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Blockage effect correction for a scaled wind turbine rotor by using wind tunnel test data

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A B S T R A C T

This paper discusses the procedure of a blockage effect correction method involving small-scale wind turbine rotor experimental data. To simulate the aerodynamic performance of full-scale rotors in the field, however, measured data from scaled model experiments need to be analyzed appropriately. One of the most important elements of such an analysis is a procedure to remove the blockage effect of the wind tunnel wall from the measured power data. In this paper, a correction algorithm proposed as part of Glauert's blockage effect correction method is used to process the data from a wind turbine rotor tested with three different wind tunnel sizes. Also, this study considered the modified blockage effect correction method, which has been used to process the rotor thrust data in closed-circuit wind tunnels and open-circuit wind tunnels. A small-scale rotor was tested under the same operating conditions, i.e., the same advance ratio, rotating speed, rotor torque and speed of the wind tunnel. The small-scale wind turbine rotor has a diameter of 1.408 m and a rotating speed according to the tip speed ratio. In each case, the effect of the blockage ratio and aerodynamic characteristics are determined using wind tunnel test results and with a simple analytical correction method. The results of the modified correction method show that the aerodynamic performance levels during a wind tunnel test are cleared by the blockage effect.

1. Introduction

In recent years, the world is paying more attention to renewable energy, specifically to the use of wind energy to produce electricity. Wind energy is a clean and inexhaustible solution that can meet the increasing demand for electrical energy and the planned targets of carbon dioxide emission reductions. The increasing fossil fuel prices and the tendency for stricter environmental legislation and cleaner environments make wind energy a vital factor for economic development. As a consequence, wind power generation is undergoing an era of rapid growth globally, with a total installed power capacity of about 282,678 MW as of the end of 2012 [1].

In order to develop an efficient wind turbine rotor blade, much effort has been put into predicting the aerodynamic performances of rotors accurately before their production. Analytical methods such as blade element theory, lifting surface theory and computational fluid dynamics have been used widely for this purpose, and the estimated performances typically show good agreement with those in the field [2]. It is often necessary, however, to carry out wind tunnel experiments beforehand if the flow field around the rotor is too complicated for a conventional analytic method to predict accurately [3,4]. One method involves the verification of results through a wind tunnel experiment at the development stage of the wind rotor to assess this problem. The wind tunnel test is an effective means of verifying the capacity of a developing product, accounting for only a small part of the cost of the development of actual products, when typically verification represents a large part of the cost of developing a wind turbine rotor.

To simulate the aerodynamic performance of full-scale rotors in the field, however, measured data from scaled model experiments need to be analyzed appropriately. One of the most important elements of such an analysis is a procedure to remove the blockage effect of the wind tunnel wall from the measured power data [5,6].

The blockage effect of the wind tunnel was introduced by Glauert [7]. It analyzed the wind tunnel blockage in connection with experimental test of propellers in the case of a constantly loaded rotor disc in a closed test section tunnel. Mikkelsen and Sørensen [9] have performed a study for the wind tunnels with open test section. It was predictions base on computational fluid

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dynamic. Fitzgerald [10] has introduced a correction methods of wind tunnel blockage corrections for propellers in the closed-circuit condition. Various wake states have been analyzed by Muyiwa S. et al. [11] for effect on the performance of a downstream with the tandem configuration of wind turbine rotor.

In this paper, the correction algorithm proposed by Glauert is used to process data from a model rotor wind turbine tested in wind tunnels of three different sizes. And, this study analyzed earlier studies of the development process of various blockage ratio conditions of wind tunnels and rotor blades used in wind turbines and performed aerodynamic characteristic measurement tests both in an open-circuit condition and in a closed-circuit condition.

2. Theoretical background

2.1. Overview of axial induction factor

The aerodynamic model of a horizontal-axis wind turbine is the actuator disk model, the wind turbine rotor becomes an incompressible disk that re moves energy from the wind. By Axial Momentum Theory and define power coefficient C_p as in Rankine – Froude theory can be reduced as follows:

$$C_P = \frac{P}{0.5\rho AU^3} = 4a(1-a)^2 \tag{1}$$

The parameter a is defined the axial induction factor and is consider of the influence of the turbine on the wind. A thrust coefficient C_T, which can also be used to characterize the different flow states of a rotor, is defined as [2]:

$$C_T = \frac{T}{0.5\rho AU^2} = 4a\left(1-a\right) \tag{2}$$

2.2. Wall effect correction in a cross-type wind tunnel

The blockage ratio is defined as the ratio of the projected area of the model and the test section. If the blockage ratio is greater than 10%, the wall effects cannot be ignored. In this case, the stream tube of a wind turbine is different from the flow pattern of free air and in a test section. In this test section, the flow speed outside of the stream tube W_1 is greater than U, leading to experimental errors. For this reason, a correction procedure is required.

Generally, correction of the wall effect can be achieved by modifying the test conditions when considering the increase in the velocity due to the wall effects, in other words by finding suitable test conditions which produce the same air load in a free air condition. However, in this research, the measured data was corrected by Glauert's method [7]. In his research, Glauert introduced classical momentum analysis for the correction of blockage and lift interference effects. Fig. 1 illustrates a comparison of the flow pattern in free air vs. a wind tunnel test section.

Initially, the thrust of an actuator disk is identical to the momentum change; thus, in a free air condition, the thrust of the actuator disk can be calculated as shown below, where A is the area of the actuator disk.

$$T = 2A\rho V(V-U') \tag{3}$$

In a wind tunnel, the next relationships can be derived. From the continuity at the inner and outer regions of the slipstream,

$$AV = A_1V_1 \tag{4}$$

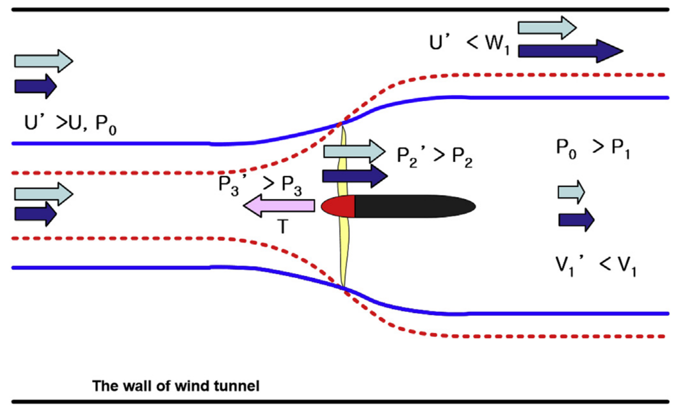

Fig. 1. Blockage effect correction.

$$CU = A_1V_1 + (C-A_1)W_1 \tag{5}$$

where, C: area of the test section, A_1: area of the slip stream at the exit

From the Bernoulli equation at the outer region of the slip stream, this relationship is verified.

$$p_1 - p_0 = 0.5\rho\left(V^2 - W_1^2\right) \tag{6}$$

From the Bernoulli equation at the inner region of the slipstream

$$T = 0.5\rho A\left(V_1^2 - W_1^2\right), \tag{7}$$

the momentum change of the complete test section area produces the relationship below:

$$T - C(p_1 - p_0) = A_1\rho V_1(V_1 - U) - (C - A_1)\rho W_1(U - W_1) \tag{8}$$

For the normalization of Eqs. (3)–(8), subsequent nondimensional parameters are introduced.

$$C_T = \frac{T}{0.5\rho U^2 A}, \quad \alpha = \frac{A}{C}, \quad \beta = \frac{A_1}{C}, \quad C_p = \frac{p_1 - p_0}{0.5\rho U^2}$$
$$V \leftarrow \frac{V}{U}, \quad V_1 \leftarrow \frac{V_1}{U}, \quad W_1 \leftarrow \frac{W_1}{U}, \quad U' \leftarrow \frac{U'}{U}, \tag{9}$$

From this relationship, the normalized expressions of Eqs. (3)–(8) are shown below.

$$C_T = 4V(V - U') \tag{10}$$

$$\alpha V = \beta V_1 \tag{11}$$

$$1 = \beta V_1 + (1-\beta)W_1 \tag{12}$$

$$C_p = 1 - W_1^2 \tag{13}$$

$$C_T = V_1^2 - W_1^2 \tag{14}$$

$$C_T\alpha - C_p = 2\beta V_1(V_1 - 1) - 2(1-\beta)W_1(1 - W_1) \tag{15}$$

From the experiment, the values of the coefficient of trust and the blockage ratio α became known, and with six equations, we can determine the remaining six unknowns. For an air screw or a propeller, C_T is positive, while for a wind turbine, it becomes negative. Fig. 2 shows the corrected wind speed V' for various C_T