

## The Beat is Getting Stronger: The Effect of Atmospheric Stability on Low Frequency Modulated Sound of Wind Turbines

G.P. van den Berg

University of Groningen - Science Shop for Physics  
Nijenborgh 4, 9747AG Groningen, the Netherlands  
g.p.van.den.berg@rug.nl

Received 3rd MARCH 2005

### SUMMARY

Sound from wind turbines involves a number of sound production mechanisms related to different interactions between the turbine blades and the air. An important contribution to the low frequency part of the sound spectrum is due to the sudden variation in air flow which the blade encounters when it passes the tower: the angle of attack of the incoming air suddenly deviates from the angle that is optimized for the mean flow. Hitherto, low-frequency sound from wind turbines has not been shown to be a major factor contributing to annoyance. This seems reasonable as the blade passing frequency is of the order of one hertz where the human auditory system is relatively insensitive. This argument, however, obscures a very relevant effect: the blade passing frequency modulates well audible, higher-frequency sounds and thus creates periodic sound: *blade swish*. This effect is stronger at night because in a stable atmosphere there is a greater difference between rotor averaged and near-tower wind speed. Measurements have shown that additional turbines can interact to further amplify this effect. Theoretically the resulting fluctuations in sound level will be clearly perceptible to human hearing. This is confirmed by residents near wind turbines with the same common observation: often late in the afternoon or in the evening the turbine sound acquires a distinct 'beating' character, the rhythm of which is in agreement with the blade passing frequency. It is clear from the observations that this is associated to a change toward a higher atmospheric stability. The effect of stronger fluctuations on annoyance has not been investigated as such, although it is highly relevant because a) the effect is stronger for modern (that is: tall) wind turbines, and b) more people in Europe will be living close to these wind turbines as a result of the growth of wind energy projects.

### 1. INTRODUCTION

Modern onshore wind turbines have peak electric power outputs of around 2 Mw and tower heights of 80 to 100 meters. In 2003, 75% of the global wind power peak electric output of 40 Gw was installed in the European Union. The original European target for 2010 was 40 Gw, but the European Wind Energy Association have already set a new target for 2010 of 75 Gw, of which 10 Gw is projected off-shore, while others have forecast a peak output of 120 Gw for that year [1]. Whether this growth will actually occur is uncertain; with the proportional increase of wind energy in total electric power the difficulties and costs of integrating large scale windpower with respect to grid capacity and stability, reserve capacity and CO<sub>2</sub> emission reductions are becoming more prominent (see, e.g., [31, 32]). However, further expansion of wind energy is to be expected, and as a result of this (predominantly on-shore) growth an increasing number of people may face the prospect of living near wind farms, and have reason to inquire and perhaps be worried about their environmen-





## The Effect of Atmospheric Stability on Low Frequency Modulated Sound

Near the Rhede wind farm we found that, because of the *near*-synchronicity of several turbines, sometimes two or three were in phase and the blade passing pulses coincided, and then went out of phase again [2]. This would lead to a doubling (+3 dB) or tripling (+5 dB) of pulse height. If in a (very) stable atmosphere individual swish pulse heights are 3–5 dB (see section 3a above), synchronicity at the Rhede wind farm or similar configurations would thus lead to pulse heights of 6–10 dB.

Synchronicity here refers to the sound pulses from the different turbines as observed at the location of the observer. So, pulses synchronise when they arrive simultaneously. This is determined by differences in phase (rotor position) between turbines and in propagation distances of the sound from the turbines. Phase differences between turbine rotors occur because turbines are not connected and because of differences in actual performance. The place where synchronicity is observed will change when the phase difference between turbines changes. With exact synchronicity there would be a fixed interference pattern, with synchronicity at fixed spots. Because of near-synchronicity however, synchronicity will change over time and place and an observer will hear coinciding pulses for part of the time only.

A second effect of the decrease in turbulence strength is that in-flow turbulent sound level also decreases. The resulting decrease in broad band sound level lowers the minimum in the temporal variations, thereby increasing modulation depth.

We conclude that the higher wind speed gradient and (near-) synchronicity increase blade swish levels at some distance from a wind farm. The higher infrasound level due to extra blade loading is not perceptible because of the high hearing threshold at the very low blade passing frequency. However, the effect of added boundary layer turbulence on the blade increases the levels at the higher frequencies that already were dominating the most audible part of the sound. Near a wind farm the variation in sound level will depend on the distances of the wind turbines relative to the observer: the level increase due to several turbines will reach higher levels when more turbines are at approximately equal distances and thus contribute equal immission levels. The increase in level variation, or beating, is thus at well-audible frequencies and has a repetition rate equal to the blade passing frequency.

Thus, theoretically it can be concluded that in stable conditions (low ambient sound level, high turbine sound power and higher modulation or swish level) wind turbine sound can be heard at greater distances and is of lower frequency due to absorption and the frequency shift of swish sound. It is thus a louder and more low-frequency 'thumping' sound and less the swishing sound than observed close to a daytime wind turbine.

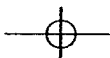
## 4. MEASUREMENT RESULTS

### 4.1. Locations

In the summers of 2002 and 2004 wind turbine sounds have been recorded in and near the Rhede wind farm on the German-Dutch border. The farm (figure 2) has a straight south to north row of ten turbines at approximately 300 m intervals, running parallel to the border, and seven less regularly spaced turbines east of the straight row. Each turbine is 98 m to the hub height, and has a blade length of 35 m, and produces nominally 1.8 MW electric power.

The measurement location at dwelling R is west of the turbines, 625 m from the nearest turbine. The microphone position was at 4 m height and close to the house, but with no reflections except from the ground. The measurement location at dwelling P, 870 m south of R, was 1.5 m above a paved terrace in front of the facade of the dwelling at 750 m distance from the nearest turbine. The entire area is quiet, flat, agricultural land with some trees close to the dwellings. There is little traffic and there are no significant permanent human sound sources.

A third dwelling Z is in Boazum in the northern part of the Netherlands, 280 m west of a single, two-speed turbine (45 m hub height, 23 m blade length, 20/26 rpm). The area is again quiet, flat and agricultural. The immission measurement point is at 1.5 m height above gravel near the dwelling. This measurement site is included here to show that the influence of stability on blade swish levels occurs also with



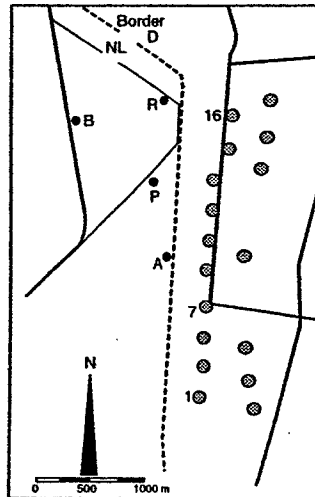


Figure 2 Turbines (grey circles) in and measurement locations (A,B,P,R) near the Rhede wind farm; solid lines are roads.

Table I. Overview of measurement locations and times and of turbine speed and wind

Location	Measurement		Turbine speed (rpm)	Wind speed (m/s)		Wind direction (° north)
	Date	Time		$v_{10}$	$v_{hub}$	
Dwelling P	June 3, 2002	00:45	20	5	14	100
Turbine 7	June 3, 2002	06:30	19	5	15	100
Turbine 1	June 3, 2002	06:45	19	5	15	100
Dwelling R	Sep. 9, 2004	23:07	18	4	14	80
Turbine 16						
Dwelling Z	Oct. 18, 2003	01:43	26	3	6	60

smaller, single turbines. At all locations near dwellings the microphone was fitted in a 9 cm diameter foam wind screen.

Table I gives an overview of measurement (start) times and dates of observed turbine speeds and of wind speed and direction, for situations for which results will be given below. The wind speed at hub height  $v_{hub}$  has been determined from turbine rotation speed  $N$  or sound power level  $L_w$  ([2], the relation  $v_{hub}-N$  follows from ref. 3 and 11 in [1]). The wind speed  $v_{10}$  at 10 m height was continuously measured at or near location A, except for location Z, where data from several meteorological stations were used showing that the wind was similar and nearly constant in the entire northern part of the Netherlands. In all cases there were no significant variations in wind speed at the time of measurement. Wind speed at the microphone was lower than  $v_{10}$  because of the low microphone height and shelter provided by trees nearby. Wind direction is given in degrees relative to north and clockwise (90° is east). The spectra near a turbine were measured with the microphone just above a hard surface at ground level 100 m downwind of a turbine in compliance with IEC 61400 [14] as much as possible (non-compliance did not lead to differences in result [2]; for reasons of non-compliance, see [34]). The levels plotted are immission levels: measured  $Leq$  minus 6 dB correction for coherent reflection against the hard surface [16]. The plotted levels near the dwellings are also immission levels: measured  $Leq$  minus 3 dB correction for incoherent reflection at the façade for dwelling P, or measured  $Leq$  without any correction for dwellings R and Z.