PROBABLE CAUSE OF AERODNYAMIC MODULATION

1. Introduction

Aerodynamic modulation is a term used to describe a larger-than-normal amplitude modulation of the aerodynamic noise from wind turbines. Aerodynamic modulation causes wind turbine noise to take on a loud, "thumping" character and to become audible at a considerable distance from the wind turbines.

In his doctoral dissertation, **The Sounds of High Winds**, Dr. Van den Berg puts forward a suggestion – based on both atmospheric physics and experimental results – that aerodynamic modulation occurs when the atmosphere becomes stable.

This note gives a summary of Dr. Van den Berg's ideas and outlines the implications for the Government's guidelines on the assessment and rating of noise from wind farms.

2. Unstable, Stable and Neutral Atmospheres

In simple terms, atmospheric conditions can be described as unstable, neutral or stable.

- An **unstable** atmosphere is characterised by significant thermal turbulence.

  The atmosphere over flat land is generally unstable during the day when the sun is shining. The sun heats the ground, which in turn warms the air immediately above it. This warm air then rises through the cooler air above it, giving rise to turbulence.

- In a **stable** atmosphere there is very little large-scale turbulence.

  During clear nights the ground cools because it radiates heat into the sky, and the air is cooled from below. The cold, denser air remains close to the ground, and there is no rising air to generate thermal turbulence.

  In stable conditions there can also be an inversion layer; i.e. a layer in which the air temperature increases with increasing height (as opposed to the normal decrease with height).

- In a **neutral** atmosphere thermal effects are less significant.

  Neutral atmospheric conditions occur when there is heavy cloud cover, so that the ground is not warmed by solar heating or cooled by outgoing radiation. They also occur during strong winds, when frictional turbulence dominates over thermal turbulence.

  Note: Atmospheric stability is of interest to people spraying crops, because an unstable atmosphere assists upward motion of air (and chemical droplets), a stable atmosphere resists such upward motion, and a neutral atmosphere neither assists nor resists it.

3. Effect on Wind Speeds

In an unstable atmosphere there is significant vertical motion of air and a good deal of interaction between air at different heights. Although not strictly accurate, it may be useful to think of the thermal turbulence creating 'friction' between different layers of air. See figure 1. Moving air in one layer 'pulls along' the layer below, which in turn pulls along the layer below that. The movement of the bottom layer of air is determined by the 'pull' of the level above and the frictional drag of the ground. The interactions between the different layers give rise to the standard wind speed profile.

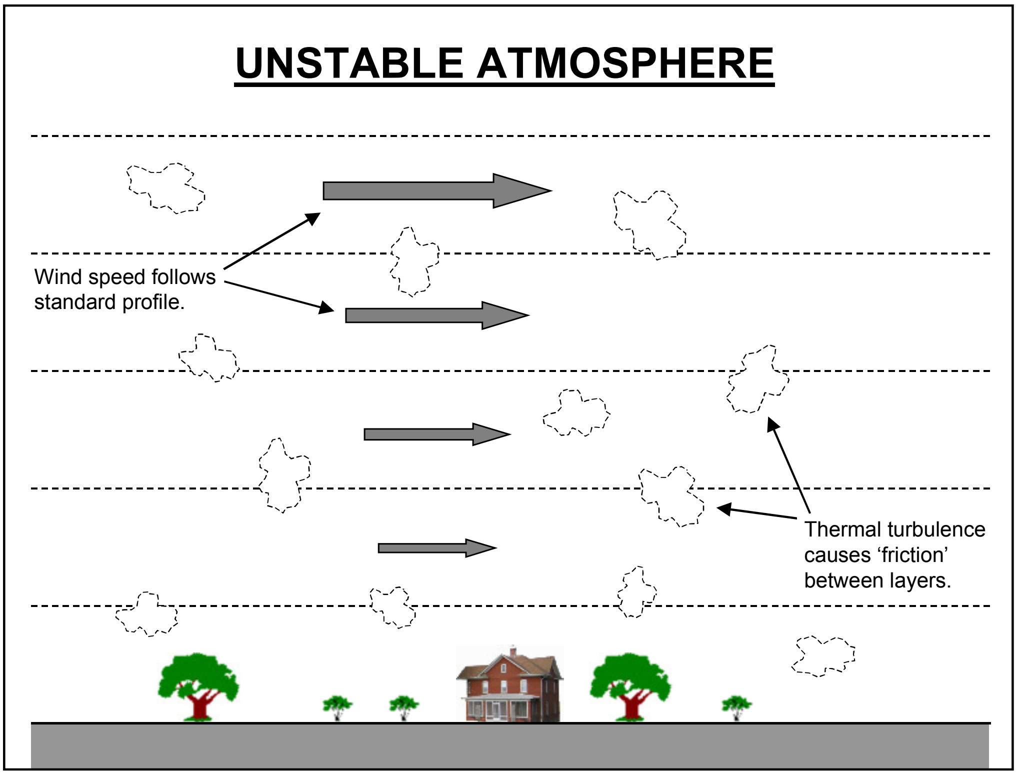

Figure 1

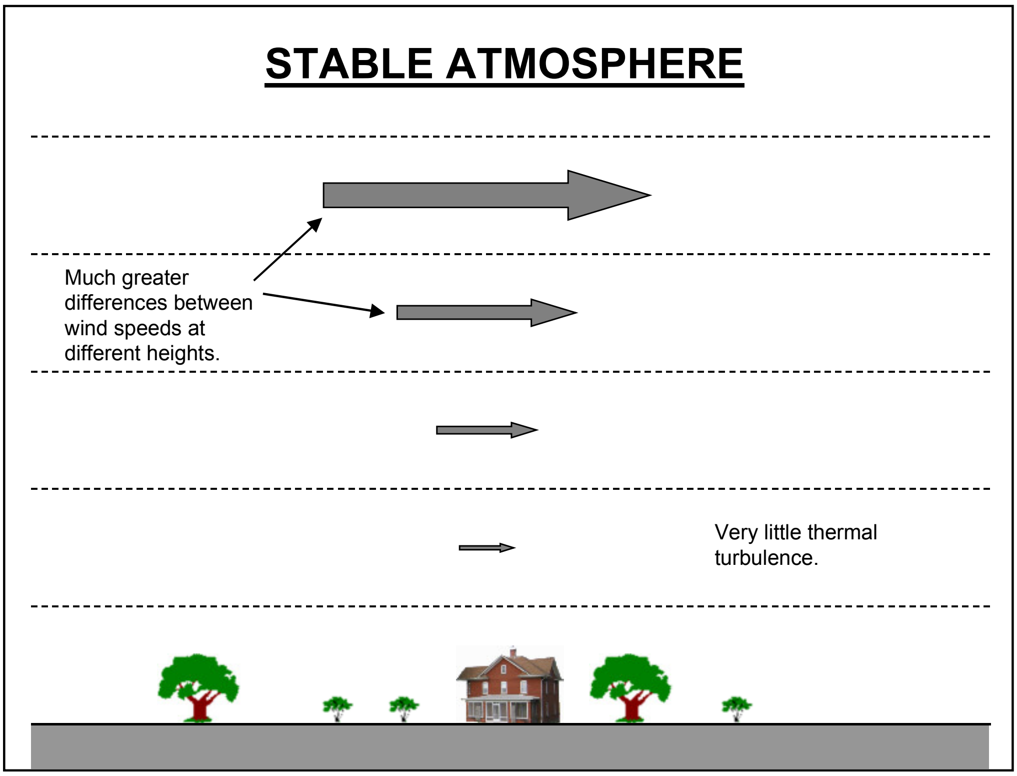

Figure 2

In a stable atmosphere the vertical movements in the air are damped, so there is little friction between layers and as a consequence there can be a larger difference between the wind velocities at different heights. See figure 2.

4. Effect of Stable Atmospheric Conditions on Wind Turbine Noise Levels

The steeper wind speed profile during stable atmospheric conditions means that:-

- The wind speed at turbine hub height is greater than would be predicted on the basis of the measured wind speed at 10 metres and the standard wind profile equation.
- The wind speed near the ground is less than would be predicted on the basis of the measured wind speed at 10 metres and the standard wind profile equation.

For example, **The Sounds of High Winds** says that for the wind farm at Rhede (near the border between Germany and the Netherlands) *"a 'stable' wind profile predicts a wind velocity* V_h *at hub height 1.8 times higher than expected and [this prediction] agrees excellently with the average measured night-time sound imission levels. Wind velocity at hub height may still be higher: at low wind velocities ...... the wind velocity* V_h *is at night up to 2.6 times higher than expected."*

Wind turbine noise depends on the wind speed at turbine hub height, and wind-induced noise depends on the wind speed near the ground, so during stable atmospheric conditions a wind turbine will produce more noise (and power) than predicted using the standard logarithmic wind speed profile, and at the same time the wind-induced background noise at ground level will be less than predicted.

5. Effect of Stable Atmospheric Conditions on Wind Turbine Noise Characteristics

The Sounds of High Winds also says that *"atmospheric stability is not only relevant for wind turbine sound levels ...... but also for the character of the sound. In conditions where the atmosphere is stable, distant wind turbines can produce a beating or thumping sound that is not apparent in daytime."*

ETSU-R-97 recognises *"blade swish"*, which it describes as *"the amplitude modulation at blade passing frequency of the aerodynamic noise"*.

Amplitude modulation of the aerodynamic noise at blade passing frequency must be due to differences in the environments experienced by a turbine blade as the rotor turns. See figure 3. From rotational symmetry, the only differences in a blade's environment as it sweeps round are due to (a) the direction of gravity, (b) the presence of the support tower and (c) the wind velocity profile across the rotor swept area.

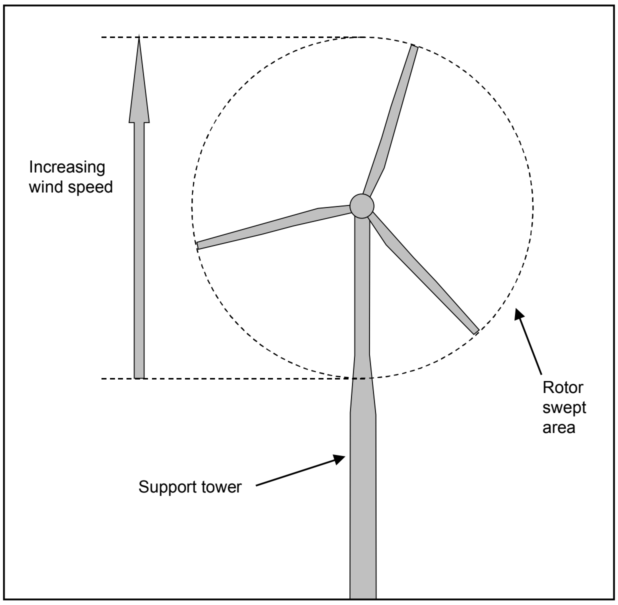

Figure 3

As a blade sweeps round it will encounter different wind velocities at different parts of its circuit. If these differences are contributing to the "blade swish" amplitude modulation of the aerodynamic noise – by whatever mechanism – then it is reasonable to expect that the magnitude of the modulation will increase when the slope of the wind velocity profile increases. Stable atmospheric conditions could therefore be expected to cause an increased degree of amplitude modulation of the aerodynamic noise; i.e. aerodynamic modulation.

This is confirmed by **The Sounds of High Winds**, which says that *"there are three factors influencing blade swish level when the atmosphere becomes more stable: a) the higher wind velocity gradient, b) the higher wind direction gradient, and c) the relative absence of large scale turbulence."* It goes on to say that the effect of wind direction gradient is negligible. However, as the blade pitch angle remains constant (optimised for the wind speed at hub height) as the rotor rotates, the angle of attack – which is the angle between the incoming air flow and the turbine blade chord – changes as the blade sweeps round and encounters different wind speeds. The change in the angle of attack affects the aerodynamic noise emitted by the blade.

The effect is exacerbated because when the blade is vertically downwards – and the blade tip is at the height with the lowest wind speed – it passes the tower, which acts as an obstruction to the wind and therefore further reduces the wind speed experienced by the blade.

In **The Sounds of High Winds**, Dr. Van den Berg calculates that *"for V_{100} = 14 m/s, the 1 - 2 dB daytime blade swish level increases to approximately 5 dB in a very stable atmosphere. The effect is stronger when wind velocity increases, up to the point where friction turbulence overrides stability and the atmosphere becomes neutral."*

6. Synchronisation of Noise from Multiple Wind Turbines

The lack of large-scale turbulence also means that during stable atmospheric conditions the wind speed at a given height is more uniform, which can cause the different wind turbines in a wind farm to run nearly synchronously, producing a reinforced 'beating' noise.

The Sounds of High Winds says that *"in unstable conditions the average wind velocity at the turbines will be equal, but instantaneous local wind velocities will differ because of the presence of large, turbulent eddies at the scale of the inter-turbine distance".* However, *"in a stable atmosphere turbines in a wind farm can run almost synchronously because the absence of large scale turbulence leads to less variation superimposed on the constant (average) wind velocity at each turbine."* The result is that in stable atmospheric conditions *"several turbines can be nearly synchronous: sometimes two or more turbines are in phase and the blade passing pulses coincide, then they go out of phase again"*.

When two or more turbines are nearly in phase their noise emissions reinforce each other, giving a louder 'beating' effect. During Dr. Van den Berg's experimental work he encountered one particular night when *"a distinct beat was audible: a period with a distinct beat alternating with a period with a weaker or no beat, repeated more or less* *during the entire night. This pattern is compatible with a complex of three pulse trains with slightly different repetition frequencies of ca. 1 Hz."* This is well illustrated in Figure V.4 on page 75 of **The Sounds of High Winds**.

In situations where two or more turbines are comparably loud, the place where their noise pulse trains combine to produce an amplified beating effect will *"sweep over the area with a velocity determined by the difference in rotational frequency"*.

7. Implications for the Government guidelines on noise from wind farms

The Government guidelines on noise from wind farms is contained in ETSU-R-97, **The Assessment and Rating of Noise from Wind Farms**.

Distance at which wind turbine noise is audible

ETSU-R-97 recommends that the noise limits should be set relative to the existing background noise at the nearest noise-sensitive properties.

However, there are consistent reports that aerodynamic modulation is difficult to detect close to wind farms but becomes much more noticeable further away; e.g. at distances of more than 500m.

In their paper on **Noise Pollution from Wind Turbines**, Julian & Jane Davis state that *"once you get closer than 600 metres detection [of AM] becomes difficult"* but that *"whoomph, roar and AM ..... can easily be detected up to 1500 - 2000 metres from the wind farm"*.

In **The Sounds of High Winds**, Dr. Van den Berg says that *"in quiet nights the wind farm can be heard at distances of up to several kilometers when the turbines rotate at high speed. In these nights, certainly at distances from 500 to 1000 m from the wind farm, one can hear a low pitched thumping sound with a repetition rate of about once a second (coinciding with the frequency of blades passing a turbine mast), not unlike distant pile driving, superimposed on a constant broad band 'noisy' sound."*

Therefore, when aerodynamic modulation is a potential issue it is not appropriate to restrict the noise monitoring (and the scope of planning conditions) to 'the nearest noise-sensitive properties'. Properties further from the wind farm also need to be included.

Lack of wind-induced masking noise near the ground

ETSU-R-97 uses the wind speed at a height of 10 metres above ground level as an indicator of the level of wind-induced 'masking noise' near the ground.

Under 'neutral' atmospheric conditions the wind speeds at different heights above the ground can be assumed to follow a standard profile, characterised by the equation

$$\frac{V1}{V2} = \frac{\ln\left(\frac{h1}{z0}\right)}{\ln\left(\frac{h2}{z0}\right)}$$

where ***V1*** = wind speed (m/s) at a height of ***h1*** metres above ground level

V2 = wind speed (m/s) at a height of ***h2*** metres above ground level

z0 = ground roughness length (m)

Note: This wind speed profile equation actually assumes a neutral atmosphere, but the profiles for unstable and neutral atmospheres are fairly similar. It is the stable atmosphere profile that is significantly different.

However, **The Sounds of High Winds** points out that in some atmospheric conditions this relationship breaks down and, in particular, there can be significant wind speeds at a height above the ground while there is virtually no wind at all at ground level. This means that wind turbines can be producing significant levels of noise when there is minimal wind-induced masking noise at ground level, and that a measurement of the wind speed at 10 metres above ground level will over-estimate the degree of wind-induced masking noise at ground level.

This is illustrated in figure 4. As the wind speed increases at 10 metres above the ground, ETSU-97-R expects the wind-induced background noise level near the ground to increase. This is reasonable when the wind speeds are in conformance with the standard profile. However, in a stable atmosphere it is possible for there to be virtually no wind – and therefore very little wind-induced background noise – at ground level even when there is wind at higher levels. In these circumstances ETSU-R-97 would allow the turbines to generate noise significantly above the background noise level.

Note: Figure 4 is adapted from Figure 9 on page 67 of ETSU-R-97.

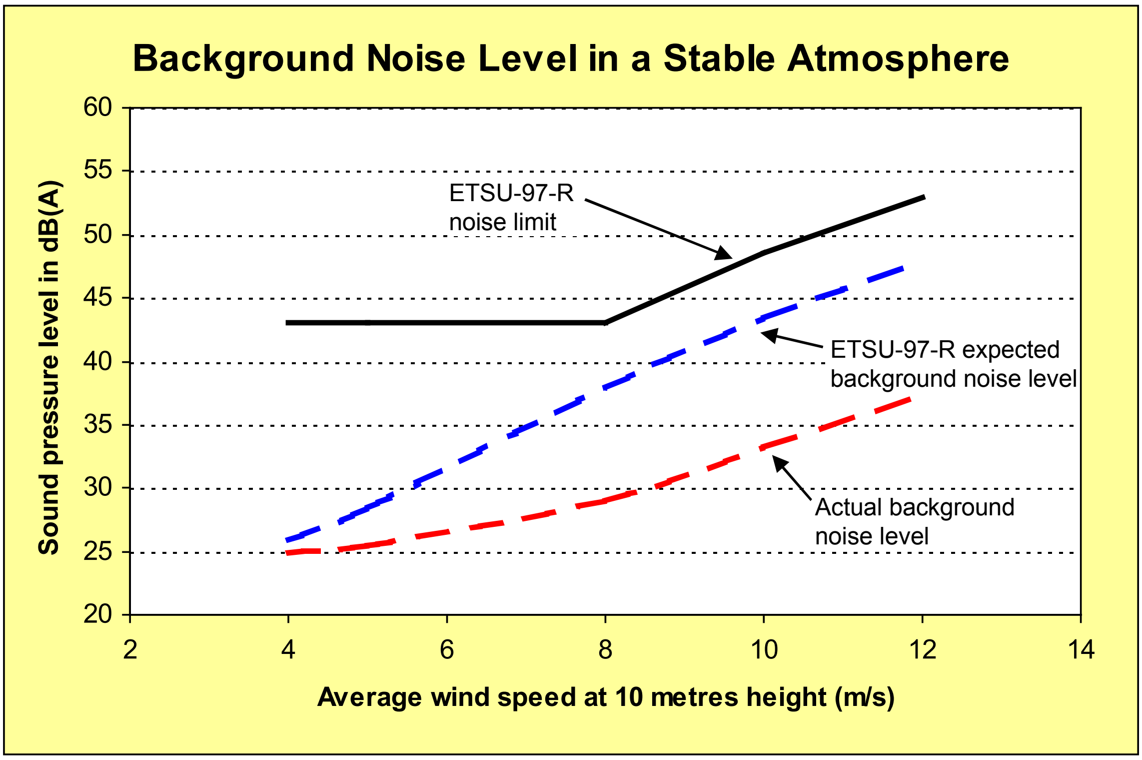

Figure 4

Magnitude of the amplitude modulation

ETSU-R-97 expects "blade swish" to *"result in a variation of the overall A-weighted noise level by as much as 3dB(A) ...... when measured close to a wind turbine"* but that *"as distance from the wind turbine / farm increases, this depth of modulation would be expected to decrease as atmospheric absorption attenuates the high frequency energy radiated by the blade".*

By comparison, from noise measurements at the Rhede wind farm, Dr. Van den Berg found that *"in a stable atmosphere, measured fluctuation levels are 4 to 6 dB for single turbines, and in long term measurements (over many 5 minute periods) near the Rhede wind farm fluctuation levels of approx. 5 dB are common but may reach values up to 9 dB."*

8. Summary

It is highly likely that one form of aerodynamic modulation (AM) is effectively an exaggerated version of "blade swish" in stable atmospheric conditions. Contributory factors are (a) the steeper wind speed profile across the rotor swept area, and (b) mutual reinforcement of the noise trains from two or more wind turbines running nearly synchronously.

As **The Sounds of High Winds** says, *"in stable conditions ...... wind turbine sound can be heard at greater distances"* and is *"a louder and more low frequency 'thumping' sound and less the swishing sound that is observed close to a daytime wind turbine".*

9. Contact information

For further information, or to make any comments about this note, please contact Alastair Mackenzie by phone on 01325-33333 or via email at alastair@batmail.co.uk.

Reference

Dr. Van den Berg's dissertation on **The Sounds of High Winds** can be downloaded from the University of Groningen web site at http://irs.ub.rug.nl/ppn/294294104.