The effects of a model forest canopy on the outputs of a wind turbine model

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Abstract. The effects of a rough surface boundary layer on the outputs of a wind turbine model were investigated experimentally in a wind tunnel. The very rough surface consisted of cylindrical pins, in order to model a forest canopy. The hub height of the turbine model was varied in order to see the effect of the presence of the model forest in the power and thrust coefficients. A small effect of the hub height was observed in the averaged power coefficient, where the turbine produced less for the lowest hub height. The difference was however reduced when scaling the power output with the available power in the wind instead of using the velocity at hub height. Consistent trends were present in the standard deviation of the thrust coefficient and the rotational speed, which both increased by decreasing the hub height. This underlines the fact that not only the rotor but also the tower and the bearings of a wind turbine must withstand to increased loads when operating close to a canopy.

1. Introduction
The flow within the atmospheric boundary layer over a forest canopy may differ substantially compared to that over low vegetation lands and this may have important consequences for wind turbines. The interactions between forest and atmospheric turbulence affect the momentum transfer towards the ground as well as the mixing and diffusion of momentum. Despite the large amount of research on the topic, the effects of the forest on the outer region of the boundary layer, where wind turbines are usually located, is still unclear: it is often assumed that the forest influence is limited to the roughness sublayer up to approximately 3 canopy heights [1], above which the flow should just be determined by the amount of momentum transferred downward provided by the wall shear stress. The logarithmic velocity profile should then be recovered, an assumption usually referred to as Townsend’s hypothesis.

The interests in both basic scientific questions as well as technological aspects of flow over canopies have pushed the development of new velocity profile fits to estimate the wind speed above a canopy (see e.g. [1, 2, 3]). The up-to-date understanding has been provided by experiments (see e.g. [4, 5, 6, 7]) but also from numerical simulations (see e.g. [8]). Despite the fact that some key mechanisms have been revealed, further research is required in order to enhance the understanding of the involved phenomena, especially if an accurate estimation of the local wind speed and the turbulence characteristics at a certain height is desired.

The influence of turbulence intensity on the power curve of a wind turbine model has previously been studied in a wind tunnel experiment by [9]. Two cases were compared: one with no free stream turbulence on the inlet and one with an added turbulence intensity of
4.5%. It was concluded that the velocity deficit profiles were quite similar until two diameters downstream of the wind turbine. From three diameters and downstream, the recovery of the wake was faster in the case with the added turbulence, due to the enhanced mixing. The drag coefficients for the two cases were observed to be similar, while the maximum power coefficient was slightly higher in the case with higher turbulence. In another study by [10], different inlet turbulence intensities, with integral length scales of the order of the chord length, were tested on a model turbine. A very small effect of turbulence on the wind turbine power and thrust was noticed. These studies have pointed out that the turbulence itself has a small effect on the performance curve (tip speed ratio versus power coefficient), and much of the observed effects in the annual energy output of a turbine are due to the unsteadiness of the inflow. However, the simplified model proposed by [11] points out the importance of turbulence on the average and fluctuating power output.

In a boundary layer above a forest both wind shear and turbulence are present with a complex structure of the flow. The incoming boundary layer characteristics have recently been shown to strongly affect the distribution of turbulence properties in the wake [12], which is linked to the total power output and fatigue loads. The exact influence of shear and turbulence on the power and thrust coefficients of wind turbines is however not yet fully understood. In field measurements, it is not possible to control the incoming flow, which makes a study on the influence of turbulence and/or shear very hard to perform. The boundary conditions in wind tunnel experiments are easy to control, but these experiments instead suffer from the drawback of the much lower Reynolds numbers as compared to full scale. This makes it hard to draw conclusions regarding full scale based on wind tunnel measurements. There is currently a need for more experiments at different Reynolds numbers within this field.

In the present wind tunnel experiment, the power coefficient and the standard deviation of the thrust coefficient for a small-scale model wind turbine were studied. By placing the model at different heights above a very rough surface, the influence of shear and turbulence on the outputs of the turbine could be investigated. The standard deviation of the thrust coefficient gives information about how much the thrust on the turbine fluctuates in time. This can potentially be an important parameter, since a fluctuating load often is more severe than a steady one, when it comes to fatigue problems. It is however not necessarily a good estimate of the total loads on the turbine, since there can be significant loads without having a variation in the thrust coefficient. It is therefore only one of many parameters to take into account when making estimations of the total loads on turbines.

2. Experimental setup

The experiments were performed in the Minimum Turbulence Level (MTL) wind tunnel at the Royal Institute of Technology (KTH) in Stockholm. The MTL wind tunnel has a closed loop configuration with a 7 m long test section, that is 0.8 m high and 1.2 m wide. The circuit is equipped with a honeycomb, a series of 5 screens and a contraction with a ratio of 9:1 (for more details, see [13, 14]).

The setup of the atmospheric boundary layer and of the canopy model is schematically shown in figure 1. The thick atmospheric boundary layer was generated with four triangular spires [15] placed at the inlet of the test section. A 3 m long aluminium grid carpet then followed to add a momentum sink near the wall and, consequently, to establish a realistic atmospheric turbulent boundary layer [16]. The canopy model consisted of four 1 cm thick flat plates (each approximately 0.5 m long) and in each plate 3500 holes were drilled in a staggered arrangement. The plates were attached to the wind tunnel floor and had the same width as the wind tunnel (1.2 m). Cylindrical pins with a diameter of 5 mm and a height of 60 mm were clamped in the holes to simulate the forest/canopy. The height of the canopy was \( h_c = 50 \) mm. The large number of holes easily allowed the density and the canopy geometry to be changed, giving the
Figure 1. Schematic representation of the canopy model and the wind turbine model setup.

opportunity to investigate the effects of clearings. The pins were in a staggered arrangement with void fraction \( \phi = 0.866 \) and equivalent EAI (Element Area Index, namely the front area per unit volume) equal to 59 m\(^{-1}\).

The velocity above the canopy was measured with a hot-wire probe at a streamwise position located 30\( h_c \) from the leading edge of the canopy. At this location, a few pins were removed to allow measurements also inside the canopy. Most of the measurements were performed with an in-house manufactured crossed hot-wire probe with 1.5 mm long wires with a diameter of 5 \( \mu \text{m} \), creating a measurement volume of 1 mm\(^3\). A DANTEC Streamline anemometer in CTA mode was used to measure the local instantaneous velocity. Close to the canopy the velocity measurements are expected to be affected by the presence of negative velocity fluid parcels. Since the hot-wire cannot sense the flow direction, this will effect the accuracy of the measured statistics. This problem is however mostly related to the region near the canopy, and will have a smaller effect on the region where the rotor is placed (\( h_{hub} \geq 4h_c \), where \( h_{hub} \) is the hub height of the turbine model).

A three-bladed wind turbine model with a diameter of \( D_{rotor} = 2R = 0.178 \) m was used. The blades were non-twisted cambered plates with the airfoil profile Göttingen 417a. At low Reynolds numbers (in the present study around 21000), the best performing airfoils are cambered plates or similarly thin airfoils [17, 18]. The pitch angle was set to 12\(^{\circ}\), corresponding to the maximum power output for the present configuration. The blade chord length varied from 26 mm close to the hub to 15 mm at the blade tip, and the Reynolds number based on the chord, \( c \), and the relative velocity, \( W \), varied from 9000 to 24000, with an average of 21000. The blockage ratio (swept area of the rotor divided by the cross-sectional area of the wind tunnel) was 2.6\%. This is far below the suggested upper limit of 10\% to avoid effects on the wake expansion due to tunnel wall interference [19]. Therefore, no blockage correction methods were applied on the measured coefficients to compensate for the presence of the wind tunnel walls. The nacelle consisted of a small electricity generator, which was connected to a known resistance and a variable number of diodes. The current through the circuit was calculated by measuring the voltage over the resistance. By applying different loads (i.e. different number of diodes in the electrical circuit), the rotational frequency of the model could be varied from 200 to 3000 rpm, corresponding to a change in tip speed ratio from 0.30 to 4.6, with a fixed free stream velocity \( U_\infty \). The tip speed ratio \( \lambda \) is defined as the speed of the tip of the blade divided by the hub velocity: \( \lambda = \omega R/U_{hub} \), where \( \omega \) is the angular velocity of the rotor and \( U_{hub} \) is the velocity at hub height. To avoid taking the electrical losses in the generator into account, the power output, \( P \), was calculated...
as the rotational torque, $M$, multiplied by the angular velocity. The generator had a torque, $M$, versus current, $I$, relationship of the form $M = k_1 \cdot I + k_2$, where $k_1$ and $k_2$ are calibration constants.

The rotational frequency of the model was measured with a photomicrosensor, which gave a pulse at the passage of a pre-marked blade. The sampling frequency for the photomicrosensor was 10 kHz and the sampling time was 3 s, which was enough to provide a converged average of the rotational frequency. Due to the fluctuations of the power and thrust, a somewhat longer sampling time was needed in this case: the sampling frequency for the power and thrust measurements was 100 Hz and the total sampling time was 20 s. This caused the mean values to be considered fully converged, in the last 2 s of the measurements the mean values changed with less than 0.05% and the standard deviations with less than 1%.

The thrust force $T$ on the model was measured with a strain gauge attached to the support of the model. The deformation of the strain gauge changes its resistance, and the output voltage has a linear relation to the force applied. The strain gauge was calibrated by applying known forces and measuring the output voltages. The assumption made is that the distribution of the thrust force over the rotor disc can be replaced by one force at the centre of the rotor. Unfortunately, it was noticed after the experiment that the strain gauge output at zero velocity should have been measured for every position of the model, since a very small shift of the model caused a non-negligible change in the output from the strain gauge. The consequence was an unknown offset in the strain gauge calibration. This systematic error had serious consequences on the evaluation of the mean thrust force, but no consequences on the standard deviations discussed in the present paper. The model and the measurement equipment have also previously been extensively tested, and the interested reader is referred to some earlier studies from Medici and co-workers [9, 20, 21].

The turbine model was placed at three different hub heights $h_{hub}$ above the wind tunnel floor, $h_{hub}/h_c=4$, 6 and 8. The hub velocity for all cases was $U_{hub}=7.0$ m/s and the turbulence levels at hub height were 13%, 7.5% and 5.6%, respectively. The corresponding free stream velocities were 9, 8 and 7.5 m/s, measured above the model canopy. These cases were also compared to a case without the canopy present. In this case, the turbine was subjected to a uniform inflow, with a turbulence level of 0.05%. Time averaged quantities will here be indicated with brackets $\langle \cdot \rangle$, with the exception of the tip speed ratio that will be generally indicated with $\lambda$. Fluctuations will be indicated with a prime superscript. Only streamwise velocity is mentioned in the paper, for which the mean value will be denoted by $U$, with the instantaneous fluctuation $u'$. The vertical coordinate is denoted by $z$, where $z=0$ is at the wind tunnel floor.

3. Results

In the present experiment, the velocity and power measurements were performed separately in order to use the undisturbed flow as an independent measurement set to assess the effect of the boundary layer on the power output of the turbine model. Figure 2 reports the mean velocity and the turbulence intensity profiles above the model canopy, without the presence of the turbine model. The turbulence intensity is defined as $T_u = \langle u'^2 \rangle^{1/2}/U$. The mean velocity profile presents the typical inflectional point close to the canopy top [22], where the maximum turbulence intensity is also observed. Such a high value is mostly due to the ejection/sweep cycle that has origin close to the canopy top and extends up to 2-3 canopy heights [23, 24]. In order to estimate the amount of shear present across the rotor disc, a power law fit of the form

$$
\frac{U(z)}{U_{hub}} = \left( \frac{z}{h_{hub}} \right)^\alpha
$$

was calculated in a least squares sense over the rotor disc location. The coefficient $\alpha$ was found to be 0.50 and 0.24 for hub heights of $h_{hub} = 4h_c$ and $h_{hub} = 6h_c$, respectively. Despite the fact
Figure 2. Velocity statistics measured in and above the model canopy without the wind turbine model present. The streamwise location is $3h_c$ upstream of the position where the turbine was later placed. (a) Mean velocity profile scaled by the free stream velocity $U_\infty$. (b) Turbulence intensity profile, $Tu = \langle u'^2 \rangle^{1/2} / U$. The solid lines in (a) indicate the vertical locations of the hub, $h_{hub}/h_c = 4, 6$ and 8.

that no free stream turbulence was forced beyond the one produced in the wake of the spires, the turbulence level even at $z/h_c = 8$ is still fairly high. Several different free stream velocities were investigated during the experimental campaign and no Reynolds number effects were observed in neither the mean velocity nor in the standard deviation of the velocity. It should be noted that the turbulence levels closest to the wind tunnel floor is high, which will make the flow angle exceed the angle of the hot-wire probe. Hot-wire is therefore not the most suitable measurement technique in this region, and the data will be associated with a very high uncertainty. This is however not a problem further away from the wall, where the rotor disc is located.

The time dependent power ($C_P$) and thrust coefficients ($C_T$) are defined as

$$C_P (t) = \frac{P(t)}{0.5 \rho \pi R^2 U_{hub}^3}, \quad C_T (t) = \frac{T(t)}{0.5 \rho \pi R^2 U_{hub}^2},$$

(2)

where $\rho$ is the air density. By measuring the power output without the canopy, a clear Reynolds number effect could be seen in the velocity range 6-10 m/s, which is shown in figure 3. Here, the rotor was subjected to a uniform inflow with a turbulence level of 0.05%. Therefore, in the measurements with the canopy present, the velocity at hub height was matched between the cases. For each hub height, the free stream velocity was changed in order to have the same velocity at hub height for all three cases. The chosen hub velocity was $U_{hub} = 7.0$ m/s.

The power coefficient curve for the different heights above the canopy is reported in figure 4. For comparison, the power coefficient measured without the canopy is also included in the figure. Two ways of calculating $< C_P >$ is presented in figure 4a and b, respectively. Normally, one would use the hub velocity in the denominator in the definition of $C_P$ (see equation 2), i.e. scale the power output $P$ with $0.5 \rho \pi R^2 U_{hub}^3$. This definition is used in figure 4a. It can however be suggested that a more adequate scaling would be to use the actual available power of the
incoming wind, $0.5 \rho \pi R^2 U_{\text{avail}}^3$, where $U_{\text{avail}}^3$ is defined according to

$$U_{\text{avail}}^3 = \frac{1}{2R} \int_{h_{\text{hub}}-R}^{h_{\text{hub}}+R} U(z)^3 \, dz.$$  \hfill (3)

This scaling is used in figure 4b. It can be seen that the case with the lowest hub height ($h_{\text{hub}}/h_c=4$) is most affected by the different scaling, which is due to the fact that the velocity profile is more curved closer to the canopy. For this case, the difference between the two methods is 4.5%. For $h_{\text{hub}}/h_c=6$ and 8, the difference is less than 0.5%. Naturally, the case without canopy (i.e. uniform inflow), is exactly the same for both methods. It should be noted that velocity measurements were not performed over the entire rotor disc location in the case with the highest hub height (see figure 2). Hence, $U_{\text{avail}}^3$ could not be calculated for this case. Since there was a very small difference between $U_{\text{hub}}^3$ and $U_{\text{avail}}^3$ for $h_{\text{hub}}/h_c=6$, it is assumed that the difference would be even smaller for $h_{\text{hub}}/h_c=8$, since the velocity profile is less curved in this case (at least up to the last measured point). The relation between $U_{\text{hub}}^3$ and $U_{\text{avail}}^3$ was therefore assumed to be the same for $h_{\text{hub}}/h_c=8$ as for $h_{\text{hub}}/h_c=6$. When full scale turbines are evaluated, it is common to use only one single velocity, $U_{\text{hub}}$, since this is often the only information available. In order to get the true efficiency of a turbine, $U_{\text{avail}}^3$ might however be a more fair measure. In either case, the differences between the cases are fairly small, given the large differences in inflow conditions. The difference in maximum power output between $h_{\text{hub}}/h_c=4$ and $h_{\text{hub}}/h_c=8$ in figure 4a is 3.5%. In figure 4b, the difference is 1%, which is within the measurements uncertainty. The case without canopy has a somewhat lower power output when scaling with the available power in the wind (figure 4b), the difference in maximum $C_P$ between this case and an average of the three cases with canopy is 3%. For the present setup, it cannot be concluded whether this difference is due to the increased turbulence, the shear, or a combination of both. In a previous study [9] with a similar model (same airfoil profile, but two-bladed), an increase of the turbulence intensity from a very low value (below 0.1%) to 4.5% led to an increase of the maximum power output of approximately 5% (the thrust coefficient remained unchanged). For the present experiment, the increase in $\langle C_P \rangle$ as compared to the case without canopy was the same for all turbulence levels tested (between 5.6% and 13%),
Figure 4. Mean power coefficient as a function of tip speed ratio $\lambda$ for different hub heights.

(a) Scaling the power output by using the velocity at hub height, $< C_P >= < P > / 0.5 \rho \pi R^2 U_{hub}^3$.
(b) Scaling the power output by the available power in the wind, $< C_{P,avail} >= < P > / 0.5 \rho \pi R^2 U_{avail}^3$, where $U_{avail}$ is defined according to equation 3.

$\circ$ $h_{hub}/h_c = 4$, ($\triangledown$) $h_{hub}/h_c = 6$, ($\heartsuit$) $h_{hub}/h_c = 8$. The solid line is the case without the model canopy present.

suggesting that it is the presence of turbulence above a certain level that causes the increased power output, independent of the specific turbulence level.

In order to further investigate the influence of the shear, the method proposed by Wilson & Lissaman [25] has been adopted were the authors suggested a Taylor expansion of the blade loads in terms of the incoming wind profile, leading to a formula to estimate the effect of wind shear in the power output as

$$C_P = C_{P,\text{no shear}} + \frac{3 \lambda}{4 \pi} \left( \frac{\mu C_t}{\bar{u}} \right)^2 \frac{\partial^2 \psi}{\partial u^2} + \frac{\partial^2 u}{\partial \mu^2} \frac{\partial \psi}{\partial u} \Big|_{u=1, \zeta = y_{hub}/R},$$

where

$$\psi = \int_0^1 \mu C_t \left( \frac{W}{U_{hub}} \right)^2 C_t d\mu \quad \mu = \frac{r}{R} \quad u = \frac{U(y)}{U_{hub}} \quad \zeta = \frac{y}{R},$$

valid for a three-bladed rotor only. Here, $y$ is the vertical coordinate, $r$ indicates the radial position and $C_t$ is the tangential force coefficient along the blade. A blade element momentum (BEM) code was subsequently developed to evaluate the tangential force coefficient and the relative velocity, $W$. The derivatives in equation 4 have been calculated numerically under the condition of constant rotational speed and by simply varying the free stream velocity by $\pm 0.5$ ms$^{-1}$. The correction was calculated at the optimal tip speed ratio $\lambda = 3$ as: -0.07$C_{P,\text{no shear}}$ at $y = 4h_c$ and -0.02$C_{P,\text{no shear}}$ at $y/h_c = 6$ and $y = 8h_c$. These corrections are of the same order of magnitude as the discrepancies observed in figure 4a. This indicates that the wind shear is mainly responsible for the power coefficient decrease and plays a part in the determination of the power output. In order to investigate this issue further, new measurements should be performed, varying only the turbulence level or only the shear.

The standard deviation of the thrust coefficient is shown in figure 5a. It can be observed from the experiments that the fluctuations of the thrust force can become more than twice as high at $h_{hub}/h_c = 4$ as compared to $h_{hub}/h_c = 8$. A scatter plot between the standard deviation of the thrust coefficient and the turbulence intensity at hub height is shown in figure 5b. Only
Figure 5. Standard deviation of the thrust coefficient as a function of (a) tip speed ratio and (b) turbulence intensity for different hub heights. ($\circ$) $h_{hub}/h_c = 4$, ($\triangledown$) $h_{hub}/h_c = 6$, ($\diamond$) $h_{hub}/h_c = 8$. The solid line represents $<C_T^2>^{1/2} = Tu$.

data above a tip speed ratio of 2 has been included in this figure, since very low tip speed ratios are less relevant. A clear trend of increasing fluctuations of $C_T$ with an increasing turbulence intensity can be recognized. A least squares approach pointed out that $<C_T^2>^{1/2} \approx Tu$, shown as a solid line in the figure. Despite the simplicity of the fit, the extrapolation towards large scale turbines operating with a different range of scales is not trivial, pointing out the need for extensive tests in both wind tunnels and in situ in order to be able to properly scale these results towards full scale wind turbines. Full scale turbines normally have a somewhat higher tip speed ratio than in the present experiment, which may also have an effect on the results.

A similar result as in figure 5a is shown in figure 6a, where the standard deviation of the tip speed ratio is reported. Again a consistent increase of the fluctuation intensity with a decreasing

Figure 6. (a) Standard deviation of the measured tip speed ratio ($<\lambda'^2>^{1/2}$) as a function of mean tip speed ratio for different hub heights. (b) Relative standard deviation of the tip speed ratio ($<\lambda'^2>^{1/2}/\lambda$) as a function of turbulence intensity $Tu$. ($\circ$) $h_{hub}/h_c=4$, ($\triangledown$) $h_{hub}/h_c = 6$, ($\diamond$) $h_{hub}/h_c=8$. The solid line represents a least squares linear fit through the data.
hub height is present. This underlines the fact that not only the rotor and the tower will suffer from increased fatigue loads due to the turbulent inflow, but also the bearings must withstand to loads caused by a continuously changing frequency, making the whole fatigue process more severe. From figure 6a, it can be seen that the standard deviation of $\lambda$ is increasing almost linearly with increasing $\lambda$, meaning that the relative standard deviation, $<\lambda'^2>^{1/2}/\lambda$, is fairly constant. This is shown in figure 6b, where the relative standard deviation is plotted as a function of the turbulence intensity, for tip speed ratios above 2. Again a linear trend is observed, this time relating the turbulence intensity to the relative standard deviation of the tip speed ratio. This is shown in the figure as a solid line, which represents a least squares fit through the data. The scatter in the data is larger with increasing fluctuations of $\lambda$ (decreasing hub height). A possible explanation is that the increasing fluctuations of the time signal of $\lambda$ introduces an additional uncertainty for the algorithm that calculates the rotational frequency from the time signal.

4. Conclusions
The performance of a small-scale wind turbine model was investigated experimentally in a wind tunnel. The turbine was placed at different heights above a very rough surface canopy, which consisted of cylindrical pins. Upstream of the canopy, an atmospheric boundary layer was created with the aid of triangular spires and a grid carpet. The average power coefficient and the standard deviation of the thrust coefficient were then evaluated for three different hub heights ranging from 4 to 8 canopy heights, where the free stream velocity was adjusted in order to have the same velocity at hub height for all three cases. The maximum power coefficient was found to be approximately 3.5% lower for the case with the lowest hub height, as compared to the two higher ones. This difference was however lost if the power output was scaled with the total available power in the wind, instead of using the hub velocity. The results were also compared to a case without the canopy, with a uniform inflow with very low turbulence intensity. In this case, the maximum power output was 3% lower as compared to the cases with canopy, when scaling with the total available power in the wind. The standard deviation of the thrust coefficient was found to increase with a decreasing hub height. This is not surprising, since the turbulence intensity is higher closer to the canopy, which is assumed to cause a more fluctuating thrust coefficient. By plotting the standard deviation as a function of the turbulence intensity for different hub heights, a linear trend could be observed between the three cases. However, in the present experiment only three different hub heights were tested, and in order to fully investigate the relation between fluctuations of the thrust coefficient and turbulence intensity, an additional number of hub heights need to be tested. A similar trend was observed in the standard deviation of the tip speed ratio, which also increased with a decreasing hub height. For the three hub heights tested, the relative standard deviation of the tip speed ratio was found to grow linearly with the turbulence intensity. The increasing levels of fluctuations in thrust and tip speed ratio with a decreasing hub height underline the fact that not only the rotor but also the tower and the bearings of the wind turbine model must withstand increased loads when operating closer to the canopy. The present experiment was performed at small-scale, with lower tip speed ratios and at lower Reynolds numbers than what is common in full scale. In order to further investigate the effects of shear and turbulence on wind turbine performance, more experiments at different Reynolds numbers are needed.

Acknowledgments
This work was sponsored by the Swedish Energy Agency, and partly via the research program Vindforsk III.
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