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Numerical analysis on the aerodynamics of HAWTs using nonlinear vortex strength correction

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ABSTRACT

Nonlinear vortex strength correction method (NVCM) based on potential flow, is developed for improvement of vortex lattice method which has difficulties to predict the separated flow conditions and the viscous effect. In this method, the bound vortex strength is determined by matching the lift force from VLM with the lift force from aerodynamic coefficients table as the same value of circulation is added to or subtracted from all chord wise vortices. For considering the nonlinearities due to the neighboring sections of the blade, sophisticated Newton–Rapson algorithm is applied. The validation of this method was done by comparing the simulations with the measurements on the NREL Phase-VI horizontal axis wind turbine (HWAT) in the NASA Ames wind tunnel under uniform and yawed flow conditions. This method gives good agreements with experiments in most cases.

1. Introduction

The wind energy industry has been growing rapidly since the mid-1990s [1] because of its technical maturity and economical feasibility which are greater than that of other new and renewable energy.

However, the wind energy is not able to replace conventional energy because of comparatively high cost. In recent years, numerous researches and developments have attempted to enhance the economical competitiveness of wind energy. Especially many studies have been devoted to develop the design tools which are robust, reliable and cost effective.

In aerodynamic part, the blade element momentum theory (BEMT) has been generally used because of simplicity to apply and low computational cost. However, the BEMT has some limitations to consider unsteady effect, 3-dimensional effect and interaction among blade elements [2]. Computational fluid dynamics (CFD) which has high level governing equations such as Navier–Stokes equations does not have these limitations. But, its computational cost is higher than other numerical methods.

The vortex method, based on the potential flow, is an alternative method for aerodynamic design. The dynamic inflow and skewed wake effect can be considered as vortex wakes. Moreover, the computational cost of this method is relatively appropriate. Therefore, the vortex method has recently been used as an aerodynamic design tool instead of the BEMT.

However, the vortex method cannot consider viscous effects such as skin friction and form drag due to inherently assumption of potential flow. Therefore, a two-dimensional table look-up procedure is generally used [3]. In separated flow, bound circulations cannot be predicted correctly by the vortex method. For this reason, incorrect effective angles of attack and incorrect aerodynamic coefficients are found by this procedure.

A new methodology, the nonlinear vortex correction method (NVCM), was developed for solving the problems. The lift from the vortex lattice method (VLM) is matched to that from the two-dimensional aerodynamic coefficient table and the circulations on the blade surface are corrected along the spanwise sections. For validation of this method, the NVCM was applied to a NREL phase VI rotor [4,5]. Good agreements with the experiments were obtained.

2. Methodology

The VLM is unable to consider airfoil thickness and viscous effect. Therefore, if curing is not, one can find differences between sectional lift from the VLM and that from the table look-up procedure. For this reason, the modification of sectional bound vortex strength by matching sectional loads from each method is required; that is the core of the NVCM.

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2.1. Unsteady vortex lattice method

Before applying the NVCM, the unsteady VLM is used for initial lift calculation. The blade surface is represented by a vortex lattice, square vortex rings. No penetration conditions are applied to each control point of vortex rings, after which linear equations are obtained.

$$\left[\sum_{j=1}^{n}\alpha_{i,j}\Gamma_j + (\vec{U}_{wind}+\vec{w}_{wake}+\vec{r}\times\vec{\Omega})_i\right]\cdot\vec{n}_i, \tag{1}$$

where $\alpha_{i,j}$ is an influence coefficient by the j-th vortex ring on the i-th control point; Γ_j is unknown vortex ring circulation; $\vec{U}_{wind}$ and $\vec{w}_{wake}$ are the free stream velocity and induced velocity by wakes, respectively; $\vec{n}_i$ and $\vec{r}$ are a normal vector and position vector of the i-th control point, respectively; and $\vec{\Omega}$ is the rotational velocity of the wind turbine. One can find Γ from Eq. (1) then calculate the aerodynamic load using by the Kutta–Joukowski theorem. In order to include the unsteady effect, the time-marching free wake is applied (see more details in Ref. [8]).

2.2. Airfoil data table look-up procedure

The local effective angle of attack on each section is calculated by the VLM at the center of the leading edge line of the leading edge vortex ring. Then, forces at the strip from airfoil data are obtained.

$$dL = 0.5\rho V^2 C_l(\alpha)dA,\ dD = 0.5\rho V^2 C_d(\alpha)dA, \tag{2}$$

where V is the onset velocity; dA is the strip area; C_l and C_d are aerodynamic coefficients; and α is the angle of attack. α is defined by

$$\alpha = \arctan(u_z/u_y) - (\beta+\phi), \tag{3}$$

where u_z and u_y are components of the total velocity calculated by VLM, β is the blade pitch angle, and ϕ is the local twist angle.

A three-dimensional stall delay model is applied to the two-dimensional aerodynamic coefficients of Ref. [6]. For the three-dimensional stall delay model, AirfoilPrep of the 3D Stall worksheet applying the Selig and Eggars adjustments is used [7].

2.3. The nonlinear vortex correction method

This method is summarized as follows:

$$\begin{aligned}&\textit{Initial stage}: \textit{if}\quad F = dL_{vortex\quad lattice} - dL_{Table\quad Look-Up} \neq 0\\ &\textit{then}\quad \Gamma_{initial}\pm\Delta\Gamma\rightarrow\Gamma_{modified}\\ &\textit{Final stage}: F\rightarrow 0,\quad \textit{then}\quad \textit{use}\quad \Gamma_{modified},\end{aligned}$$

where $dL_{vortex\ lattice}$ and $dL_{Table\ Look-Up}$ indicate sectional lift from the VLM and table look-up procedure, respectively; and Γ indicates bound vortex strength of each blade strip. F is modified to be zero by using the addition or subtraction of equal value along all chordwise bound vortices in one section, from initial bound vortex strength.

However, the bound vortex strength is connected nonlinearly with the angle of attack in this process due to neighboring blade strips. For this reason, this process should be represented by a nonlinear system of equations:

$$\begin{aligned}F_1(\vec{x}) &= (dL_{vortex\quad lattice})_1 - (dL_{Table\quad Look-Up})_1\\ F_2(\vec{x}) &= (dL_{vortex\quad lattice})_2 - (dL_{Table\quad Look-Up})_2\\ &\vdots\\ F_n(\vec{x}) &= (dL_{vortex\quad lattice})_n - (dL_{Table\quad Look-Up})_n\end{aligned} \tag{4}$$

where

$$\vec{x} = (x_1, x_2, \ldots x_n)$$
$$x_1 = \Delta\Gamma_1, x_2 = \Delta\Gamma_2, \ldots, x_n = \Delta\Gamma_n,$$

Subscript n is a number of blade spanwise sections, x_i represents the difference between the initial and modified sectional bound vortex strength, $\Delta\Gamma$. The vector form of the preceding equation is represented as

$$\vec{F}(\vec{x}) = 0. \tag{5}$$

To solve this equation, a sophisticated Newton–Raphson iterative algorithm [8] is used. Results from the VLM are used for reasonable initial conditions. To eliminate a tendency to wander from the solution of equations in any conditions, the rapid local convergence algorithm and a globally convergent strategy [9] are applied.

3. Results and discussion

The validation of the NVCM is done by comparing the simulations with measurements on the NREL Phase-VI rotor performed in the NASA Ames wind tunnel [10–12].

Fig. 1 shows the low speed shaft torque. The results calculated by the NVCM are in good agreement with the experiments. The table look-up procedure overpredicts the torque at wind speeds of 7, 10, 13, and 15 m/s.

Fig. 2 indicates radial distributions of the effective angle of attack and lift and drag coefficient, which were calculated by the VLM and NVCM at each wind speed. At wind speeds 13 m/s, the flow condition is partially separated along the blade. In these conditions, the lift force from the VLM is larger than that from table look-up because lift from the VLM continuously increases regardless of flow separation (see Fig. 2). Therefore, in order to equalize the lift from the VLM to that from the aerodynamic coefficients table, the bound vortex strength should be decreased through the NVCM (see Fig. 3(a) and (b)). Consequently, larger downwash due to larger bound vortex strength causes table look-up to predict lower effective angles of attack than the NVCM (see Fig. 2). The lower angle of attack causes table look-up to produce lower drag coefficients in the aerodynamic coefficients (see Fig. 2). In conclusion, table look-up overpredicts shaft torque because of the lower drag coefficient at wind speeds of 13 and 15 m/s.

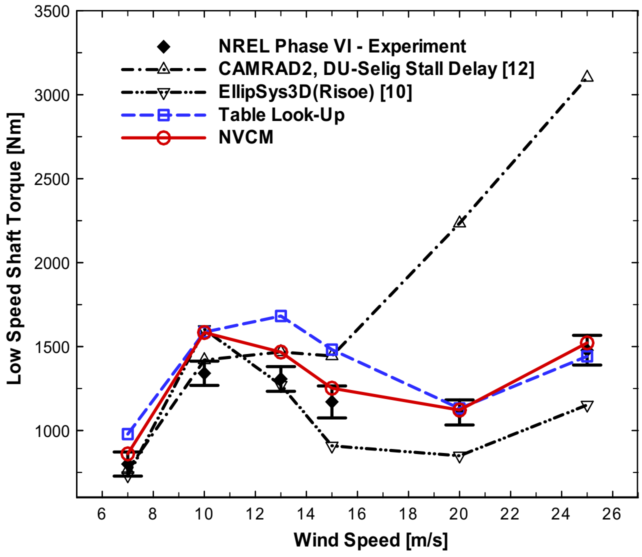


Fig. 1. Shaft torque with various methods.

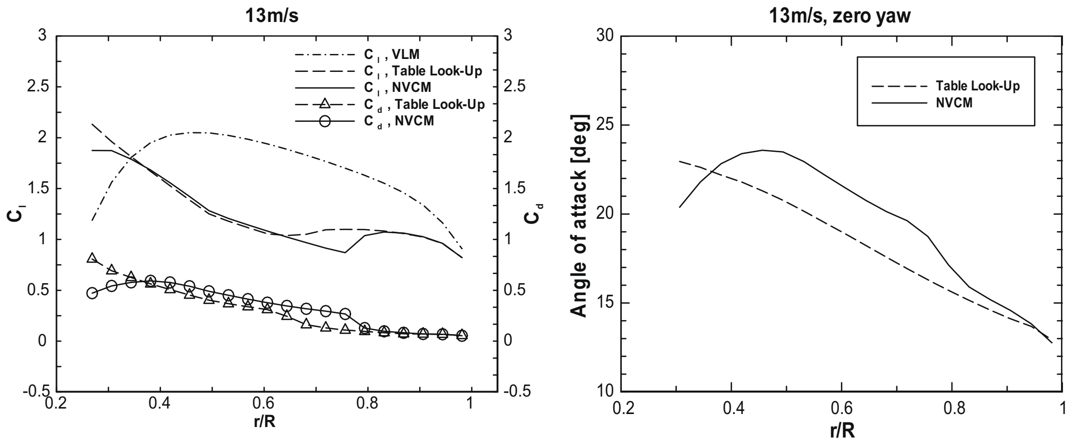
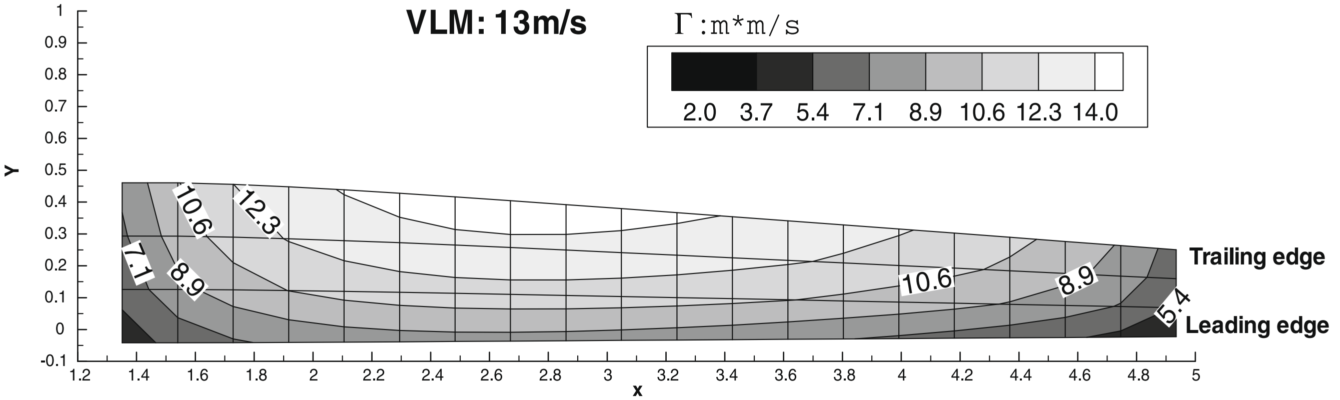
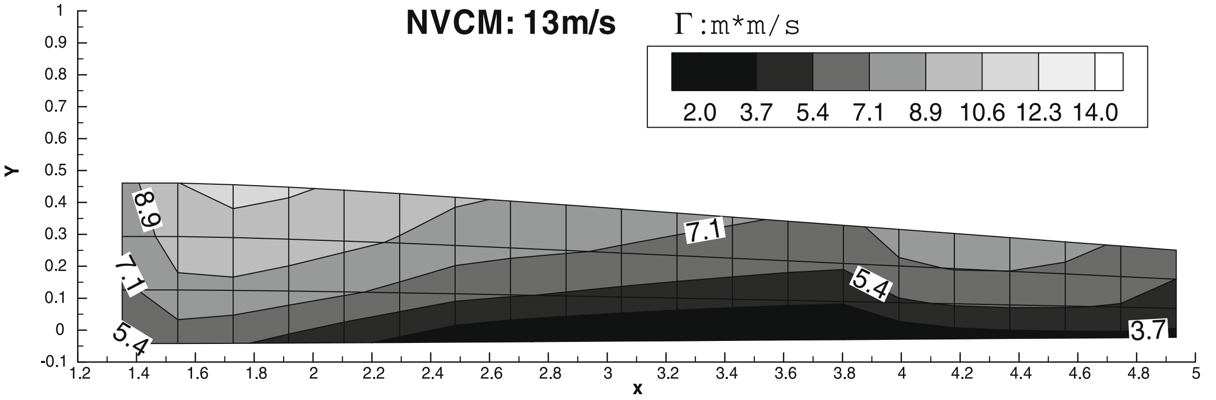


Fig. 2. Radial distribution of lift and drag coefficient (left) and angles of attack (right) at 13 m/s and zero yaw.



(a) VLM

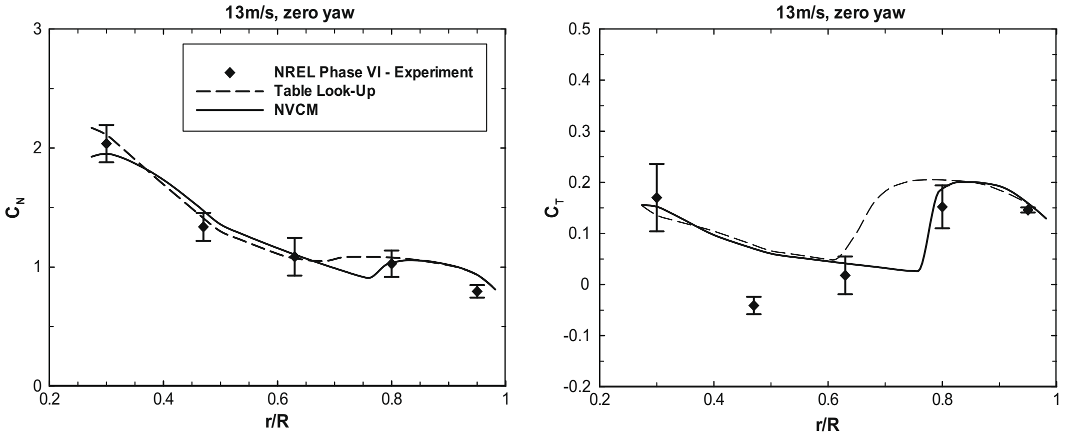


(b) NVCM

Fig. 3. Bound vortices distribution at 13 m/s and zero yaw.

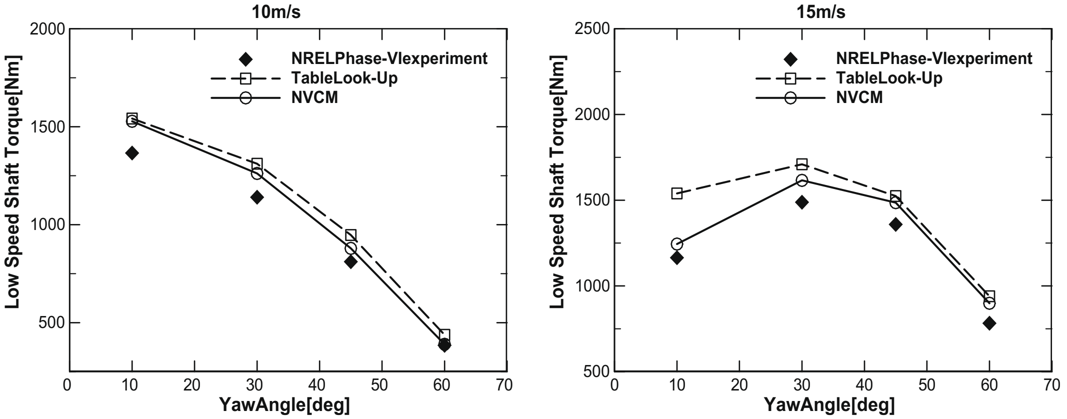
Fig. 4 shows the sectional normal force coefficient and tangential force coefficient at the partially separated condition of 13 m/s. Because C_N is mostly affected by lift coefficient and the lift force is not sensitive to the angle of attack variation, the sectional normal force coefficient calculated by NVCM is similar to that of table look-up procedure, even though table look-up predicts lower effective angles of attack. However, because the slope of the drag coefficient is steep after stall in 13 m/s of wind speed and the effective angle of attacks of table look-up than that of NVCM, C_T calculated by the NVCM are mostly in good agreement with experiment.

By comparison with the low speed shaft torque of the experimental result in yaw error case, the NVCM calculates good predictions as the results calculated by that are in good agreements in the uniform flow condition. Fig. 5 indicates the low speed shaft torque at wind speeds of 10 and 15 m/s with yaw error of 10, 20, 30, 45 and 60 degree.



(a) Normal force coefficient (b) Tangential force coefficient

Fig. 4. Normal force (a) and tangential force coefficient (b) distribution at 13 m/s and zero yaw.



(a) 10m/s (b) 15m/s

Fig. 5. Shaft torque in various yaw error conditions.

4. Conclusions

The NVCM, in which the lift force from the VLM is matched to that from table look-up through the adjustment of circulations, has been developed. This numerical method can predict the flow around the blade properly in the separated flow condition. In this method, the distributions of bound vortices are determined by the VLM. A sophisticated Newton–Rapson algorithm is applied in order to consider the nonlinearities between one section and the other sections.

Experiments with the NREL Phase-VI rotor have been compared with the calculations of the NVCM. The results from the NVCM are in better agreement with experiment than those by table look-up. Especially, when the flow around the rotor is partially separated (10 m/s, 13 m/s, and 15 m/s), the NVCM gives reasonable agreement with experiment. However, table look-up cannot give the proper results because the lift from potential flow without bound vortex strength corrections is greater than that of the real flow field.

Acknowledgments

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