Attachment A. Wind turbines Wake Turbulence and Separation

Introduction

This paper is a summary of research extracted and credited to the references included at the end of this paper.

The summary is the opinion of the author Ralph Holland, B Sc., Dip Ed., Dip Com. Sc.

Assumptions

Certain assumptions were made during the construction of this data:

- The blade tip speed for the wind-turbines employed in the Crookwell proposal,
- and that the turbines are operating at the Betz limit when operating at the max rpm.

These two assumptions were used to arrive at the expected max operating speed and used to calculate the subsequent wind-speeds for the turbines under consideration, and as itemised in table-1.

Blade Diameter m	**Total height m**	**Max RPM**	**max tip speed kph**	**Max tip speed knots**	**tip speed ratio**	**wind speed at max tip speed Knots**	**wind speed at max tip speed m/s**	**16 * blade diam. m**
93	126.5	17	298.0	160.9	6.0	26.8	13.8	1488
120	195	17	384.5	207.6	6.0	34.6	17.8	1920

Table-1 Proposed wind-turbine parameters for Crookwell

Turbine wake turbulence

There are two contributions to the wake of a wind turbine:

- The reduction to airflow due to power extraction, where the free airflow speed is reduced to 1/3 of the free-flow rate (e.g. from 26.8 Knots to 9.9 Knots) behind the turbine
- The generation of blade-tip vortices due to the air counteracting the blade torque, and in part to aerodynamic effects due to the finite extent of the blades.

Figure 1. Smoke trail passed over blade-tips showing vortices [Ref 1]

The blade-tip vortices are caused by the blade rotation, so vortex cells have rotational components caused by the blade tips travelling at the tip speed, e.g. 160 Knots in the case of the smaller turbine operating at the maximum designed tip speed. Further the blade-tip vortices are pushed down-stream and start to mix with the downstream air-flow, and additional rotational components can be observed to form parallel with that downstream air flow. These vortices will eventually dissipate as energy is lost due to mixing and through the generation of heat.

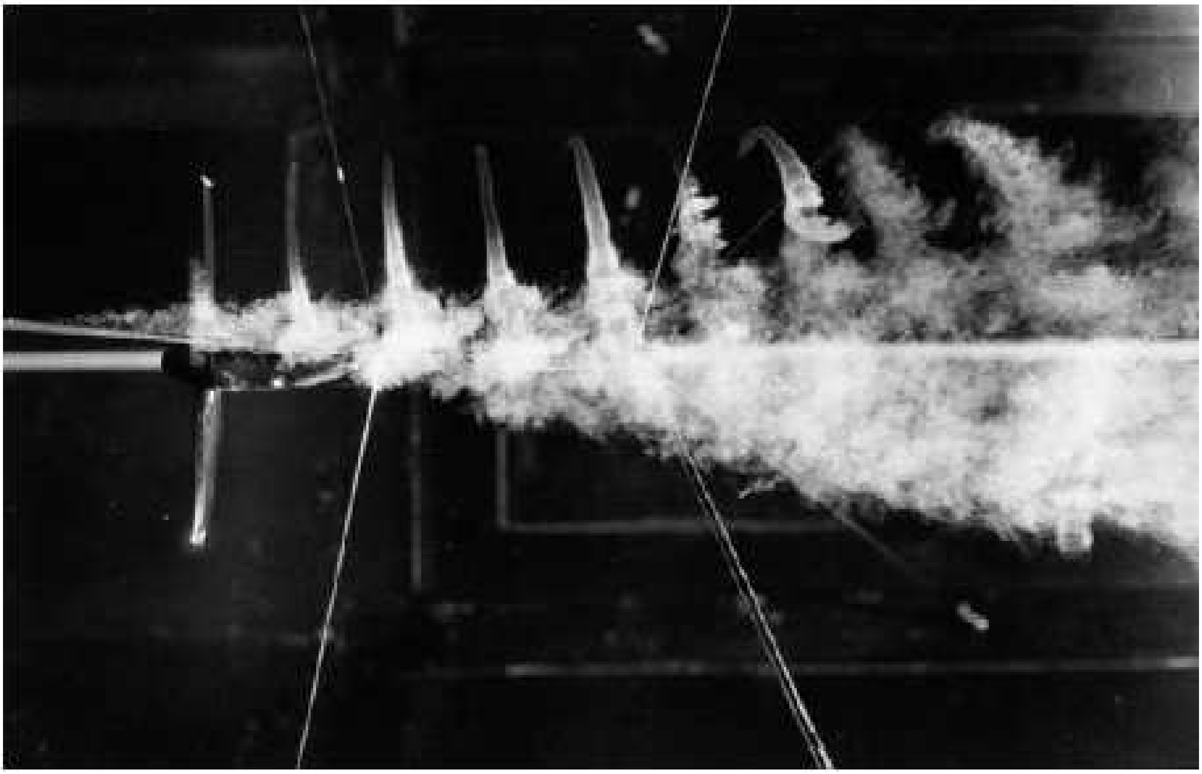

Figure 2. Smoke trail injected through centre of turbine showing expansion [Ref 1]

Studies show that the near-field wake turbulence behind a horizontal axis turbine extends downstream to 3 to 7 blade diameters. The exact extent depends on the blade torque coefficient and the tip speed ratio. Traditionally the near-field wake is considered to be 3 blade-diameters, but Figure 2 shows that it extends further.

The airstream is turbulent until at least this distance, and it is no coincidence that turbine separation in wind-farms clusters is 6 to 7 diameters in the direction of the prevailing wind direction, and 3 diameters perpendicular to the prevailing conditions. The more powerful the turbine, (i.e. bigger) this spacing is typically greater.

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Figure 3 down-stream containment of the wake with low thrust [ref 2]

From NASA Ames wind-tunnel tests , where the turbine was operating at low thrust, you can see that the wake field is contained behind the turbine for up to 8 or 9 blade rotations, showing the extent of the near field propagation.

At higher thrust (or power recovery) the wake field expands and more mixing occurs and the wake field is not as contained, but rather spreads out. The turbulence being generated is in proportion to power captured via aerodynamic surfaces and represents drag.

Clearly the effect of a wind turbine reduction in wind speed behind it will extend beyond the near turbulence field, and the 3 to 7 blade diameter separation employed by wind-farm designers may be inadequate. The affect of additional blades is to alter the frequency of the turbulence components, but the same, if not potentially more turbulence may be present because in general a three-blade turbine has more drag than a two-blade turbine.

In aviation terms air-traffic control is required to provide 2 minute separation of aircraft taking off and landing to avoid wake-turbulence, so wake turbulence is considered a very real danger to aircraft.

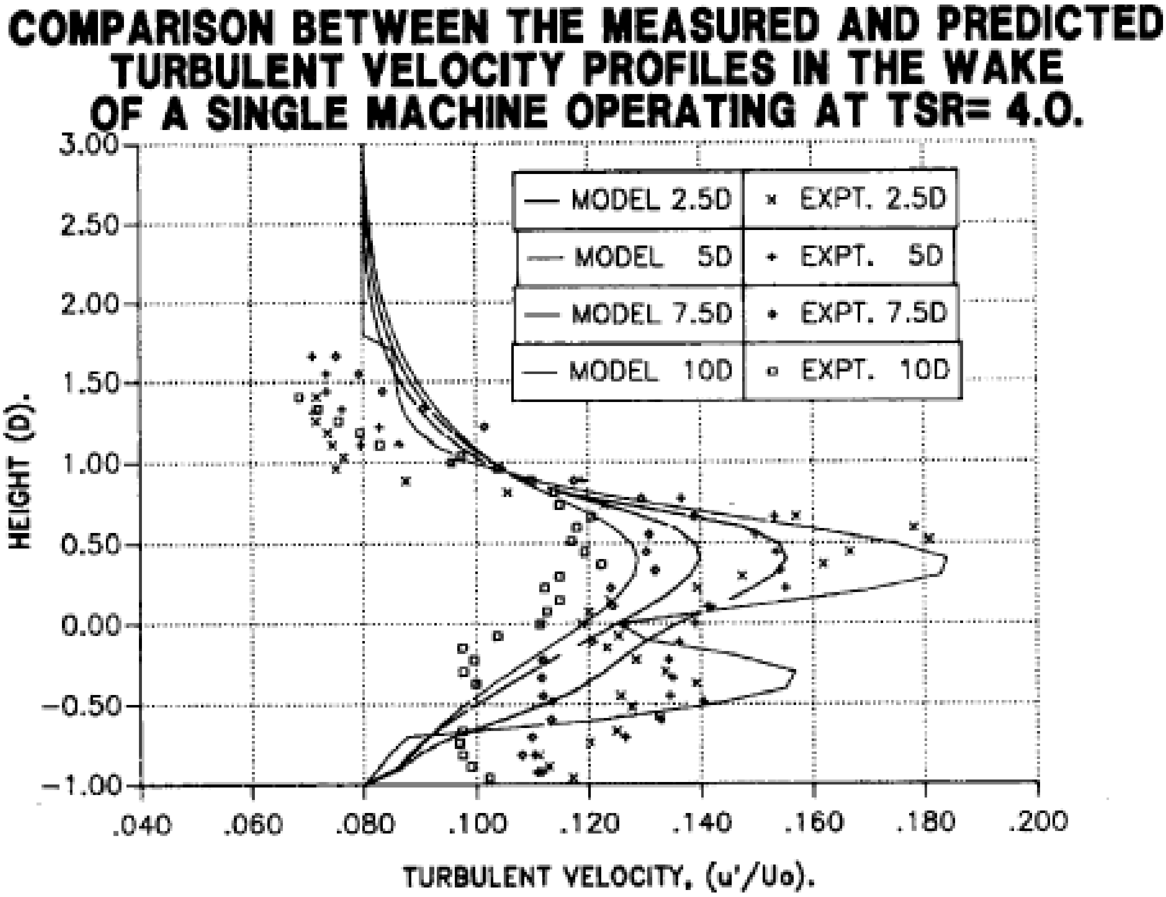

Figure 4 Downstream turbulence from various model and experimental measurements [ref 3]

Note in figure 4 that the velocity stream behind a turbine has been measured and is still prevalent at 10 times the blade diameter for a wind-turbine operating at a tip speed ratio of 4.0. It also shows the variation of the velocity profile with height, the zero height being the centre of the turbine. Note that the upper-half has more turbulence than the lower half of the distribution and this is backed by other references found in the further reading material at the end of this report. (Note u’ is actually the square-root of the difference between the measured velocity and the free-flow velocity.)

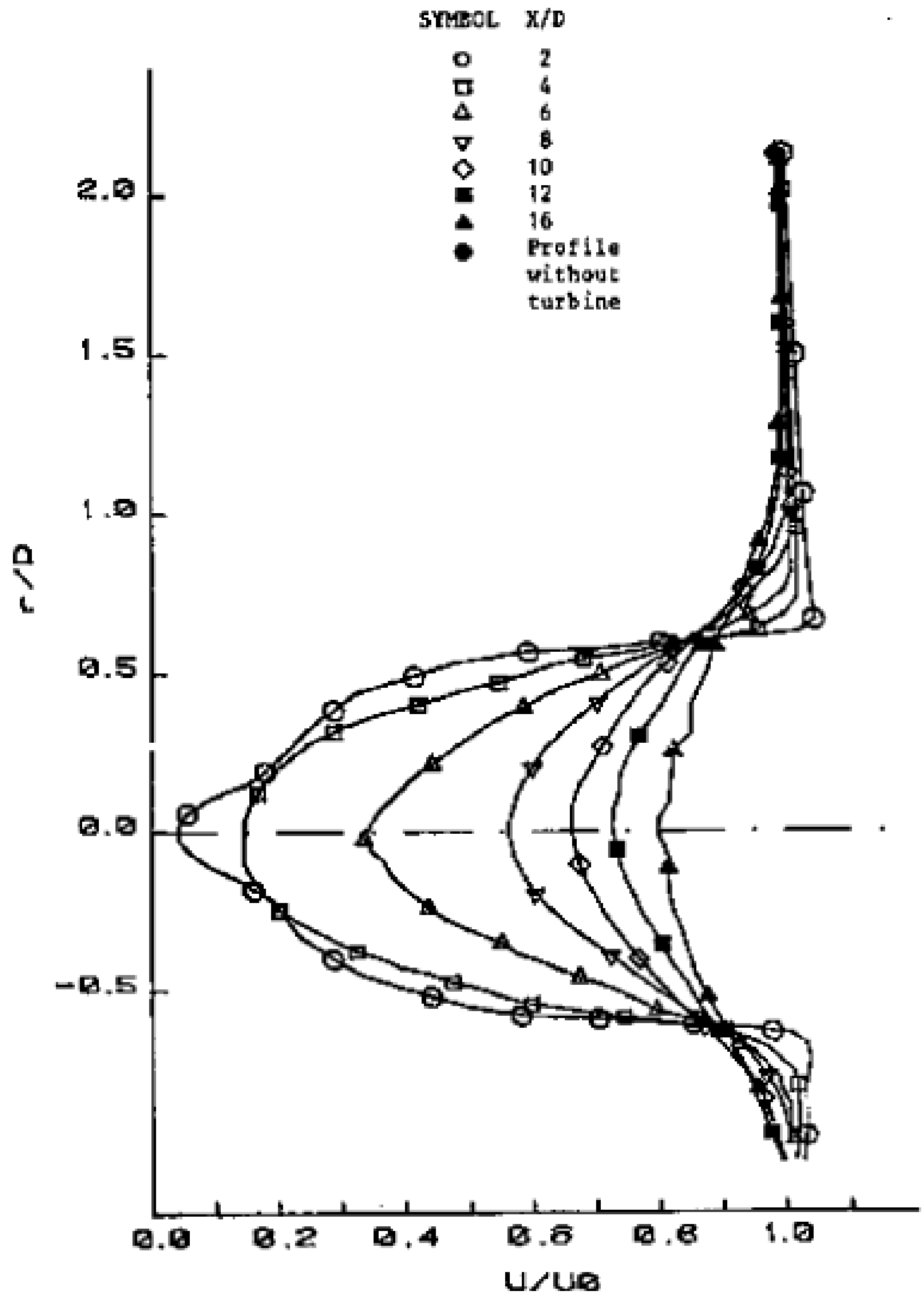

Figure 5 – mean velocity behind a turbine [Ref 3]

Figure 5 shows that the disruption to wind-velocity occurs even at 16 times the blade diameter. This is largely due to the extraction of power from the air-stream, and the time it takes the airstream to recover back to the free-airflow. So it may be necessary to require separation beyond 16 blade diameters. (This represents 1.488 kilometres for the smaller turbine, and 1.92 km for the larger turbine measurements used in Table 1.)

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Summary

Wake turbulence behind a single wind turbine can extend beyond 16 blade diameters, being composed of both blade-tip vortices and the reduction of wind speed due to power extraction. It takes time for the airstream to become laminar, and further time for it to recover to the original free airstream velocity.

There is a tendency for the downstream to rotate initially at the blade rate, and it has been shown that this rotation moves downstream to extents that are not insignificant.

The near-field turbulence is coupled with a significant down-stream reduction in wind velocity, which represents wind-shear, a phenomenon that is known to be dangerous to flight.

The wind velocity typically decreases to 2/3 of the free-stream velocity just in front of the turbine, and is further reduced to 1/3 of the free stream flow behind the turbine when the turbine is operating at maximum power extraction i.e. the Betz limit.

So an observer crossing such a stream would see an abrupt variation in wind speed between 2/3 to 1/3 less than the surrounding free-flow airspeed. For a 27 knot wind this would represent a variation of 17.9 Knots below the ambient wind speed, and couple this with the rotational velocity of the blade-tip vortices, then there is the capacity to be caught in what started out as a 160 Knot rotational field - from the smaller turbine operating at 17 rpm.

In the case of aircraft flying into such a wake, this represents a significant reduction in airspeed and flying conditions that might easily cause an aircraft to tip and stall.

I also believe that when wind-turbines are arranged into wind-farm clusters, that there is more chance of wake-turbulence interaction between turbines, and greater potential for interaction of the wake-turbulence with the surrounding environment, such as mechanical turbulence induced by the very hills on which they a located, under adverse wind conditions.

Strangely, studies show that the turbulence can be greater when the turbine is operating at lower wind-speeds.

Credit and References:

1. Alfredson P-H, Dahlberg J-A. A preliminary wind tunnel study of windmill wake dispersion in various flow conditions. Technical Note AI-1499, Part 7, FFA, Stockholm, Sweden, September 1979.
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2. Wind turbine wake aerodynamics, L.J. Vermeer, J.N. Sorensen, A. Cresp. Progress in Aerospace Sciences 39. http://www.google.com.au/search?sourceid=navclient&ie=UTF-8&rlz=1T4DAAU_enAU230AU230&q=2%2e+Wind+turbine+wake+aerodynamics

3. Hand M, Simms D, Finger L, Jager D, Coteril J, Schreck S, Larwood S Unsteady aerodynamics experiments phase VI: Wind tunnel test configuration and available data campaigns. Technical report BREL/TP-500-29955, NREL, December 2001. http://www.google.com.au/search?sourceid=navclient&ie=UTF-8&rlz=1T4DAAU_enAU230AU230&q=Unsteady+aerodynamics+experiments+phase+VI

4. Wind Turbine Wakes – Control and Vortex Shedding by Davide Medici. Technical Reports from KTH Mechanics Royal Institute: http://www.vindenergi.org/Vindforskrapporter/Medici_2004_Wakes.pdf

Further Reading

- http://www.sandia.gov/wind/2007ReliabilityWorkshopPDFs/Mon-6-DanBernadett.pdf shows wind-turbine spacing versus turbulence and wind-speed.
- http://www.risoe.dk/vea/recoff/Documents/Sec_3/RECOFFdoc068.pdf turbulence inside and outside wind farms
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Updates

1.1 20080923 Correction to statements of rotational field and wind shear.

1.0 20080922 Initial Draft.