used [3-9] to get global data:

Drag coefficient:

\[ C_d = B_1 \sin^2 \alpha + B_2 \cos \alpha \quad \alpha = 15^\circ \text{ to } 90^\circ \]  

(2)

\[ C_{d_{\text{max}}} = 1.11 + 0.018AR \quad \alpha = 90^\circ \]  

(3)

where: \( B_1 = C_{d_{\text{max}}} \)  

(4)

\[ B_2 = \frac{C_{d_{\text{max}}} - C_{d_{\text{max}}} \sin^2 \alpha_{\text{stall}}}{\cos \alpha_{\text{stall}}} \]  

(5)

Lift coefficient:

\[ C_l = A_1 \sin 2\alpha + A_2 \cos^2 \alpha \quad \alpha = 15^\circ \text{ to } 90^\circ \]  

(6)
where:

\[ A_1 = \frac{B_1}{2} \] (7)

\[ A_2 = (C_{l,\text{stall}} - C_{d,\text{max}} \sin \alpha_{\text{stall}} \cos \alpha_{\text{stall}}) \frac{\sin \alpha_{\text{stall}}}{\cos^2 \alpha_{\text{stall}}} \] (8)

An initial angle of attack (\( \alpha_{\text{stall}} \)) with its associated lift (\( C_{l,\text{stall}} \)) and drag (\( C_{d,\text{stall}} \)) coefficients with the blade aspect ratio (AR) is required. The \( C_l/C_d \) will not agree with the flat plate theory if the \( C_l/C_d \) at the initial angle of attack is not satisfied. These global \( C_l \) and \( C_d \) data are used to develop the surrogate models.

4. KRIGING MODEL CONSTRUCTION

In developing surrogate model by Kriging method the choice of correlation function should be motivated by the underlying phenomenon that is the function we want to optimize or the physical process we are modeling. If the underlying phenomenon is continuously differentiable, the correlation function will likely show a parabolic behavior near the origin, which means that the GAUSSIAN, CUBIC or the SPLINE function should be chosen. Conversely, when the physical phenomena shows a linear behavior near the origin the EXP, EXPG, LIN or SPHERICAL correlation would perform better.

In the present work we first choose the gauss correlation function. The model developed for FX63137 with gauss correlation function did not accurately represent the approximated points. This is one of the challenges to choose the model type to approximate the data. The exponential correlation function was chosen next to make the approximation model. Figure 2 below is the approximation model of the lift and drag coefficients of the FX63137 airfoil using the exponential correlation. The data points of the lift and drag coefficients are represented by the black straight lines. This is a reasonably good representation of the shape of the data points. This model now can be used for prediction at untried sites.

Figure 3 shows the Mean Square Errors (MSE) for the airfoil. From the figure it could be seen how areas with few design sites have high MSE values. In its simplest form, a Kriging estimate of the field at an observed location is an optimized linear combination of the data at the observed locations. The coefficients of the Kriging estimate and the associated error measure both depend on the spatial configuration of the data, the unobserved location relative to the data locations, and spatial correlation or the degree to which one location can be predicted from a second location as a function of spatial separation [12]. Essentially in the Kriging model, the data points between Reynolds numbers must be close together to have small Mean Squared Errors (MSE) between the untried sites. Where there are large differences in the Reynolds numbers there are high MSE.

There were no Reynolds number runs of the wind tunnel experiment at \( 2 \times 10^5 \) to \( 3.5 \times 10^5 \) and close to \( 5 \times 10^5 \). This does not preclude the surrogate model from making accurate predictions at the untried site. For example to predict the lift and drag coefficients at Reynolds number \( 2 \times 10^5 \) and angle of attack at \( 10^6 \) of the airfoil (which are untried points), the surrogate model predicted a \( C_l \) value of \( 1.2337 \) and MSE in the range of 0 to 0.0015. The drag coefficient \( C_d \) is predicted to be 0.0343 and the range of MSE is 0 and 0.012. Another useful performance characteristic of this approximation model is the estimated process variance which is \( \sigma^2 = 0.0029 \) for the \( C_l \) model and \( 2.18 \times 10^{-4} \) for the \( C_d \) model.
5. COMPARISON OF PREDICTED OUTPUTS

MSE is one of several ways to measure the difference between values implied by an estimator and true values of the quantity being estimated. MSE is a risk function, corresponding to the expected value of the squared error loss. Minimizing MSE is a key criterion in selecting estimators.

Table 1: Predicted Cₜ, Cₚ, and Cₐ of the FX63137 airfoil at untried sites are also presented in Table 1.

6. BEM THEORY

In this work, the BEM theory is used to predict the performance of wind turbines. The BEM theory is used to predict the wind turbine performance across various wind speeds. The power is assumed constant across speed. The wind turbine produces the output at maximum power coefficient condition Figure 6. The blade element model of the performance condition Figure 6. The power coefficient of the FX63137 airfoil using the BEM theory was developed by the Oregon State University as the PRO proper code has been rewritten and modernized.

Table 1: Predicted Cₚ and Cₜ of the FX63137 airfoil at untried sites are also presented in Table 1.
7. CONCLUSIONS

Several innovative techniques have been developed for predicting the lift and drag coefficients of wind turbine blades over a wide range of angle of attacks and Reynolds numbers. This unique Kriging method optimizes the target data and accurately predicts or simulates the lift and drag at untried sites. The Kriging model generates important design parameters such as the generalized least square estimate, correlation factors and the estimate of the process variance. With the right combination of learning and training parameters more could be done with designing wind turbine blades and simulating the performance parameters using Kriging method. The MSE and the Regression are important measurements of how the Kriging method fits the experimental data. Depending on the sensitivity of the experimental data Kriging method in this research produced close approximation models. The Kriging method increased the accuracy of the BEM theory through accurate prediction of the lift and drag coefficients.

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8. REFERENCES

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