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学 位 論 文 の 概 要 及 び 要 旨

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題　　目　Method to Predict Rotor Outputs of VAWT Cluster by Using Wake Model Mimicking the CFD-Created Flow Field
数値流体力学解析(CFD)により生成された流れ場を模擬する後流モデルを用いた垂直軸風車群のロータ出力を予測する方法

学位論文の概要及び要旨

The main objective of this thesis was to propose a method to predict the outputs of two-dimensional vertical-axis wind turbine (VAWT) rotors (or VAWT cluster) in a short time, for the purpose of the future exploration of an optimal arrangement of VAWT rotors which can increase the total power of a wind farm. Therefore, this study basically adopted the potential-flow-based method proposed by Whittlesey et al. (2010), which can predict the flow field around VAWT rotors in a short time. To express the wake flow behind VAWT rotors precisely, a new wake model was proposed, which mimics the flow field created by the computational fluid dynamics (CFD). In the CFD analysis of this study, the Dynamic Fluid / Body Interaction (DFBI) model that can change the rotational speed of VAWT rotors according to the flow condition was applied to simulate the realized power of each rotor. In this study, the unsteady incompressible Reynolds averaged Navier-Stokes (RANS) equations were solved and the unsteady flow field was averaged to give the flow field equivalent to that which was simulated by the present model. The averaged flow field data were utilized to obtain the wake function representing velocity deficit.

The proposed wake model was based on the super-Gaussian function proposed by Shapiro et al. (2019), which can reproduce the wake profile transformation from a top-hat shape to the Gaussian shape. This study modified the super-Gaussian function to include the acceleration regions and wake shift which were observed in the wake of a VAWT. The modified wake model was named ultra-super-Gaussian function. The fitting parameters to mimic the CFD results were determined for an isolated single rotor, which was assumed to be a small two-dimensional rotor equivalent to the cross section of an experimental rotor used in the wind tunnel tests conducted by Jodai et al. (2021). Although Whittlesey et al. (2010) did not consider the modification of the y-component of the flow velocity, this study modified the cross-flow component (y-component) to mimic the details of the flow field in accordance with CFD. As the correction functions of the y-component, the four Gaussian-type functions and the four resonant-type functions were introduced and the fitting parameters were also determined to mimic the CFD profiles.

The proposed wake model introduced the Biot-Savart law to mimic the flow behavior caused by the circulations of the rotors and to improve the variations in the wake shift and the width owing to the interaction between the rotors.

This study proposed a new method to predict the appropriate flow filed and rotor powers using the conservation of x-direction momentum in a control volume (CV). In this method, for a given combination of the circulations of rotors, the flow field around the VAWT cluster and the net momentum change in the x-direction was calculated using the boundary flow states. The thrust force and the net pressure force (or pressure loss) of each rotor were calculated using the relations obtained by CFD of an isolated single rotor. The pressure loss was modified by introducing the interaction functions which indicated the strength of the superposition of the wakes of a selected paired rotors according to the layouts: co-rotating (CO)-like, counter-down (CD)-like, counter-up (CU)-like, and tandem (TD)-like. Therefore, the present method needed the CFD simulations of four specific paired rotors in the CO, CD, CU, and TD layouts in addition to the CFD of an isolated single rotor. The present momentum balance method calculated all the combinations (i.e., round robin) of circulations of rotors in the given searching ranges. After the sub-searching processes, a combination of circulations which gave the minimum difference between the momentum change and the total net force was obtained as the final result. Since there is a possibility to yield a false result if the searching range is not adequate, this study proposed a procedure to limit the searching range according to the layout of other rotors enclosing a rotor at issue in the calculation process.

The proposed method was applied to the prediction of the wind-direction dependence of the power of paired rotors in the co-rotating (CO) and inverse-rotating (IR) configurations and was compared to the CFD analysis. Although the results in the case of the short inter-rotor gap ($0.5D$) suggested the necessity to improve the interaction functions, the results in the case of the inter-rotor gap longer than $1.0D$ showed the proposed method successfully worked. The prediction of the wind-direction dependence of the power of three-rotor clusters in the CO and IR configurations was carried out and showed the good agreements in trend of the averaged power distribution between the present model and CFD. The application to the four-rotor clusters in line at the parallel or tandem layouts did not give satisfactory results in quantity but showed the same tendency of the rotor powers for both layouts (Fig. 1 and Fig. 2).

Although the further improvements are necessary, this study proposed a method to predict the flow field and the rotor powers of a VAWT cluster in incomparably shorter time than the CFD with the DFBI model.

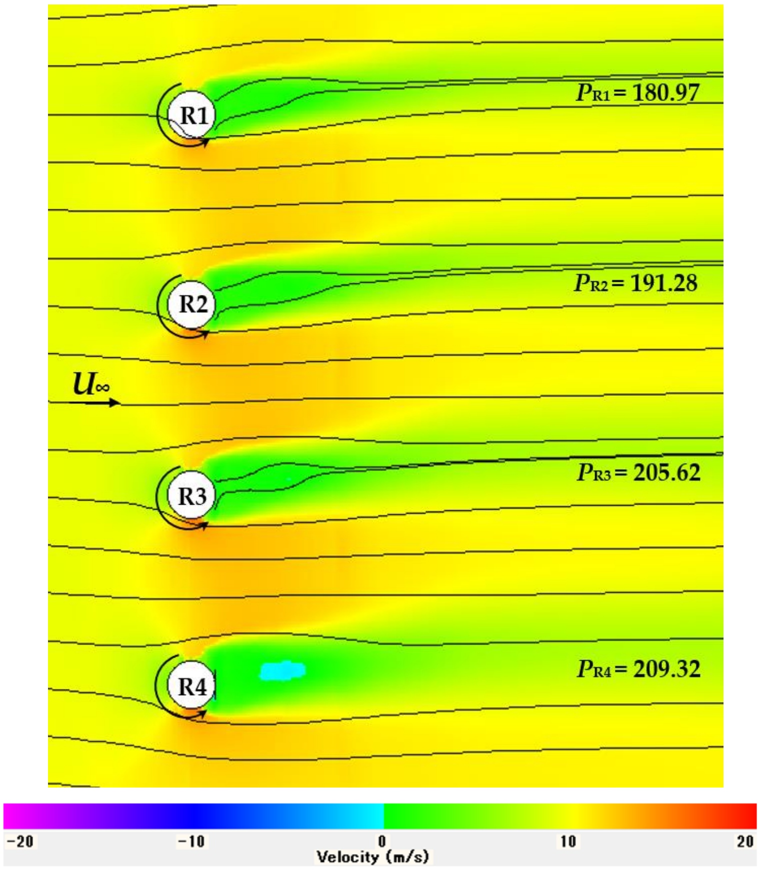

Fig.1 Prediction by the proposed method of the averaged distributions of x-direction velocity components around four-rotor parallel layout (U_∞= 10 m/s, inter-rotor space (*gap*) = 3.0*D*)

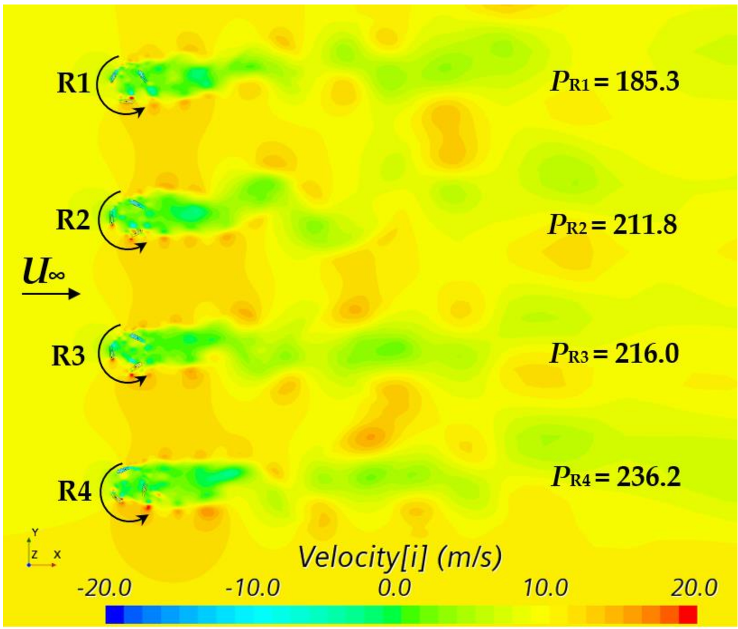

Fig. 2 Unsteady flow field (x-component) around the four-rotor parallel layout simulated by CFD analysis using the DFBI model (U_∞= 10 m/s, inter-rotor space (*gap*) = 3.0*D*)