AIAA JOURNAL
Vol. 44, No. 8, August 2006

Wall Correction Model for Wind Tunnels with Open Test Section

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DOI: 10.2514/1.15656

In the paper we present a correction model for wall interference on rotors of wind turbines or propellers in wind tunnels. The model, which is based on a one-dimensional momentum approach, is validated against results from Navier–Stokes computations using a generalized actuator disc principle. In the model the exchange of axial momentum between the tunnel and the ambient room is represented by a simple formula, derived from actuator disc computations. The correction model is validated against Navier–Stokes computations of the flow about a wind turbine rotor. Generally, the corrections from the model are in very good agreement with the computations, demonstrating that one-dimensional momentum theory is a reliable way of predicting corrections for wall interference in wind tunnels with closed as well as open cross sections.

Nomenclature

C	=	area of tunnel cross section
C_p, C_T	=	pressure and thrust coefficients, respectively
C_T^*, T^*, u^*, V_0^*	=	equivalent quantities in free air
p_0, p_1, p_2, p^+, p^-	=	pressure at different positions
S, S_1	=	area of cross section at the disc and in the far wake, respectively
T	=	thrust
u, u_1, u_2	=	axial velocity
$\tilde{u}$, $\tilde{u}_1$, $\tilde{u}_2$	=	nondimensional axial velocity
V_0	=	inflow velocity
β	=	S/C
$\Delta\tilde{T}$	=	momentum loss
σ	=	S_1/C

Introduction

IN a wind tunnel the flow past a propeller is constrained by the walls of the tunnel and the inflow velocity differs from the one that would occur in free air under the same operating conditions. It is therefore necessary to correct the performance data for wall interference. Corrections for wind tunnel blockage in connection with experimental tests of propellers were treated by Glauert [1] in the case of a constant loaded rotor disc in a wind tunnel with closed working section. Employing one-dimensional axial momentum theory, a complete set of equations was established with the purpose of deriving a simple expression for correcting the velocity through the rotor to correspond to a rotor in free air. Although a variety of correction models have been developed since then, e.g., Ewald , the model of Glauert still remains the most popular. Recently, Mikkelsen and Sørensen [3] presented a variant of the model that reduces the set of equations to a single equation for the induced wind speed through the rotor. Up to now, however, correction models based on momentum theory have only been established for rotors in wind tunnels with closed working sections.

For tunnels with open working sections the flux of axial momentum from the surroundings into the wind tunnel has to be determined and added to the axial momentum balance. However, the magnitude of the flux depends on the geometry of the wind tunnel and on the thrust acting on the rotor, and it cannot be determined from simple momentum analysis. Instead, it is needed to resort to detailed velocity measurements or predictions based on computational fluid dynamics (CFD).

The motivation for the study is the need for deriving a simple correction model to be used in the EU-sponsored project, model rotor experiments under controlled conditions (MEXICO). In this project a wind turbine rotor is to be tested in the German–Dutch wind tunnel's (DNW) 9.5×9.5 m open test section wind tunnel.

In the present work we have derived a correction formula, corresponding to the one established in Mikkelsen and Sørensen , for a wind tunnel with an open working section. The missing data regarding the momentum flux have been obtained from detailed CFD computations using a Navier–Stokes approach in combination with an actuator disc method [4–7]. As a test case, we employ the geometry of the DNW wind tunnel in which the MEXICO experiment is going to take place. To validate a correction model, it is necessary to have access to data from experiments both in wind tunnel and in free air. This is rarely the case, and generally, one has to rely on the validity of the basic assumptions behind the model. In the present work, however, the correction model is validated by comparing it to CFD computations using data from a Nordtank 500 kW wind turbine. The CFD computations are carried out in a geometry corresponding to the one of the DNW tunnel as well as in free air. To study the influence of using an open test section, the obtained results are compared with computations of the same wind turbine located in a wind tunnel with a closed test section. Finally, it shall be emphasized that although we use the DNW tunnel as a test case, the methodology and the obtained results are quite general, and result in a technique that can be used to correct experimental data from any wind tunnel with open (as well as closed) test section.

Modeling of Blockage

Closed Test Section

To derive a blockage correction model for a wind tunnel with an open test section it is instructive first to show how it works for a tunnel with closed test section. Based on the one-dimensional momentum approach of Glauert , a closed section blockage model was recently developed and validated by Mikkelsen and Sørensen [3]. In the following subsection we give a short description of the model.

Consider a uniform stream of air with inflow velocity V_o passing through an actuator disc located in a wind tunnel with a cylindrical cross section of area C, as shown in Fig. 1. To apply the momentum approach, we assume the flow to be incompressible and axisymmetric, and divide the flow into an inner region and an outer region. The inner region governs the flow through the rotor disc and

Received 21 January 2005; revision received 19 January 2006; accepted for publication 15 March 2006.

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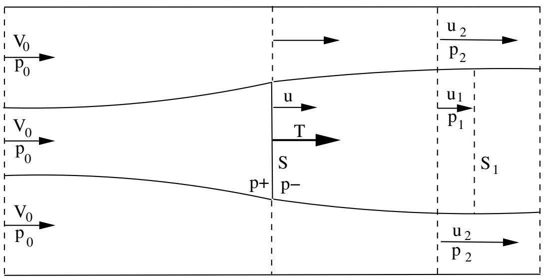

Fig. 1 Sketch of rotor disc in closed wind tunnel.

comprises the volume between the axis and the limiting stream-surface that passes through the tip of the rotor (i.e., the edge of the actuator disc). The outer region governs the flow between the limiting tip stream-surface and the wind tunnel wall. The fluid that passes through the actuator disc forms a cylindrical column whose cross-sectional area increases from far upstream of the disc to S at the disc and to S_1 in the far wake. The axial velocity decreases to u at the disc and to u_1 in the far wake, while the velocity outside increases to a value u_2 to maintain continuity. In the ultimate wake behind the disc, the flow is assumed parallel. Hence the pressure inside the wake equals the pressure outside $p_1 = p_2$. Assuming that the flow is inviscid, with density ρ, continuity inside the slipstream and in the space between the slipstream and the tunnel wall yields, respectively,

$$u_1 S_1 = uS \tag{1}$$

$$u_2(C - S_1) = V_o C - uS \tag{2}$$

Outside the slipstream the Bernoulli equation applies, and the total pressure thus remains constant, i.e., $p_o + \frac{1}{2}\rho V_o^2 = p_1 + \frac{1}{2}\rho u_2^2$, hence

$$p_1 - p_o = \frac{1}{2}\rho(V_o^2 - u_2^2) \tag{3}$$

Inside the slipstream the decrease in total head equals the pressure jump through the disc, $p^+ - p^-$, where p^+ and p^- are the pressures immediately upstream and downstream of the rotor, respectively. The pressure jump across the disc corresponds to the thrust,

$$T = S(p^+ - p^-) = S\left[\left(p_o + \frac{1}{2}\rho V_o^2\right) - \left(p_1 + \frac{1}{2}\rho u_1^2\right)\right] \tag{4}$$

where the thrust is defined positive when it is pointing in the flow direction. Combining Eqs. (3) and (4) gives

$$T = \frac{1}{2}\rho S(u_2^2 - u_1^2) \tag{5}$$

Finally, applying the momentum theorem on the whole tunnel, we get

$$-T - (p_1 - p_o)C = \rho u_1 S_1(u_1 - V_o) - \rho u_2(C - S_1)(V_o - u_2) \tag{6}$$

With thrust, inflow velocity, ambient pressure and tunnel area as known quantities, the resulting system consists of five equations, Eqs. (1–3), (5), and (6), and five unknowns, u, u_1, u_2, S_1, and p_1. It should be noted that in establishing the preceding set of equations, the momentum theorem has not been applied on a control volume going through the actuator disc. The reason is that the axial force from the pressure on the lateral boundary of the control volume is unknown.

Introducing the following nondimensional quantities,

$$\beta = \frac{S}{C}, \qquad \sigma = \frac{S_1}{S}, \qquad \tilde{u} = \frac{u}{V_o}, \qquad \tilde{u}_1 = \frac{u_1}{V_o}, \qquad \tilde{u}_2 = \frac{u_2}{V_o}$$

in dimensionless form the resulting set of equations is rewritten as

$$\tilde{u}_1\sigma = \tilde{u} \tag{7}$$

$$\tilde{u}_2(1 - \beta\sigma) = 1 - \beta u \tag{8}$$

$$C_T = \tilde{u}_2^2 - \tilde{u}_1^2 \tag{9}$$

$$C_p \equiv \frac{2\Delta p}{\rho V_o^2} = 1 - \tilde{u}_2^2 \tag{10}$$

$$-\beta C_T - C_p = 2u_1\beta\sigma(\tilde{u}_1 - 1) - 2\tilde{u}_2(1 - \beta\sigma)(1 - \tilde{u}_2) \tag{11}$$

where $C_T = 2T/\rho S V_o^2$ is the thrust coefficient. It is possible to derive an explicit expression that gives a unique relation of $\tilde{u}$ in terms of β and σ. This was shown in Mikkelsen and Sørensen, [3] where the following expression was derived:

$$\tilde{u} = \frac{\sigma(\beta\sigma^2 - 1)}{\beta\sigma(3\sigma - 2) - 2\sigma + 1} \tag{12}$$

Employing σ as independent variable, with β known, $\tilde{u}$ can be determined directly from Eq. (12), and the remaining terms can be derived explicitly from Eqs. (7–11).

Open Test Section

A sketch of an open test section wind tunnel is given in Fig. 2. The fundamental difference between this and the closed one is that there is an exchange of axial momentum between the tunnel and the ambient room. As shown in the figure, this causes the stream-surfaces to deflect, hence forming a bulb that goes into the plenum chamber. Comparing the modeling of this case with the one of the closed section wind tunnel, it is interesting that only the axial momentum equation, Eq. (6) or Eq. (11), is changed, whereas the one-dimensional analysis leaves the other equations unchanged.

When including the momentum exchange, the only change of Eqs. (1–6) [or Eqs. (7–11) in dimensionless form] is that an expression for the exchange of axial momentum has to be added to Eq. (6), as shown next:

$$\begin{aligned} -T - (p_1 - p_o)C &= \Delta\tilde{T} + \rho u_1 S_1(u_1 - V_o) \\ &\quad - \rho u_2(C - S_1)(V_o - u_2) \end{aligned} \tag{13}$$

If the exchange of momentum only takes place in the open test section, the momentum loss can be determined from the integral

$$\Delta\tilde{T} = \int_{CS} V_x \rho \vec{V} \cdot d\vec{A} \tag{14}$$

where $d\vec{A}$ is the outward pointing area, V_x denotes the axial velocity (i.e., specific axial momentum) and the integration is carried out along the control surface given by the (imaginary) tunnel wall defining the open cross section (shown as the dotted lines in Fig. 2).

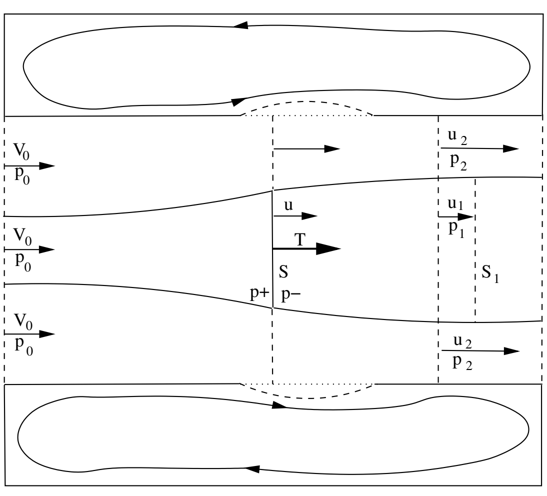

Fig. 2 Sketch of rotor disc in wind tunnel with open cross section.

The value of $\Delta\tilde{T}$ depends on the loading of the actuator disc and the geometry, and it cannot be determined from simple momentum analysis. Instead one has to resort to velocity measurements or a detailed numerical analysis using computational fluid dynamics.

To derive a relation between $\Delta\tilde{T}$ and T we use an axisymmetric version of the CFD code *EllipSys*, combined with the actuator disc model by Sørensen et al. [4–6]. The *EllipSys* code has been developed through a collaboration betweeen Risø National Laboratory and Technical University of Denmark, and details about it can be found in the papers of Michelsen and Sørensen [8–10]. As basic geometry we consider a cylindrical cross section of same area as the one of the DNW wind tunnel and an actuator disc corresponding to the size of the test rotor. The mesh is nearly equidistant in axial direction and stretched towards the blade tip and walls in radial direction, with 40 points along the rotor blade and a total of 192 mesh points in axial direction and 144 points in radial direction (including the plenum chamber). In earlier works with the combined Navier–Stokes/actuator disc technique [5,6], different types of meshes were tested to ensure mesh independency. The physical parameters of importance for the study here are mainly the resulting velocity distribution along the rotor blade. For the employed grid the velocity along the blade deviated less that 2% as compared with a mesh with twice as many mesh points, hence the present resolution was deemed sufficient.

Figure 3 shows the isolines of axial velocity from a computation of the flow about an actuator disc with constant loading and thrust coefficient $C_T = 0.8$. In the figure all dimensions are made dimensionless with rotor radius and, due to axisymmetry, only a meridional half-plane is shown. The rotor is located at $x = 0$ and the inlet is located 3.8 radii upstream and the outlet 7.5 radii downstream of the rotor.

From the figure it is seen that there is a concentration of axial momentum not only at the open cross section, but also along the tunnel wall. The origin for this is the presence of a shear layer that is formed at the edge of the open test section. The contribution of this is taken into account by also including the axial momentum at the exit of the domain just below the tunnel wall. In Fig. 4 we present the outcome of a numerical study in which the loss of axial momentum was computed using Eq. (14). To derive a general relation for the momentum loss, the thrust coefficient and the ratio between the radius of the tunnel and the radius of the actuator disc were changed systematically. Both positive and negative C_T values were used to generalize the result to include both wind turbines and propellers. From the figure the net effect is shown to be a gain in axial momentum (i.e., negative momentum loss). When the rotor is operating in the propeller mode the added axial momentum is seen to be so small that it can be neglected and the tunnel correction can be treated as for a tunnel with closed cross section. Furthermore, the added momentum flux is largely seen to be independent of the ratio of tunnel to rotor radius.

A simple curve fit shows that

$$\frac{\Delta\tilde{T}}{1/2\rho S V_o^2} \cong -a\left|C_T\right|^b \tag{15}$$

where $a \cong 0.03$ and $b \cong 3$. Equation (15) is introduced into Eq. (13), which subsequently is put into nondimensional form. Thus, Eq. (11) is replaced by

$$-\beta(1-a|C_T|^{b-1})C_T - C_p = 2u_1\beta\sigma(\tilde{u}_1 - 1) - 2\tilde{u}_2(1-\beta\sigma)(1-\tilde{u}_2) \tag{16}$$

and Eq. (12) takes the form

$$\tilde{u} = \frac{\sigma(\beta\sigma^2 - \gamma)}{\beta\sigma(3\sigma - 2\gamma) - 2\sigma + \gamma} \tag{17}$$

where $\gamma = 1 - a|C_T|^{b-1}$. Because of this additional term in Eq. (17), the solution of the resulting system of equations has no closed form. However, a simple iterative solution procedure can be devised by guessing C_T and then solve the system as before.

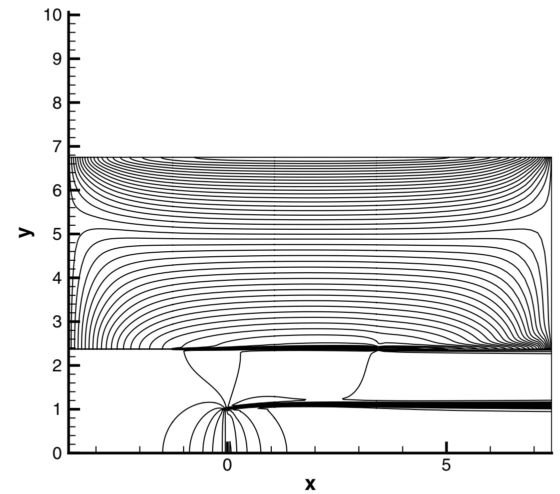

Fig. 3 Isolines of axial velocity about actuator disc in the open cross section wind tunnel, $C_T = 0.8$.

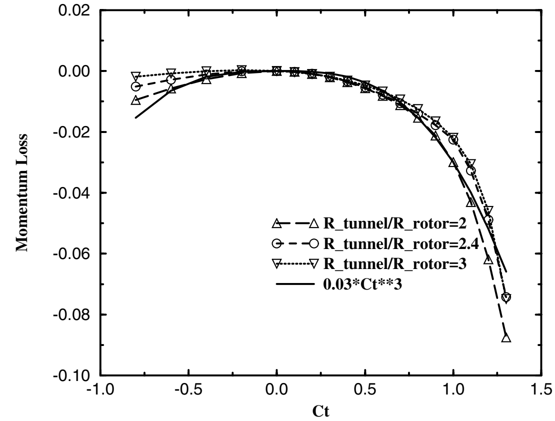

Fig. 4 Momentum loss as function of thrust coefficient and ratio of tunnel to rotor radius.

Correction Formulas

In the present work we are looking for a simple way to compute the influence of wall interference to apply wind tunnel measurements to free airflow conditions. As suggested by Glauert [1], this is done by correcting the inflow velocity such that it corresponds to an equivalent free air speed, V_o^*, which for a given value of thrust provides the same axial velocity at the rotor as that observed in the wind tunnel [11]. From this definition we get

$$C_T V_o^2 = C_T^*(V_o^*)^2 \tag{18}$$

$$u = u^* \tag{19}$$

For an actuator disc subject to freestream conditions, one-dimensional momentum theory gives the classical result,

$$T^* = \frac{1}{2}\rho S(V_o^*)^2 C_T^* = 2u^*\rho S(V_o^* - u^*) \tag{20}$$

Combining Eqs. (18–20), we get the following correction formula:

$$\frac{V_o^*}{V_o} = \tilde{u} - \frac{1}{4}\frac{C_T}{\tilde{u}} \tag{21}$$

where the terms on the right-hand side are computed from Eqs. (7–12) for the case of a rotor in a wind tunnel with closed test section. In the case of a wind tunnel with open test section, Eq. (11) is replaced by Eq. (13), and Eq. (12) does not apply anymore. The additional exchange of momentum flux is taken from Eq. (15) that has been established by CFD computations of the DNW wind tunnel. The values for a and b only apply for the DNW wind tunnel. In general, however, it may be assumed that the fundamental form of Eq. (15) is valid, but one has to determine the actual coefficients from experiments or detailed computations.

Correction formulas may also be established directly from CFD computations by computing the flow about a rotor in a wind tunnel and comparing the results to those of a rotor subject to the same flow conditions under free air flow conditions.

Comparison to Computed Results

Rotor with Constant Loading

To validate the results from the one-dimensional momentum analysis we have performed a series of CFD computations using the Navier–Stokes/Euler actuator disc (AD/NS) model. Because the model earlier has been used to study various aspects of wind turbine aerodynamics, such as dynamic inflow , wake states [5], and flows about coned rotors , it will not be presented further.

In Fig. 5 we present a comparison between corrections using momentum theory and the CFD model, assuming a constant axial loading, for the case of a rotor in a wind tunnel with closed test section. The correction is shown as a function of thrust coefficient at various ratios of tunnel to rotor radius. As seen from the figure there is an excellent agreement between momentum theory based on the solution of Eqs. (7–12) and results from the AD/NS computations.

In Fig. 6 the same comparison is carried out for a rotor placed in a wind tunnel with open test section and a geometry corresponding to the one of the DNW tunnel. Again we observe a very good agreement between the momentum model and the constant loading AD/NS computations.

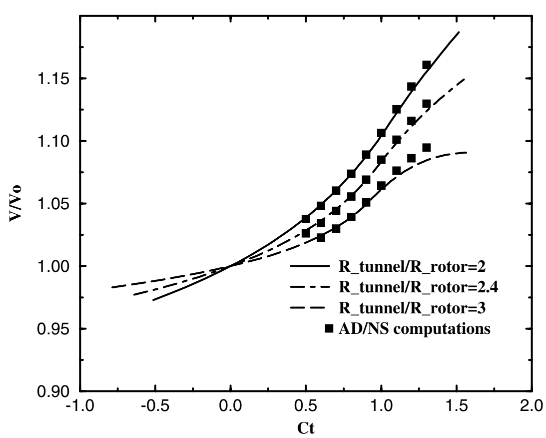

Fig. 5 Ratio of corrected and uncorrected stream velocities as function of thrust coefficient and ratio of tunnel to rotor radius in a solid wall wind tunnel.

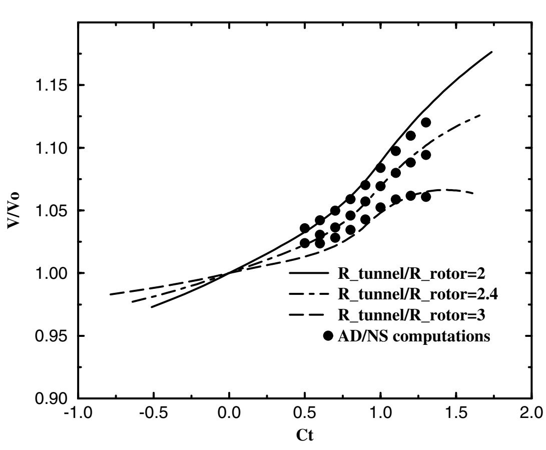

Fig. 6 Ratio of corrected and uncorrected stream velocities as function of thrust coefficient and ratio of tunnel to rotor radius in a wind tunnel with open test section.

Wind Turbine Rotor

As a further validation, we here compare the one-dimensional correction model with CFD computations of the flow about a wind turbine rotor. The employed rotor corresponds to a Nordtank 500 kW machine equipped with three LM 19.1 blades that are scaled to fit

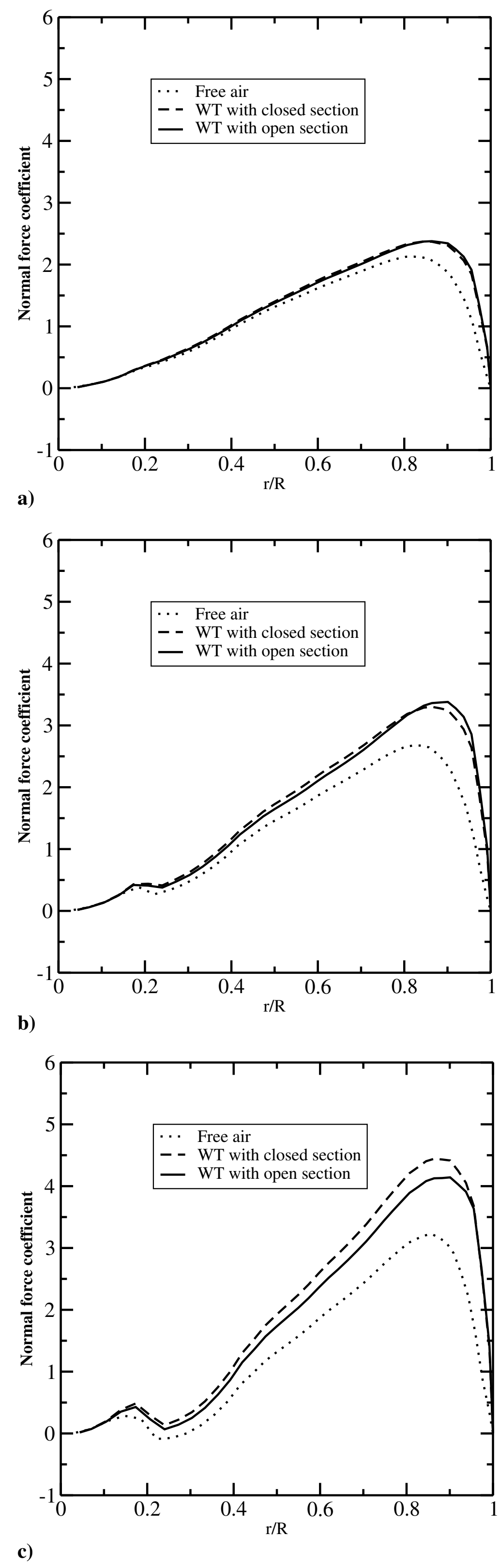

Fig. 7 Computed distributions of normal load coefficients along the rotor disc of a scaled Nordtank wind turbine rotor at various tunnel configurations and tip speed ratios a) 7, b) 10, and c) 14.

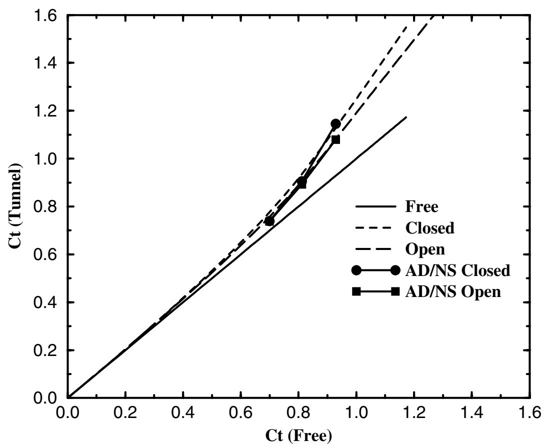

Fig. 8 Correlation between thrust coefficients of rotors operating in free air and in wind tunnel.

with the dimension of the rotor to be used in the MEXICO project. The kinematics of the flow are determined from the axisymmetric Navier–Stokes equations, using the AD/NS model, and the influence of the rotor blades on the flowfield is included using tabulated airfoil data to represent the loading on the blades. Thus the local angles of attack are determined iteratively from the movement of the blades and the computed flowfield. Computations are carried out for a rotor operating in free air as well as in wind tunnels with closed and open test sections. In Figs. 7a–7c we compare computed distributions of the normal force coefficient along the rotor disc of the Nordtank rotor at various tunnel configurations and tip speed ratios TSR = 7, 10, and 14. The comparisons show that the load distributions for a rotor in free air, independent of the tip speed ratio, differ from those obtained for rotors operating in a wind tunnel. Further, the difference between the loading for turbines operating in closed and open cross sections is only significant at high tip speed ratios and hence only for heavily loaded rotors. The computations show that the flow at TSR = 14 has become unstable in the sense that vortical structures are developed downstream. This causes the flow to become unsteady. If the rotor is put into a wind tunnel with closed test section and run under the same conditions, however, the flow becomes more stable and the expansion of the wake is restricted because of wall interference.

By running the rotor at different wind speeds it is possible to quantify the influence of wind tunnel blockage. In Fig. 8 we show the correlation between thrust coefficients of a rotor operating in a wind tunnel and a rotor subject to a free air-stream for both the AD/NS model and the momentum model. The agreement between the two models is quite good. In particular it is seen that for thrust coefficients below about 0.8, the size of the corrections are approximately the same for open test section and closed test section wind tunnels. Thus, based on the comparison we conclude that one-dimensional momentum theory is a reliable way of predicting corrections for wall interference in wind tunnels with closed as well as open cross sections.

Conclusions

A general correction model, based on a one-dimensional momentum approach, for wall interference of a wind tunnel with open test section has been developed and validated. The motivation for the study is the need for deriving a simple correction model to be used in the EU-sponsored project MEXICO. The correction model can be employed for correcting test results of both propellers and wind turbines in wind tunnels with closed as well as open test sections. The model has been validated against computations using a hybrid Navier–Stokes/actuator disc CFD model. Comparisons with results from the CFD model indicate that a simple one-dimensional momentum approach is sufficient for correcting the global aspects of wall interference for rotors tested wind tunnels with closed as well as open test sections. The comparison comprised both rotors subject to a constant loading as well as a realistic loading from a Nordtank wind turbine scaled to the geometry of the rotor to be tested in the MEXICO project.

Acknowledgments

This work was partly supported by the European Commission in the framework of the EU Non-nuclear Energy Programme (MEXICO, contract: ENK6-CT2000-00309). Some of the computer simulations were performed at the High Performance Computing Centre (HPC) at DTU and sponsored by Danish Center of Scientific Computing (DCSC).

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