Torque fluctuations caused by upstream mean flow and turbulence

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Abstract A series of studies are in progress investigating the effects of turbine-array-wake interactions for a range of atmospheric boundary layer states by means of the EnFlo meteorological wind tunnel. The small, three-blade model wind turbines drive 4-quadrant motor-generators. Only a single turbine in neutral flow is considered here. The motor-generator current can be measured with adequate sensitivity by means of a current sensor allowing the mean and fluctuating torque to be inferred. Spectra of torque fluctuations and streamwise velocity fluctuations ahead of the rotor, between 0.1 and 2 diameters, show that only the large-scale turbulent motions contribute significantly to the torque fluctuations. Time-lagged cross-correlation between upstream velocity and torque fluctuations are largest over the inner part of the blade. They also show the turbulence to be frozen in behaviour over the 2 diameters upstream of the turbine.

1. Introduction
The mean wind shear and the turbulence in the upstream flow impose fluctuations in the torque generated by a turbine rotor on the drive train system, and indeed is a major contributor to the cause of drive train failure [1]. The torque fluctuations arising from the mean shear of an atmospheric boundary layer (ABL) are in essence straightforward once the mean velocity profile is known. The major issue of concern here is the effect of turbulent velocity fluctuations whether these are from an unperturbed upstream ABL or from one or more turbine wakes, the response depending prima facia on the intensity and spectrum of the fluctuations.

An important aspect will be the degree to which the turbulence in the flow approaching the rotor disk is correlated. Large-scale turbulence will be highly correlated (by definition of large) over the face of the rotor disk, so that what is ‘seen’ by one blade will be ‘seen’ by the others. Conversely, small-scale turbulence will be uncorrelated so that the turbulence ‘seen’ by one blade will be different from that ‘seen’ by the others. Moreover, large-scale turbulence will affect the whole of a blade; while small-scale will affect one part independently of another. Thus, the effect of the rotor will be like a low-pass filter; torque fluctuations can be expected to be predominantly caused by the larger scales of turbulent motion. Each blade will be an integrator of the instantaneous loading along its length. Blade element theory indicates that the fluctuation in lift is more sensitive to axial fluctuations that to azimuthal fluctuations, radial fluctuations playing no part.

A series of studies are in progress investigating the effects of turbine-wake interactions for neutral, stable and unstable atmospheric boundary layers by means of wind tunnel simulations in the EnFlo meteorological wind tunnel. The three-blade model wind turbines drive 4-quadrant motor-generators. Measurements in stable and unstable boundary layers requires the mean flow velocity to be ‘low’ in order to achieve the required level of buoyancy force at practicable expense in terms of surface heat flux, etc. The reference wind speed here is about 2m/s, and therefore the torque fluctuation signals were expected to be weak. Nevertheless, investigations showed that the motor-generator current can be measured with
adequate sensitivity by means of a current sensor allowing the mean and fluctuation torque to be inferred. Measurements have been made of the spectra of torque fluctuations and their correlation with velocity fluctuations in the approaching flow, and two-point velocity measurements in the upstream flow. So far this has only been done for a single turbine in a neutrally stable ABL, but the effects of upstream wakes and non-neutrally stable (offshore) ABLs will be investigated in future work. No dynamical model of the model turbine rotor or of the motor-gearbox drive train and controller is included in the present consideration. The more immediate objective here, prompted by the broader range of concerns of the supporting Supergen consortium, was to see to what extent useful information could be gained in regard to torque fluctuations from the low cost, relatively small turbine models required for wind tunnel multiple-turbine wake experiments. The present paper gives some results of preliminary investigations.

As the wind flow approaches a turbine (that is extracting momentum) there is necessarily a reduction of mean velocity and in principle a distortion of the turbulence. If this turbulence for the moment is assumed to be homogeneous and the distortion rapid and axisymmetric then it is possible to use the analysis given by Batchelor [2] to predict the change in turbulence. This is shown in figure 1, the turbulence at the turbine disk, as a function of the wind turbine thrust coefficient, $C_T$, were $u'$ and $w'$ denote the rms of the axial and lateral fluctuations, $q'$ the overall rms level, suffix 0 denoting the upstream level of these, and $U$ the axial mean velocity. $u'$ and $w'$ change relatively little, and $q'$ almost not at all. In contrast, the intensities $u'/U$ and $w'/U$ increase significantly. But it must be noted that such a calculation ignores entirely the impeding effect of the turbine itself, which would be expected to reduce the streamwise fluctuations (much as the effect of a wind tunnel settling chamber screen, for example) by the imposed blockage. Some evidence for this is seen in the near-wake measurements of [3], where $u'$ in the near wake falls below the external level.

![Graph](image1.png)

**Figure 1** Change of a) turbulence levels and b) intensity with turbine thrust coefficient, at the rotor disk. Idealised, and ignoring turbine blockage. Based on [2] and actuator disk theory.

2. Experimental arrangement

2.1 **EnFlo meteorological wind tunnel and turbine model**

The working section of this suck-down wind tunnel is 1.5 m in height, 3.5 m in width and 20 m in length, with a speed range of 0.3 to 4 m/s. The wind profile was generated by means of Irwin-type spires [4] at the working section inlet complemented by surface roughness elements, with the mean velocity and turbulence profiles based on ESDU [5] guidelines, assuming a 10m/s mean wind speed at 10 m height, at a model scale of 1:300. In the presentation of results $X$ (axial), $Y$ (lateral) and $Z$ (vertical) denote distances from the model turbine tower hub, and $z$ from the surface. $U$, $V$ and $W$, and $u$, $v$ and $w$ are respectively the mean and fluctuating velocities in the $X$, $Y$ and $Z$ directions. $X$ is zero on the plane defined by the turbine...
blade pitch axis. The free stream reference velocity, $U_{ref}$, was taken at a fixed upstream location from an ultrasonic anemometer.

Velocity measurements were made using a Dantec two-component 40 MHz frequency-shifted laser Doppler anemometry (LDA) system, and a standard 27mm Fibre-flow probe. This optical set-up produces a measurement volume of 0.074 mm in diameter and 1.57 mm in length. The seeding particles with a nominal size of 1 µm in diameter were generated from the sugar solution aerosol by the hydrosonic seeding machine. In the two-component measurements two such probes were used, but for one component only from each.

The turbine model comprised a three-blade rotor with a diameter of $D$ of 416 mm, a micro motor with a gear box on a solid steel tower 13 mm in diameter at a hub height of 300 mm, a modified representation of the Supergen 5MW exemplar turbine. The blade was made of fibreglass and resin with a shape of a twisted thin plate without an airfoil cross-section. The chord and twist angle were calculated to give a constant lift coefficient of 0.6 along the blade span, at a tip speed ratio of 6. The turbine was controlled through a 4-quadrant controller in order to maintain a constant rotation speed with an uncertainty less than 1 rpm.

The turbine speed was measured separately from the controller system, by means of reflective tape at the hub of one blade (a weaker signal coming from the other two blades) and an optical sensor. To measure the fluctuating torque a current sensor, Honeywell CSLA1CD with a 3µs response rate, was placed around the supply loop between the controller and motor-generator, combined with a purpose made signal processing unit that allowed the offset and gain to be adjusted. A filter was added to the standard bench top power supply input to reduce noise. The current and speed sensors were sampled at ‘high’ frequency, uniformly in time. Cross-correlations with the LDA signal, which is inherently non-uniform in time and also at a ‘low’ frequency, was achieved by taking the nearest (about 10 times faster) high-data-rate sample. A similar approach was adopted for the cross-correlation of LDA signals; the nearest in time, subject to a threshold maximum interval.

3. Results

Measurements show that there is much less change in turbulence in the approach flow as close as can be measured than suggested by figure 1, implying any such affect is roughly matched by the impeding effect of the turbine. This being the case, it follows that there would not be much change in frequency spectra or length scale of the energy-containing motions. Figure 2 shows $\overline{u'^2}$ and figure 3 the two-point correlation $u(Y)u(Y+\Delta Y)$ in the range $X/D = -2$ to $-0.2$, from which it is seen that there is negligible effect of the turbine’s presence, except at $-0.2$, where a slight reduction in $\overline{u'^2}$ can be seen. (Measurements at smaller $Y$ were not possible without probe interference effects on the turbine). The length scale implied by figure 3 is inline with earlier measurements in the wind tunnel in agreement with the field data survey of [6].

Figure 2 Streamwise Reynolds stress ahead of turbine, normalised by $U_{ref}$.

Figure 3 Lateral correlation ahead of turbine.
Figure 4 shows the frequency spectra of the torque signal against that of the rotor-speed sensor. The latter shows peaks at the rotor frequency and the first and second harmonics (a characteristic of the speed sensor). These frequencies are also seen in the torque time signal (τ(t)), and are assumed to be caused by the mean-flow non-uniformity for the blade-passing frequency (the second harmonic) and either slight blade variability or turbulence for the fundamental and first harmonic, or both these. Unexpectedly, there is also a peak in the torque signal at a lower frequency – subsequently confirmed to be a feature of the controller - but not in the rotor speed, though its presence is not significant in the main conclusions here.

Figure 5 shows the spectra for the streamwise and azimuthal fluctuations, u and w, at high height, at r/R = 0.5, X = −0.1D, where r is the radius, R=D/2 the tip radius, and X < 0 is upstream of the rotor disk. The major point to see here is that shape of the u-component spectra is much the same as that as the torque spectral density at low frequencies, but at higher frequencies the torque spectral density is smaller. In contrast, the w-component spectra is flatter and smaller in magnitude at low frequencies, and does not have the same shape as the torque spectra, consistent with the effect of the u-fluctuations being dominant.

Positive axial and azimuthal fluctuations (the latter taken in the direction of blade rotation) will each cause an increase in blade incidence and therefore in blade lift. The lift will also increase as a result of an increase in velocity magnitude. The torque will increase as a result of the increase of lift and the increase of blade incidence, the increase in incidence causing a change in the direction of lift such as to increase the torque. Though not pursed in detail here, blade element theory can be extended to show how the
torque from an element of the blade depends upon the axial and azimuthal fluctuation. The sensitivity to azimuthal fluctuations is smaller by about an order of magnitude. Figure 6 shows a vertical profile - at \( Y = 0.5R \) and \( X = -0.1D \) - of the time-lag correlation coefficients of velocity and torque: \( u(t)\tau(t+\Delta t)/u'\tau' \) and \( w(t)\tau(t+\Delta t)/w'\tau' \), for maximum correlation magnitude, where the prime denotes r.m.s. The hub axis is at \( z = 300 \) mm and at this lateral position (of \( Y = 0.5R \)) the rotor disk ‘cuts’ the vertical profile at \( z = 120 \) and 480 mm. Clearly, there is a significant correlation with \( u \), largest at hub height. It is not clear why there is also a positive correlation with \( w \), assuming the sensitivity to \( w \) is small. The measurements were made in front of an upward-going blade, and a positive fluctuation would be expected to give a positive fluctuation in torque (for this blade). But, on average, \( u \) and \( w \) are negatively correlated; were the sensitivity to \( w \)-fluctuations negligible, a negative correlation would be expected, arising from the fluctuation in \( u \). This needs further investigation. (Note, with the LDA probe orientation employed in these preliminary measurements, \( w \) is equal to the azimuthal velocity only at \( z = 300 \) mm.)

Figure 7 shows the time lag, \( \Delta t \), for maximum correlation (of figure 6) against the convective time-scale based on mean velocity and the distance to the upstream measuring point (0.1D). Clearly, as might be expected, there is a link in the correlation between the measured velocity and the convective ‘arrival time’.

Figure 8 shows the correlation coefficient (at fixed \( Y \) and \( Z \)) between the streamwise fluctuations and the torque fluctuations, further upstream from the turbine, showing none of an anticipated decrease with increasing distance. For the same set of measurements, figure 9 shows the time delay, \( \Delta t \), to give maximum correlation against a mean convective time based on the local mean velocity, the five points corresponding to those in figure 8. This shows a clear and straightforward trend between the two, and is broadly what would be anticipated, a larger time for a larger distance. This latter observation makes it more difficult to doubt the measurements shown in figure 8 though, notwithstanding, it initially remains a curious result.

On a finer point, the earlier stations in figure 9 (i.e. at shorter time) the points lie above that given by an assumed mean convective equal to the mean velocity (which only changes by about 5% over these five stations), whereas the earlier results (figure 7) at –0.1D showed the delay time and the mean convective times to be about equal. It is inferred that, with the relatively sharp decrease in mean velocity close to the turbine disk (as implied by vortex theory), there is in effect an offset in a plot such as that in figure 9.

Figure 10 compares the maximum of the time-lagged correlation with that of zero time lag, as a function of velocity-measurement position, \( Y \) (at \( Z = 0 \)), at \( X/D = -0.2 \) and –2. For the zero time lag the correlation coefficient is smaller at its peak value by more than half at \( X/D = 2 \) compared with that at 0.2.
At least qualitatively, this is what would be expected; a weaker correlation between the torque fluctuations and velocity fluctuations further upstream. The time-lagged maximum correlation is strikingly different in the two cases, with a much larger difference compared with the zero-time lag for $X/D = 2$ (figure 10b). In fact, it appears there is almost no difference between the two profiles, as can be seen from figure 11. (There is no reason why, from an experimental techniques point of view, an error of technique could account for such a coincidence.)

![Figure 10](image1.png)

**Figure 10** Comparison of maximum $u$-$\tau$ correlation coefficients with zero-time-lagged coefficients. $X/D = \text{a)} -0.2, \text{b)} -2$.

![Figure 11](image2.png)

**Figure 11** Comparison of time-lagged maximum correlation coefficient, at $X/D = -2$ and $-0.2$.

Another point to draw from these plots is that the cross correlation falls monotonically to about zero when the velocity probe is a little beyond the tip radius. Because of tip loss, the tip of the blade does not give any power output but, nevertheless, it is at first sight surprising that the correlation falls over the span of the blade as the outer part of the blade generates most torque (excluding the tip loss region). However, the blade mean velocity is increasing with blade radius, roughly proportionally, and so a given velocity fluctuation, $u$, will have a relatively smaller effect at larger radius. This leads to the rather interesting conclusion – which should perhaps have been an obvious expectation - that torque fluctuations are generated primarily from the inner part of the blade, while most of the mean torque is generated from the outer part.

The sustained correlation behaviour seen in figures 8 and 11 can be explained in terms of timescales. If $L$ is the length scale of the energy-containing eddies approaching the turbine, the time scale is $L/u'$. Assuming the convective speed of the eddies is approximately the mean velocity $U$, then the length corresponding to an eddy-turn-over time is $UL/u'$. Since $L$ is comparable with $2D$ (see figure 3), and $U/u'$ is larger than $\sim 10$ (at hub height), this length is large compared with a distance of $2D$, meaning that
the turbulence will not have changed greatly over this distance; the turbulence is approximately ‘frozen’ for this distance. This is in fact the condition for the calculations leading to figure 1.

4. Concluding comments
A preliminary investigation of making measurements of fluctuating torque on a small, ‘low speed’ model wind turbine have been made. It has been shown that in terms of the time-lagged correlation coefficient between streamwise velocity fluctuations at some point 0.1D to 2D upstream of the rotor disk, the turbulence behaves as if it is frozen. The impeding effect on the turbulence imposed by the turbine’s blockage which also gives rise to the streamtube divergence and the distortion of the turbulence caused by this divergence are such as one approximately compensating the other. Torque fluctuations arising from velocity fluctuations in the upstream flow are generated predominantly over the inner part of the blade. Therefore, the ‘input’ of torque fluctuations to a turbine’s drive-train system would appear to depend up on the blade parameters in this part. The present results may also have useful implications for wind-flow monitoring systems intended to use turbine-based upstream measurements for load alleviation.

No representation of the model turbine by way of a dynamic model has been included. In the first instance this was deliberate as the investigation was intended to see what would follow without the additional complexity. In the instance that a turbine control system is such as to keep the speed constant, as is closely the case here, there are no dynamical acceleration terms; the current in the motor then responds only to change in imposed torque from the blades. The frequency spectra of figure 4 shows a very narrow peak at the rotor frequency. Further analysis of the width of this peak should give an indication of the likely significance of the dynamical terms.

The flexibility of the blades has also been ignored, though there was no indication in the present work that flexibility might have had an observable effect. Significant flexibility would not show up in the frequency spectra of rotational speed as the control system is designed to keep the speed constant. While observation and measurement showed the blades not to move significantly, some further specific investigations would be desirable to be certain. This could include making measurements at different wind speeds and rotational speeds (matched via TSR), or using an aerodynamically identical rotor with stiffer blades.

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