The sound of high winds

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VII THINKING OF SOLUTIONS: measures to mitigate night time wind turbine noise

VII.1 Meeting noise limits

Sound from modern wind turbines is predominantly the result of turbulence on the blades; reduction of this source is the topic of dedicated research, such as the SIROCCO (*Si*lent *ro*tors by a*c*ousti*c* *o*ptimisation) program which seeks to improve the design of the wind turbine blade; in the near future a reduction of approximately 2 dB might be achieved [Schepers *et al* 2005]. Sound reduction by reducing blade speed is an option already available in modern turbines.
In this chapter we will deal with the ('added') sound produced by a wind turbine due to increased atmospheric stability. To address this problem two types of mitigation measures can be explored:

1. reduce the sound level down to to the pertinent (legal) limit for environmental noise;
2. reduce the level variations due to blade swish/beating.

The first measure of course must be pursued as it is a legal obligation. The need for reduction depends on the type of limit. *E.g.*, in Germany the limit applies to the maximum sound immission level (the level produced at nominal maximum power), regardless of wind velocity as such. In many countries the limit is based on the wind velocity related background ambient sound level (L_{95} or L_{90}). In the UK and elsewhere the limit is a constant at low 10-m wind velocities and 5 dB above ambient background level (L_{90} + 5 dB) at higher 10-m wind velocities. In the Netherlands the standard limit is a reference curve constructed from a constant value at low 10-m wind velocities and a wind velocity dependent part at higher 10-m wind velocities (see figure VII.1). For wind farms over 15 MW other limit values may apply, and local authorities may enforce other limits in 'non-standard' local conditions.

In assessments of wind turbine noise immission the effect of atmospheric stability has usually been disregarded and the 10-m wind velocity was erroneously used for all atmospheric conditions. In that case high sound levels only occur at high wind velocities and this can be accommodated by limit values as in figure VII.1. In reality however these limits are not always met as high immission sound levels already occur at a lower 10-m wind velocity. This implies that an extra effort to reduce the immission level may be necessary.

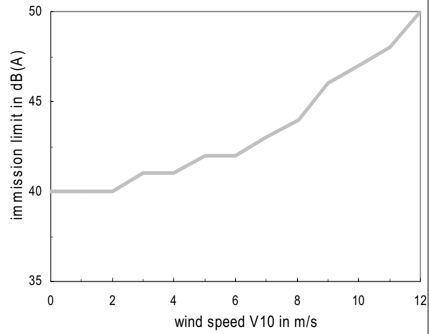

Figure VII.1: standard Dutch limit for night time wind turbine immission sound level

In hilly and certainly in mountainous terrain this change in wind profile may be influenced or even overridden by relief related changes. For example: in a valley a down flowing (decelerating) wind may enhance the effect of stability, whereas an up flowing (accelerating) wind may compensate the effect of stability. Furthermore the wind profile as well as the temperature profile will simultaneously influence the propagation paths of sound. Combined effects are therefore complex and, though readily understood qualitatively, not easily predicted quantitatively.

The second measure is worth considering when the noise limit incorporates a penalty for a sound having a distinctive (impulsive or fluctuating) character. In that case either the sound immission level should be reduced by a value equal to the penalty (usually 5 dB) or the sound character must change.

VII.2 Reduction of sound level

When the sound immission level is limited to a value depending on the 10-m wind velocity or the (supposedly 10-m wind velocity dependent) ambient sound level, the problem is that hub height wind velocity is not uniquely related to 10-m wind velocity and the sound emission as well as immission level can have a range of levels depending on atmospheric stability. The turbine thus operates at hub height wind velocity, but must be controlled by a 10-m based wind velocity. To decrease the sound level from a given turbine the speed of rotation can be decreased, either by directly changing blade pitch or indirectly by changing the mechanical load (torque) on the rotor. This implies a lower efficiency at the turbine as the tip speed ratio $\Omega \cdot R/Vo$ will decrease and deviate from its value optimized for produced power. It is necessary to find a new optimum that also takes noise production into account.

VII.2.1 Wind velocity controlled sound emission

As a result of opposition to wind farm proposals in the relatively densely populated central province of Utrecht in the Netherlands all proposals were cancelled but one. The exception is in Houten (incidentally 8 km east of Cabauw; see previous chapter), where the local authorities want to stimulate wind energy by allowing the constructing of several 3 MW turbines, at the same time ensuring that residents will not be seriously annoyed. Atmospheric stability is taken into account by not accepting the usual logarithmic relation between 10-m and hub height wind velocity. The official permission will require that the immission sound level at specified locations must not exceed the background level of all existing ambient sound. Of course ambient sound level depends on wind velocity if the wind is sufficiently strong, but in this area it also depends on wind direction as that determines audibility of distant sources: a motorway to the west, the town to the north-east and relatively quiet agricultural land to the south-east. So the ambient background level, measured as L_{95}, must be measured in a number of conditions: as a function of wind velocity (1 m/s classes), wind direction (4 quadrants) and time of day (day, evening, night). These values equal the limit values for the immission level L_{imm}, and from this it can be calculated what the maximum allowable sound power level L_{Wmax} per turbine is at every condition, presuming all (or perhaps a selection of) turbines produce. It is advisable to determine wind characteristics and turbine performance over a period of at least five minutes, as wind velocity variations are relatively strong at frequencies above approximately 3 mHz (inverse of 5 min) and weak at lower frequencies down to the order of 0.1 mHz (inverse of several hours) [Wagner *et al* 1996]. On the other hand it is desirable to adapt to changing conditions, so averaging over 5 minutes seems a good choice.

Control will thus be achieved in a number of steps:

1. measure wind direction D_{10} and wind velocity V_{10} in open land over a 5-minute period; from this determine the ambient back ground level from the previously established relation $L_{95}(D_{10},V_{10})$.
2. determine the limit value for the sound power level L_{Wmax} from the previously established relation $L_{imm}(L_W)$; the limit value is determined by $L_{imm} = L_{95}$.
3. determine the actual sound power level $L_{W,5min}$ from wind turbine performance (electric power or speed);
4. if $L_{W,5min} > L_{Wmax}$ (equivalent to $L_{imm} > L_{95}$) the control system must decrease sound power level for the next period; if $L_{W,5min} < L_{Wmax}$ the reverse applies (until maximum speed is attained).

The pro's of this control system are that it is straightforward, simple, easy to implement and directly related to existing Dutch noise limits. However, it is based on the assumption that L_{95} depends on three parameters only: wind velocity, wind direction and diurnal period (day, evening, night). In reality background level will also vary within a diurnal period (*e.g.* traffic: nights are very quiet at around 4 AM and most busy just before 7 AM), and it will depend on the day of the week (*e.g.* Sunday mornings are quieter than weekday mornings), the season (vegetation, holidays), the degree of atmospheric stability (no wind in low vegetation in stable conditions, even when 10-m wind velocity is several m/s) and other weather conditions such as rain. Also sound immission from distant sources will differ with weather conditions.

Measurements show that indeed 10-m wind velocity is not a precise predictor of ambient sound level. These measurements were performed from June 9 through June 20, 2005 at two locations: wind velocity was measured at 10-m height in open terrain, at least 250 m from any obstacles over 1 m height (trees lining the busy and broad Amsterdam-Rhine Canal to the northeast) and over 1000 m from obstacles in any other direction; the sound level was measured close to a farm next to the canal (see figure VII.2). Total measurement time was 220 hours.

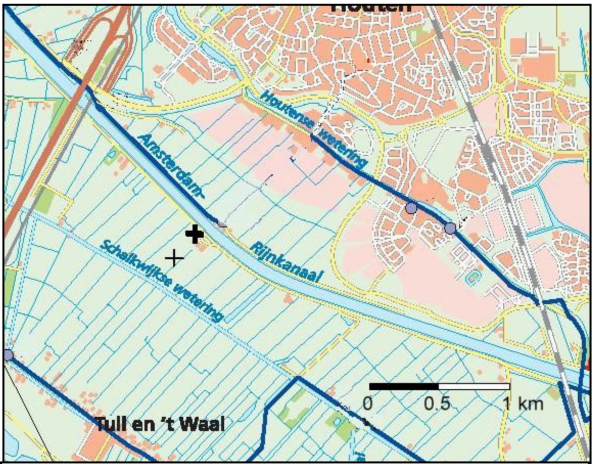

Figure VII.2: measurement locations for wind speed and direction (light cross) and ambient sound level (heavy cross) close to Houten (in upper part of map); top is north

Some results are plotted in figure VII.3: L_{95} per 5-minute period as a function of wind velocity, separately for two opposite wind directions (left and right panel) and two periods (black and blue markers). The periods are night (23 PM – 7 AM) and day (7 AM – 7 PM), the wind directions southeast (90° - 180° relative to north) and northwest (270° - 360°), where respectively the lowest and highest ambient levels were expected. The northwest data total 675 5-minute periods or 26% of all measurement time, the southeast data cover 511 periods or 19% of the measurement time.

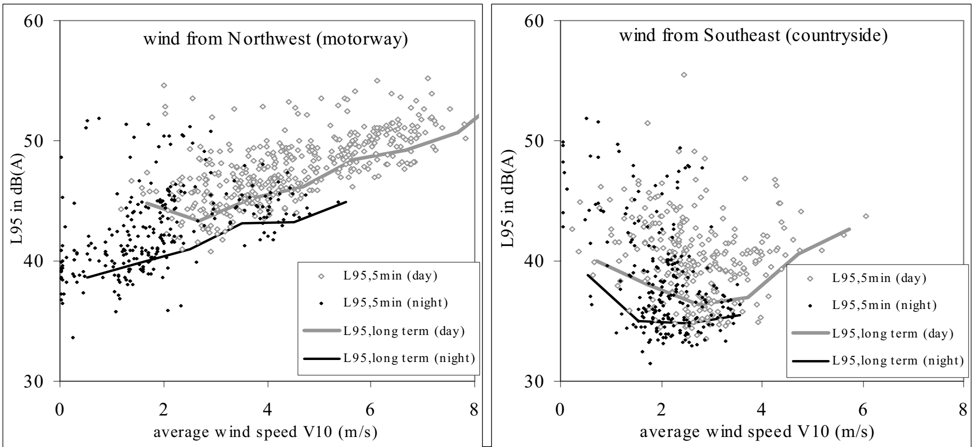

Figure VII.3: 5-minute $L_{95,5min}$ in day (open, grey diamonds) and night time (solid, black dots) and long-term L_{95} (lines) as a function of 10-m wind velocity in open terrain for two different wind directions

The values of $L_{95,5min}$ are calculated from all (300) 1-second samples of the sound pressure level within each 5-minute period, wind velocity is the average value of all 1-second samples of the wind velocity. To determine a long-term background level an appropriate selection (wind direction, period) of all measured 1-second sound levels can be aggregated in 1 m/s wind velocity classes (0-1 m/s, 1-2 m/s, etc.). In figure VII.3 these aggregated values (connected by lines to assist visibility) are plotted for day and night separately. It is clear that in many cases the 5-minute period values of L_{95} are higher, in less cases lower than the long-term value. This means that if the immission limit is based on the measured long-term background sound level, then in a significant amount of time the actual background level will not be equal to the previously established long-term background level. In many instances the actual value of L_{95} is higher than the long-term background level $L_{95,lt}$, which would allow for more wind turbine sound at that time.[1]

VII.3.2 Ambient sound level controlled sound emission

An alternative to a wind velocity controlled emission level is to measure the ambient sound level itself and thus determine the actual limit value directly. If the limit is L_{95}, then the immission level must be $L_{imm} \leq L_{95}$. To achieve this the background ambient sound level can be determined by measurement (*e.g.* in 5-minute intervals) and compared to the immission level calculated from the actual turbine performance. If the immission level L_{imm} would exactly equal the ambient background level L_{95} without turbine sound, it would attain its maximum value $L_{imm,max} = L_{95}$. Then background sound level including turbine sound would be L_{95+wt} = log.sum($L_{imm,max}$ + L_{95}) = $L_{imm,max}$ + 3 dB or $L_{imm,max}$ = L_{95+wt} - 3 dB. If the calculated immission level exceeds the measured ambient level L_{95+wt} - 3, turbine sound apparently dominates the background level and the turbine should slow down.

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[1] perhaps for this reason the approach in the British ETSU-R-07 guideline [ETSU 1996] is to not use the long-term $L_{A90,lt}$, but an average of 10 minute $L_{A90,10min}$ values; this odd statistical construction can be viewed as an inefficient compromise that effectively allows excess of an appropriate limit in half of the time and a too severe limit in the other half

This type of control can also be achieved in several steps. Again assuming 5-minute measurement periods, these are:

1. determine the actual sound power level $L_{W,5min}$ (integrated over 5 minutes) from turbine power production or speed.
2. determine L_{imm} from the previously established relation $L_{imm}(L_W)$.
3. measure actual background level $L_{95+wt,5min}$ at a location where the limit applies;
4. if $L_{imm} > L_{95+wt,5min} - 3$ dB, then $L_{W,5min} > L_{Wmax}$ and the control system must decrease sound power level for the next 5-minute period, if $L_{W,5min} < L_{Wmax}$ the reverse must happen (until maximum speed is attained).

Here it is assumed that the microphone is on a location where immission level must not exceed the ambient background level. If a measurement location is chosen further away from the turbine(s), the immission sound level will decrease with a factor ΔL_{imm} at constant L_W, whereas L_{95} will not change (assuming that 5-minute ambient background sound does not depend on location). In this case a correction must be applied to the measured L_{95+wt} ($L_{imm,max} = L_{95+wt} - 10 \cdot \log(1+10^{-0,1 \cdot \Delta Limm})$ to determine what sound power level is acceptable. An advantage of a more distant measurement location is that it is less influenced by the turbine sound. A similar approach may be used if the limit is not L_{95} itself, but L_{95} + 5 dB. In that case, is it not possible to determine L_{95} from measurements at a location where this limit applies, as the turbine sound is allowed to be twice as intense as background sound itself. In that case a measurement location may be chosen where, *e.g.*, ΔL_{imm} = 5 dB.

An apparent drawback of this sound based control is that measured ambient sound may be contaminated by local sounds, that is: from a source close to the microphone, increasing only the local ambient sound level. Also, figure VII.3 suggests that there are significant variations in $L_{95,5min}$, which could imply large control imposed power excursions if these variations occur in short time.

The first drawback can be solved by using two or more microphones far enough apart not to be *both* influenced by a local source. The limit value is then either $L_{95,5min}$ determined from all measured sound levels within the previous 5-minute period, or the lowest value of $L_{95,5min}$ from each microphone location. It must be borne in mind that the value of $L_{95,5min}$ is not sensitive to sounds of short duration. Sounds from birds or passing vehicles or airplanes do not influence a measured $L_{95,5min}$ significantly, except when they are present for most of the time within the 5 minute period.

With regard to the second point: large variations in either wind velocity or background sound level are rare, as is shown in figure VII.4 where the difference is plotted between consecutive 5-minute values of L_{95} and average free 10-m wind velocity. The change in wind velocity averaged over consecutive periods of 5 is less than 0.5 m/s in 72% of the time, and less than 1.5 m/s in 99% of the time. The change in background sound level over consecutive periods of 5 minutes is less than 2.5 dB in 88% of the time and less than 3.5 dB in 94% of the time. So, if the adjustment of sound power level is in steps no larger than 3 dB, most changes can be dealt with in a single step. This also holds when a longer averaging period of 15 minutes is chosen: the change in background sound level over

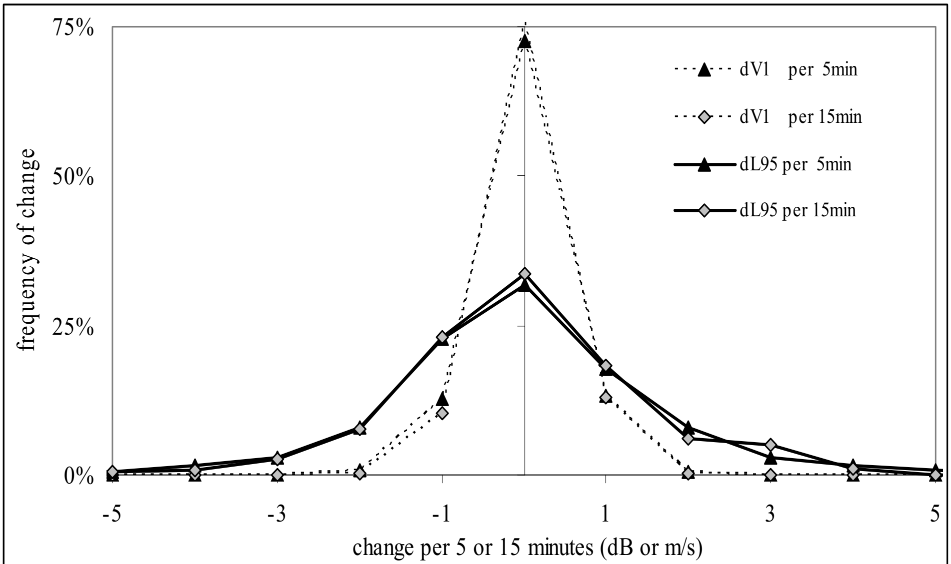

Figure VII.4: frequency distributions of changes per 5 and per 15 minutes of average wind velocity and background ambient sound level in classes of one unit (dB or m/s)

consecutive periods of 15 minutes is less than 2.5 dB in 89% of the time and less than 3.5 dB in 96% of the time.
The frequency of changes between 5-minute periods that are 10 minutes apart (that is: with two 5-minute periods in between) is very similar to the distributions in figure VII.4. This means that when there is a change of 3 dB for two consecutive periods, it is unlikely a similar change occurs within the next one or two periods.

VII.4 Reduction of fluctuations in sound level

The level variation due to blade swish increases when the atmosphere becomes more stable because the angle of attack on the blade changes. As a result the turbulent layer at the trailing edge of the blade becomes thicker and produces more sound. In a wind farm the increased level variations from two or more turbines turbines may coincide to produce still higher fluctuations. The increase of blade swish, or rather: blade beating, may be lessened by adapting the blade pitch angle, the increase due to coincidence (also) by desynchronizing turbines.

VII.4.1 Pitch angle

When a blade rotates in a vertical plane the optimum blade pitch angle α is determined by the ratio of the wind velocity and the rotational speed of the blade. As the rotational speed is a function of radial distance (from the hub), blade pitch changes over the blade length and is lowest at the tip. As the wind velocity closer to the ground is usually lower, the wind velocity at the low tip (where the tip passes the tower) is lower than at the high tip. As a result the angle of attack changes within a rotation if blade pitch is kept constant. For a 100 m hub height and 70 m diameter turbine at 20 rpm this change (relative to hub height) is about 0.5° at the lower tip in an unstable atmosphere, increasing to almost 2° in a very stable atmosphere (see section V.1). Added to this is a further change (of the order of 2°) in the angle of attack in front of the tower due to the fact that the tower is an obstacle slowing down air passing the tower. At the high tip the change in angle of attack is -0.3º (unstable) to -1.7º (very stable).

The optimum angle of attack of the incoming air at every position of the rotating blade can be realized by adapting the blade pitch angle to the local wind velocity. Pitch must then increase for a blade going upward and decrease on the downward flight. Such a continuous change in blade pitch is common in helicopter technology. If the effect of stability on the wind profile would be compensated by pitch control, blade swish due to the presence of the tower would still be left. This residual blade swish can be eliminated by an extra decrease in blade pitch close to the tower. If the variations in angle of attack can be reduced to 1° or less, blade swish will cause variations less than 2 dB which are not perceived as fluctuating sound.

VII.4.2 Rotor tilt

If the rotor is tilted backwards, a blade element will move forward on the downward stroke and backward on the upward stroke, thus having a varying velocity component in the direction of the wind. As a result the angle of attack will change while the blade rotates because the flow angle will depend on blade position. If the tilt angle changes from zero to θ, the flow angle at the low tip increases from φ to φ' (see figure III.2). From geometrical considerations (see figure VII.5) of a blade segment tilted around a horizontal axis, it follows that $C \cdot \sin\varphi + r \cdot \tan\theta = r \cdot \tan(\theta + \gamma)$, where $\gamma = \arctan(C\sin\varphi/r)$. This leads to:

$$\sin\varphi' = S\cdot\left(\tan[\theta + \arctan(\sin\varphi/S)] - \tan\theta\right) \quad \text{(VII.1)}$$

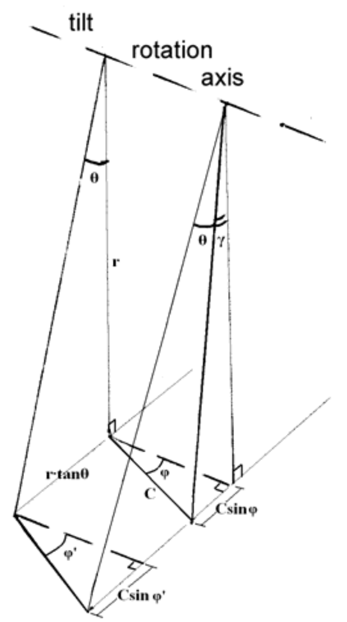

Figure VII.5: change of flow angle φ → φ' when blade is tilted over an angle θ around a horizontal axis

where S = r/C is the ratio of radius r and blade width (or chord length) C at radius r. For small blade pitch angles and blade slenderness S between 10 and 40 the increase of blade pitch with tilt (from 0 to θ) can be approximated with:

$$\Delta\varphi = \varphi' - \varphi = 1.1\cdot\varphi\cdot\theta^2 \qquad \text{(angles in radians)} \qquad \text{(VII.2a)}$$

For values of φ, S and θ in the range $\varphi \leq 10°$, $30 \leq S \leq 50$ and $\theta \leq 20°$, the standard deviation of the constant 1.1 is 0.01. With angles expressed in degrees, equation VII.2a reads:

$$\Delta\varphi = 33\cdot10^{-5}\cdot\varphi\cdot\theta^2 \qquad \text{(angles in degrees)} \qquad \text{VII.2b)}$$

This means that for a tilt angle of 2° and a 6° blade pitch (tip rotational speed 70 m/s, induced wind velocity 10 m/s, angle of attack 2º), the change in angle of attack (relative to a vertical rotor with zero tilt) is negligible (0.008°). Rotor tilt could now compensate a 1° change in angle of attack at the low tip when the tilt angle is 22°. In this case the horizontal distance between the low tip and the turbine tower increases with approximately 15 m. This will in turn lead to a smaller change in angle of attack as at this distance the velocity deficit due to the presence of the tower is lower. For higher values of the blade pitch angle (*ceteris paribus* implying lower values of the angle of attack) increasing the tilt angle has a bigger effect. A substantial tilt however has major disadvantages as it decreases the rotor surface normal to the wind and induces a flow component parallel to the rotor surface which again changes the inflow angle. It therefore does not seem an efficient way to reduce the fluctuation level

VII.4.3 Desynchronization of turbines

When the atmosphere becomes stable, large scale turbulence becomes weaker and wind velocity is more coherent over larger distances. The result is that different turbines in a wind farm are exposed to a wind with less variations, and near-synchronization of the turbines may lead to coincidence of blade beats from two or more turbines for an observer near the wind farm, and thus higher pulse levels (see section V.2.4). To desynchronize the turbines in this situation, the random variation induced by atmospheric turbulence (such as occurs in an unstable and neutral atmosphere) can be simulated by small and random fluctuations of the blade pitch angle or the electric load of each turbine separately.

In an unstable atmosphere turbulence strength peaks at a non-dimensional frequency n = $fz/V \approx 0.01$, where V is the mean wind velocity and z is height (this is according to custom in acoustics; in atmospheric physics traditionally f is non-dimensional and n physical frequency). At z = 100 m and V = 10 m/s this corresponds to a physical frequency $f = nV/z = 1$ mHz. At higher frequencies the turbulence spectral power density decreases with $f^{-5/3}$. When atmospheric instability decreases, the maximum shifts to a higher frequency and wind velocity fluctuations in the non-dimensional frequency range of 0.01 to 1 tend to vanish. So, to simulate atmospheric turbulence the blade pitch setting of each turbine (or the load imposed by the generator) must be fed independently with a signal corresponding to noise such as pink (f^{-1}) or brown (f^{-2}) noise, in the range of appr. 1 to 100 mHz. The (total) amplitude of this signal must be determined from local conditions, but is of the order of 1°.

VII.5 Conclusion

Wind turbine noise has shown to be a complex phenomenon. In the future quieter blades will be available, reducing sound emission by some 2 dB. The only presently available effective measures to decrease the sound impact of modern turbines are to create more distance or to slow down the rotor.

In existing turbines the sound immission level can be decreased by controlling the sound emission, which in turn is decreased by slowing down the rotor speed. When the limit is a single maximum sound immission level, this in fact dictates minimum distance for a given turbine and there is no further legal obligation to control.

In other cases the control strategy will depend on whether the legally enforced limit is a 10-m wind velocity or an ambient background sound level dependent limit. The 10-m wind velocity or the background sound level act as the control system input, blade pitch and/or load on the rotor is the controlled parameter. In both cases a suitable place must be chosen to measure the input parameter. For background sound level as input it is probably necessary to use two or more inputs to minimize the influence of local (near-microphone) sounds. It may however be the best strategy in

relatively quiet areas as it controls an important impact parameter: the level above background or intrusiveness of the wind turbine sound.
Controlling sound emission requires a new strategy in wind turbine control: in the present situation there is usually more room for sound in daytime and in very windy nights, but less in quiet nights.

A clear characteristic of night time wind turbine noise is its beating character. Even if the sound emission level does not change, annoyance may decrease by eliminating the rhythm due to the blades passing the tower. Again, a lower rotational speed will help as this reduces the overall level including the pulse level. A better solution is to continuously change the blade pitch, adapting the angle of attack to local conditions in each rotation. This will also be an advantage from an energetic point of view as it optimizes lift at every rotor angle, and it will decrease the extra mechanical load on the blades accompanying the sound pulses.
When the impulsive character of the sound is heightened because of the interaction of several turbines in a wind farm, this may be eliminated by adding small random variations to the blade pitch, mimicking the random variations imposed by atmospheric turbulence in daytime when this effect does not occur.

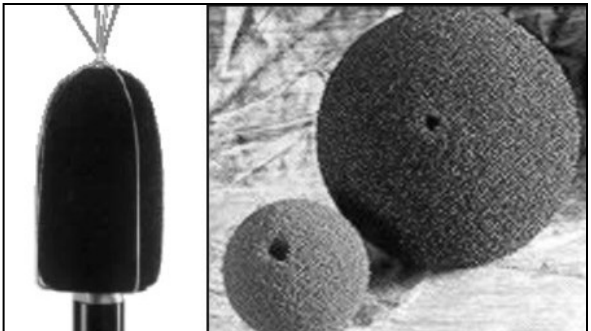

Figure VIII.0: foam wind screens