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WIND SHEAR AND ITS EFFECT ON NOISE ASSESSMENT OF WIND TURBINES

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1 ABSTRACT

In 2003 and the following years van den Berg pointed out that the impact of wind shear on turbine noise at night had two effects – that of increasing turbine noise levels for a constant 10m high wind speed and that of increasing amplitude modulation due to greater variation in wind speed. But it is still not widely agreed when and where excess wind shear is most prevalent.

This paper looks at wind shear conditions at different locations and at different times of day and times of year using actual data collected at wind farm sites. It examines the effect of this on the relative level of turbine noise and background noise.

The paper looks at both vertical shear and horizontal shear ("twist") and at differences in wind speeds and wind directions round the blade tip trajectory that might cause excessive amplitude modulation.

2 INTRODUCTION

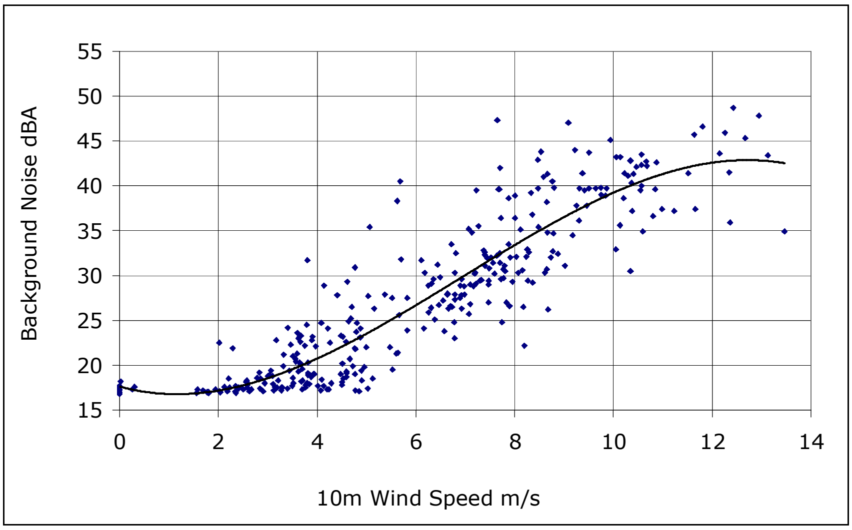
Most of this paper was presented to the Third International Meeting on Wind Turbine Noise at Aalborg, Denmark on 17th to 19th June 2009. Since then I have added some further analysis – in particular some analysis of wind shear in forestry and more detailed analysis of wind shear in different topographical areas and different time periods.

The first question we need to ask is why are we interested in wind shear in relation to turbine noise? There are three answers to that question. The first is that it has an influence on the way sound is propagated from the wind turbine to the neighbouring housing. On the whole we tend to deal with this by calculating the "worst case", that is to say the most efficient propagation method; downwind with hard ground and a low air absorption coefficient. I do not intend to deal with this further in the paper.

The second reason that wind shear is important is that we reference turbine sound power levels to the 10m wind speed using a fixed wind shear. This is because IEC 61400-11 measures sound power level related to hub height wind speeds but reports them related to 10m high wind speeds using a standard wind shear equal to a roughness length of 0.05m. As van den Berg pointed out in 2003[1] increasing wind shear results in increasing sound power level output of the turbine for the same 10m wind speed – and so the sound level may be higher than expected.

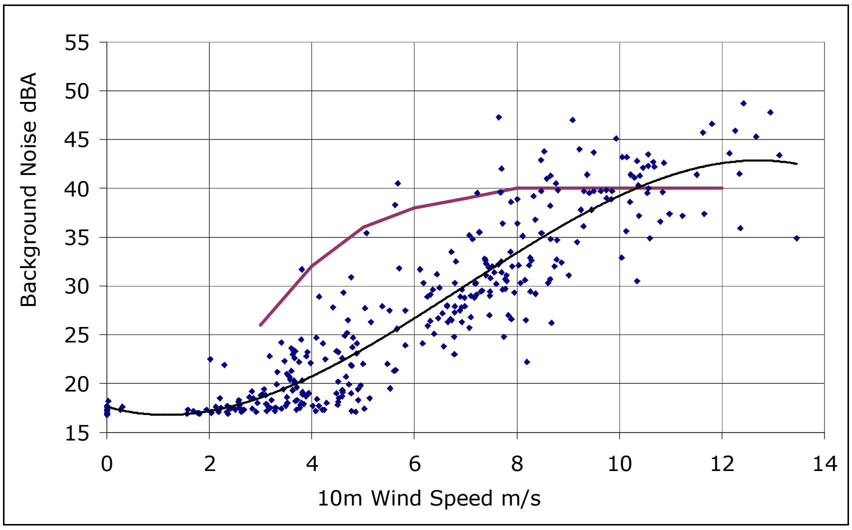
The graph below shows a typical plot of background noise levels. Each marker is a ten minute reading of background noise plotted against a ten minute reading of wind speed at 10m height taken at the same time. The black line is a third order best fit polynomial.

Fig 1



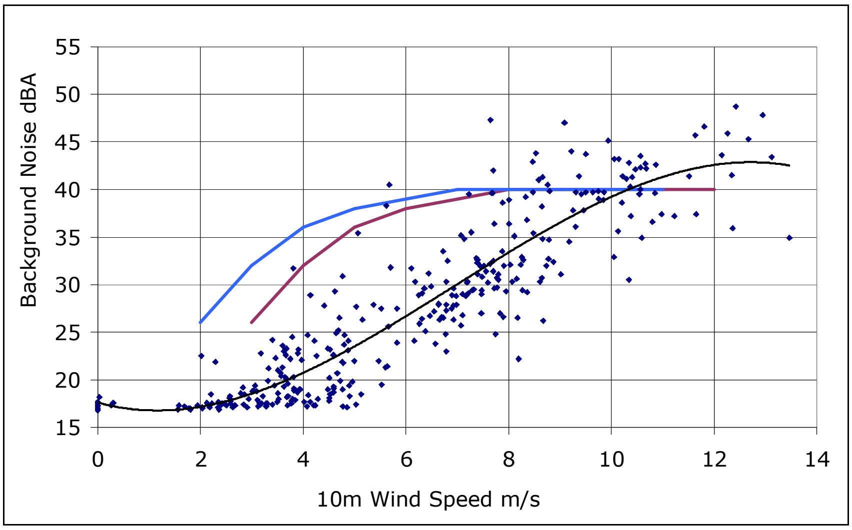
The next step in the assessment process is to calculate the turbine noise at each wind speed and superimpose it on the background noise graph. If we simply use the manufacturers wind turbine sound power levels then it is implicit that we are using the standard shear with a roughness length of 0.05m. The result is shown in Fig 2 below.

Fig 2



However, if there is excess wind shear – that is to say shear with a roughness length of more than 0.05m – then the turbine noise may be higher than expected at any particular wind speed. What happens is that the turbine noise level curve shifts to the left as shown by the blue curve in Fig3 below. The effect is to increase the margin of turbine noise over background noise.

Fig 3



In fact, in the UK it is now becoming more common to shift the background noise curve to the right using background noise levels standardised to a roughness length of 0.05m and leave the turbine noise the same. The result is the same.

The third reason for an interest in wind shear is that there is some evidence (again from van den Berg[2] and others) that increased wind shear across the face of the turbine results in increased amplitude modulation which may be perceived as exacerbating the noise.

Sites 1 and 4 are flat sites in Eastern England. Sites 2, 3 and 6 are about 200 to 250m above sea level with gently rolling hills as is common in areas of South West England, parts of Northern England and the lower lands of Scotland. Site 5 is a very exposed site in Scotland but rolling moorland, not mountainous and 100m above sea level.

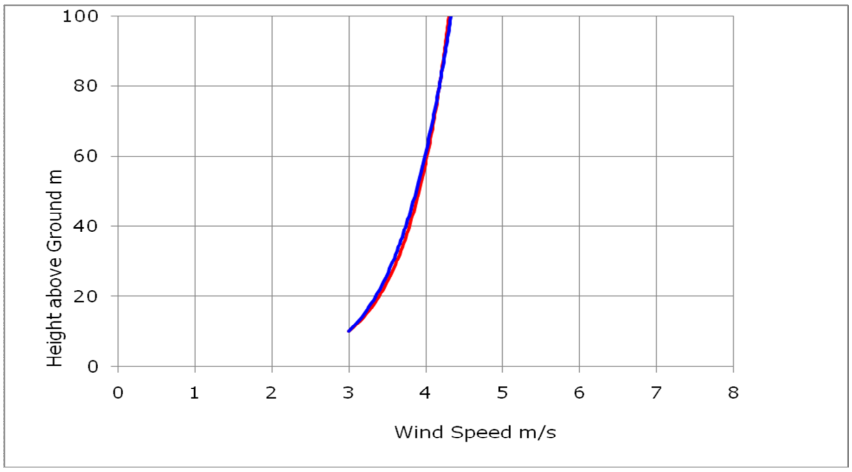
3 How Wind Varies with Height

Wind speed normally increases with height above the ground. This is first due to the fact that winds at higher level are slowed down near the ground because of the friction of the surface. This resulted in an algorithm for the variation of wind speed with height using a "roughness length". It was thought that the length of the "roughness" of the ground would be the determining factor in how much friction there was. For example a roughness length of 50mm might represent short grass. The actual dimension used however bore little relation to the real life dimension. For example the European Wind Atlas states that "Very large cities with tall buildings and skyscrapers" should have a roughness length of 1.6m. Nevertheless the algorithm provided a useful tool as long as the actual values were not taken too seriously.

The second factor influencing wind shear is meteorological conditions for which the wind shear exponent is normally used. This is a formula with an arbitrary exponent designed to fit the wind shear described in practice. These two methods are described in many publications so I do not intend to detail them here.

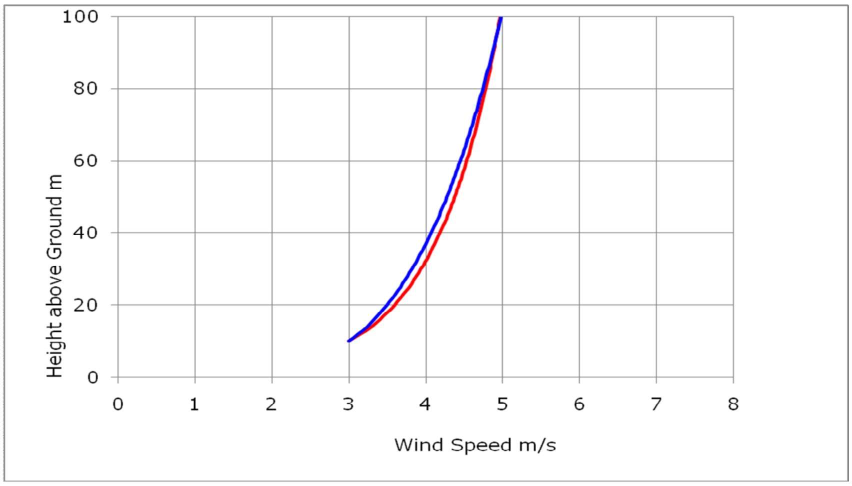
An examination of the two methods shows that there is nothing to choose between them as far as providing a fit to a given situation. Fig 4 shows the graphs of Roughness length 0.05 (in red) and exponent 0.16 (in blue).

Fig 4



The graphs are so close together as to be indistinguishable. Fig 5 shows the curves for a Roughness length of 0.3 and an exponent of 0.22. Again the curves are very close.

Fig 5

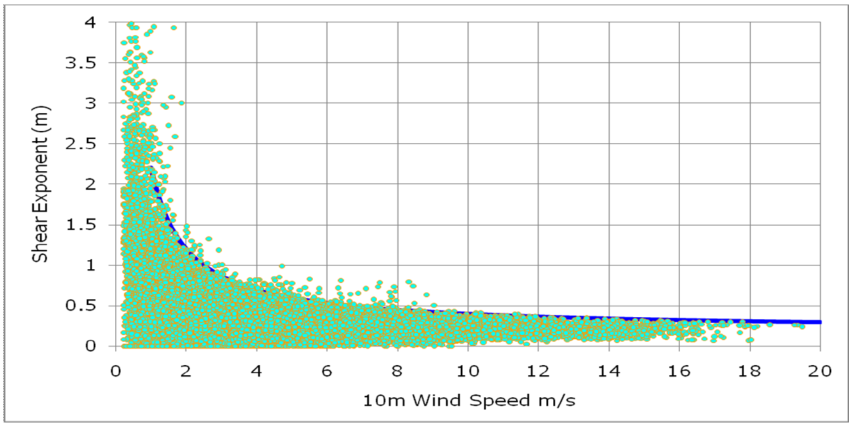


In this paper I use the exponent method for all the calculations and presentations.

4 WIND SHEAR

Fig 6 shows the result of measurements of wind speed on Site 2. The measurements are 10-minute periods over about nine months making over 30,000 data points in all. The horizontal axis shows the 10m wind speed as measured by a 10m anemometer. The vertical axis is the value of the shear exponent "m" calculated from wind speeds at 60m and 40m. It can be seen that, with the exception of a few outliers, there is a well defined maximum value of m for each wind speed. The blue line is an approximation to the maximum shear value and is the line defined by the formula $m=2/V_{10}+0.2$ where V_{10} is the 10m wind speed and m is the shear exponent.

Fig 6

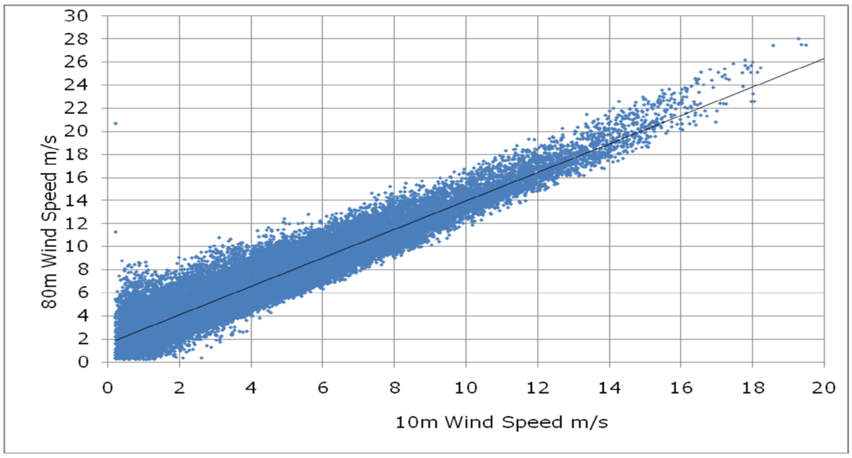


This is a typical pattern shown by all analysis of shear data. On flat land and hill land, in principle, the pattern is always the same irrespective of location, time of day or time of year. There are differences in detail which I will come to later.

At low wind speeds the wind shear can be very high but the degree of shear reduces with wind speed. In this case at a 10m wind speed of 8m/s the shear exponent can more or less be said never to exceed m=0.5. (Put into context the handful of points on the graph above the blue line compare with the total number of over 30,000 points on the graph). The other feature is that above 6 to 8m/s there is always some shear as can be seen where the markers lift off the x-axis.

If we take the data in fig 6 and use them to plot the 80m wind speed against the 10m wind speed we get the result shown in Fig 7. 80m is chosen to represent a typical hub height so that wind at hub height can be compared with the standard 10m wind.

Fig 7



The graph shows that there is a greater proportional spread of 80m wind speeds at low wind speeds. At a 10m wind speed of 4m/s the 80m wind speed can vary between 4 and 10m/s, a range of 150% of the 10m speed but at a 10m wind speed of 10m/s the range is only 40%. The absolute spread also decreases from 6 to 4m/s in the two cases described.

Generally the most sensitive 80m wind speeds for residents are between 7m/s and 10m/s. This is when background noise levels may not have started rising significantly but turbine noise is often near its maximum. It is the wind shear in this area that is important for assessing the impact of noise on residents.

5 DIURNAL PATTERNS

The first variation of wind shear that I want to look at is diurnal variation. Van den Berg[3] and others have shown that wind shear is greater at night during the day. Fig 8 below shows 10 minute data for Site 4 (flat site) between 1000 and 1600hrs over a year. These times of day are chosen because they are in daylight for the whole year. Fig 9 shows data from the same site recorded between 2200 and 0400hrs, the time that is in darkness throughout the year.

Fig 8

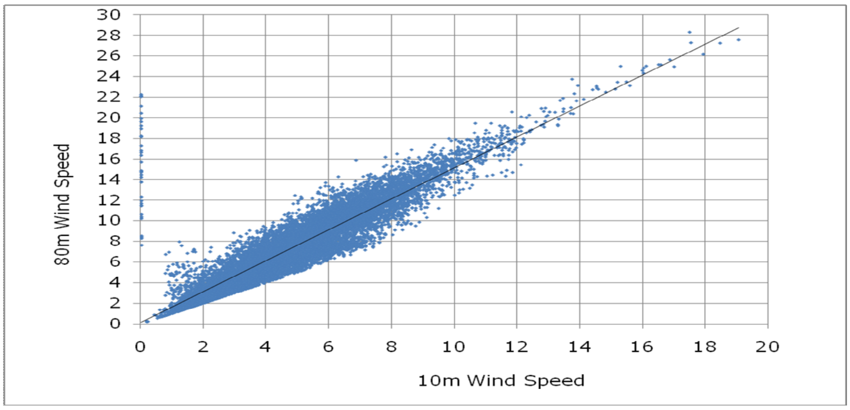
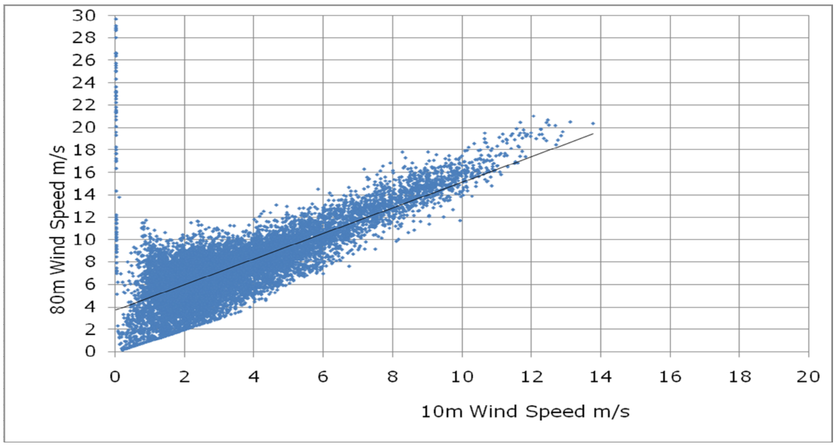


Fig 9



The difference between the two can be clearly seen. Perhaps the most striking result is the much greater spread of 80m wind speeds at night. This means that, at a 10m wind speed of 2m/s, when background noise is likely to be very low the turbines could be running at full sound power in a wind of 8m/s for a small but significant amount of time whilst during the day the hub height wind speed would never exceed 6m/s. The large spread of data indicating high wind shear that can be seen at lower wind speeds in the 24 hour graph, Fig 7, is entirely due to the large spread that occurs at night time.

Figs 10 and 11 show the same situation but this time for hilly sites. The principles are exactly the same in that the actual wind shear and the spread of wind shear are greater at night than during the day in particular at low wind speeds.

Fig 10

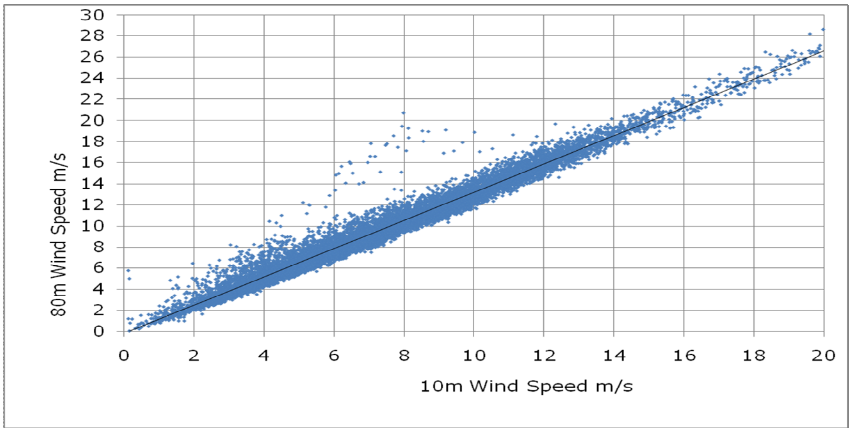
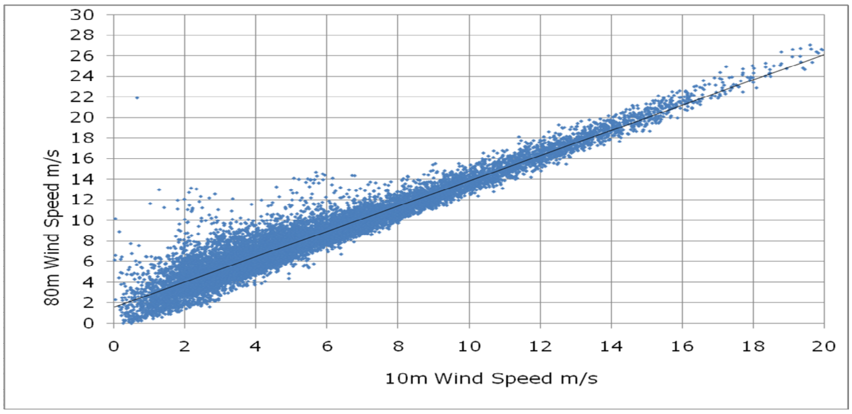


Fig 11



6 Annual Patterns

Fig 12 shows the plot of 80m wind speed against 10m wind speed again, this time for all times of day and night in the months April to September – the Summer period – for site 4. Similarly fig 13 shows the same thing for the winter months of October to March.

Fig 12

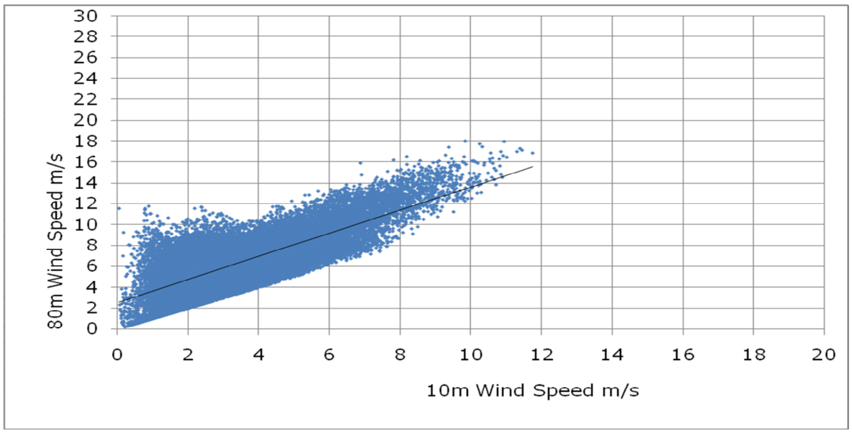
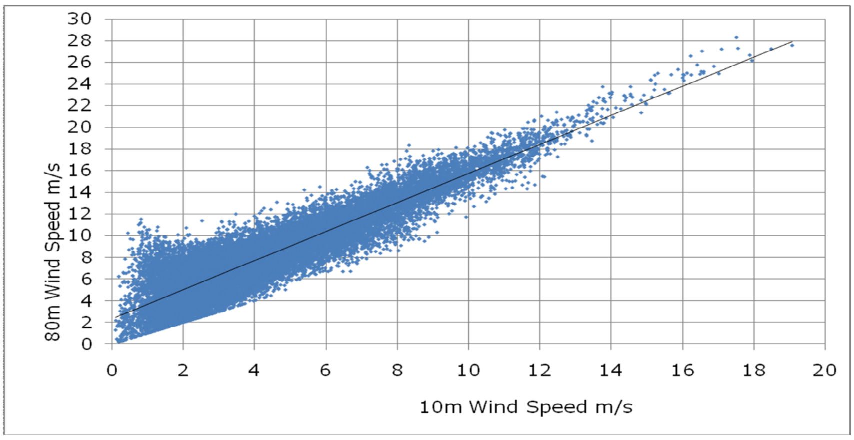


Fig 13



The main difference between summer and winter is that the there are more higher wind speeds in winter. The average wind shear exponent in winter is 0.35 and in summer is 0.30 for this site. The figures suggest a slightly greater wind shear in winter but it might be expected that there would be higher wind shear in winter because of the longer nights.

7 TOPOGRAPHY

It is often thought that wind shear is higher on flat sites. Figs 10 and 11 show the conditions on a hilly site during the day and night (6 hours duration each as described previously). Comparing these with Figs 8 and 9 for a flat site it is clear that, overall, there is much less spread and much lower wind shear, particularly at night, on the hilly site than the flat site. There is still the same pattern of more spread at night and higher shear generally at night.

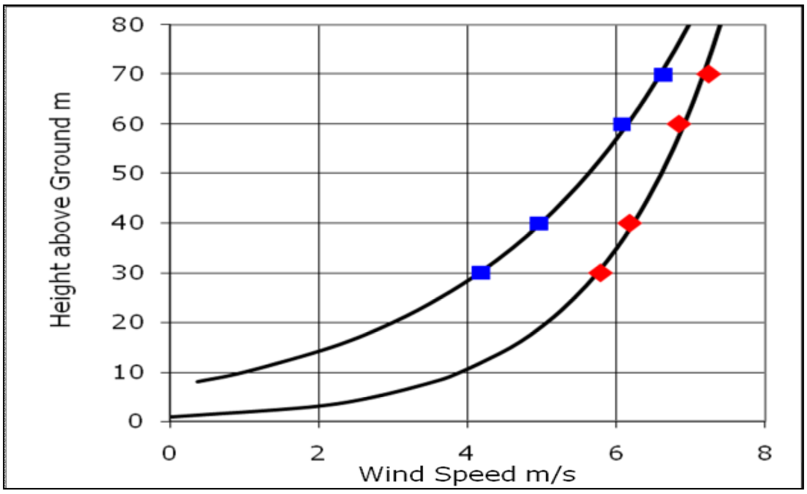
8 FORESTRY

Conveniently we have a series of masts set up for a number of wind farms in the same region that are all within about 10km of one another. In particular there are two masts with anemometers at the same height for which I have data overlapping so that there are comparative data for about two months. One of these is in forestry around 15m high and the other in open ground.

The average shear exponent for the period was 0.54 for the mast in the forestry but only 0.32 for the mast outside.

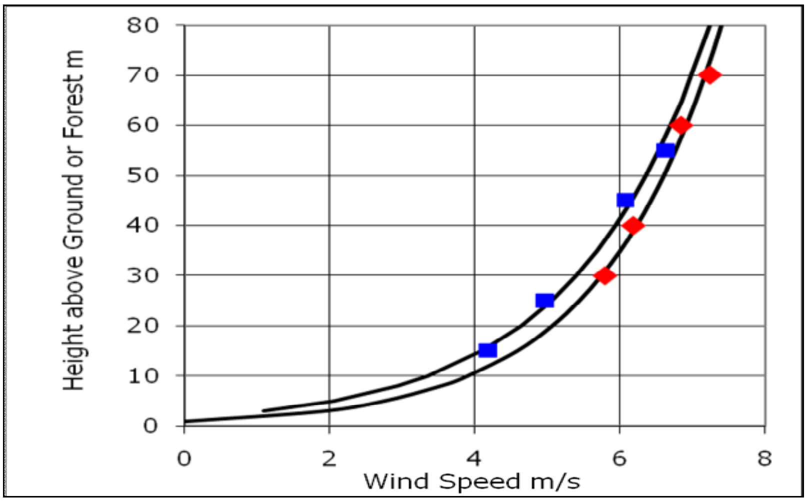
Fig 14 shows the variation of wind speed with height together with the best fit lines. It can be seen that, over the forestry there is a much greater wind shear.

Fig 14



If we shift the forestry curve so that we measure the height of the anemometers as height above the forest canopy instead of the ground then we see from fig 15 that the curves are much closer.

Fig 15



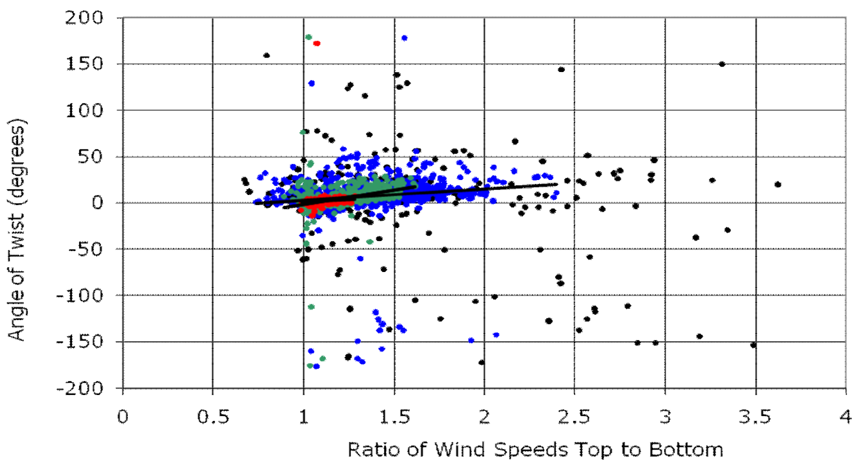
Even treating the tops of the trees as ground level there is still some additional wind shear, presumably due to the roughness of the forest canopy. So if turbine towers are increased for forestry to account for the additional height of the trees, roughness for forestry of 0.3m should nevertheless still be used to assess shear.

9 Twist

It is not only wind speed that changes with height but wind direction. Meteorologists appear to call the variation of wind direction with height "shear" in the same way as the variation of speed with height. I have called it "twist" to distinguish the two. It seems unlikely that twist will make a significant difference to sound power output, though it may make a difference to the sound characteristics of the turbine in that increased amplitude modulation may take place where the wind direction at the top of the trajectory is significantly different from that at the bottom.

The convention I have used for describing twist is that it is positive when the wind direction at the upper level is clockwise of the wind direction at the lower level. Twist is normally positive in the northern hemisphere and negative in the southern hemisphere.

Fig 16



The diagram shows a typical pattern of wind variation with height.

The X-axis shows the ratio of wind speed at 125m to the wind speed at 45m. The further to the right we move the greater the vertical shear. The Y-axis shows the angle of twist. These heights are chosen to represent the top and bottom of the trajectories of a typical turbine blade.

Black shows wind speeds up to 2.5m/s at 10m. These would be wind speeds where it is unlikely that the turbine would be operating. As it can be seen the vertical shear and the twist are widely scattered around the graph.

The blue series shows wind speeds at 10m of 2.5 to 4.5m/s. At these speeds the turbines would normally be operating but not at maximum noise level. As can be seen the points are tighter together but still with significant twist. On average there is a wind speed ratio around 1.5 and a twist of about +10 degrees. However, there are many data points where the twist is as high as 30 to 40 degrees.

The green series is 4.5 to 7.5m/s 10m wind speed which is the speed where turbines are most likely to have noise levels in excess of background by the greatest margin. Here the twist is generally less than 10 degrees and the speed ratio less than 1.5. Finally the red series shows wind speeds greater than 7.5m/s at 10m high where both shear and twist are much smaller.

The distinct trend is that increasing twist is associated with increasing vertical shear and that the highest levels of both occur at lower wind speeds. If a high wind speed ratio and high twist are contributory factors in excessive amplitude modulation then it is more likely to occur at lower wind speeds than at higher ones

10 CONCLUSIONS

Wind shear is highest and exhibits the greatest spread at low wind speeds. It reduces with increasing wind speed to the point where it is, on average, of a similar value as that used in IEC 61400-11 to define wind turbine sound power levels.

The spread at low wind speeds is more predominant at night on all sites. Night time wind shear is, on average, higher than day time.

There does not appear to be a large difference between average wind shear in summer and winter. The evidence suggests that shear in winter may be slightly higher but this may be due to the fact that there are longer nights when shear is higher.

Wind shear on a flat site is significantly higher than that on a hilly site, even a hilly site with low rolling hills. The spread of wind shear is also higher on a flat site. This is true at all times of day and all times of the year.

At a hub height wind speed of between 7 and 10m/s the sound power level of most turbines levels off and as wind speed further increases the background noise rises more quickly than the turbine noise. Hence this is the area where turbine noise is at its greatest margin over background noise and so is most intrusive. If we take a hub height of 80m we can calculate the average wind speed at 10m above the ground which is more likely to determine the masking background noise level. In other words the lower the 10m wind speed the lower the background noise but the turbine noise is always the same. The “Standard” line in the tables showing a 10m wind speed of 6.1m/s is the wind speed that would be expected using a roughness length of 0.05m. So where 10m wind speeds are less than this there is “excess” shear and so background noise levels will be lower.

10m Wind Speed re 8.5m/s at Hub		
	Day	Night
Standard	6.1	6.1
Exposed	6.5	5.6
Hilly	6.4	5.0
Flat	5.4	3.5

It should be noted that these are averages. For example the average 10m wind speed for a flat site at night is 3.5m/s but reference to Fig 9 shows that it can often be as low as 1 to 2m/s.

The table below shows the differences between winter and summer.

10m Wind Speed re 8.5m/s at Hub		
	Winter	Summer
Standard	6.1	6.1
Exposed	6.0	6.1
Hilly	5.5	5.6
Flat	4.4	4.5

High twist tends to occur together with high vertical shear. Twist is more significant, like shear, at lower wind speeds.

11 REFERENCES

[1] G.P.van den Berg. Wind turbines at night: acoustical practice and sound research. Euronoise 2003.

[2] G.P.van den Berg "Do wind turbines produce significant low frequency sound levels?" 11th International Meeting on Low Frequency Noise and Vibration. 2004.

[3] G.P.van den Berg. As note 1.