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# MEASUREMENT, ASSESSMENT & CONTROL OF TONAL NOISE RADIATION FROM WIND TURBINES

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## 1. INTRODUCTION

The operation of mechanical elements located within the nacelle of a wind turbine can result in tonal noise radiation to the environment. An audible tone in an otherwise broad band noise spectrum will cause that noise to be sound more annoying than the broad band noise would on its own, even though the tonal contribution may not significantly add to the overall noise level. It is therefore common practice that, when an environmentally radiated noise contains audible tones, a 5dB(A) penalty is added to the overall noise level to account for the increased perception resulting from the tones. In rural areas where wind tubines are often installed the background noise level may be very low. This fact makes the elimination of audible tones from wind turbines essential from two points of view. First, wind farm developments often have imposed on them very low noise limits in recognition of the low pre-existing background noise levels, and therefore they can ill afford a 5dB(A) penalty. Second, the perception of tones heightens when the absolute level of overall noise is very low. This paper addresses the specific problems of measuring, assessing and controlling tonal noise radiation from wind turbines.

## 2. CHARACTERISTICS OF WIND TURBINE NOISE

Most discussions on wind turbine noise differentiate between tonal and broad band noise radiation. A noise spectrum from a current wind turbine designed to limit tonal noise radiation is shown in Figure 1. Whilst Figure 1 clearly shows the presence of the two types of noise, with tones being evident at 505, 610, 900 and 1135Hz, these tones are of such a low level relative to the broad band masking noise that they are inaudible and therefore insignificant.

The dominant source of broad band noise from wind turbines is the passage of the rotor blades through the air. It is this broad band aerodynamic noise that usually determines the overall A-weighted sound power output level of the wind turbine, with the tip speed being the dominant parameter controlling the radiated noise level.

The main source of tonal noise is from mechanical elements within the nacelle, the most likely contributors being, in descending order of importance, the gearbox, the generator, the yawing mechanism, the forced cooling system and the pitch control mechanism. Recent measurement experience has shown that tonal noise radiation from current production wind turbines usually increases the overall radiated sound power by less than 1dB(A). This fact is recognised in PPG22, Planning Policy Guidance Note: Renewable Energy [1], which states that *"over the last few years there has been a significant reduction in the mechanical noise generated by wind turbines, and it is usually less than, or of a similar level to, the aerodynamic noise"*. This reduction in mechanical noise has not only been desirable but, for the U.K. market, it has been an almost essential development for the acceptance of wind technology. The reasons for this need to reduce tonal noise radiation will be addressed in the section 4 of this paper.

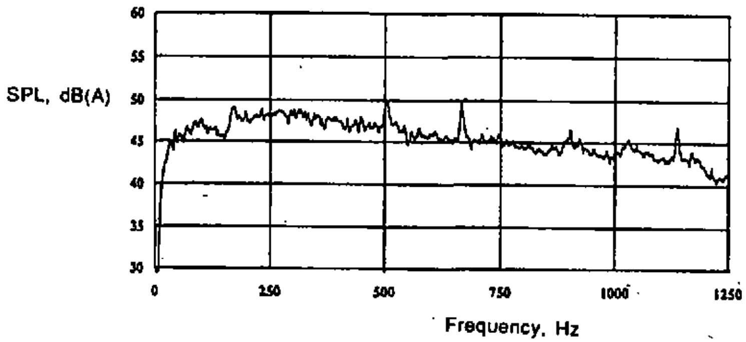


FIGURE 1.
A typical two minute averaged noise spectrum from a current production wind turbine on which mechanical tones have been attenuated to a sufficient degree to render them inaudible.

3. SUBJECTIVE PERCEPTION AND OBJECTIVE ASSESSMENT OF TONAL NOISE

The presence of an audible tone in an otherwise broad band noise spectrum can significantly increase the perception of the noise, even though the tone may not significantly increase the overall level of the noise. Robinson [2] describes the situation clearly; *"if one adds a discrete tone to a broad band noise three things happen. First, the sound pressure level is itself raised; secondly the loudness also increases* (but not in general by as much as the sound pressure level is raised)*; thirdly, the perceived quality change in the signal engenders annoyance over and above that represented by the increment in loudness"*.

The fact that tones lead to decreased acceptability of noise is acknowledged in BS4142 [3], the standard often referred to as being most relevant to wind farm development, which recommends that a 5dB(A) penalty be added to the specific noise level of a source if the spectrum of that source contains an audible tone. In addition to BS4142, BS7445 [4] also recommends an adjustment of 5 or 6dB *"if tonal components are clearly audible and their presence can be detected by a 1/3 octave analysis"*. BS7445 continues *"if the components are only just detectable by the observer and demonstrated by narrow band analysis, an adjustment of 2 to 3dB may be appropriate"*. However, neither BS4142 nor BS7445 present an objective method of determining whether or not a tone should attract a penalty.

The need for an objective assessment of tonal prominence has been recognised by the authorities responsible for setting noise measurement procedures for wind turbines. These methods all focus on classical critical band theory [5], [6] & [7]. The application of this method requires that a narrow band noise spectrum is measured at a reference location downwind of the test turbine. This spectrum is averaged using an averaging time of one or two minutes. The level of the prominent tone (or tones) and the level of the masking noise is then calculated from the measured spectrum. The masking noise level is established by placing a critical band such that it includes the largest possible number of the most prominent tones. The critical band is 100Hz wide if the centre frequency of the band is between 20Hz and 500Hz, and is 20% of the centre frequency of the critical band for frequencies above 500Hz.

The overall tone level, $L_{pt}$, within the critical band is determined by summing on an energy basis the tone levels within the band. The sound pressure level of the masking noise, $L_{pn}$, is determined either by energy summing all the analysis band values within the critical band not due to tones or by visually averaging the broad band level across the critical band. The difference between the tone level and the level of the masking noise, $\Delta L_{tn}=L_{pt}-L_{pn}$, is then compared to a threshold curve. This is actually two separate curves; the upper curve gives the tone level difference at which tones become *"prominent"* or *"clearly audible"*, whilst the lower curve gives the tone level difference at which tones become *"audible"*. The threshold curves are frequency dependent, but as an example a tone of 1000Hz becomes *"audible"* at a tone level difference of $\Delta L_{tn}=-2.8$dB, and the same tone becomes *"prominent"* at a tone level difference of $\Delta L_{tn}=+3.6$dB.

Whilst the critical band method described above takes into account the relative level of the tone and masking noise along with the effect of the frequency of the tone(s), it takes no account of the absolute level of the masking noise. The perception of tones, however, does depend on the absolute level of the masking noise [2] because, for a given tone level difference, tonal prominence increases with decreasing overall noise level. This may have some significance with regard to wind farms which are often located in areas of low background noise.

## 4. PRACTICAL EXPERIENCES OF TONAL NOISE AT LARGE DISTANCES FROM WIND TURBINES

As a result of measurements undertaken both for the purpose of establishing the noise output characteristics of wind turbines in accordance with IEA recommended practices [5], and also for the purpose of tracking down sources of tonal noise radiation, considerable experience has been gained of the potential problems of analysing tonal noise radiation from wind turbines. Some of these issues are now discussed.

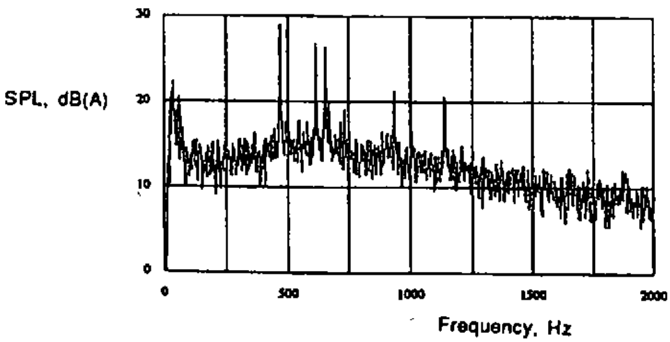


FIGURE 2.
Noise spectrum measured in a sheltered location approximately 400m from a wind turbine which emits a noise signature containing audible tones

Figure 2 shows a narrow band noise spectrum due to the operation of a wind farm measured at a typical minimum separation distance between a residence and a wind farm. The wind farm is located in an exposed hilltop location, and the measurement point was in a sheltered position approximately 400m from the nearest turbine, some 60m below turbine foundation level. Whilst the absolute noise level at the measurement location was deemed to be acceptable, the broad band noise experienced at the location was tainted by clearly audible tones. Strangely the tones, which are clearly visible in Figure 2, were not subjectively so significant close to the wind turbine as they were at some distance from it. This was at odds with the general thinking on tonal noise at the time of the investigation which suggested that, whilst mechanical tones might be audible close to turbines, they would become inaudible at distances in excess of around 200m.

The general concept of audible tones becoming inaudible with distance had been gained from experience on the Continent, where wind turbines are often located on flat terrain. In such areas, where nearby residences are located at a similar level to the wind farm, the wind speeds at the residences will be closely correlated with the wind speeds at the wind farm. Therefore, close to the wind turbine, both the broad band noise level and the tone level are dominated by the wind turbine. As the distance from the wind turbine increases the noise due to the wind turbine decreases and, at a certain distance, the broad band noise becomes dominated by the general wind noise. Beyond this point the level of the tones relative to the broad band noise decreases, and therefore the perception of the tones also decreases.

In exposed areas, such as on the flat terrain of many Continental wind farms, the point at which this changeover occurs will be around 200m from the wind farm. However, in the case of U.K. wind farms which are often located on hill tops, the background noise at residences lying in sheltered hollows around the wind farm may remain low even when the wind speed at the wind farm is high. When these sheltered residences have a direct line of sight with the wind turbines then both the broad band noise and the tonal noise may become dominated by wind turbine noise. It therefore follows that, if tones are audible close to the wind turbine, they will also be audible at these sheltered residences. It is for this reason that tonal noise has had to be controlled to within acceptable limits for the U.K. market.

In some circumstances the situation with regard to tones has been found to be worse than that described above, and tones that are subjectively inaudible or only just audible at the wind farm become clearly audible at sheltered locations some distance from the wind farm. This occurs because tones are often wind speed dependent, only becoming evident at higher wind speeds. At these higher wind speeds the broad band noise created by wind around the ears of the listener standing amongst the turbines can be higher than the noise due to the wind turbines themselves, which is likely to be around 55dB(A) at 50m from a turbine. This broad band noise created by wind blowing around the ears can mask tonal noise at the wind farm. However, in a sheltered hollow the wind masking noise will not be present and tones may become audible. This is one of the reasons why the method of noise measurement using a ground plane microphone has been developed for wind turbines, to minimise the effects of wind induced noise on the microphone. The subjective character of noise radiated from a wind turbine can change totally from listening through a tripod mounted microphone to listening through a ground plane microphone.

## 5. PRACTICAL EXPERIENCES OF TONAL NOISE MEASUREMENTS CLOSE TO WIND TURBINES

The discussion of the preceding section has demonstrated the increased potential for problems with tonal noise radiation from wind turbines when these turbines are located on hill tops. Examples are now presented of potential problems that may be experienced when undertaking diagnostic noise measurements on wind turbines. Such noise measurements are usually undertaken relatively close (approx. 50m) to the wind turbine in order to exclude the effects of background noise from extraneous sources. The measurements are also undertaken using a ground plane microphone on a reflecting board [5]. This is to minimise the effects of wind induced noise on the microphone. Even the lowest wind speeds in which measurements are taken is around $5ms^{-1}$, and for diagnostic purposes it is sometimes desirable to measure in wind speeds as high as $20ms^{-1}$.

Figure 2 has already shown a typical noise spectrum measured approximately 400m from a wind turbine which radiated audible tones. The wind turbine in question was a single speed, horizontal axis machine with a rated power output of 400kW. This section presents an outline case study of efforts made to reduce tonal noise radiation from this turbine to within acceptable limits. In doing so, the problem will also be addressed of establishing whether or not the objective of reducing tonal noise has actually been achieved.

Possible sources of mechanical noise have already been listed as gearbox, generator, yawing mechanism, forced cooling system and pitch control mechanism. The source of the tonal noise in this instance was found by measurement to be associated with various meshing orders of the gearbox middle stage and high speed shaft. However, whilst the source of the tones was easily identified, it was not so easy to establish the dominant transmission path to atmosphere. Tonal noise from these elements could be radiated to atmosphere by any combination of four transmission paths:

i) direct airborne noise radiation from the mechanical plant themselves
ii) structureborne transmission into and subsequent radiation from the nacelle bedplate
iii) structureborne transmission into and subsequent radiation from the turbine tower
iv) structureborne transmission into and subsequent radiation from the rotor blades/hub

The simplest solution to reducing the level of tonal noise would be if the far field radiated noise was due to direct airborne noise radiation from the gearbox casing. This source of noise could be treated by reducing the noise level within the nacelle, either by enclosing the gearbox or by installing acoustic absorption within the nacelle, or it could be treated by upgrading the sound insulation properties of the nacelle itself.

The reduction of structureborne noise radiation via the machinery bedplate/tower could be effected by mounting all the major mechanical elements in the nacelle on resilient mounts or, more realistically in an installed turbine, by treatment of the tower and bedplate themselves by suitably modifying their stiffness and damping. However, the reduction of structureborne noise radiation via the rotor assembly would be virtually impossible to control on a post production basis other than by modifying the gearbox itself to reduce the force input. This is because the low speed shaft forms an integral part of both the gearbox and the rotor hub.

As the simplest solution was seen to be the reduction of direct airborne noise radiation this was tackled first. Initial measurements of noise level within the nacelle revealed "reverberant" noise levels of around 98dB(A) at a wind speed of approximately $10ms^{-1}$. In its supplied form the interior finish of the nacelle was bare GRP. Acoustic foam was therefore installed in the test turbine and the measured internal noise level within the nacelle was reduced by approximately 4dB(A) to 94dB(A), as had been calculated. Unfortunately this reduction in noise level in the nacelle did not result in any measurable effect on the level of tonal noise radiated to the environment. The gearbox on the test turbine was then temporarily encased with an acoustic barrier material which reduced the noise level in the nacelle by a further 9dB(A) to approximately 85dB(A), but again there was no measurable effect on the level of tonal noise radiated to the environment. The findings of the above tests were confirmed by locating a loudspeaker sound source in the nacelle of the non-operating test turbine and playing back turbine noise recorded in the same nacelle with the turbine operating. The results of this test showed that direct airborne radiated noise was at least 10dB(A) below the tone levels being radiated to the environment by the operational wind turbine.

Attention therefore focussed on establishing the relative levels of structureborne noise radiation from the blades and tower. Simultaneous vibration measurements on the rotor hub/blades and on the tower with the turbine operating could have been used to determine the relative vibration levels at the problem frequencies, and from these vibration levels the sound power radiated from each of the elements could have been inferred. However, this would have assumed prior knowledge of the radiation characteristic of the various elements, and this was not the case. It was therefore decided to establish whether or not the blades and the tower are actually capable of noise radiation at the frequencies of interest. In order to achieve this objective wavenumber analysis [8] was employed. The mathematical theory behind wavenumber analysis will not be considered here but a descriptive overview is considered useful.

When any structure is excited into motion vibrational waves may spread out from the point of excitation to propagate through the structure. Depending on the frequency of excitation, propagating vibrational waves travel through the structure at a particular speed which is determined by the material properties and the geometry of the structure. Waves of different frequencies generally travel at different speeds. This is unlike acoustic waves in air where all waves travel at the same speed of around $340ms^{-1}$, regardless of their frequency. In the case of mechanical tonal noise radiation from either the blades or the tower of a wind turbine, sound waves are generated by the surface of the wind turbine structure vibrating and exciting the surrounding air. However, it is a fundamental property that unless the vibrational wave in the structure is travelling faster than the speed of sound in air, then the acoustic wave it excites will not propagate away from the structure. Instead the pressure disturbance will remain close to the structure as a reactive acoustic near field. Therefore even if a structural element is vibrating with a high amplitude at any given frequency, there is no guarantee that it will be contributing significantly to the far field radiated sound. Wavenumber analysis provides an experimental means of determining the speed of vibrational wave propagation at any given frequency by means of tests undertaken with the turbine not operating. The method therefore allows the determination of whether or not a given element of a structure is capable of radiating a particular tone to the environment.

Wavenumber analysis was performed on the in-situ blades and the tower by tapping the structural element under test along a linear array of equally spaced locations with an instrumented force hammer. The frequency response functions between the force input at each tapping point and the acceleration response at a fixed accelerometer location were then determined. The frequency response functions themselves were analysed to identify any structural resonances around the tonal frequencies of interest, and no such resonances were identified in either the blades or the tower. Post processing of the frequency response functions was then undertaken to establish the speeds and relative amplitudes of the forward and backward travelling waves at each frequency. The wave parameter usually plotted is not wave speed, but wavenumber. The wavenumber, k (rad/m), is defined as the frequency, $\omega$ (rad/s) divided by the structural wave speed, c (m/s), or $k = \omega/c$. Provided the wavenumber of the vibrational wave in the structure is lower than the wavenumber of acoustic waves in air at the same frequency, then the structure is capable of noise radiation at that frequency.

Figure 3 shows a sample wavenumber spectrum measured along the blades [9]. Also shown on the plot as sloping straight lines are the acoustic wavenumbers. Provided the vibrational waves lie within these lines then the structure is capable of efficient noise radiation. It had been hoped that the results of the wavenumber analysis would clearly show either the blades or the tower as an inefficient radiator of noise at the frequencies of interest, but this was not the case.

With the failure of the wavenumber analysis to eliminate one of the structural elements as a potential radiator of tonal noise a second series of tests was undertaken. These tests relied on the travelling nature of the blades to result in different in–plane to out–of–plane radiated noise characteristics. The tests were implemented by simultaneously recording the turbine noise at two microphones located in the plane of the rotor either side of the turbine and at a third microphone located downwind of the turbine out of the rotor plane. Synchronous data analysis was effected using a once per revolution pulse from an optical tachometer located on the low speed shaft. Tonal noise radiation from the blades would exhibit a significant frequency shift in the noise spectra measured in the plane of the

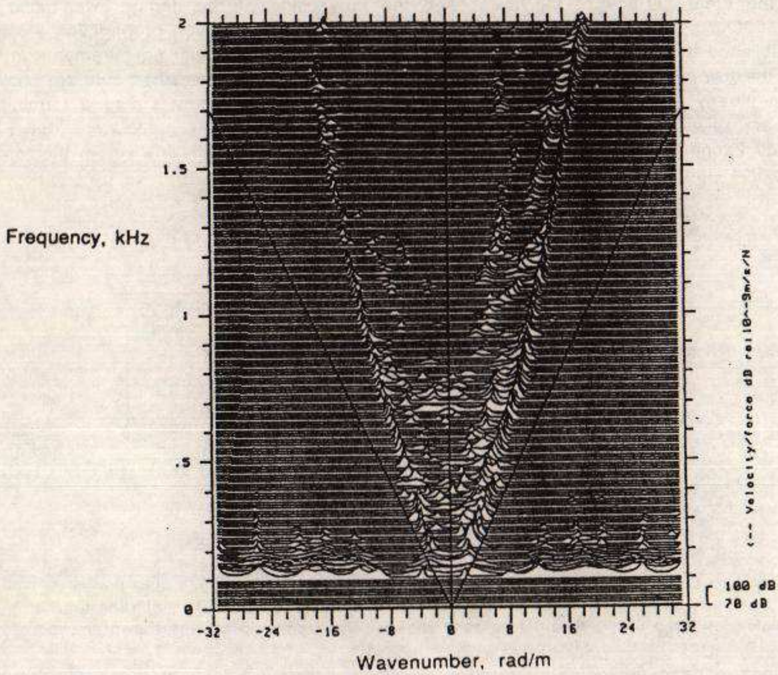


FIGURE 3.
Sample wavenumber spectrum measured along the rotor blades

rotor. The results of these tests successfully demonstrated that the tone levels radiated from the blades at the frequencies of interest were well below the total radiated tone levels. It was therefore concluded that the major radiator of tonal noise was the tower and all further tests concentrated on this element of the turbine. This conclusion assumed that radiation from the rotor hub was not significant. A further series of tests would have been desirable to positively eliminate the rotor hub as the dominant source of tonal noise radiation by, for instance, encasing it in an acoustic barrier material. Time and circumstances did not allow this further investigation to be undertaken.

Having concluded that the dominant source of tonal noise radiation was the excitation of the tower by the gearbox, the reduction of this noise reduced to one of....

i) modifying or replacing the gearbox to remove the high tonal force inputs at source
ii) isolating the propagation path between the gearbox and the tower
iii) reducing the response of the tower to the force input by altering its dynamic response.

In response to the need to reduce tonal noise radiation the manufacturer of the turbine designed and installed a cylindrical sand filled damper to be fitted around the inside of the uppermost part of the upper tower half. This sand damper comprised an inner skin of approximately 1mm thick steel which extended downwards from a point some 2.5m below the top of the tower. The approximate 100mm gap between the inner surface of the tower and the inner skin of the damper was filled with approximately 1600kg of sand. The effect of this damping band on vibration propagation along the tower was established by undertaking a series of frequency response function measurements at 0.5m intervals down the tower. The results of the third octave frequency band measurements are shown in Figure 4 which clearly shows the effectiveness of the damping band as providing a reduction in vibration level across it of approximately 20dB. However, it is also interesting to note from Figure 4 that the bolted flange joining the two halves of the tower together at 14m down from the top also provides approximately 10dB attenuation.

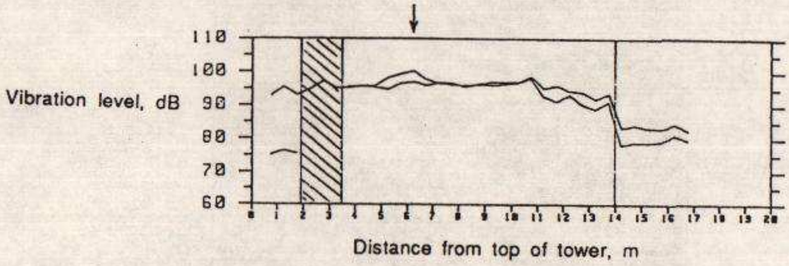


**FIGURE 4.**
Vibration levels measured vertically down the turbine tower both before and after the sand damper had been installed. The results are based on tapping tests undertaken with the turbine not operating, with the 500Hz third octave band shown. The tapping location is shown arrowed.

In order to validate the expected 20dB loss in practice, a further series of measurements were undertaken with the wind turbine operating. These measurements involved the simultaneous acquisition of 14 data channels: 4 accelerometers located above the damping band, 7 accelerometers located below the damping band, a signal proportional to the total electrical power output of the turbine, a tachometer signal from the low speed shaft and a microphone signal from a location 50m downwind of the turbine. In order to make valid comparisons between the "before" and "after" measurements the turbine power was recorded to enable vibration and noise data to be selected corresponding to the same power output of the turbine. This was because, from the tonal noise measurements that had been taken to this stage, it had become very apparent that the tone levels were highly time variable and depended on the load transmitted through the gearbox.

The results of these "before and after" vibration tests indicated that, for the same turbine electrical power output, the average of the 4 vibration levels measured above the damping band remained virtually unchanged (to within 3dB) over the entire frequency spectrum from 0 to 2000Hz. The average of the 7 vibration levels measured below the damping band showed a reduction in vibration level from around 100Hz, increasing gradually to approximately 10dB reduction for frequencies above 400Hz. The sand damper therefore offered a significant insertion loss to structural waves propagating down the cylinder, but somewhat less than the 20dB expected from the non–operational frequency response function tests. This poorer performance may be due to noise radiated into the tower from the underside of the machinery bedplate short circuiting the damping treatment although this effect was not formally proved.

The comparison of the "before and after" acoustic test results were less conclusive than the vibration measurements. Unlike the vibration levels, which correlated excellently from test to test provided the electrical power output of the turbine was the same over the typical 20 second averaging times used for the comparative tests, the acoustic data did not follow this same trend. The problem is caused by the variability of the sound propagation path from the turbine to the measurement point, believed to be caused primarily by wind effects. When observing real time narrow band spectra measured 50m downwind of a turbine the tone levels can be seen to vary by more than 10dB over periods of only a few seconds. Even taking two minute averages as recommended in the IEA practices for wind turbine testing [5] tone levels can vary by similar levels.

Due to the limited time available, which also coincided with a period of several weeks of low winds, it was difficult to accurately assess the true effect of the sand damper. Initial indications were that the damper had been successful in attenuating the tones. However, when the wind speeds rose above approximately 10 to 12ms$^{-1}$ the tonal noise radiation again became subjectively apparent. This finding reinforced the problems mentioned previously that, firstly, wind turbine noise is critically dependent on wind speed so measurements must be taken over the full range of operational wind speeds and, secondly, the variability of radiated tone levels even for a constant wind speed make it difficult to establish the true picture from a limited number of noise spectra.

It was therefore concluded that the assessment of tonal noise radiation would have to be undertaken using a procedure similar to that recommended in the IEA Recommended Practices for overall noise level. The IEA procedure requires that multiple measurements of the overall "A"–weighted noise level are measured downwind of the test turbine and plotted against the simultaneously averaged wind speed on a scatter plot. The resultant data is analysed on a statistical basis to establish the average noise level and its distribution. The same process was adopted for tonal noise assessment by developing a semi–automatic application of the objective tonal assessment procedure described earlier [6]. The implementation allows a prominant tone or tones to be selected. The tone level difference over the relevant critical band is then calculated for multiple narrow band spectra averaged typically over 10 second periods. The results of this analysis allow a scatter plot to be produced of multiple measurements of tone level difference against wind speed. This level difference is then used for the assessment of tonal prominence.

Before looking at results obtained using this analysis technique it is worth noting the specific problems introduced by variable speed wind turbines with variable frequency tones. The automatic method of tonal assessment described above assumes fixed frequency tones. Order analysis would have to be employed to cater for variable frequency tones, although this would require the added complexity of accessing rotational speed information from the wind turbine under test. Recommendations are made in the various measurement procedures for handling non–stationary tones which should be applicable both to variable level and variable frequency tones. These modified tone assessment procedures require that the broad band masking noise level should be established from spectra averaged over two minutes, whilst the equivalent of a fast response on a sound level meter should be used to establish the highest tone levels encountered during the two minute averaging period. In practice this method has often been found to result in radiated tones exceeding the "prominent" rating on an objective basis, even though they may only just be subjectively audible.

Returning now to the case study, having been only partially successful in reducing tonal noise radiation by treating the transmission paths, the source itself was tackled. This was done by re-shaping the gear teeth on the high speed shaft to minimise dynamic transmission error at high loads by modifying local contact deflection. Following several attempts it was found that, whilst this process could achieve good reductions in tone levels at certain wind speeds, it would either be ineffective or even increase tone levels at other loads. This is a well known feature of gear trains, that gear profiles can only be optimised to minimise dynamic transmission error for certain loads. Figure 5 clearly demonstrates this effect. It is unlikely that the strong dependence of tone level as a function of wind speed shown in Figure 5 would have been so conclusively identified had the measurement procedure described above not been adopted.

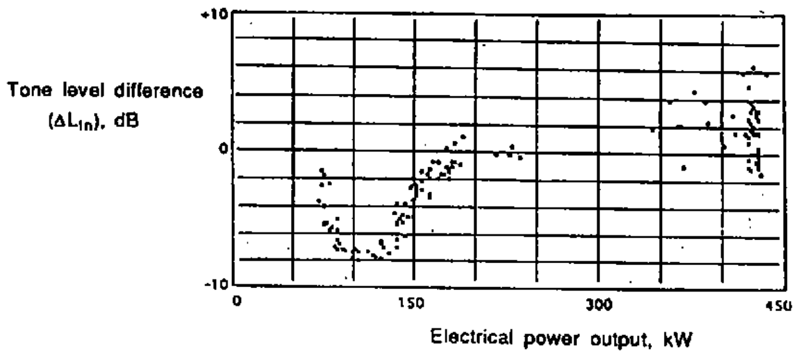


FIGURE 5.
Tone levels measured 50m downwind of the test turbine assessed according to the Joint Nordic Method and plotted as a function of wind speed.

As a result of the extensive tests carried out on the case study wind turbine, of which only a relevant subset have been included in the foregoing discussion, it was finally concluded that the entire geartrain in the offending gearbox would need to be replaced. This was done by replacing the gearbox as a whole unit, and the wind turbine now exhibits no tonal noise radiation problems at any wind speeds. The radiated noise spectrum already shown in Figure 1 is a sample result from the modified wind turbine.

## 6. CONCLUSIONS

The assessment of wind turbine noise presents unique acoustical problems not encountered in other fields of acoustics.

Wind farm sites where the turbines are located on hilltop locations are particularly sensitive to tonal noise radiation. This is because nearby dwellings may lie in sheltered hollows protected from general wind noise but not shielded from the noise radiated by the wind turbines.

TONAL NOISE FROM WIND TURBINES

Tonal noise usually emanates from mechanical plant located in the wind turbine nacelle. Provided the nacelle cover offers a reasonable degree of airborne sound insulation the gearbox is usually the dominant source of tonal noise which escapes to the environment via a structure-borne transmission path.

Tone levels are often strongly correlated with wind speed. Measurements undertaken to assess tone levels should therefore be taken as a minimum over the cut-in to rated power wind speed range of the turbine.

Tone levels in the radiated noise signatures of turbines vary by as much as 10dB over a few seconds, even when measured just 50m from the turbine and even when the power of the turbine remains relatively constant. This is believed to be due to changes in the noise propagation path from the turbine to the measurement location.

Due to the scatter in tonal levels radiated from wind turbines, all evaluative measurements of tones should be plotted as multiple samples of tone level difference against wind speed or turbine power output in a similar manner to the recommended practices for evaluating overall sound power outputs of wind turbines.

The methods for the objective assessment of non-stationary tones suggested in existing procedures for wind turbine testing do not adequately address the problems. Using the recommended procedures can result in a subjectively inaudible or only just audible tone being objectively assessed as "prominent". Variable speed wind turbines introduce still further complexities in the objective assessment of tone levels.

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