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The Audibility of Low Frequency Wind Turbine Noise

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Abstract

Conventional assessment of the audibility of low-frequency wind-turbine noise has usually relied on direct graphical comparison between the hearing threshold, and narrow-band or 1/3 octave wind-turbine spectra. But the hearing threshold is defined using single, isolated pure-tone test signals, whereas the latter spectra represent a measure of broadband rms energy which inevitably varies in amplitude according to the precise measurement bandwidth.

Since these two measures are derived according to two entirely different measurement conventions, any direct, unqualified comparison between the two is completely inappropriate. Moreover, it will be shown that accurately derived, historical low-frequency sound data relating to complex sound fields that have been reported as being clearly audible, possess spectral levels that according to this simplistic criterion would be dismissed as inaudible.

A procedure will be given which enables rigorous first assessment, based on the running integration of the rms energy, weighted by the inverse frequency response of the hearing threshold. This reveals that for the particular characteristics of typical wind-turbine spectra, the 1/3rd octave measurement provides a fortuitous comparison, based on integrated energy, which at first sight can be justified.

But this is based on comparing the rms energy of the acoustic sound field with the rms energy of individual pure sinusoids, and fails to take account of the larger crest-factor of actual acoustic signals. Typical low-frequency sound signals which have proven to be readily audible in practice generally have much higher crest-factors than pure sinusoids, while possessing lower overall rms levels.

Dynamic time-domain simulation of the response of the ear will be shown to provide a consistent explanation for the audibility of such signals. As a direct consequence, this approach reveals that typical wind-turbine infrasonic and low-frequency noise can be readily audible at very much lower levels than has hitherto been acknowledged.

Introduction

The increasing deployment of wind-turbines in the neighbourhood of residential properties has led to frequent complaints of the effects of low-frequency noise, and possible infrasound. Acoustic assessment of the severity of these effects has usually relied upon direct comparison of narrow-band or 1/3rd octave spectral levels relative to the conventionally accepted threshold of hearing. Such assessments, however, amount to comparing two entirely different measures of sound, and this disparity can lead to conclusions that may be misleading. On the one hand, the threshold of hearing is determined experimentally by using individual sinusoidal test tones, and the test subject is required to identify the sound level at which a single test tone first becomes audible. In contrast, 1/3rd octave and narrow-band sound pressure levels of wind-turbines are measures of the sound energy occurring in multiple different bandwidths simultaneously, so that individual components of the sound are present, not in isolation, but in (possibly correlated) continuous conjunction with each other.

Moreover, dependent on whether the components of sound represent essentially discrete frequency or random broadband sound, the precise sound level measured in any specific frequency band can depend upon the bandwidth, so that different measurement bandwidths give rise to apparently different levels relative to the threshold of hearing.

This problem was clearly identified in 2008 by Pedersen [1], where he showed how comparison of the same sound measured in different bandwidths, against the threshold of hearing, could lead to very different conclusions.

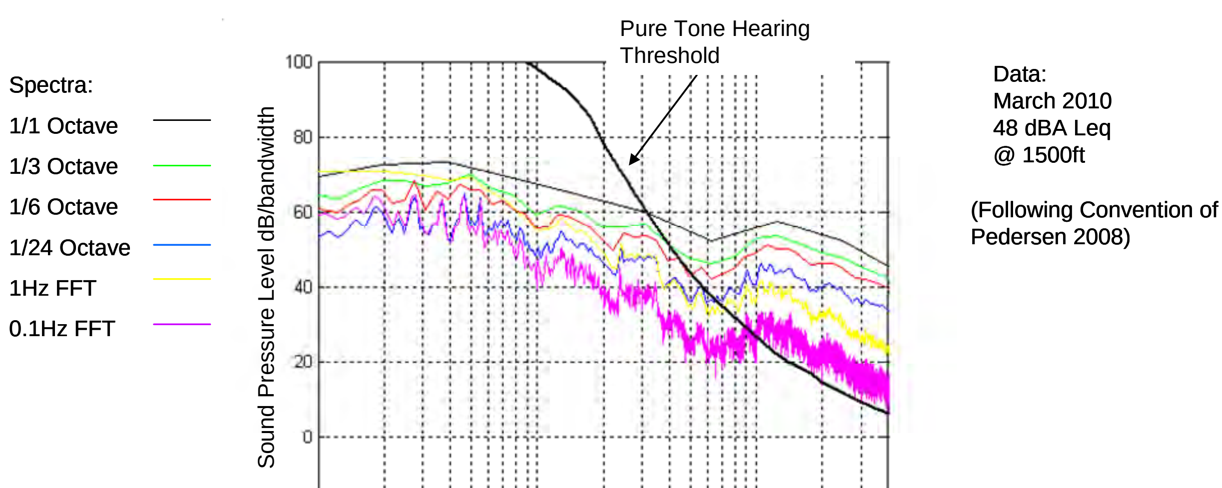


Figure 1

He stated "... it can be seen that a direct comparison of the hearing threshold and the spectrum of the wind turbine is not meaningful…"

“... have been discussed with a number of researchers (Henrik Moller, Aaborg University, Torsten Dau, Danish Technical University, Hugo Fastl and Geoff Leventhall) and solutions have been sought for without result.”

To address this problem, he proposed a method of weighting the measured sound spectra by the inverse hearing threshold (HT-weighting) and for low-frequency assessment, summing the resultant weighted spectra over the first two critical bands of hearing, namely 0-100Hz, and 100-200Hz respectively. Under this particular weighting of the spectra, the threshold of hearing itself is transformed into a straight line at 0dB, so subsequent assessment as to whether or not the sound in each critical band is audible is defined by its level relative to the 0dB threshold.

This approach undoubtedly provides a starting point, enabling the effects of differing bandwidths to be integrated-out, thus yielding a common resultant value. Since, however, the proposed criterion involves integrating over the entire frequency range of the first critical bandwidth, from 0-100Hz, it provides no insight into the exact frequencies within this range at which the sound first becomes perceptible. This critical band encompasses simultaneously, the infrasonic region, (0-20Hz), the very low-frequency region (~20-50Hz), and a higher octave range 50-100Hz.

In addition, the criterion only evaluates the rms level of the sound over this frequency range, relative to the threshold of hearing. It takes no account of the character of the sound, nor of the increased peak levels that may occur when different frequency components combine coherently to provide an overall enhanced effect.

In this respect, it is important to acknowledge the work performed by NASA during the 1980’s into the audibility of low-frequency wind-turbine noise. NASA collaborated with Boeing in the construction and practical assessment of the first megawatt-sized two-bladed wind-turbines. At that time, the convention was to mount the wind-turbine rotor downwind of the supporting tower, because this represents a naturally stable position enabling weathercock action to yaw and align the turbine blades with the incident airflow. At an early stage, however, it was identified that such configurations give rise to extremely impulsive low-frequency noise as a result of the blades passing through the downstream wake of the tower. Numerical analysis [2] and practical experiments on the MOD-2 turbine in both downwind and upwind rotor configurations quickly showed that an upwind-rotor configuration gives rise to significantly lower blade-wake-tower interaction, and is correspondingly quieter, resulting in substantially reduced amplitude of low-frequency harmonic components.

During this early work, NASA tested and reported results relating to the audibility of low-frequency impulsive components [3], [4]. For these tests, sound simulating the impulsive noise of the downstream rotor configuration was played to test subjects, and the corresponding threshold of hearing was determined. It was found that this sound was apparently audible when individual harmonics were at much lower levels than the conventional threshold of hearing, amounting to as much as -20dB lower for the dominant harmonics, under otherwise quiet background conditions.

NASA Audibility Curves: Impulsive Wind-Turbine Noise in Ambient Background Noise

(Curves represent Envelope of Dominant Spectral Components)

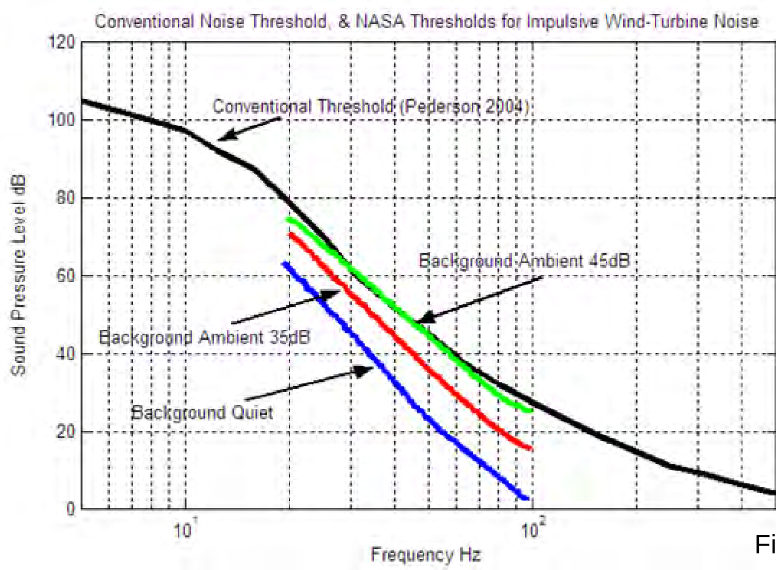


Figure 2

It is often assumed that such effects related only to the old-fashioned downwind-rotor configurations. In 1989, however, NASA assessed the noise generated by several upwind-rotor WWG-600 turbines in Hawaii, and were surprised to find that there were multiple low-frequency harmonics, representing excess low-frequency noise [5], [6]. Hitherto, it had been considered that this effect was confined only to downwind turbines, and that this problem had been largely eliminated by the adoption of upwind rotors.

NASA concluded that the explanation was due to the effects of wind-gradients and wind-shadowing, resulting in a spatially non-uniform wind velocity profile impinging on the rotor of the turbine. The variations in the velocity incident on the blades throughout the rotation cycle result in changes in the net incidence angle of the blades, and corresponding periodic variations in the total blade lift force. For a wind-turbine rotor operating in clean, uniform flow, the lift forces remain steady and uniform throughout the rotation cycle, and acoustic theory for steady rotating forces shows that the very low-frequency blade-rate harmonics decrease extremely rapidly with increasing frequency. If the lift forces vary periodically throughout the cycle, however, this can give rise to significantly increased amplitude of the higher harmonics, and the sound can start to assume a more impulsive character.

NASA performed numerical studies of the effects of wind-gradients of varying severity acting on the lift forces of the blades, and showed that the sharper the wind-gradient, the higher the frequencies to which this distribution of harmonics can extend. Although the frequencies do not cover the full frequency range encompassed by the original downwind configurations, they nevertheless can be manifest in the infrasonic regime. Consequently, the present author considers that correct assessment of the effects of the infrasonic components must take account of this process.

In 2003, G.P.van den Berg published a widely acknowledged paper on the significance of wind-gradients on the audibility of higher frequency, amplitude modulated wind-turbine dBA-levels from a 17-turbine windfarm [7]. In a parallel 2004 document [8], he subsequently speculated on the audibility of infrasonic and low-frequency components, showing comprehensive 3rd octave spectra from this same windfarm. He described how very low-frequency harmonic components could be generated by the rotor passing through the displaced airflow immediately upstream of a tower, giving rise to variations in blade incidence angle, and corresponding variations in lift forces. He considered that such effects could once again give rise to harmonics at multiples of blade-rate in the infrasonic regime, extending up to the region of 20Hz. Although he conjectured these effects as being due to the upstream flow-field around the tower, whereas NASA had attributed them to the vertical variation of velocity in the wind-gradients, the resultant acoustic effects resulting from regular periodic variation of blade lift-forces are of an essentially similar nature.

It should be noted that there is a link between such low-frequency fluctuating lift forces, and the more widely acknowledged higher frequency “amplitude modulation”. Variations in lift force give rise to variations in the chordwise circulation around the turbine blades, resulting in changing boundary conditions at the trailing edge of the blades. The resultant turbulence and vorticity at the trailing edge is therefore modulated in a similar periodic fashion to that of the very low-frequency components, yielding corresponding modulation of the higher frequency sound associated with these turbulent boundary and trailing edge effects.

In order to illustrate the fact that modern wind-turbines can indeed generate very low-frequency impulsive noise, the following figure 3 shows the sound measured indoors, in the bedroom of a house near to the boundary of a recently commissioned windfarm.

Multiple Low-Frequency Impulses Measured Indoors in March 2010 at a Modern, Upwind-Rotor Windfarm. 6 Separate Turbines can be Identified

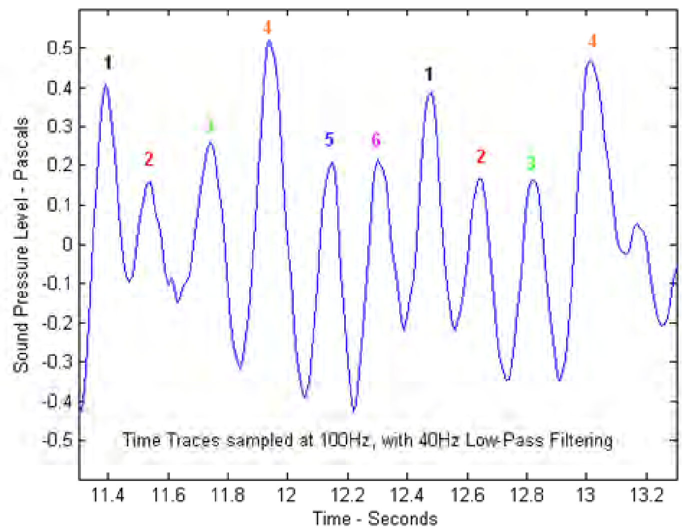


Figure 3

The peak SPL corresponding to impulse number 4 represents 88dB. This data was obtained under wind conditions such that the house was immediately downwind of 6 turbines at varying distances.

A final aspect relating to the audibility of low-frequency sound derives from the author's own experience. In 1979, he was asked to investigate the application of active sound control techniques to address the full-scale problem of attenuating the low-frequency noise generated by an industrial gas-turbine compressor installation, used for compressing natural gas in the UK distribution pipelines.

This specific installation was situated in a rural area, and had given rise to complaints from residents in a village situated over ½ mile from the compressor site. The compressor installation was visually unobtrusive, but during operation it could give rise to a low-frequency "rumble" which became objectionable to village residents late at night.

The problem arose as a consequence of the turbulent hot exhaust from the gas-turbine exciting acoustic resonances in the vertical column of the stack. The author successfully tackled this problem, and demonstrated substantial attenuation amounting to 11-12dB in the lowest audible octave, using an array of 72 12" loudspeakers distributed around the exit of the 10 foot diameter gas-turbine exhaust.

A few years later, the author was asked to tackle another similar installation, this time having more powerful gas-turbines and taller stacks. The resultant acoustic resonances were at lower frequencies because of the increased stack height.

In both these cases, the low-frequency noise was successfully suppressed, but on examining the corresponding low-frequency 1/3rd octave noise levels, shown in figure 4, it becomes apparent that the levels which had given rise to complaint were very similar to documented wind-turbine low-frequency noise levels. Moreover, if a simplistic criterion is adopted of comparing these levels to the tonal threshold of hearing, it is clear that the resonant peak levels would be considered to fall below this threshold.

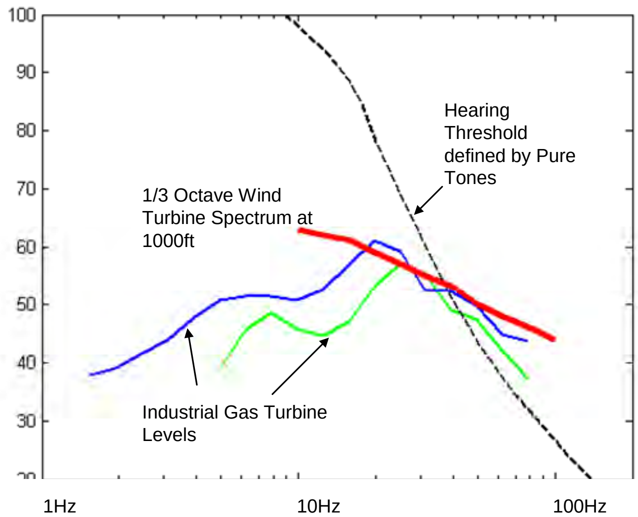


Figure 4

Example of LF Wind Turbine Spectrum, Considered to be not Audible to the Average Person up to about 31.5Hz – 40Hz (from [9]). Compared to Industrial Gas Turbines with Peak Levels at 20Hz & 25Hz, Reported as Audible.

Yet it was clear that these levels were of sufficient amplitude to give rise to complaints, while the subsequent active sound attenuation was considered to resolve these complaints.

It is therefore appropriate to revisit the assessment of low-frequency noise and infranoise, to establish more rigorous criteria for evaluating its effects relative to the threshold of hearing, and to attempt to reconcile these different effects, namely the audibility of individual pure tones, the apparently enhanced audibility of periodic or impulsive noise, and the audibility of low-frequency random noise.

A Hearing Threshold Criterion based on Cumulative Energy

As commented in the previous section, Pedersen [1] proposed a method of weighting different spectral resolutions with the inverse of the hearing threshold (HT-weighting). The result of applying such a weighting is shown in figure 5.

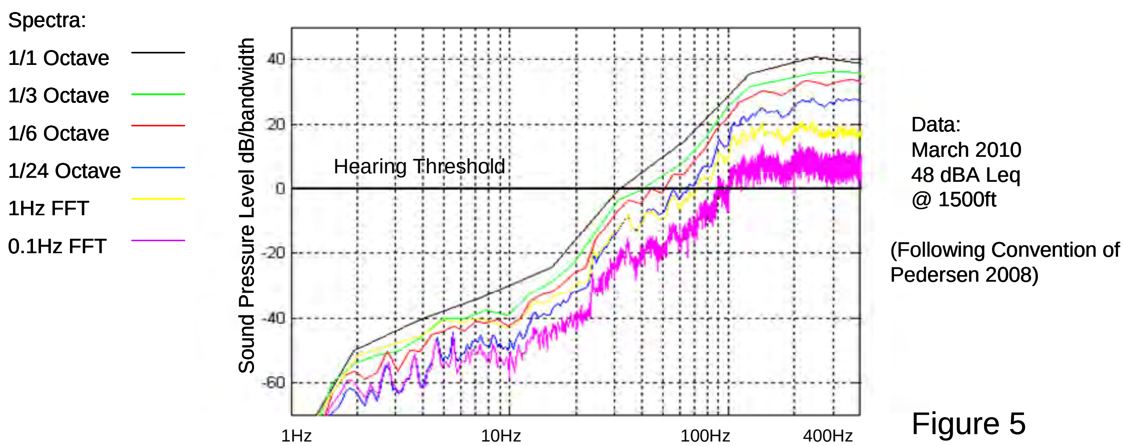
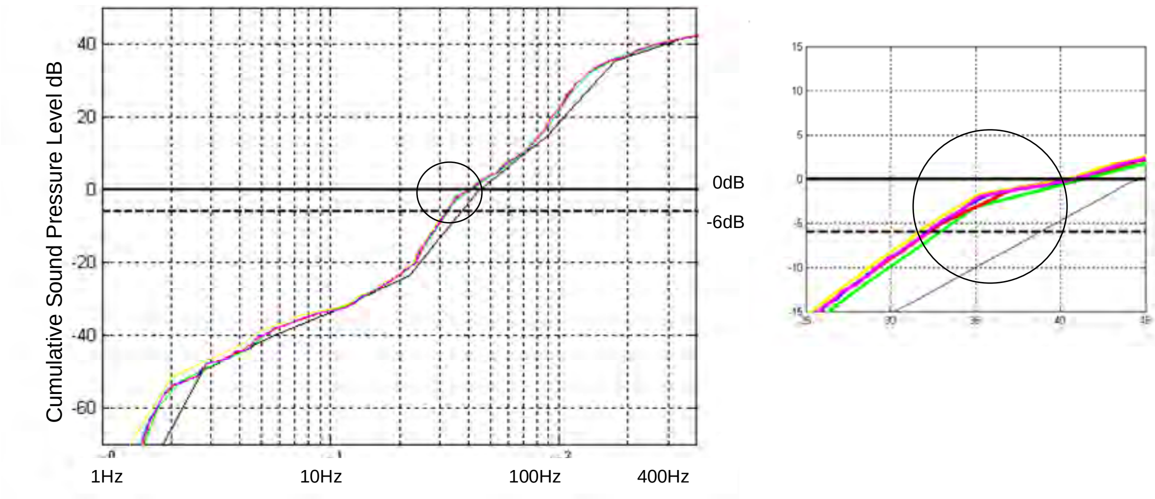


Figure 5

He then integrated these spectra over the fixed bandwidths 0-100Hz, and 100-200Hz, corresponding to the first two critical hearing bands. This integration yields two single, well-defined values, common to all the curves, for each of these two critical bands respectively. The resultant dB values can then be compared directly to the hearing threshold, which is now represented by a straight line at 0dB. This process does not however, provide information as to exactly where within the overall 0-100Hz band the hearing threshold is actually crossed. Indeed, for the particular set of curves shown, they have all crossed the hearing threshold by 100Hz, so one could conclude simply by inspection that sound in the 100Hz critical band must be audible.

To address the need for more detailed information, the present author proposes a modification to this approach. Rather than integrating over two fixed bandwidths, it is recommended that a running, cumulative integration is performed over the entire frequency range. For example, integration can be performed from 1-2Hz, from 1-3Hz, from 1-4Hz, thus deriving cumulative total values for each of the upper frequencies 2Hz, 3Hz, 4Hz etc.

The result of performing this integration using the various spectra of figure 5 is shown in figure 6, and it can be seen that this condenses these spectra of differing resolution onto an essentially unique ascending curve, which intersects the 0dB axis at a single well-defined frequency. The interpretation of this frequency value is that the sum total acoustic low-frequency energy up to this frequency, weighted by the hearing threshold frequency response, is exactly equal to the energy of an equivalent ”just audible” single pure tone.



At 0dB Intersection, total Perceived Energy equals Energy of Perceived Sine Wave at Threshold

Figure 6

While this defines the frequency at which the cumulative (weighted) energy first becomes equal to the (weighted) energy of a tone at the hearing threshold, it does not yet define the full extent to which frequencies below this value actually contribute. Noting, however, that a -6dB reduction in energy results in residual energy of 25% the initial value, by defining a second horizontal threshold at -6dB, one can deduce that 75% of the relevant contributing energy lies between the -6dB and 0dB limits.

It should be noted that this particular choice of -6dB, representing 75%, is arbitrary. One might alternatively choose a lower threshold at -10dB, which would then encompass 90% of the relevant contributing energy.

It is appropriate to compare the upper 0dB intersection at 40Hz to the various different intersection points given by the original unweighted spectra of figure 1, shown below.

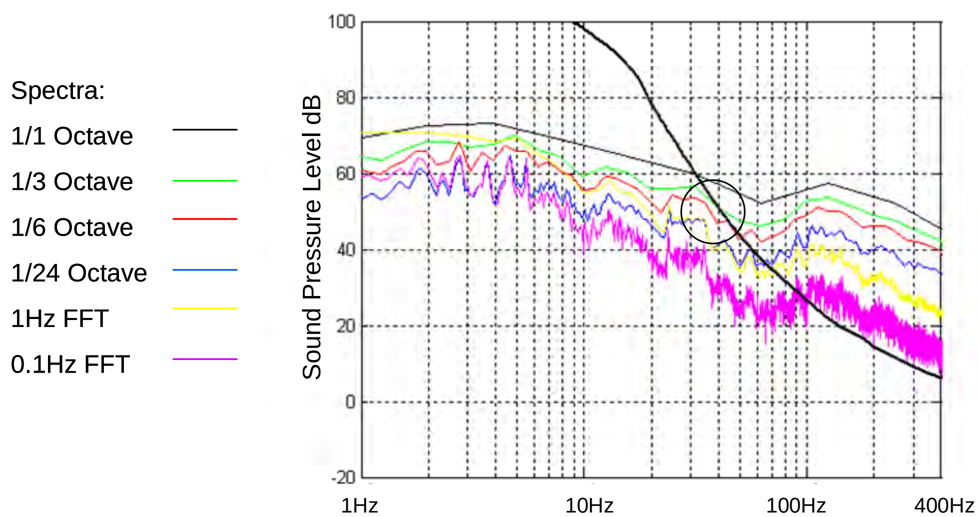


Figure 7

Close examination shows that the nearest intersection to 40Hz corresponds to the 1/3rd octave representation. So for spectra of this general shape, the 1/3rd octave intersection with the hearing threshold, and the cumulative energy 0dB criterion, yield a common value. It should be noted however, that the 75% cumulative energy band lies entirely to the left of this value, with a lower frequency of 32Hz.

In conclusion, a rigorous method of reconciling multiple different spectral representations can be proposed, yielding a well-defined band of frequencies representing the lowest frequencies for which the total (weighted) sound energy equals the energy of a single tonal at the corresponding threshold of hearing. For a typical wind-turbine spectrum, the upper frequency of this band does indeed correspond closely to the 1/3rd octave intersection with the tonal hearing threshold.

This approach, however, effectively equates the rms value of the (weighted) sound field over the appropriate bandwidth with the corresponding rms value of a "just audible" sinusoidal tonal. It does not take account the fact that real sounds can be much more sharply peaked than ideal sinusoids, or possess random amplitudes which vary significantly on a continuous basis. The ratio of peak signal-value to rms signal-value is the "crest-factor". An ideal sinusoid is one of the most smoothly varying signals, having a crest-factor of 3dB, but more realistic signals can have crest-factors of 10-12dB or greater. So it is possible that a signal having a lower rms value, but with a high value of crest-factor, may be of sufficient amplitude to penetrate the threshold of hearing. This aspect will now be addressed in the following section.

Crest Factor, & Time-Domain Simulation of Hearing Response

It has been argued that comparison of acoustic signals with the hearing threshold based purely on rms values fails to take account of the crest factor of real signals. When the author worked on the active sound control installation described in the introduction, the power amplifiers required to drive the loudspeakers had to be sized at 11kW total, to accurately reproduce the peak values of the sound signal, yet the rms power consumption was only around 1kW. This represented 10dB headroom, and implied a crest factor of similar magnitude. These increased peak levels may explain figure 4, showing the projected sound levels from such installations, since it is clear that the 3rd octave levels at 20 - 25Hz corresponding to silencer acoustic resonances lay below the nominal threshold of hearing, yet they were reportedly audible and led to complaints.

Similarly, the 1982 work of NASA on low-frequency impulsive signals revealed that in very low-background levels, the audible envelope of harmonics could be up to 20dB below the nominal hearing threshold, while a general statement was made to the effect that " coherent-phase " noise was audible at 7-10dB below random noise. [3]

In the case of purely impulsive noise, the ascending frequencies of the separate harmonics cannot be considered independent, because these harmonically related frequencies combine coherently, in-phase, to produce much larger peak levels. The resultant crest factor, peak-to-rms level, can become very large. Moreover, from the description provided in [3] it seems to have been unnecessary for the sound to be fully impulsive – NASA stated that they had investigated different relative phase relationships, and this aspect was found not to be critical. Their less stringent requirement, namely for “phase-coherence”, appears to represent the difference between phase-locked, repetitive noise, and random noise of continuously varying relative phase.

In order to investigate the crest-factor effects, the author chose to simulate the dynamic response of the ear close to the hearing threshold, by constructing a numerical filter to reproduce the inverse frequency response of the low-frequency hearing-threshold curve. A sampling frequency of 1kHz was chosen, and a 5-pole, 6-zero ARMA (autoregressive moving-average) filter was fitted to match the amplitude response. The phase characteristic cannot be specified, since practical audiometric testing, of necessity, is confined to determining only the amplitude of tonal signals that meet the hearing threshold. Therefore the filter was specified to exhibit a causal phase characteristic with minimum phase change. The overall gain of this filter was set so that a tonal sinusoid at the hearing threshold, scaled in pascals and normalized by the factor 2e-5 would yield a unity output of 0dB rms.

The simulated frequency response, and the inverse hearing threshold, are shown in figure 8.

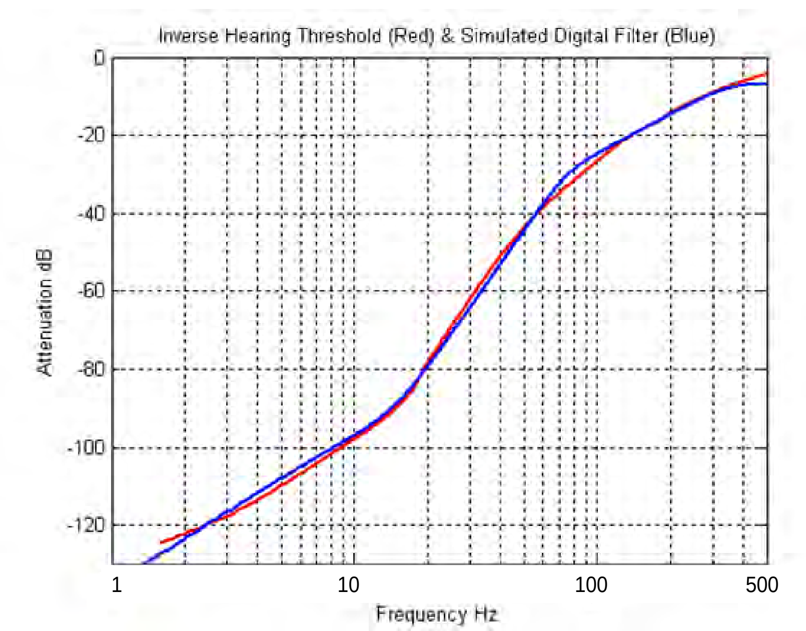


Figure 8

Simulated signals were then constructed to reproduce the characteristics of the sound signals under consideration. Although this filter was fully defined over a 500Hz bandwidth, all signals were restricted in frequency to less than 100Hz, to ensure that effects were confined entirely within the lowest critical band of hearing. Indeed, the ultimate signals analysed were restricted to significantly lower frequencies.

The simulated signals were chosen to reproduce 3 conditions, namely the two separate gas-compressor signals corresponding to figure 4, and an impulsive signal representing the NASA wind-turbine signal of reference [5], for the velocity profile of wind-gradient ‘B’ of that report.

The precise shape of the NASA spectrum is defined by the detailed assumptions relating to the change in lift-force as the blade passes through the wind gradient, so a simpler impulse was defined which possessed the same overall envelope as that shown in the report. Additionally, taking account of G.P. van den Berg’s comments about the number of blade-rate harmonics likely to be present, the signal was severely low-pass filtered at 20Hz to restrict it only to the infrasonic components. The objective was to establish representative effects associated with such a signal.

Two different approaches were adopted for defining the actual amplitude of the test signals. In the case of the gas-turbine signals, the amplitude in each case was set to correspond to the 1/3rd octave spectral levels shown in 4. For the impulsive signal, the initial amplitude was defined to match the NASA envelope, but subsequently the gain was modified to establish a signal which, when passed through the simulated hearing-threshold filter, resulted in a response at the same amplitude as a simple sinusoid at the threshold of hearing.

Results of the Dynamic Simulation

The results of the simulations will now be presented, as set out in the following figures. Figure 9 shows the time traces for the response to each of the two gas-turbine signals, corresponding to the blue and green curves previously shown in figure 4. Each signal was low-pass filtered with an 8-pole Butterworth filter, the turnover frequency of which was progressively increased until the output level began to exceed the limits that would be associated with a simple sine-wave at the hearing threshold. In figure 9, the rms level of such a sine-wave would be 1 unit, corresponding to 0dB, and the peak level would be +/- 1.4 units. These latter limits are shown by the red, broken lines.

It was found that in both cases, a turnover frequency of 35Hz yielded the required effect, indicating that the upper frequency of the lowest audible band is approximately 35Hz.

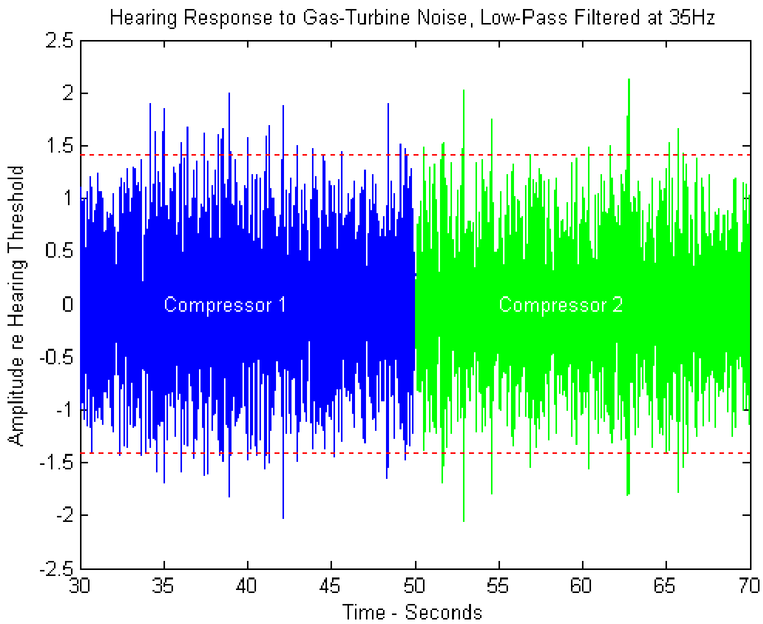


Figure 9

In the next figure 10, the cumulative unfiltered HT-weighted spectra for the two gas-turbine signals are shown. It can be seen that the two curves have much in common, although the blue curve runs approximately 5dB higher up to 25Hz, since the peak of its 1/3rd octave spectrum occurs at the lower frequency of 20Hz. Over the frequency range 25-35Hz, however, the two curves interlace, and as also indicated by the time-traces above, there seems to be little to choose between them. Thus one would conclude that the sound signals for these two different installations should demonstrate very similar audibility at their respective observation distances.

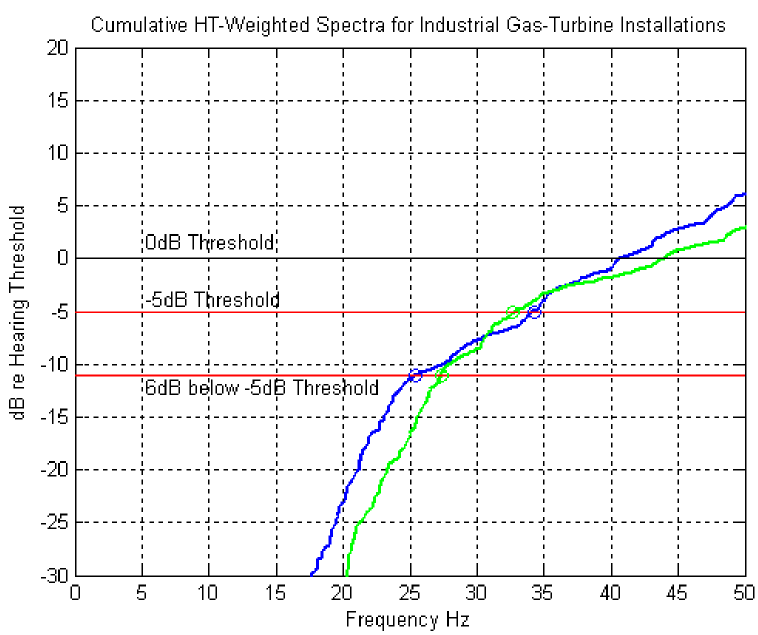


Figure 10

The red threshold limits have been set to -5dB and -11dB to define the likely 75% audibility bandwidth. The upper frequency was chosen slightly lower than 35Hz, because the 8-pole Butterworth filter depresses the response at 35Hz by -3dB. The higher level intersections with the 0dB threshold occur at the frequencies of 40Hz and 44Hz respectively, corresponding closely to the 1/3rd octave intersections with the hearing threshold shown in figure 4. Following the arguments that have been set out, however, it is considered that the actual limits of low-frequency audibility lie between 25Hz and 35Hz as shown, which is also indicated by the filtered time-response. This is consistent with the fact that attenuating the resonant response of the gas turbine exhaust stacks, at 20Hz and 25Hz respectively, was considered in practice to have successfully alleviated the complaints.

The following set of three figures now relate to the simulation of the extremely low frequency impulsive sound signals. These were defined to correspond to a fundamental wind-turbine blade-passing rate of 1Hz, then low-pass filtered with an 8-pole Butterworth filter at 20Hz, to restrict the overall spectra to the infrasonic regime. In contrast with the simulation of the gas turbines, where the signals possessed a predefined amplitude and the Butterworth low-pass frequency was adjusted to define audibility, in this second example, the low-pass filter frequency was fixed, and the amplitudes of the respective signals were adjusted to establish the resultant threshold.

Four different signals were examined, corresponding to different levels of random noise mixed in with the periodic signals. The spectrum of the Gaussian random noise was shaped to yield a similar overall envelope to that of the periodic components.

The time traces for the response of the hearing simulation are shown in figure 11.

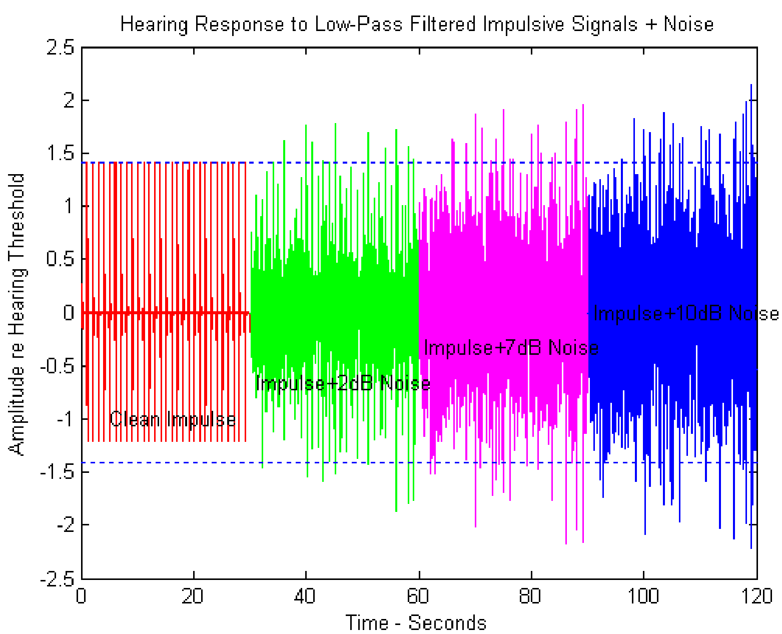


Figure 11

The amplitude for the “clean” impulse was set to meet the upper limit of 1.4, and the subsequent traces with increasing levels of added noise were set to values judged to be similar to those obtained in the preceding gas-turbine example. The progressively increasing colour density at the centre of the traces reflects the presence of increasing levels of random noise.

The spectra for three of these signals, namely the three containing the added noise, are shown below, after each signal amplitude had been adjusted to yield time-traces at the hearing-threshold as set out above. The spectra are analysed using a 0.1Hz bandwidth, to enable the individual impulsive harmonics to be identified. These low-frequency spectral levels are higher than would be expected from a modern wind-turbine, since for purposes of calibration, the infrasonic level has been adjusted to correspond to the median threshold of hearing. In practice, it is unlikely that wind-turbine infrasound would be audible to someone whose hearing sensitivity coincided with this median threshold.

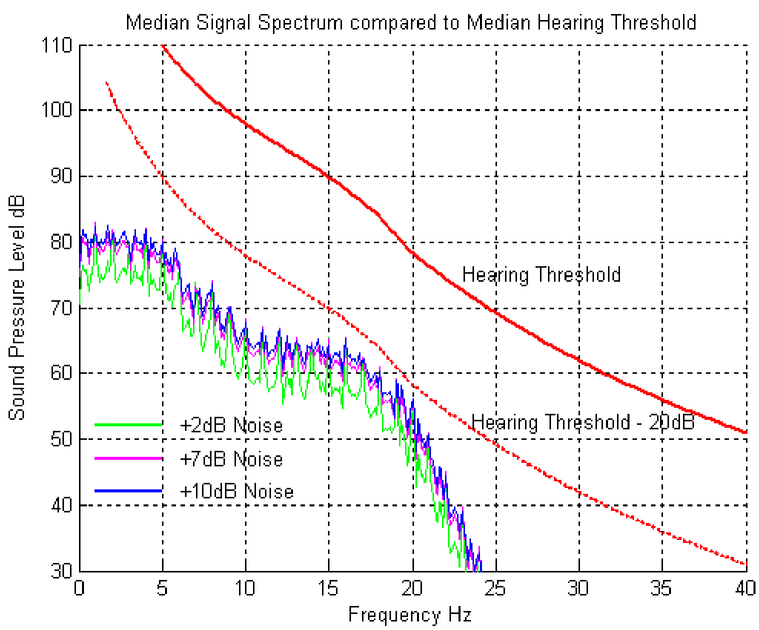


Figure 12

An important feature nevertheless becomes immediately apparent. The median hearing threshold is shown as a solid red line, and the broken red line defines a level -20dB lower than this threshold. Yet the overall envelopes of the spectra lie below this lower line.

It should be noted that the discrete frequency components corresponding to the impulsive harmonics would not be expected to change their amplitude according to the precise spectral resolution, since they represent pure tonal components. The same amplitudes would be expected, regardless of the specific spectral analysis bandwidth, providing that the individual tones remain separately resolved, so that multiple harmonics do not occur within the same analysis bandwidth.

This result appears to be largely consistent with the original NASA audibility tests conducted on impulsive noise in 1982, when they showed that the envelope of the dominant harmonics could be as much as -20dB below the hearing threshold. Consequently, it is incorrect to conclude that simply because an array of harmonic components lies well below the threshold of hearing, the resultant sound will not be perceptible.

The next figure shows the cumulative HT-weighted spectra for each of the four test signals.   Unlike the previously shown cumulative spectra which continued to increase in amplitude with frequency, these curves all flatten out above 20Hz, since the signals have been constructed and pre-filtered to exclude the components of sound above these frequencies.

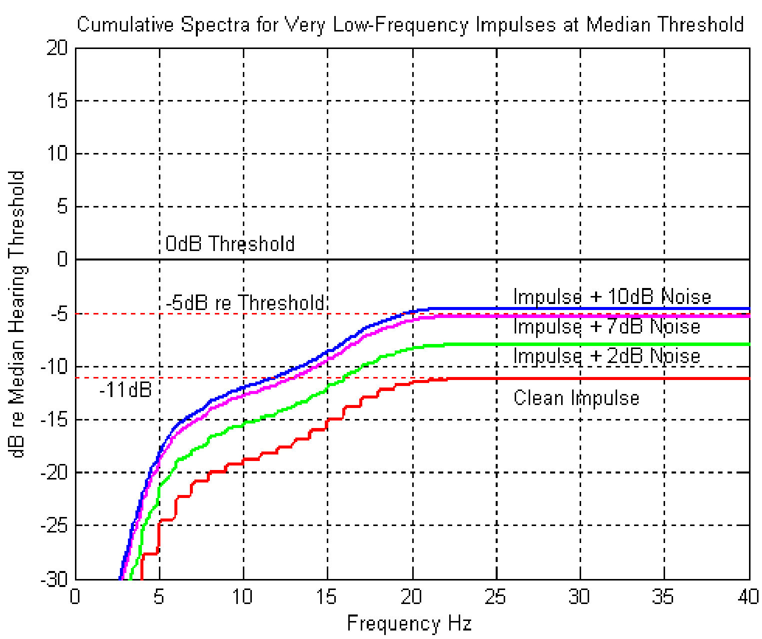


Figure 13

It can be seen immediately that the clean impulse can become perceptible at a level 11dB below the 0dB nominal median threshold, while the signal with +2dB added noise is perceptible at -8dB.   This comes very close to the original NASA assessment of an increased audibility of 7 to 10dB for phase-coherent noise.

As the level of added noise is increased, it can be seen that the threshold level necessary for perception progressively rises, until it appears to converge around -5dB. This corresponds to the similar -5dB criterion identified in the case of the purely random gas-turbine noise.

Thus, taken overall, these simulations have indicated that for clean, impulsive noise, the threshold of perception can be -8dB to -11dB lower for purely impulsive signals, but as the signal becomes mixed with noise and progressively starts to assume a more random character, this threshold of perception rises to -5dB. For the low frequency, but locally resonant random noise of the industrial gas turbines, the corresponding figure appears to be -5dB.

Application of Results to a Specific Example of Wind Turbine Noise

These results will now be applied to a specific example, namely the 1/3rd octave noise levels reported by G.P.Van den Berg [8]. The present author extracted the data from figure (1) of this paper, and used it to construct the following two figures. An important qualification must first be made. Van den Berg had stated in his text that the measurements were taken on the veranda or terrace of a house 750m (2500ft) from the nearest wind-turbine, but to compensate for enhanced sound reflection at the façade of the building, -3dB had been subtracted from the 3rd octave levels to establish the free-field sound levels.

In the present context, the objective is to determine the general audibility or perception of the wind-turbine low-frequency signals, so the appropriate sound level is the actual level observed at this location. The author has therefore taken the liberty of reinstating a +3dB correction to the levels presented in [8].

In figure 14, the HT-weighted cumulative spectrum has been constructed from the 3rd octave levels, with this +3dB correction applied. The 0dB threshold is shown, together with a lowered threshold derived as follows:

The threshold of hearing for 10% of young adults is on average -8dB lower than the conventional threshold of hearing. Moreover, Van den Berg described the low-frequency sound-levels as impulsive, so based on the preceding analysis, a further -6dB has been subtracted from the threshold, yielding a total -14dB. (This value of -6dB was chosen as a conservative value, given the overall range of values that have been identified in the previous section.)

Based on these assumptions, it can be seen that the band representing 75% of the lowest perceptible sound power lies over the frequency range 17Hz to 21Hz. This includes the upper limits of the infrasound regime.

(In an earlier presentation [10], this author had assumed a slightly lower threshold, but this was based on the stated NASA 7-10dB criterion, rather than the more detailed analysis set out here.)

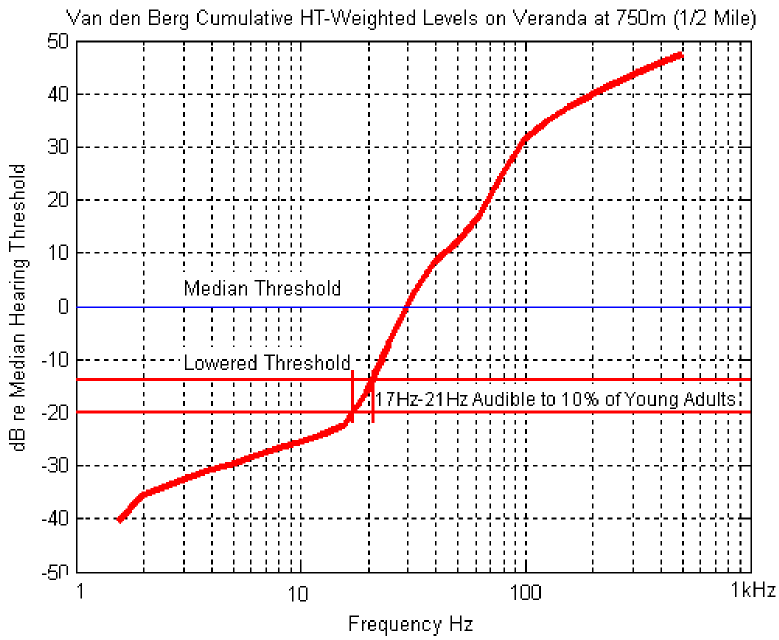
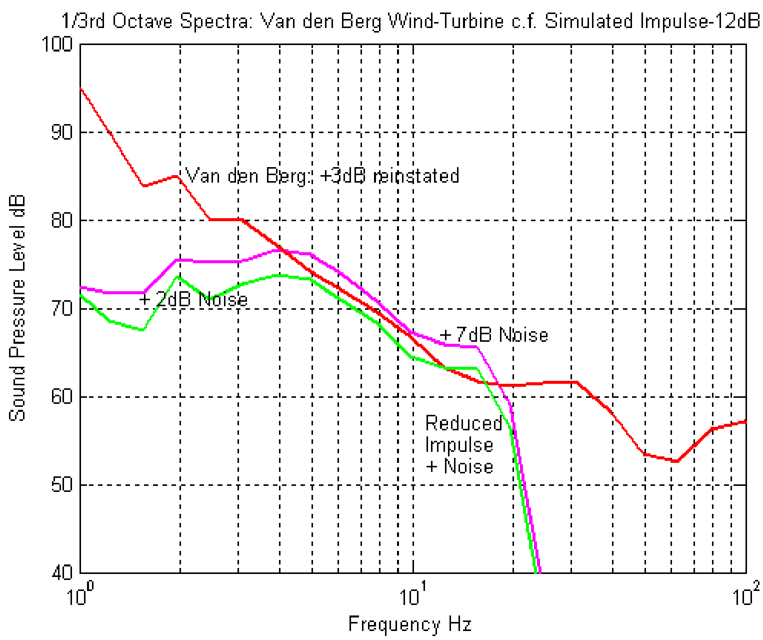


Figure 14

A further result is shown in the next figure. The threshold of hearing for all adults is frequently quoted as having a standard deviation about its median value of +/-6dB, so that two standard deviations is typically +/-12dB. Approximately 2.5% of adults are expected to have a more sensitive hearing threshold of -12dB relative to the median value.

Taking the simulated impulsive wind-turbine signals of the previous section, 12dB was subtracted to yield levels -12dB lower than the median perceptible levels. The corresponding 1/3rd octave sound levels were then plotted for these reduced signals.



. Figure 15

The results are compared directly with the Van den Berg 1/3rd octave levels.   It can be seen that the sound levels for the -12dB reduced amplitude impulsive noise with +2dB added random noise, together with impulsive noise with +7dB random noise, almost exactly straddle the Van den Berg data over much of the infrasonic frequency range

This immediately leads to the conclusion that under the circumstances reported by Van den Berg, a small proportion of adults, namely 2.5%, may indeed have been able to perceive a broader bandwidth of infrasound level.

Conclusions

A rigorous method of defining the lower limits of audibility or perception, based on the cumulative integration of spectra of arbitrary bandwidth has been investigated.   It has been shown that for typical wind-turbine spectra, the upper frequency limit associated with this criterion corresponds closely to the intersection of 1/3rd octave levels with the conventional threshold of hearing. This criterion is, however, based on comparison of the cumulative mean square energy level of the signal, and does not take account of the much greater peak levels that occur in actual wind-turbine sound fields.   Time-domain simulation of the low-frequency hearing response, using signals believed typical of wind-turbines and industrial gas-turbines has shown that sound can be perceptible at significantly lower levels than those defined solely on the basis of mean square energy.

The resultant enhanced sensitivity is related to the crest-factor of the signals.   The effects are consistent with audibility tests carried out and reported by NASA in 1982, and are also consistent with the author's own experience obtained during the 1980's relating to industrial gas turbine installations.

Modern upwind-rotor configuration wind-turbines can indeed give rise to very low-frequency impulsive sound-patterns. This effect is believed to be due to wind-gradients and shadowing by obstructions, and was first identified and reported for upwind-rotor turbines by NASA in 1989.

Based on these results, it is considered that a clean impulsive low-frequency signal can be audible at levels 8-11dB below the threshold defined according to mean square energy. As in-band broadband noise is increasingly mixed with this clean spectrum, this margin progressively reduces to a value approximately 5dB below the conventional threshold. This latter figure appears to be the appropriate allowance for the enhanced audibility of random, low-frequency spectra corresponding to the industrial gas-turbine installations previously investigated by this author.

A consequence of these results is that low-frequency and infrasonic noise due to wind-turbines may be audible at significantly lower sound levels than has hitherto been acknowledged.

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