Numerical analysis of wake wind field of horizontal axis wind turbine by vortex panel method
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Abstract

For the optimization of arrangement of wind turbines in wind farms, numerical analysis of wake wind field is needed for prediction of increased fatigue load and reduced power output due to wake. The purpose of this study is development of a calculation method of wake wind field for various inflow and operation conditions. For the purpose, the expanding vortex core model is introduced to vortex panel method. In the model, induced velocity from a vortex line is calculated by Rankine vortex model. The growth of vortex core is calculated by the differential equation used in Core-Spreading method. The method is validated with results of wind tunnel experiment for various ambient turbulence intensities generated by active turbulence grids. In the experiment, the flow field behind the test wind turbine was measured by an X-type hot wire anemometer. The expansion of wake diameter and recovery of wind speed are obviously promoted by higher ambient turbulence intensity. The calculation results show good agreement with the experimental results for different ambient turbulence intensities. It indicates that the model is capable of calculate the influence of ambient turbulence intensity on wake wind field.

Vortex Panel Method

In this study, vortex panel method with free wake model is adopted for calculation of aerodynamic load and flow field. The lattice panels, which have four vortex filaments with circulation, represent the aerodynamic effects of the blade. The unknown circulation for each panel is derived by applying Neumann type boundary condition at a collocation point of each panel. The circulation around the blade section is corrected in accordance with Kelvin’s circulation theorem and the vortex panels are released from the trailing edge of the blade and shed into the wind turbine wake with the advance of time. The free wake model is applied to the advection of the vortex panels by using Euler method.

Vortex Core Model

Induced velocity from a vortex line is calculated by Rankine vortex model. In the model, the velocity field around the vortex line is assumed by a forced vortex in its vortex core and a free vortex outside. The radius of vortex core is obtained by following differential equation.

\[ \frac{dx}{dt} = \frac{c}{2\kappa} \]

where \( c \) is a constant (=2.2418) and \( \kappa \) means eddy viscosity. Madsen et al. [1] formulated the eddy viscosity in wake as following,

\[ \frac{1}{\kappa} = \frac{F_1(k_u, k_v)}{F_2(k_u, k_v)} \]

where \( h \), \( R \), \( U_i \), \( U_{0i} \), \( T_{iamb} \), \( k_u \), and \( k_v \) are wake half width, rotor radius, ambient wind speed, the minimum wake wind speed, ambient turbulence intensity, calibration factor and an empirical constant, respectively. \( F_1 \) and \( F_2 \) are filter functions and calibrated by Madsen [1] and Larsen [2].

Experiment for Comparison

The experiment for the comparison was carried out in an open test section of Goettingen type single-return wind tunnel. The test wind turbine has two-bladed rotor with \( D=500 \) [mm] diameter. The wind field is measured by using an X-type hot wire probe attached on a traverse system. To change the turbulence intensity in wind tunnel, active turbulence grids were used. In this study, the wake measurements were performed in the conditions \( T_{iamb}=1.4 \) [13.5\%].

Reference


Results

Effects of Ambient Turbulence Intensity on Wake Wind Field

Comparing the distributions calculated by different ambient turbulence intensity conditions, they are similar except at the just behind the wind turbine rotor, however, differences can be found at far from the wind turbine. The recovery of wake wind speed is obviously promoted by higher ambient turbulence intensity. For \( T_{iamb}=1.4 \), 13.5\%], the calculation results show good agreement with the experimental results. It indicates that the model is capable of calculate the influence of ambient turbulence intensity on wake wind field.

Effects of Yawed Inflow on Wake Wind Field

Figures show longitudinal velocity distribution in wake in 30 degrees yawed inflow condition with different ambient turbulence intensity \( T_{iamb}=1.4 \), 13.5\%]. For yawed inflow, the deflection of deficit area to \( -y \) direction can be found. It is because of the existence of the lateral velocity component in wake due to the axial velocity component induced by the thrust force on the rotor plane. The calculated velocity distribution shows slightly smaller deficit far from the wind turbine \((\omega=5, 7, 10)\) compared with the experimental results, it shows modest agreement.

Conclusions

For development of the calculation method of wake wind field for various inflow and operation conditions, the expanding vortex core model is introduced to vortex panel method. The method is validated with results of wind tunnel experiment for various ambient turbulence intensities generated by active turbulence grids. The main results obtained in this study are shown as follows:

1. The expansion of wake diameter and recovery of wind speed are obviously promoted by higher ambient turbulence intensity. The calculation results show good agreement with the experimental results for different ambient turbulence intensities.

2. For yawed inflow, the deflection of deficit area can be found in both the calculated and experimental results. The calculated velocity distribution shows slightly smaller deficit far from the wind turbine \((\omega=5, 7, 10)\) compared with the experimental results, it shows modest agreement.