Wind Turbines:
Low-Frequency Noise & Infrasound Revisited

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One-Day Workshop

Environmental Protection UK

Where now with Wind Turbine Assessment ?

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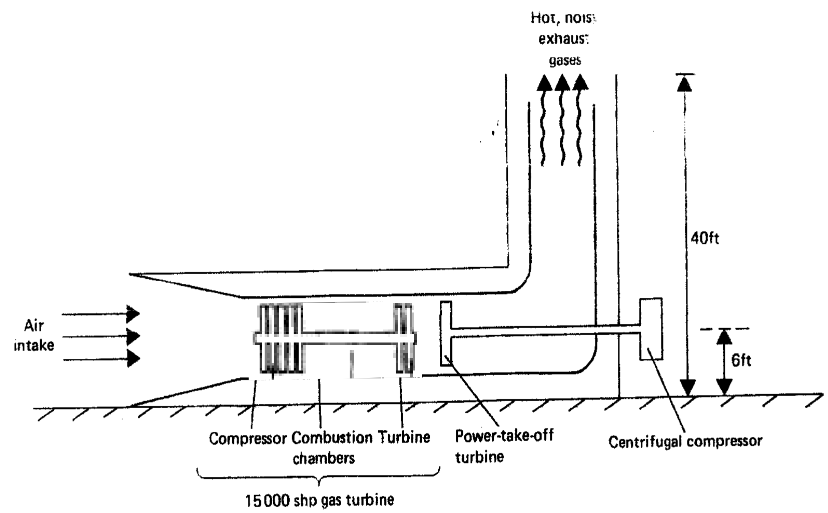
Wind Turbines: Low-Frequency Noise & Infrasound Revisited

M.A.Swinbanks

I first became interested in Low-Frequency Sound when tackling theoretical & practical research problems relating to the Active Control of Sound, in the 1970's

Following successful laboratory experiments, in 1979 I was asked to tackle the specific problem of excess low-frequency noise from an industrial gas turbine located in a rural area.

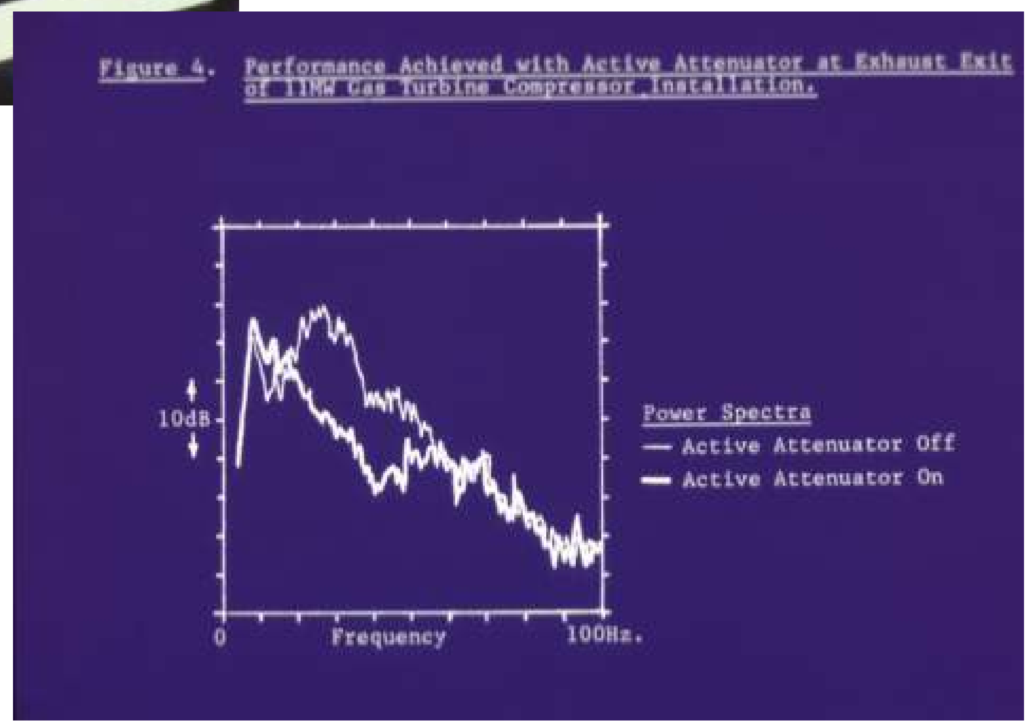


The noise was generated by the gas turbine exhausting into a vertical silencer 40 ft high and 10 ft diameter. The exhaust turbulence induced resonances in the air column of the silencer, giving rise to unacceptable very low-frequency sound levels around 20-30Hz.

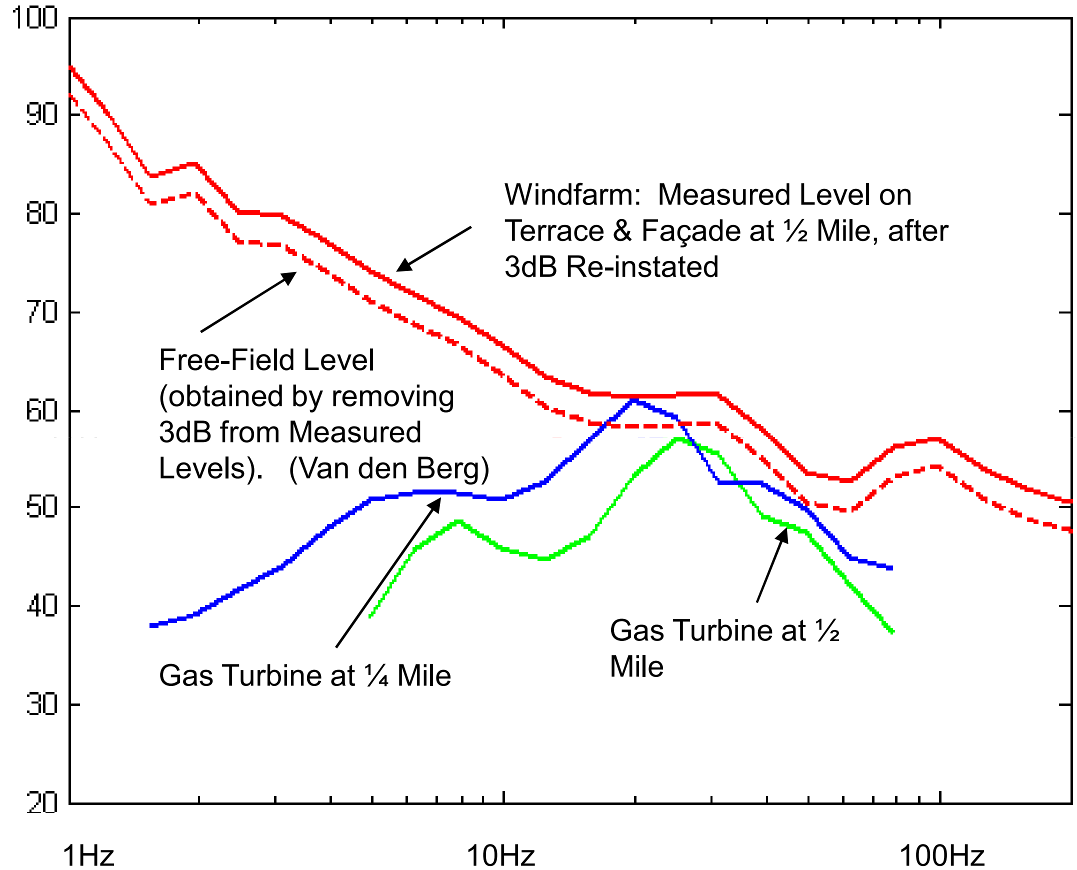
As a result of spending long hours working on the site, in the presence of significant levels of very low-frequency noise, I acquired considerable familiarity with its effects and consequences.

Exit of Gas Turbine Exhaust, showing Perforated Covers over Loudspeaker Array
72 Loudspeakers, 12” Diameter,

Measured Spectra (1Hz Bandwidth), Active Silencer Off & On



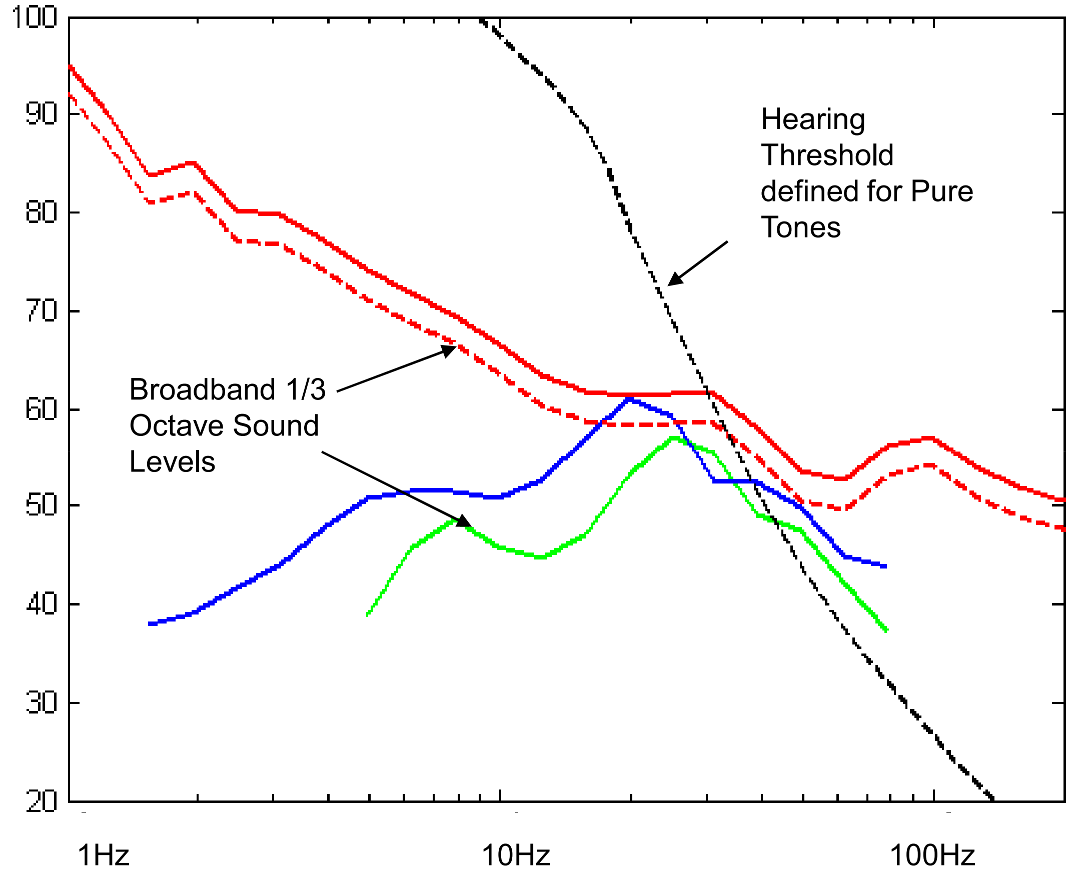
Low Frequency 3rd Octave Sound from 2 Separate Gas Turbine Installations which Generated Noise Complaints at ¼ - ½ Mile, compared to Windfarm 3rd Octave Levels at 750m ~ ½ Mile (Van den Berg 2004 *)



Note: Gas Turbine Noise Levels projected to Relevant Distances.

* Do wind turbines produce significant low frequency sound levels? G.P.van den Berg 11th International Meeting on Low Frequency Noise, Maastricht, The Netherlands, September 2004

Comparison of Noise Levels with Threshold of Hearing.



Subsequent Active Reduction of Gas Turbine Noise Levels over 20-40Hz successfully resolved Complaints. So the 20-40Hz Sound Level had been Perceptible, despite being Below the Nominal Threshold of Hearing

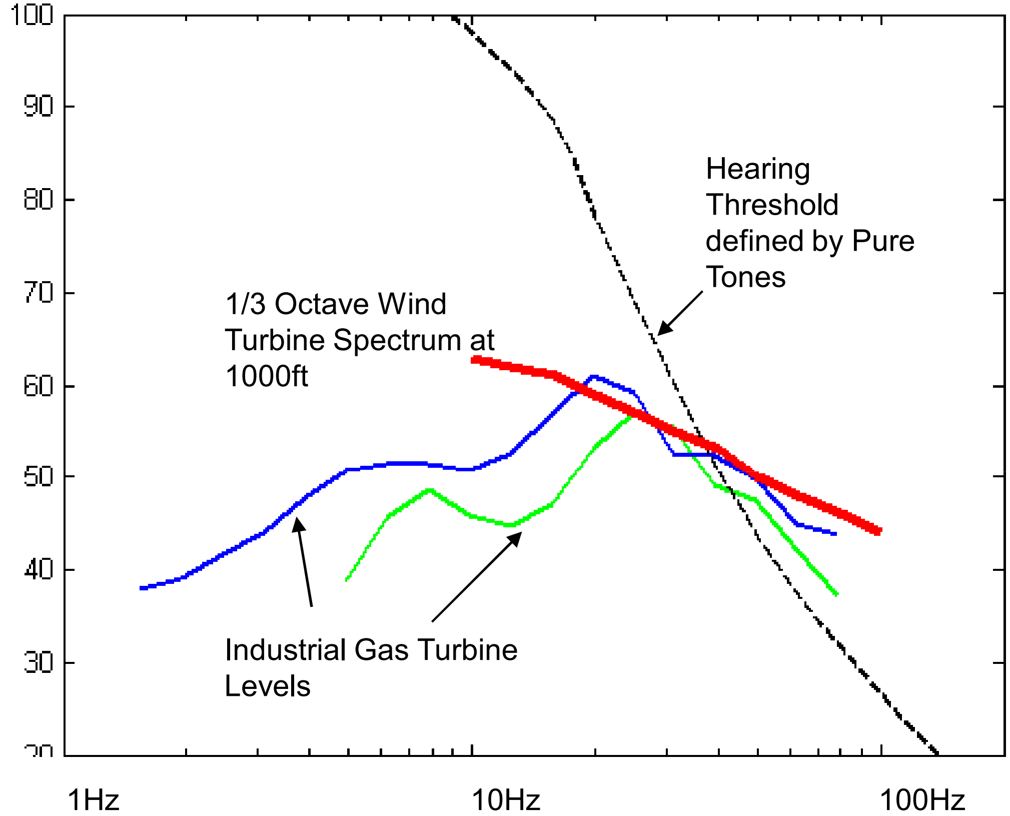
Subsequent Follow-Up

This work on the active control of industrial gas turbine silencers defined new benchmarks for achievable performance, and provided an incentive to improve the overall standards of low-frequency gas-turbine silencing.

Tighter low frequency specifications were then placed on all subsequent installations.

Silencer manufacturers ultimately succeeded in meeting these stringent specifications, with significantly improved passive designs.

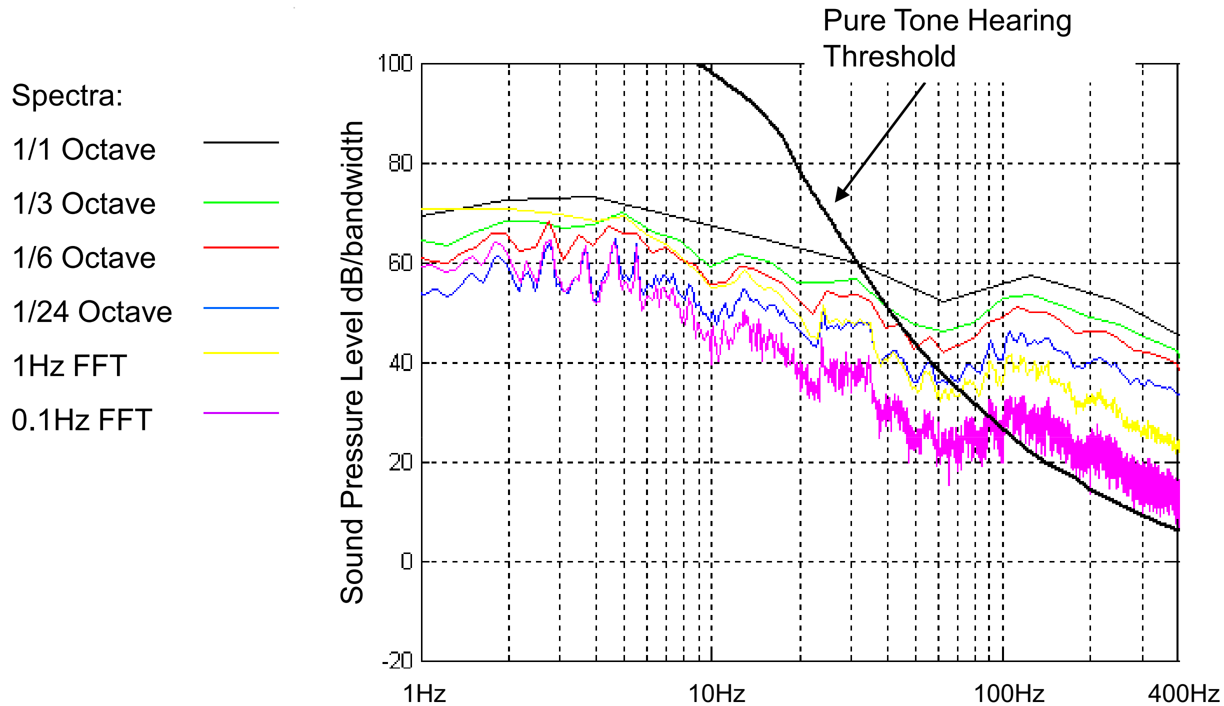
Example of LF Wind Turbine Spectrum, Considered to be not Audible to the Average Person up to about 31.5Hz – 40Hz. (Dr Geoff Leventhall to Public Service Commission of Wisconsin)



Present Author's Opinion: Wind Turbine LF Spectra compare directly to (projected) Industrial Gas Turbine Levels that gave rise to complaints, 25-30 years ago.

Care must be taken when comparing broad-band measurements, having noise simultaneously present at all frequencies, against a threshold defined by individual, stand-alone pure tones.

T.H.Pedersen (2008) Emphasized that Different Resolutions of the Same Wind Turbine Spectra would yield Different Conclusions



Data:
March 2010
48 dBA Leq
@ 1500ft

(Following Convention of Pedersen 2008)

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

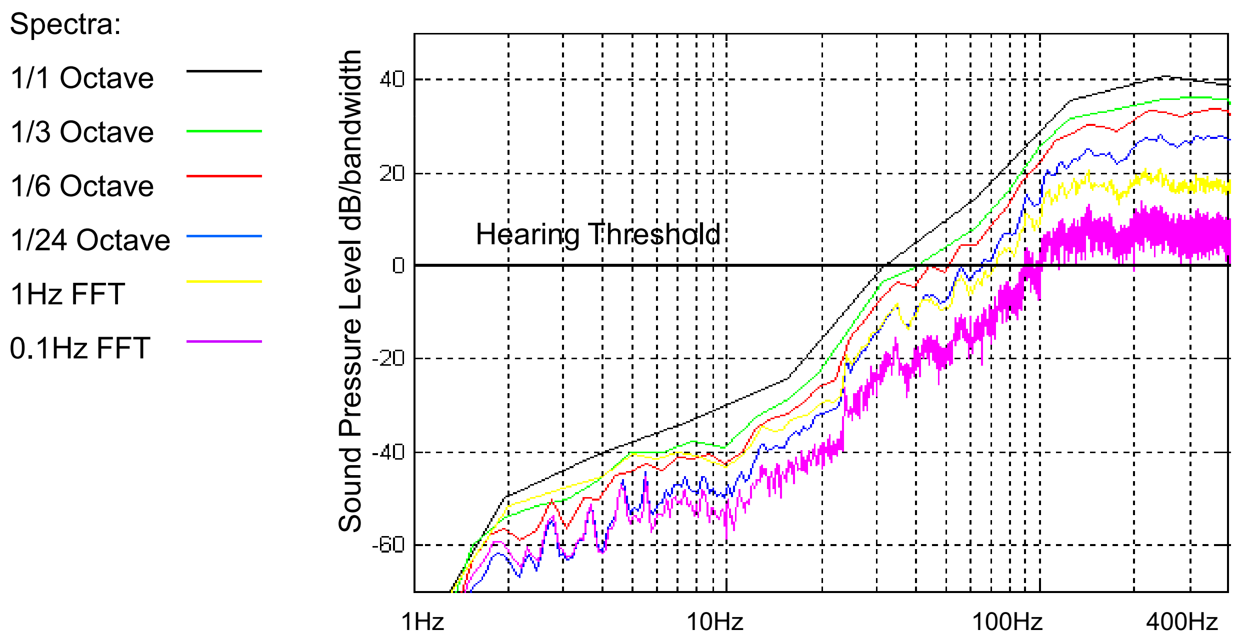
" …….. have been discussed with a number of researchers (Henrik Moller, Aaborg University, Torsten Dau, Danish Technical University, Hugo Fastl and Geoff Leventhall) and solutions have been sought for without result." *

* Reference: DELTA Danish Electronics, Light & Acoustics EFP-06 Project Low Frequency Noise from Large Wind Turbines - Quantification of the Noise and Assessment of the Annoyance. T.H.Pedersen Client: Danish Energy Authority 30 April 2008

Pedersen* applies an inverse weighting corresponding to the Hearing Threshold, (HT-Weighting).

The Hearing Threshold translates to a straight line at 0dB

He then Integrates over the Bandwidths 0-100Hz, and 100-200Hz, since these are the lowest two “Critical Bands of Hearing”. The multiple <u>different</u> spectral resolutions then each add up to the <u>same</u> value.



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*Reference: DELTA Danish Electronics, Light & Acoustics   EFP-06 Project   Low Frequency Noise from Large Wind Turbines - Quantification of the Noise and Assessment of the Annoyance.   T.H.Pedersen Client: Danish Energy Authority 30 April 2008

This corresponds to calculating the total perceived energy after accounting for the ear's dynamic response at the Hearing Threshold. If this total energy adds up to the 0dB level, it represents the same amount of energy as an equivalent "just audible" simple tone (sine wave).

But this procedure does not yet define the lowest frequencies at which the sound first becomes audible. 0-100Hz makes no distinction between 0-20Hz (Infrasound), 20-50Hz (Very Low Frequencies), or 50-100Hz (Moderately Low Frequencies)

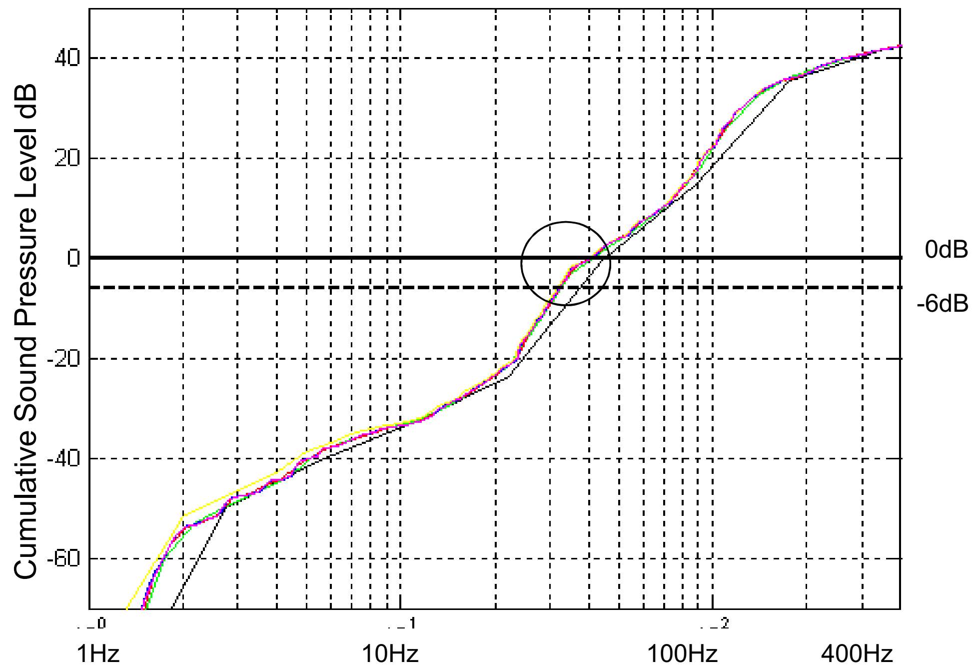
To address this, the present author suggests a modification to the approach:

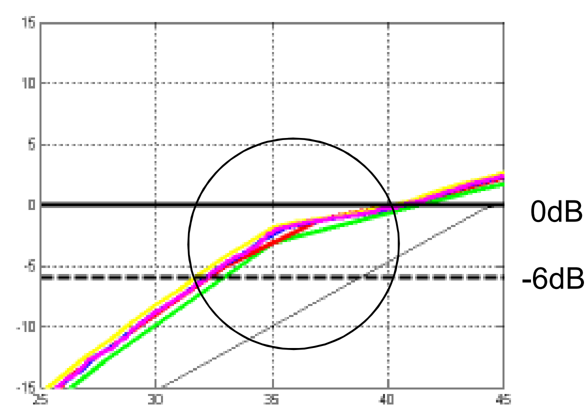
Instead of integrating over a fixed, predefined bandwidth, the integration can be performed as a cumulative, running integration over a progressively increasing bandwidth 1 – 100Hz.

The multiple separate curves condense to form a single curve, representing the increasing amount of total perceived energy as the bandwidth is broadened.

Cumulative Integration Starting from 1Hz Condenses all Spectra to a Common Line.

For any frequency, this represents the Total Perceived Sound Energy up to that frequency.



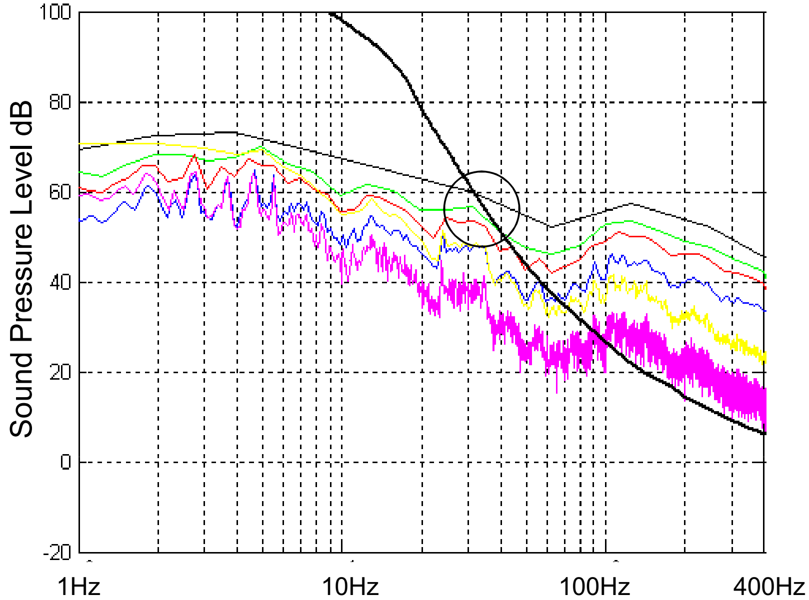


At 0dB Intersection, total Perceived Energy equals Energy of Perceived Sine Wave at Threshold

At -6dB Intersection, total Energy is only 25%

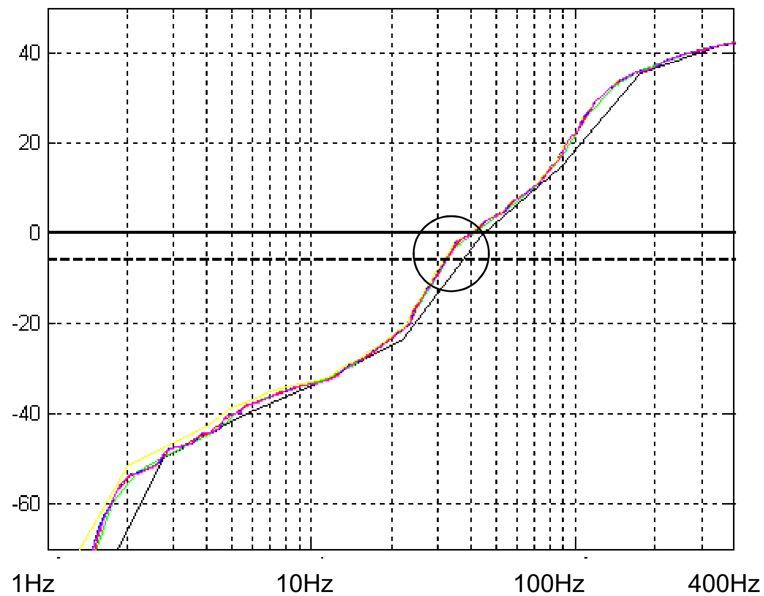
So 75% of Contribution lies between -6dB & 0dB Limits

Comparison of Different Spectra / Hearing Threshold Intersections shows that the Closest Intersection corresponds to the 1/3 Octave Spectrum



So 1/3 Octave Intersection does represent a definable comparison.

But this only corresponds to equating RMS Sound Energy. It does <u>not</u> take any account of Waveform Shape and Peak Levels.



The Important Effect of Waveform Shape, Peak Levels and Crest Factor

Pure Tone Signals are amongst the most efficient in maximising energy with minimum overall amplitude. The ratio of Peak Level to RMS Level is 3dB,and is termed the Crest Factor.

More complex signals have much greater Crest Factors.

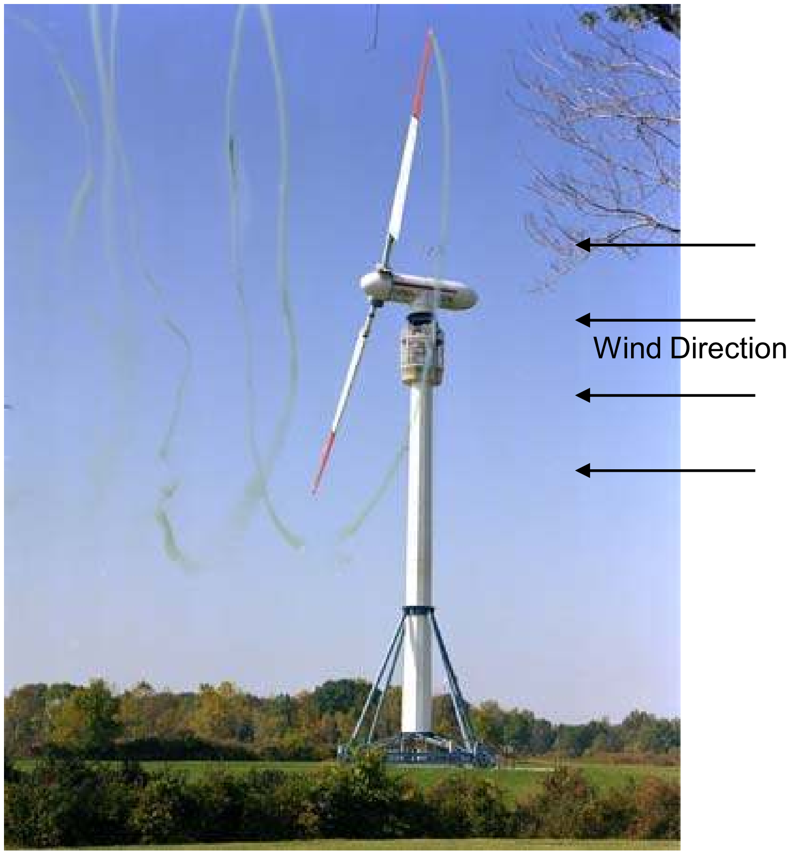
For the first Gas Turbine Active Silencer, the mean (RMS) Electrical Power required to reproduce the acoustic waveforms was only about 1kW. But the amplifiers had to be sized at 11kW, to take adequate account of transient increased excursions. Even with this overhead, the amplifiers were sometimes driven into saturation.

This represented 7.5dB additional Crest Factor compared to a Pure Tone Signal.

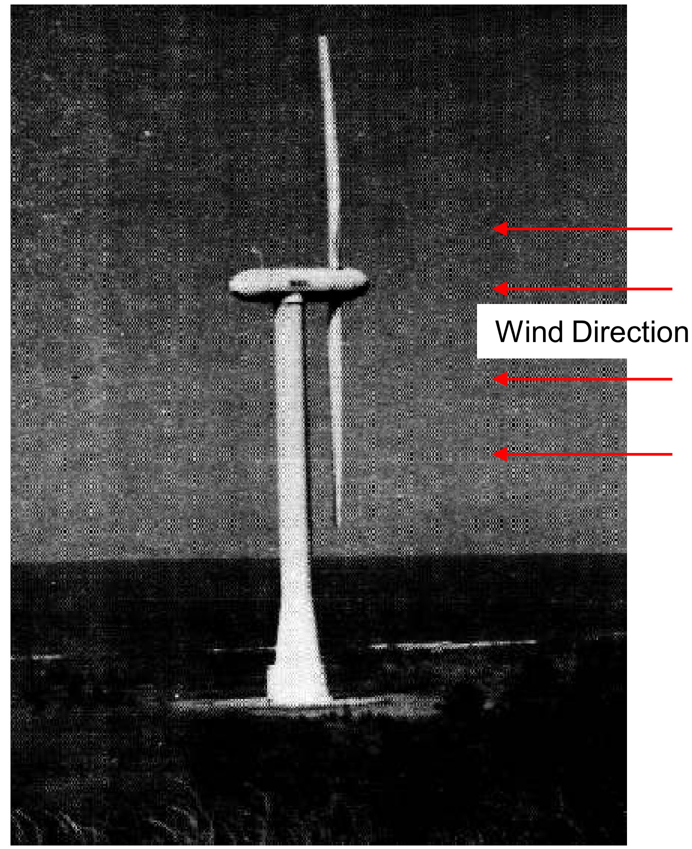
Assessing audibility based on RMS levels alone will definitely underestimate the effect of Peak Levels.

Greater effects may be associated with Wind Turbine Low Frequency noise, which may contain significant repetitive components that can be particularly intrusive.

NASA Tests on Downwind Rotor



WWG-600 Upwind Rotor



Noise Radiation Characteristics of the Westinghouse
WWG-600 (600kW) Wind Turbine Generator
NASA Technical Memorandum 101576 July1989

During 1980's NASA Tested both Downwind & Upwind Configurations, and Showed why Upwind Configurations were Much Quieter

NASA Also Identified and Investigated Important Low Frequency Effects that are not Cured by Modern Upstream Rotors

(1) Atmospheric Wind Gradients lead to Low Frequency Impulsive Noise, even from Modern Upwind Designs **[1]** (1989)

(2) The Threshold of Hearing can be up to 10 Times more Sensitive to the Dominant Components of Low-Frequency Impulsive Noise **[2]** (1982)

(3) The Threshold of Detection was found to be lower in level (7-10dB) for Coherent Phase (Repetitive) rather than for Random Phase Low Frequency Components **[3]** (1982).

Some Parties Dismiss this NASA Research as Out-of-Date, 1980's, and No Longer Relevant

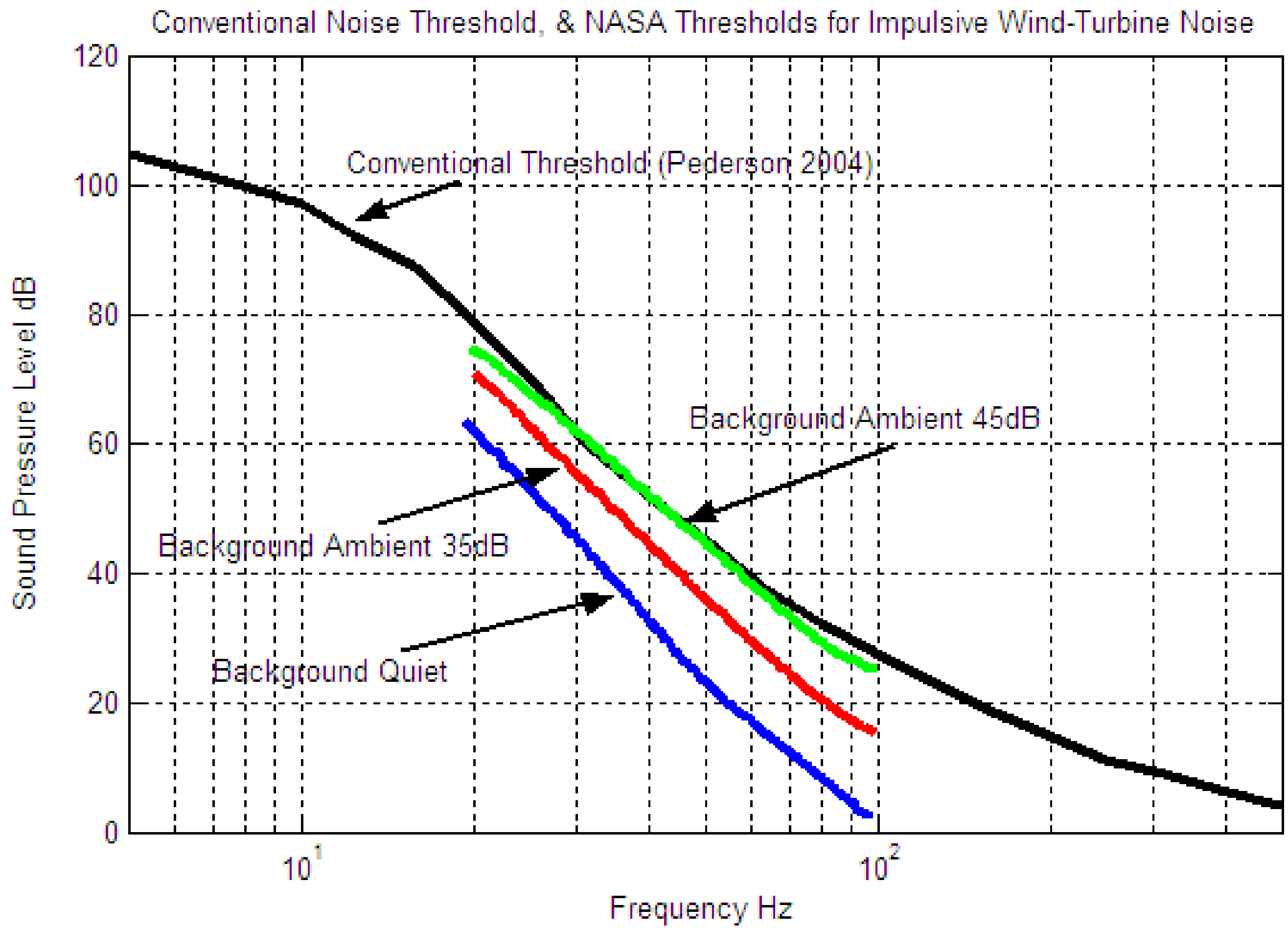
The Author believes it is Incorrect to do so – It is Directly Relevant

The properties of the winds, and the characteristics of human hearing, have not changed.

[1] Low Frequency Acoustic Emissions from Large Horizontal Wind Turbines, H.H.Hubbard & K.P.Shepherd* Inter-Noise 89, 4-6 December 1989
[2] Acoustical Criteria Applicable to Large Wind Turbine Generators K.P.Shepherd* & D.G.Stevens Inter-Noise 82, 17-19 May 1982
[3] Guide to the Evaluation of Human Exposure to Noise from Large Wind Turbines D.G.Stephens, K.P.Shepherd, H.H.Hubbard,,F.W.Grosveld NASA Technical Memorandum 83288 March 1982/

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

(Curves represent Envelope of Dominant Spectral Components)



Acoustical Criteria Applicable to Large Wind Turbine Generators K.P.Shepherd* & D.G.Stevens Inter-Noise 82, 17-19 May 1982

Aerodynamic Effects of Wind Gradients:

Modern Rotors can be 80 – 100m diameter, so they sweep through a huge vertical arc.

In the presence of wind gradients, with wind speed and wind direction varying with height, the incidence angles of the blades are constantly changing, on a repetitive, cyclic basis.

So the lift forces on the blades fluctuate throughout the cycle.

The principal component of low-frequency sound radiation comes from the effect of lift forces, which are dipole acoustic sources. For a rotating blade, rotating steady forces have low radiation efficiency, but once these forces vary throughout the cycle, the low frequency radiation increases significantly.

At the same time, the changes in lift forces are associated with changes of circulation around the blades, which causes unsteady vortex shedding from the trailing edge.

These effects can cause the thumping, pile-driving low-frequency noise that has been reported from modern turbines, together with the higher frequency amplitude modulation associated with the periodic shedding of the trailing edge vortices.

Wind Turbines & Sailplanes: High-Aspect-Ratio Airfoils in Vertical Wind Gradients & Wind Shear

Related effects are well-known to the pilots of high-performance sailplanes, with long slender wings of high aerodynamic efficiency. These wings are not unlike wind-turbine blades.

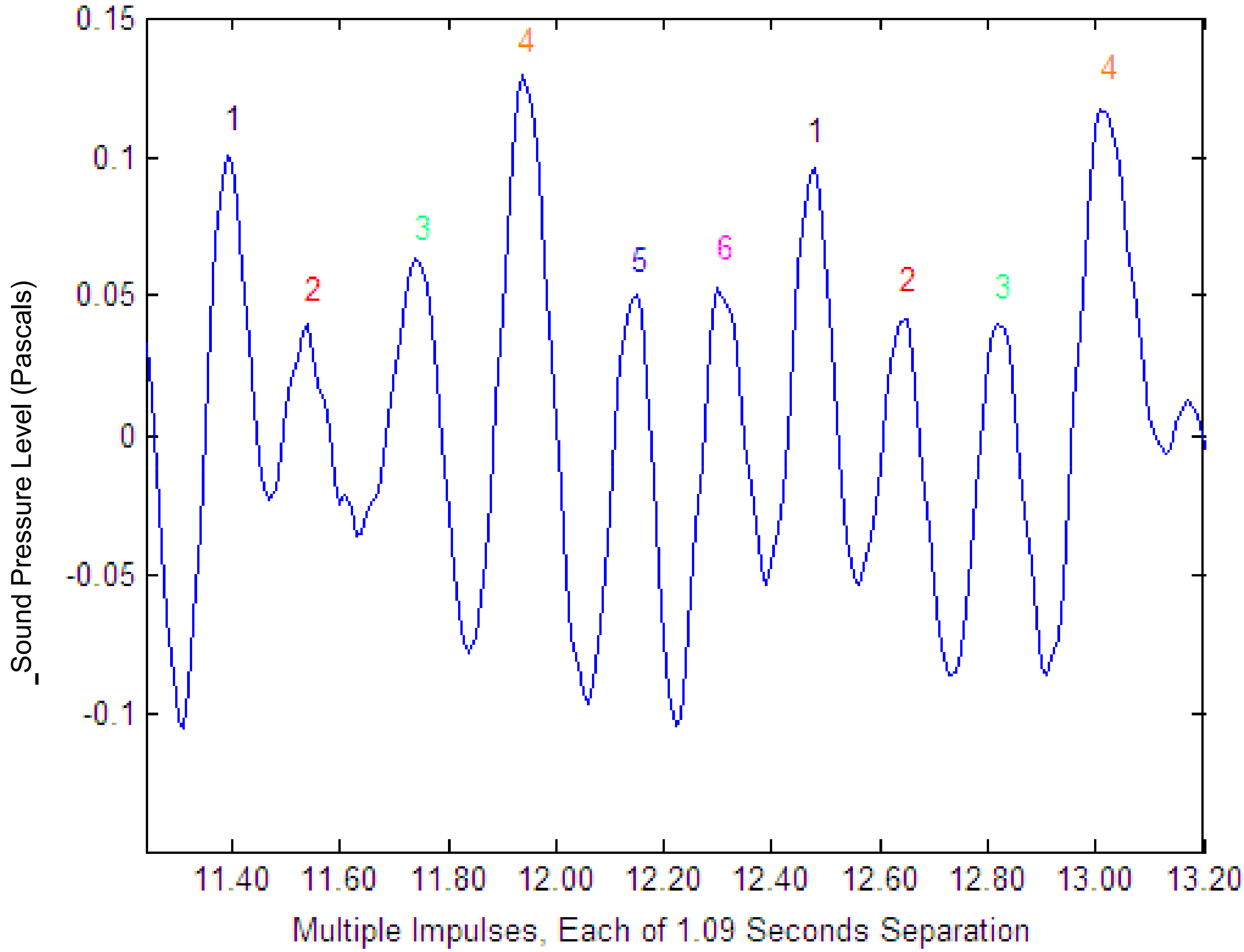
It can be dangerous to maneouvre a sailplane in steep turns close to the ground in severe wind-gradients without adequate airspeed, because the different wind conditions give rise to very different incidence angles along the span.

As a result, the lower wing-tip may find itself in slower-moving air. The incidence angle will increase, possibly leading to wing-tip stall and subsequent loss of control, with fatal consequences.

For wind turbines, such changes in incidence inevitably result in increased low-frequency noise and amplitude modulation. The effects of undulating ground, the presence of trees and other wind-shadowing obstacles contribute to this effect, as correctly identified by NASA in 1989.

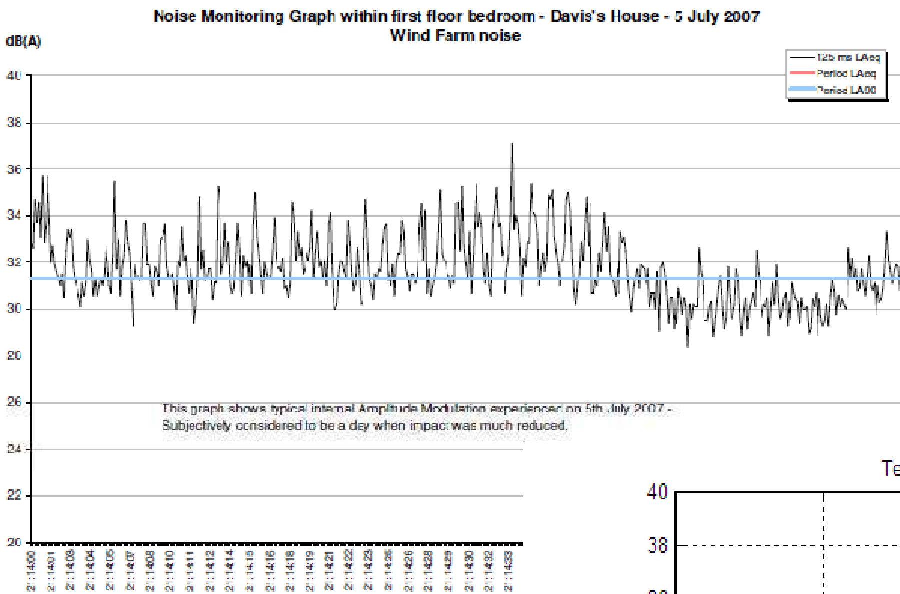
Similar effects can be induced by the wake turbulence of other wind-turbines in a windfarm array, but the latter can at least be mitigated by ensuring adequate turbine separation. Local airflow and wind gradients from surrounding terrain and atmospheric conditions cannot be controlled in this way.

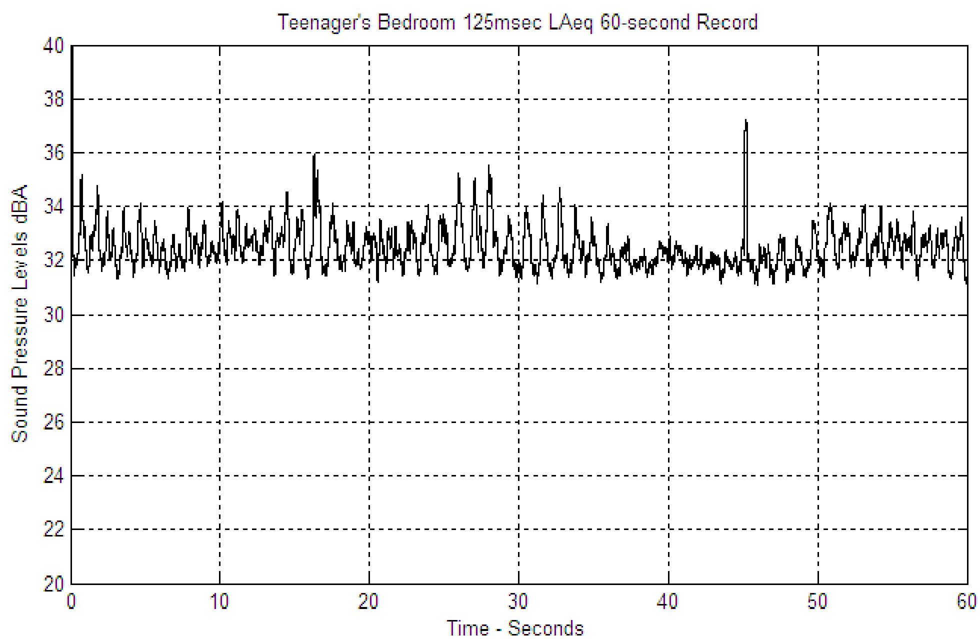
Multiple Low-Frequency Impulses Measured Indoors in March 2010 at a Modern, Upwind-Rotor Windfarm.   6 Separate Turbines can be Identified



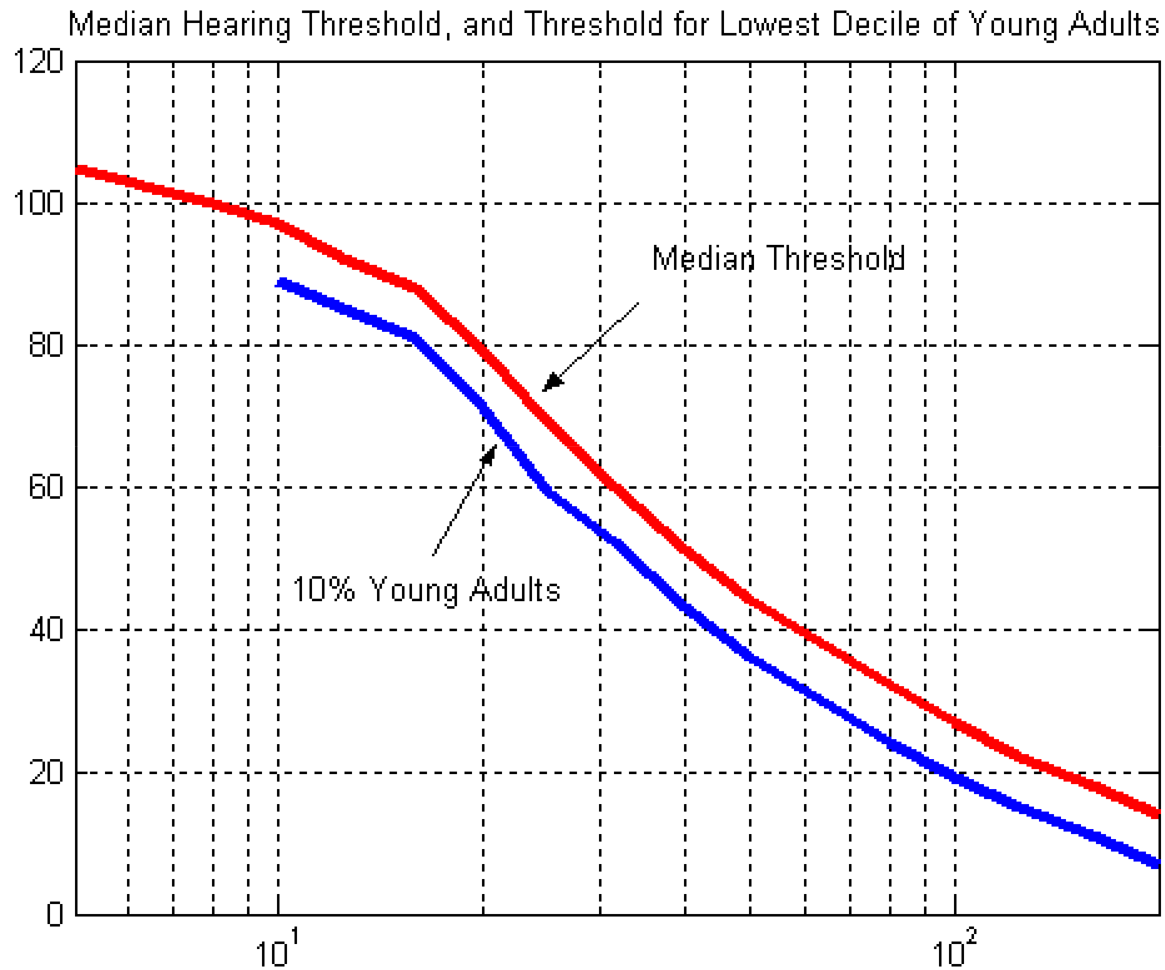
Time Traces sampled at 100Hz, with 40Hz Low-Pass Filtering

The Corresponding Amplitude Modulation - almost Identical Wind Turbine Noise in Two Teenager's Bedrooms: USA & UK





10% of Young Adults are ~8dB More Sensitive to Low Frequency Noise than the Median Threshold for All Adults



Overall Assessment of Wind Turbine Low Frequency Noise based on the Aspects Already Discussed

This information is summarised and drawn together, resulting in a single graph intended to demonstrate the overall consequences.

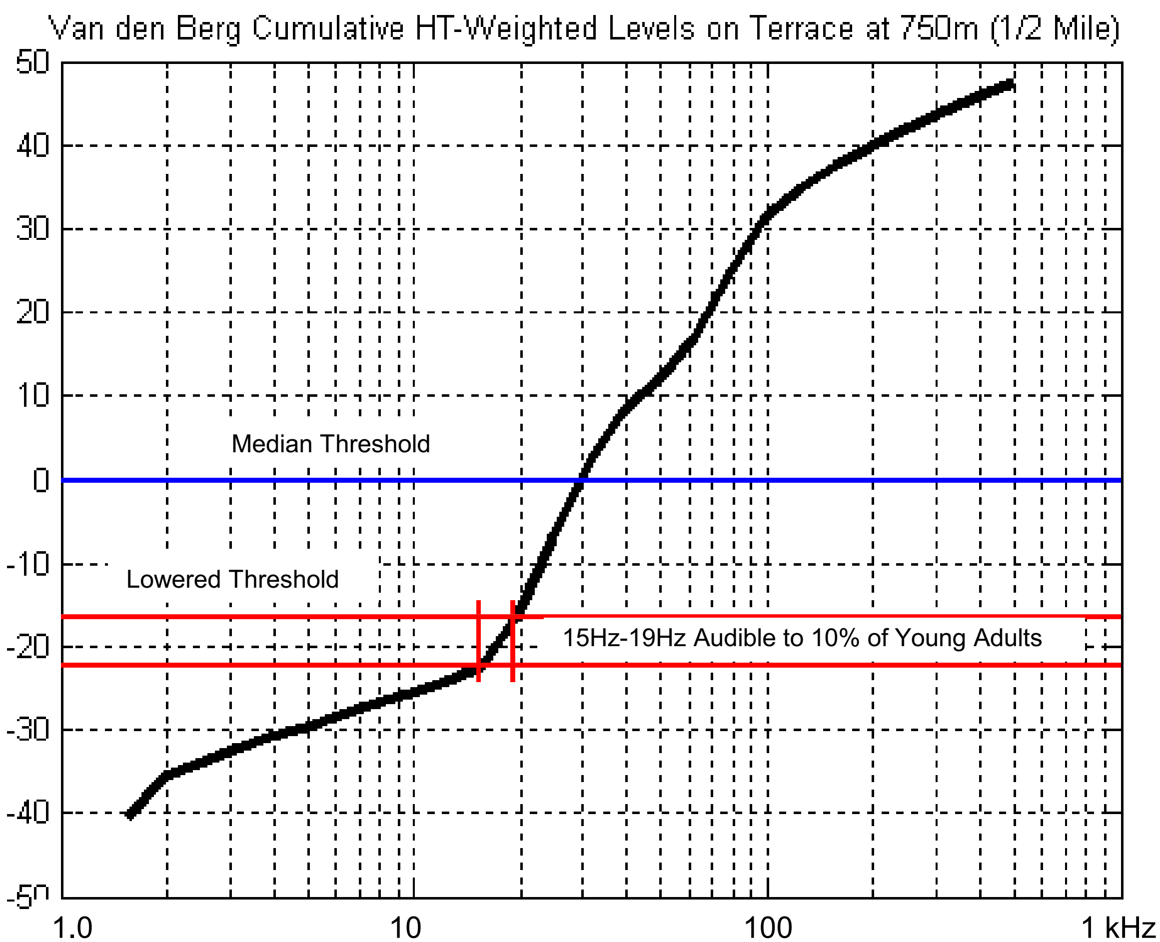
(1) The Published Van den Berg 1/3rd Octave Data at 750m, taking account that the levels actually experienced were reportedly 3dB higher on the terrace.

(2) A Rigorous Procedure for Establishing the Frequency at which the Hearing Threshold is first crossed, according to basic RMS Criteria.

(3) The Increased Sensitivity to Low Frequency Repetitive & Impulsive Noise based on NASA Research in the 1980's

(4) The Increased Hearing Sensitivity of 10% of Young Adults

The graph shows that 10% of Young Adults might be expected to have been sensitive to infrasound and low-frequencies at this particular windfarm, starting as low as the frequency range 15-19Hz.



Assumptions:

Van den Berg 1/3 Octave Levels were increased by 3dB on Terrace & Facade

Hearing Threshold for 10% Young Adults (Lowest Decile) is 8dB lower (more sensitive)

NASA : 7dB to 10dB (average 8.5dB) Increased Sensitivity to Phase-Coherent (Repetitive) Low Frequency Wind-Turbine Noise

Net Reduction in Overall Threshold -16.5dB

Resolving an Obvious Discrepancy

The report by DELTA [1] has been referenced in arriving at this conclusion. The DELTA report included the G.P.van den Berg Paper [2] in their evaluation. But their conclusions differ from the present author.

"There is general agreement that wind turbines do not emit audible infrasound. The levels are far below the hearing threshold…..

Audible low frequency sound occurs both indoor and outdoor but the levels are in general close to the hearing and/or masking threshold. There seem to be agreement that it is not considered to be a problem, or it have not been shown that this is a major factor contributing to annoyance."

Delta had reduced the van den Berg data to the equivalent of 1 single wind-turbine at a distance of 6 Hub Heights (600m). They then compared this result to a <u>normal</u> ambient background.

The van den Berg windfarm consisted of 17 wind-turbines. The essential feature of his paper was that the night-time ambient could be very low, while wind-speeds at hub-height are high, so that the turbine noise dominates over the ambient. He also considered "More turbines can interact to further amplify this effect".

So Delta's conclusions do not necessarily relate to the actual G.P. van den Berg conditions.

[1] DELTA Danish Electronics, Light & Acoustics EFP-06 Project Low Frequency Noise from Large Wind Turbines - Quantification of the Noise and Assessment of the Annoyance. T.H.Pedersen Client: Danish Energy Authority 30 April 2008

[2] G.P.van den Berg 11th International Meeting on Low Frequency Noise, Maastricht, The Netherlands, September 2004 Do wind turbines produce significant low frequency sound levels?

<u>Overall Conclusions</u> - 1

Two Examples of Wind Turbine Spectra at Distances of ¼ - ½ mile have comparable levels to (projected) Gas Turbine Low Frequency Spectra that evoked complaints in the early 1980's.

These complaints were resolved successfully, using Active Sound Control Techniques.

The Relevance of Comparing 1/3rd Octave Broad Band Spectra with a Pure Tone Hearing Threshold has been considered.

It is shown to be near Equivalent to a Rigorous Comparison based on True RMS Levels.

Such Comparison does not take Account of Waveform Shape, Peak Levels and Crest Factor.

Overall Conclusions - 2

NASA Research of the early 1980's reported that Impulsive and Phase Coherent (Repetitive) Low Frequency Noise can be Significantly more Intrusive (7dB-10dB) than Random Phase Noise.

The Effect of Wind-Gradients and Wind Shadowing can cause a Modern Upwind Rotor Turbine to generate Impulsive & Repetitive Low Frequency Noise

The Threshold of Hearing of 10% Young Adults is (on average) 8dB Lower than the Median Threshold.

Consequently, the Van den Berg Windfarm may have been audible to 10% Young Adults at Frequencies as low as 15-19Hz.