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Infrasound noise and wind farm noise

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Sound

- Infrasound, frequency below 20 Hz
- Audible sound, frequency between 20 Hz and 20 kHz
- Ultrasound, frequency above 20 kHz
- Hypersound, frequency above 10 GHz

Sound

Media of propagation:

- Infrasound: air (atmosphere, outdoor)
- Audible sound: air (outdoor and indoor)
- Ultrasound: air below 100 kHz, water and other liquids, solids
- Hypersound: solids (crystals)

Wavelength in air

$\lambda = c/f$; c- speed of sound, 344 m/s for t=20°C

Frequency [Hz]	Wavelength [m]
0,02	1720
2	172
20	17,2
200	1,72
2000	0,172
20000	0,0172

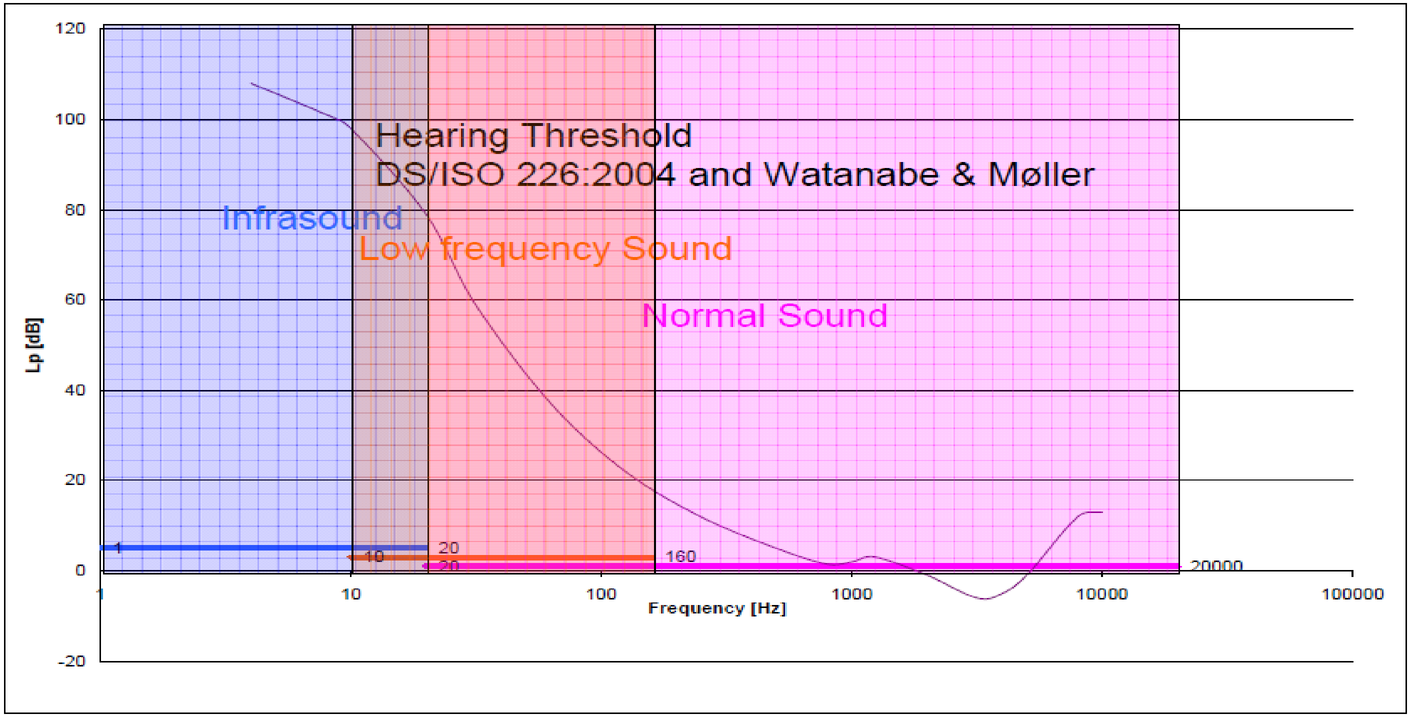
DEFINITIONS OF AUDIBLE NOISE, LOW-FREQUENCY AND INFRASOUND

Sounds in the audible frequency range are, according to ISO 7196, sounds or noise, whose spectrum is mainly contained in the frequency range from 20 Hz to 20 kHz.

There are different definitions for infrasound noise. Most often, infrasound noise is considered to be noise whose spectrum is mainly in the 1 Hz to 20 Hz band. In the International Terminology Dictionary of Electricity, Acoustics and Electroacoustics, infrasound is defined as acoustic oscillations whose frequency is below the lower limit of audible sounds (approx. 16 Hz). This definition is incomplete because infrasound at sufficiently high levels can be heard at frequencies below 16 Hz.

The concept of low-frequency noise refers to noise covering high infrasound frequencies and the lower audible frequency range and typically the range is from 10 Hz to 200 Hz (this is not a strictly defined range and e.g. according to EN 61400-11 is a range from 20 Hz to 100 Hz).

DEFINITIONS OF AUDIBLE NOISE, LOW-FREQUENCY AND INFRASOUND



Bands of infrasound frequencies, low frequencies and audible frequencies with plotted hearing threshold

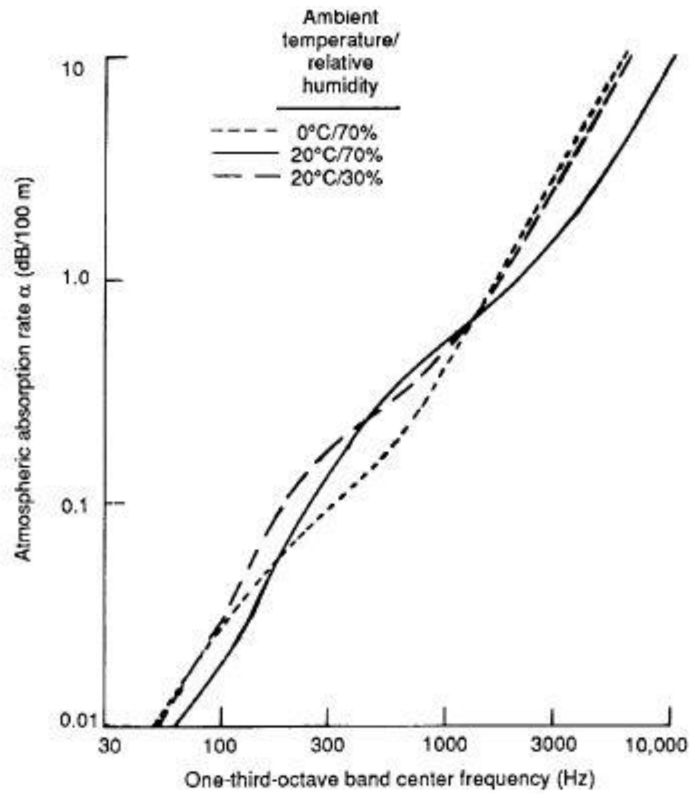
Sources of infrasound (natural)

Source	Frequency [Hz]	Acoustic pressure [Pa]	Mechanism
Earthquakes	0,03-0,125	0,1 – 2 (at thousans km)	Ground motion
Volcanic erruptions	<0,01	15 (Mt. St. Helens at 10000 km)	Explosive compression of atmosphere
Avalanches	0,5 - 2	0,02-0,05 at 100 km	Periodic leading-edge roll
Mountain associated waves	0,02-0,1	0,1-3	Turbulence from wind flow over mountain ridges
Microbaroms	0,125 – 0,5	0,01 - 1	Nonlinear interaction of ocean waves
Severe storms	0,02-10	0,05 – 3 at 30-800 km	Uncertain

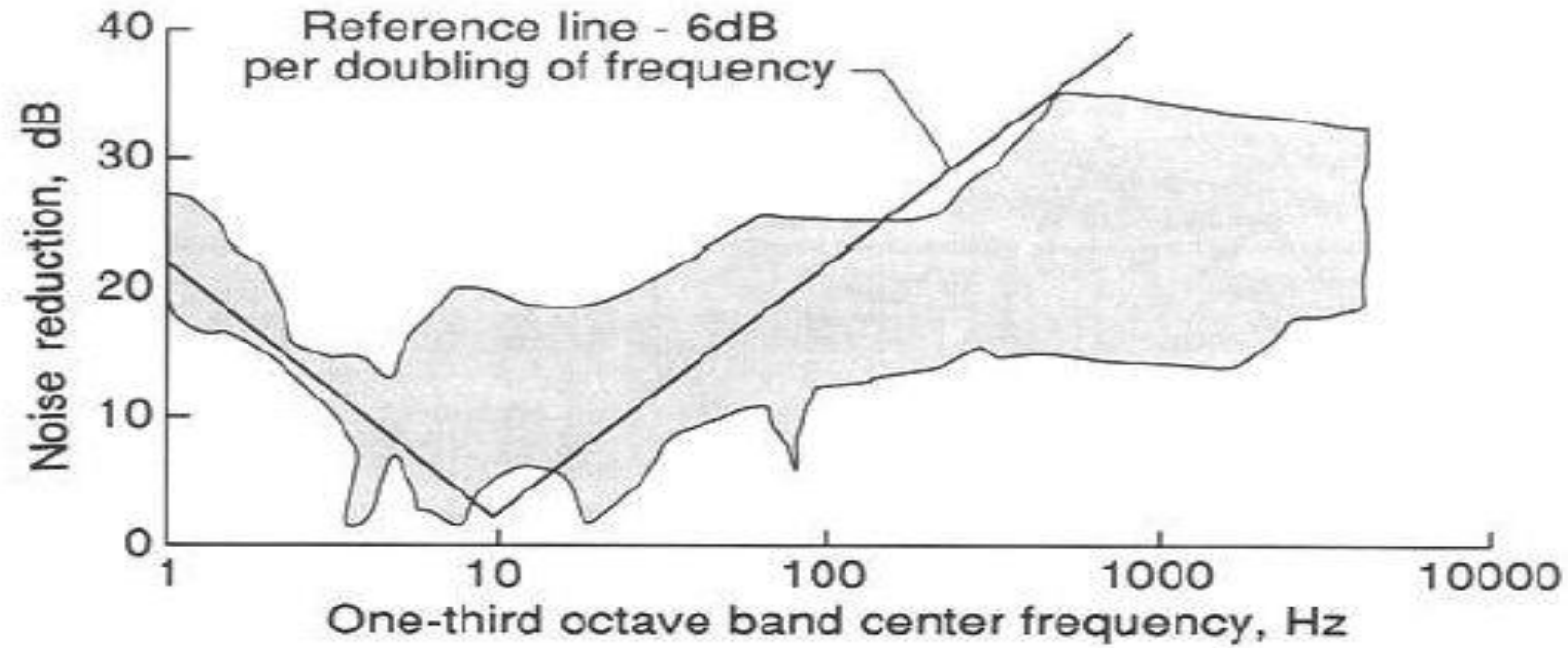
Sources of infrasound and LF noise (human activity)

- Sonic booms, explosions (chemical and nuclear)
- Low speed compressors, ventillators, motors etc.
- Mills, boilers, chimneys
- Blast furnances
- Foundry eqiupment: shock bars, moldings
- Wind turbines, wind farms
- Special subwoofers, bass musical instruments (drums)

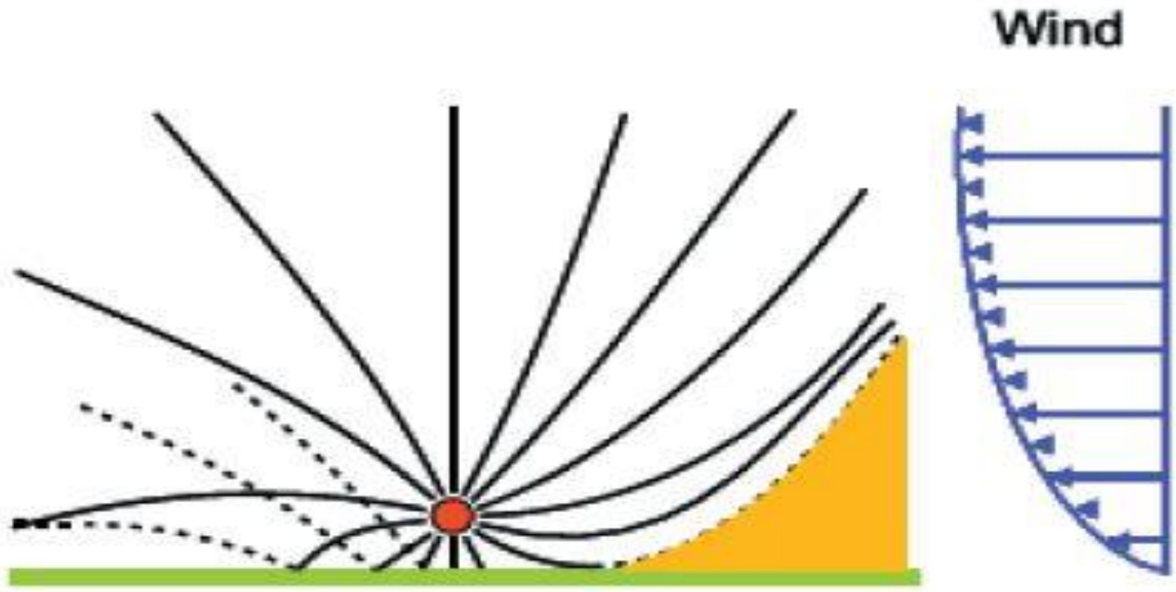
Propagation of Infrasound and LF-noise (attenuation in air)



Propagation of Infrasound and LF-noise (Insulation of walls)



Influence of wind on LF-noise propagation



Propagation of sound from a source located at a certain height in the downwind (left) and upwind (right) for variable in height wind speed profile.

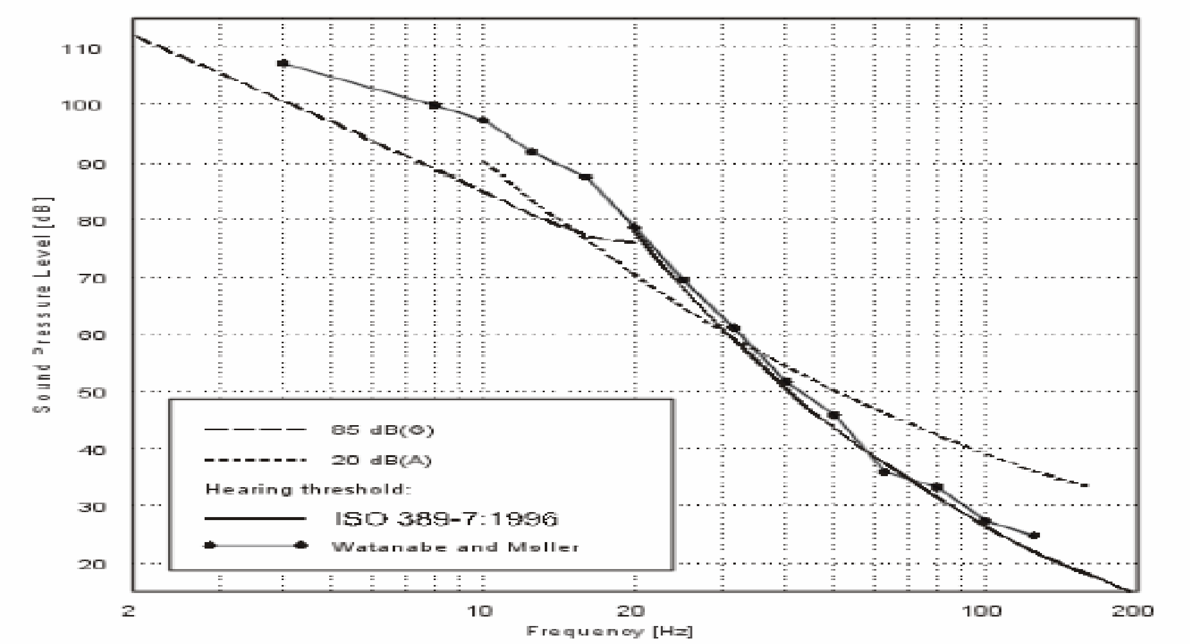
Influence on humans

- Audibility by hearing organ, sensation of pressure on eardrum
- Resonance of internal organs (heart, liver,eye)
- Disturbance of brain waves cycles
- Effects of annoyance, fatigue, sleep disturbances, nausea, decrease of blood pressure (for very high levels only)
- Resonance of eyes (at 19 Hz may cause ghost sighting)

Influence on humans

Frequency [Hz]	SPL[dB]	Exposure duration [min]	Number of subjects	Diease symptoms
2 - 15	105			In 50% of patients prolonged visual response time; 10% imbalance
1 - 2	150			Shifting the hearing threshold, the sensation of eardrums sliding
2 - 15	110 -120		7	4% increase in response time
3 - 15	115	30		Symptoms like after alcohol abuse
10	135	15	6	Sensation of internal organs vibrating. Feeling of tympanic membrane vibrations, middle ear pain, acceleration of pulse and breathing, shifting of the hearing threshold by 15-20 dB during the tests, and immediately by the end of the tests by 8-10 dB
7	90	35	30	A drop in blood pressure, a decrease in pulse frequency
1 - 100	154	0,4 - 2		The sensation of rocking the walls, headache and dizziness, shortness of breath, ringing in the ears, lockjaw

HEARING PERCEPTION OF INFRASOUND AND LOW FREQUENCY NOISE



Frequency dependencies of the hearing threshold in the audible frequency range (EN ISO 389-7); - hearing threshold determined in Watanabe and Moller studies in the field of infrasound and low frequencies; - limit level G values for 85 dB (up to 20 Hz) and level A 20 dB (in the range 10 Hz - 160 Hz)

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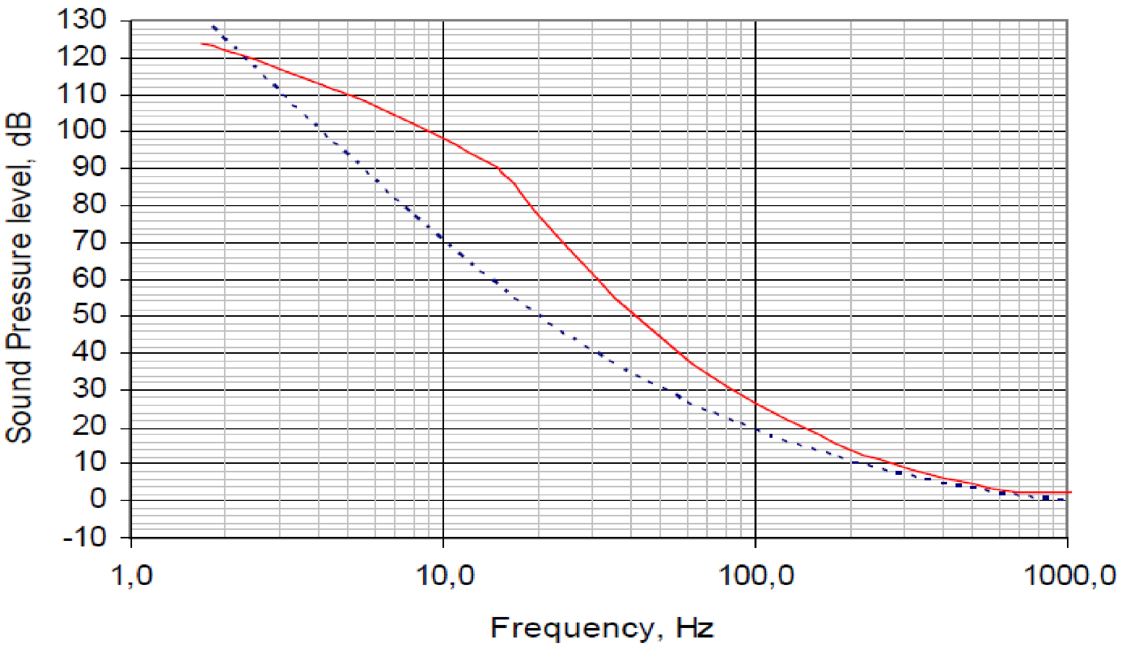
Threshold of hearing



Dashed line – upside-down A-curve

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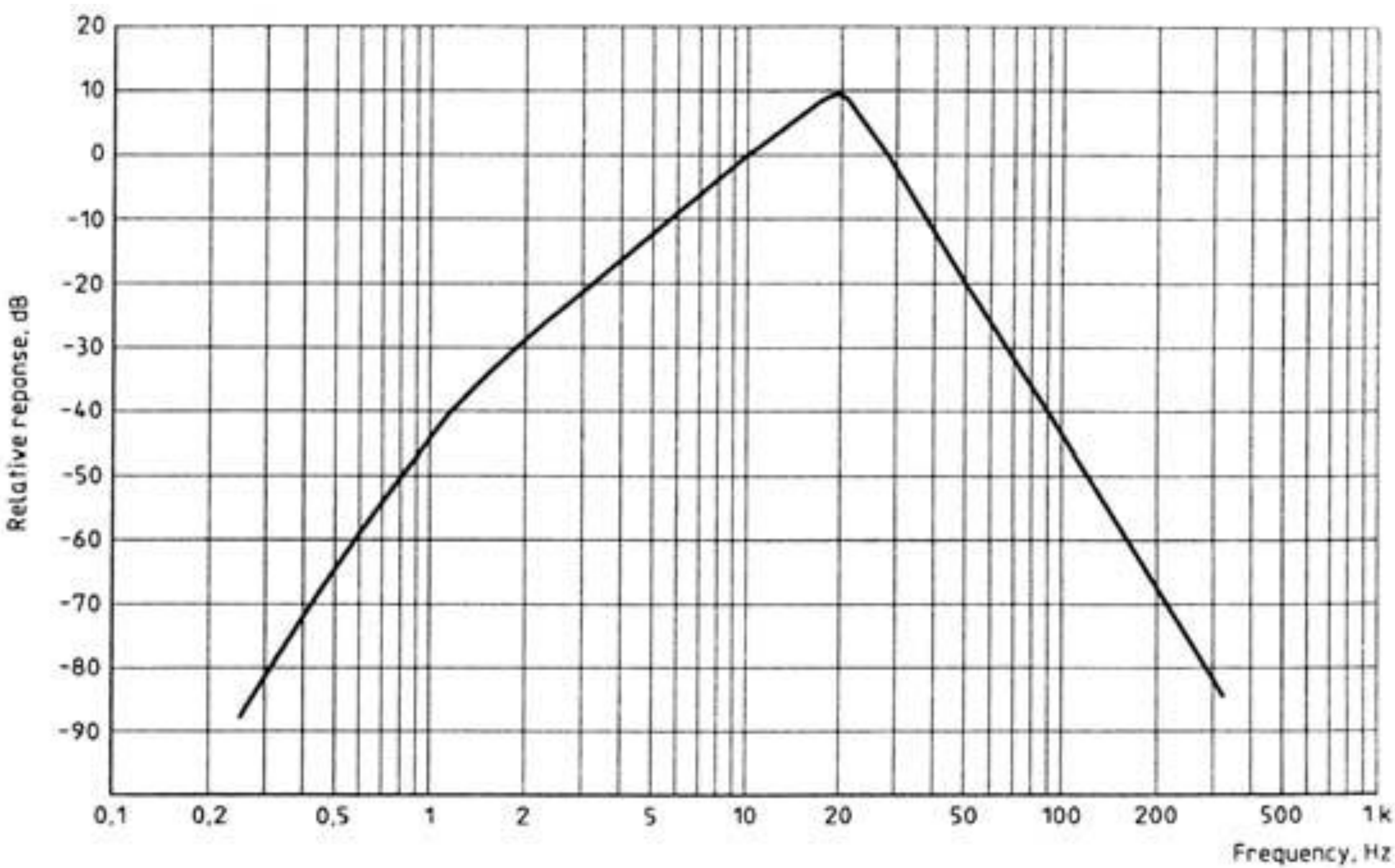
Frequency weighting curve G



Limit values (according to Polish law) at working places

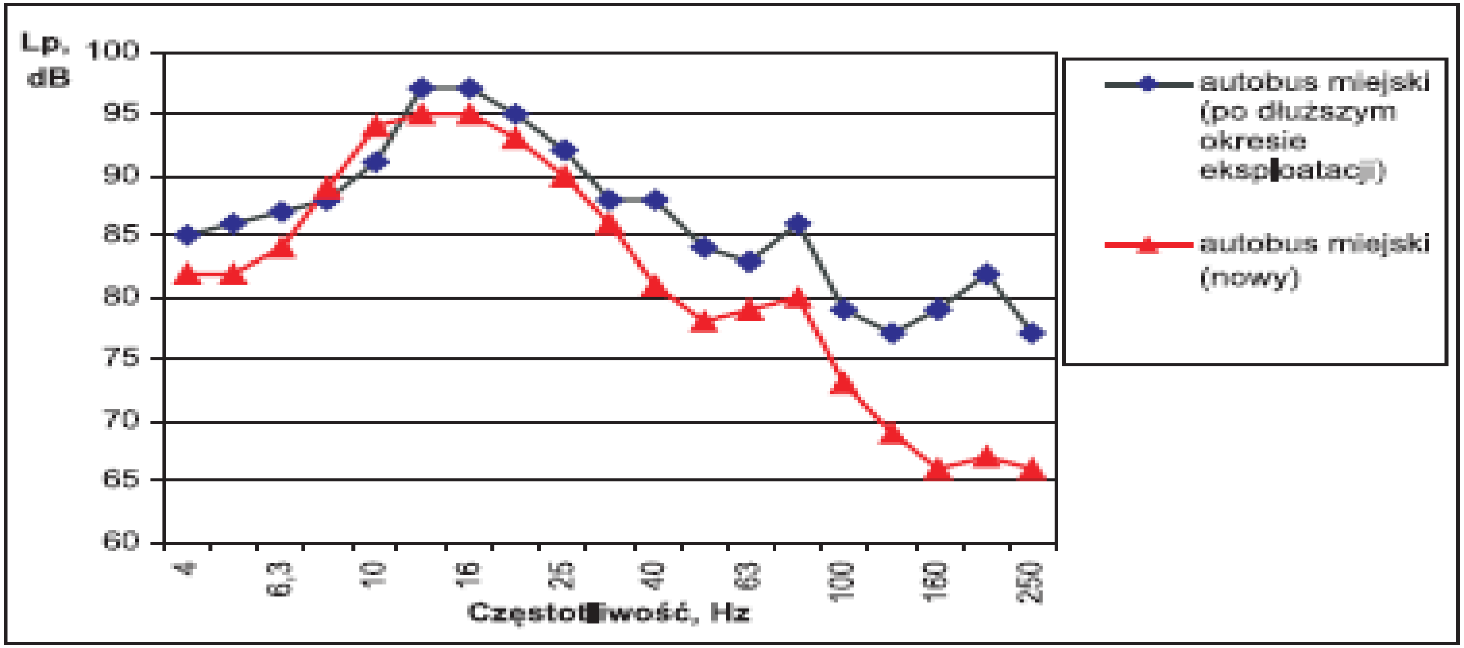
- $L_{G,eq,8h}$=102 dB
- L_{peak}=145 dB
- For adolescents and pregnant women:

Middle frequency of octave, Hz	$L_{eq,8h}$, dB
8; 16	85
31,5	80

NOISE LEVELS WEIGHTED WITH G-CURVE

Noise	Level of infrasound G [dB]
Inside a passenger car when riding on a basalt road (v = 30 km/h)	115,7
Inside a passenger car for v=100 km/h	102,7
In a office (60 m^2, air conditioning and many computers on)	73,6
Wind turbine 500 kW at the distance of 200 m	63,9
16 Hz test tone at 115 dB SPL with pink noise at 45 dB SPL in 1/3-octave bands	122,8

NOISE LEVELS AND SPECTRA IN INFRASONIC RANGE



Spectrum of infrasound and low-frequency noise in 1/3-octave bands measured inside a city bus (asphalt road, v = 50km / h)

Wind turbine as a noise source

Noise generated by wind farms can be considered due to the source of its generation as:

- mechanical noise
- aerodynamic noise.

Noise located in the power plant nacelle is responsible for mechanical noise. These include gears, generators, a system to align the position of the turbine with the wind direction, cooling system and other auxiliary systems (e.g. hydraulic pumps and disc brakes). Because this sound is associated with the rotational movement of mechanical and electrical components of the structure, it may have a tonal character. The broadband component of mechanical noise comes from other components such as gears and hydraulic systems.

Wind turbine as a noise source

The sound generated inside the nacelle can be emitted from the source to the environment either directly (air-borne) or indirectly through the vibrations of the entire structure of the power plant (structure-borne). In modern wind farms, mechanical noise is limited by the sound insulation of the gondola and continuous improvement of the devices placed in it. Thanks to this, except in situations of component failure or operational wear, this noise has been limited to a negligibly low level compared to aerodynamic noise.

The sources of mechanical noise of the wind turbine together with marked values of the sound power level and the marked contribution of aerodynamic noise are illustrated in the next slide.

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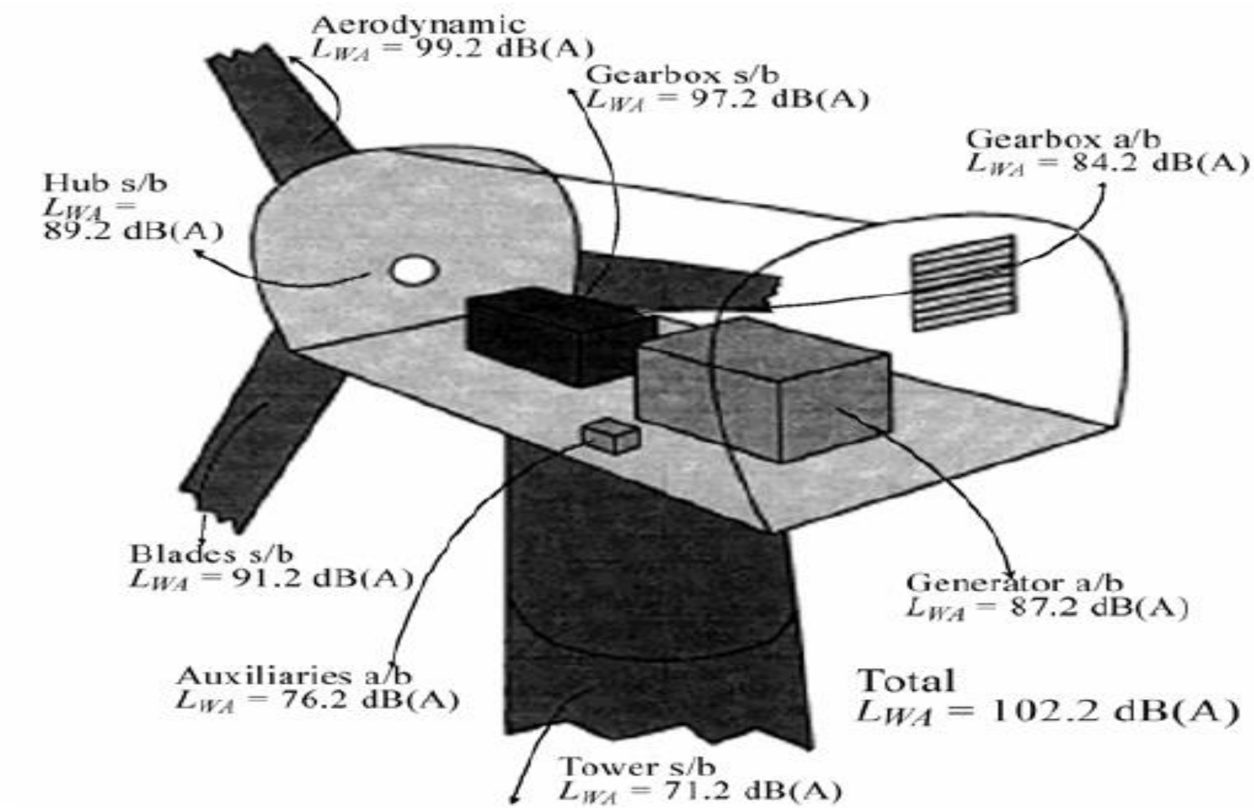
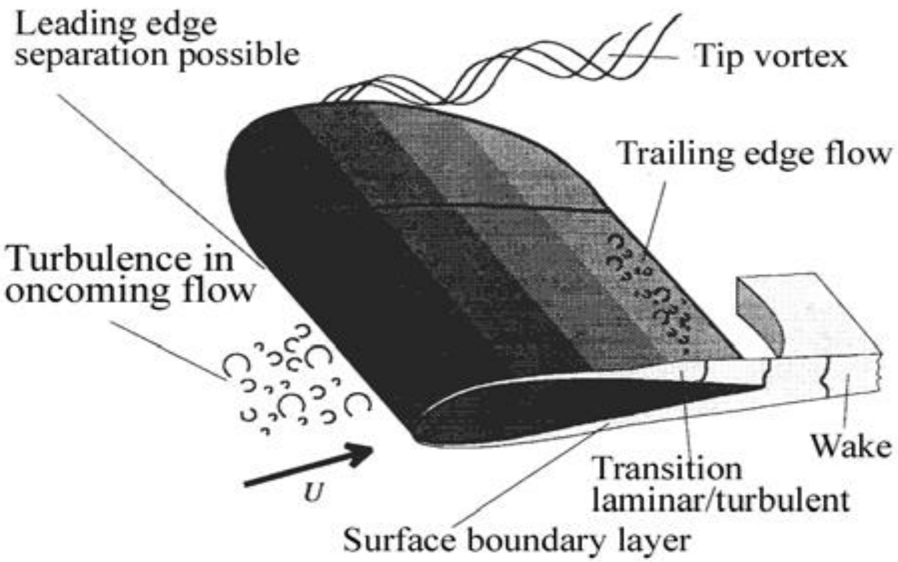
Wind turbine as a noise source



Examples of acoustic power of individual wind turbine noise sources and resultant power together with marked air (a / b) and material (s / b) transmission routes

Wind turbine as a noise source

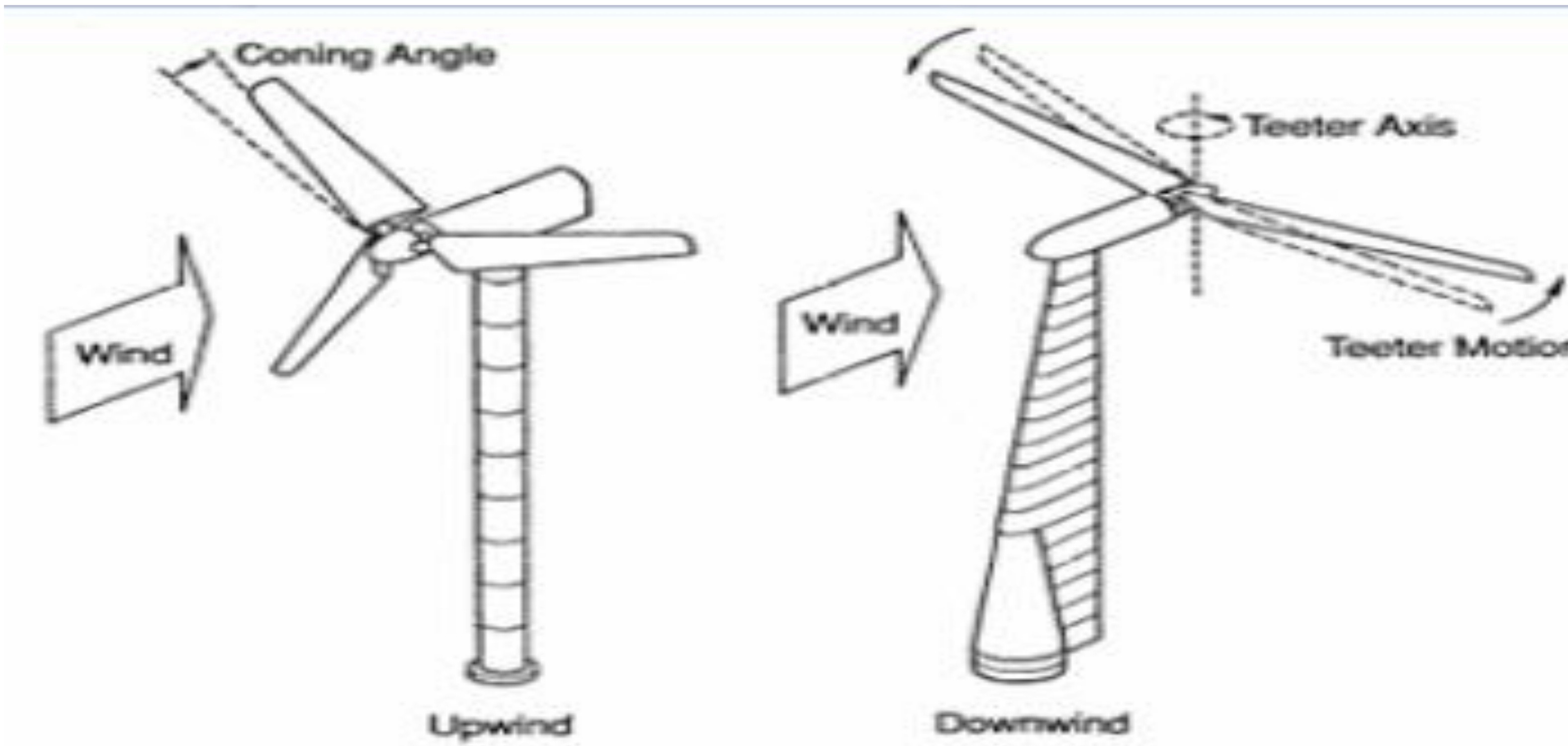
Aerodynamic noise is generated by airflow around power plant blades. The level of this noise depends on the speed of the linear tip of the turbine blade. Therefore, the blade's length and rotational speed have the greatest impact on the sound power of a wind farm.



Wind turbine as a noise source

Aerodynamic noise can be divided into three groups. The first group is low-frequency noise arising as a result of the blade passing through areas with lower air pressure due to its circulation around the power plant tower. The formation of this type of noise is also favored by rapid changes in air flow speed and uneven wind distribution causing greater stress on the blades located in places with stronger pressure. This noise depends on the type of turbine: whether it is set with the wind (downwind) or against the wind (upwind). The spectrum of this noise contains infrasound components at levels greater than levels in the audible band.

Wind turbine as a noise source



Turbine settings a) against the wind (upwind), b) with the wind (downwind).

Wind turbine as a noise source

Characteristic for this type of noise is the non-stationarity (strictly cyclostationarity) of the time course of noise. The mechanism of this phenomenon is explained in the figure below

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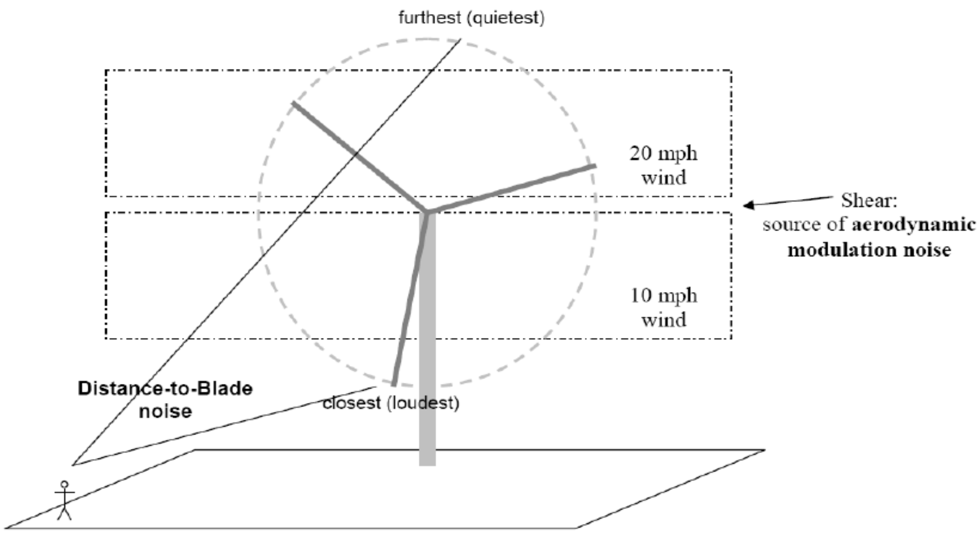

Scheme of creating amplitude modulation (AM) by wind turbine aerodynamic noise.

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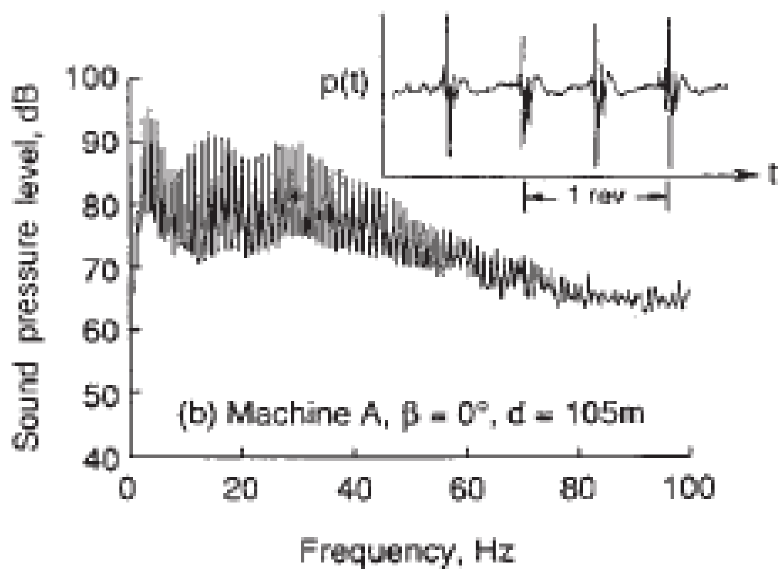
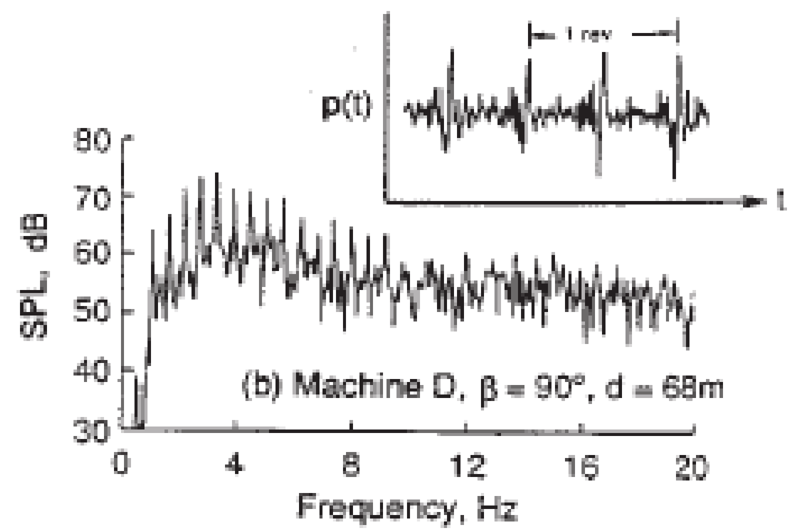
Wind turbine as a noise source





Examples of narrow-band spectra (FFT) of the MOD-1 wind turbine noise from General Electric (figure left, downwind turbine) and MOD-5B from Boeing (figure right, upwind turbine).

Wind turbines:
left: MOD-1 wind turbine from General Electric (downwind turbine)
up: MOD-5B from Boeing (upwind turbine)

Wind turbine as a noise source

The second group includes noise resulting from the intersection of local air swirls by the blades, which results in the formation of local pressure fluctuations and force exerted on the turbine components.

The third type of noise is related to the air-flow around the moving airfoil. This noise is usually broadband, although tonal components may occur as a result of blunting of the cutting edges of shovels or gaps and holes on its surface.

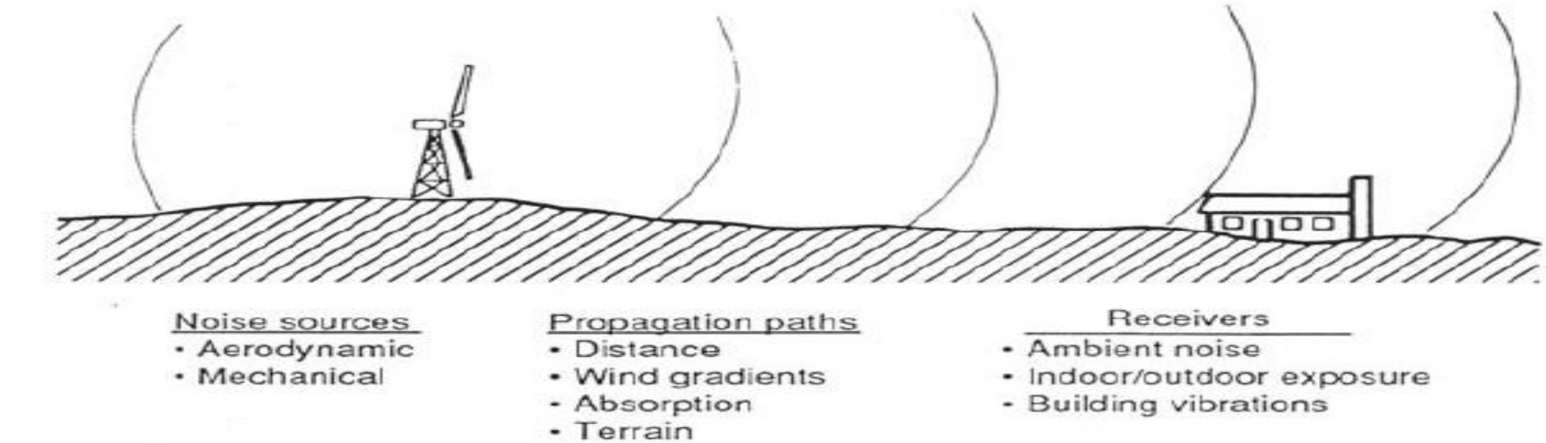
PROPAGATION OF THE NOISE EMITTED BY WIND FARMS

Three factors contribute to the nuisance of noise emitted by a source such as a wind turbine:

- The turbine sound power, which determines how much noise is emitted. An important role is also played by the distribution of this power as a function of frequency, i.e. the sound spectrum (the human ear reacts in different ways to different components of the spectrum) and the spatial distribution of radiation, i.e. directivity characteristics. These factors determine the properties of the source.
- Propagation conditions, i.e. the distance from the sound source to the listener, terrain and obstacles on the path between the source and the receiver, as well as wind direction and speed, as well as other noise sources that may mask noise from the source in question. These factors occur

PROPAGATION OF NOISE EMITTED BY WIND FARMS

The listener's surroundings, i.e. the insulation of the room walls, building vibrations, and other sound sources that may affect the level of acoustic background. These factors determine the properties of the noise receiver.



Noise propagation emitted by a wind turbine and factors affecting its perception.

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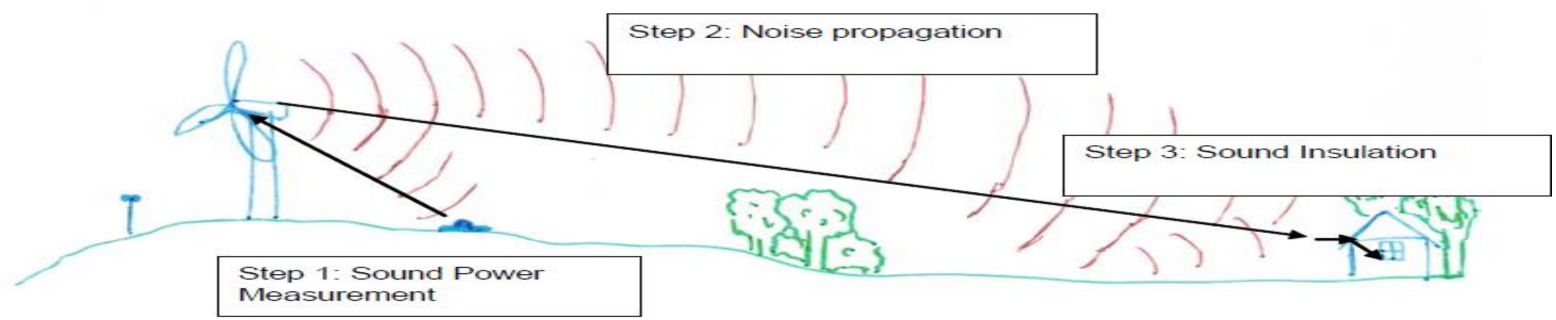
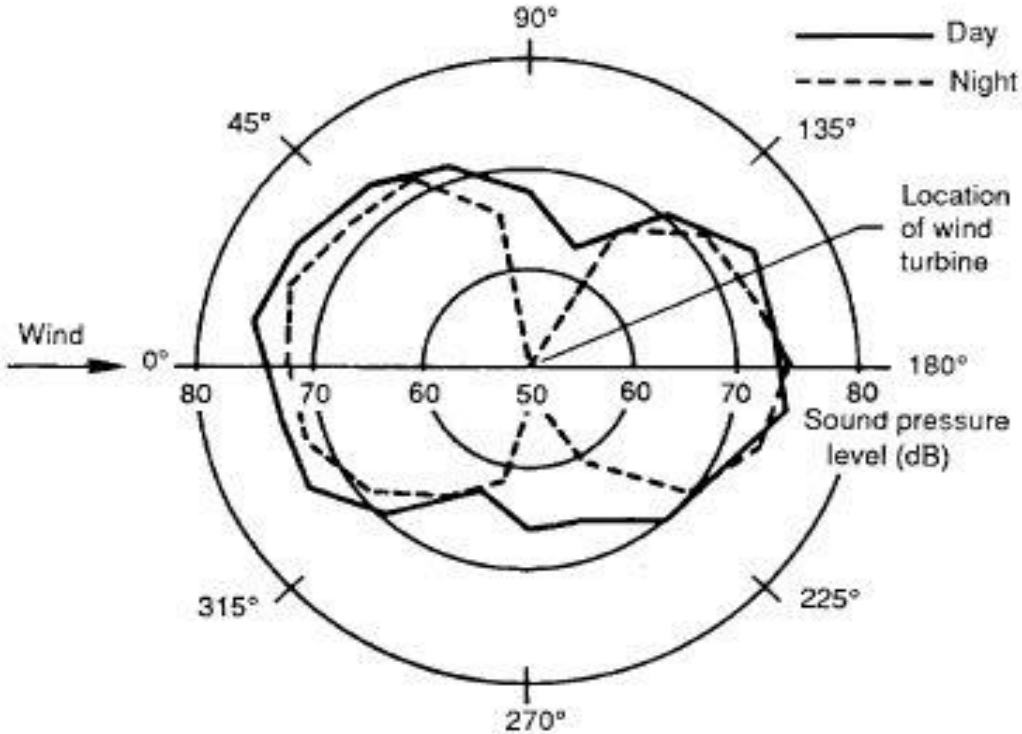
PROPAGATION OF NOISE EMITTED BY WIND FARMS

Determining the level of noise reaching the listener consists of three stages:

- Determination of source properties (sound power, directivity)
- Determination of propagation conditions (distance, absorption, refraction)
- Determining the properties of the receiver and its immediate environment

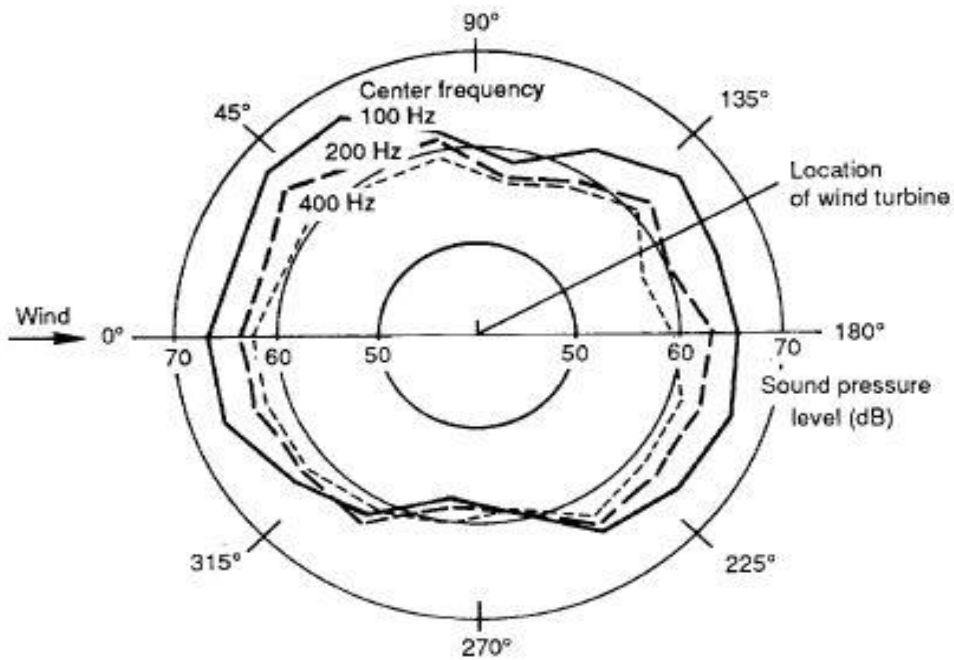


PROPAGATION OF NOISE EMITTED BY WIND FARMS



Directional characteristics of infrasound radiation at a frequency of 8 Hz by a large turbine with a horizontal axis measured at a distance of 200 m from the turbine during the day and at night.

PROPAGATION OF NOISE EMITTED BY WIND FARMSE

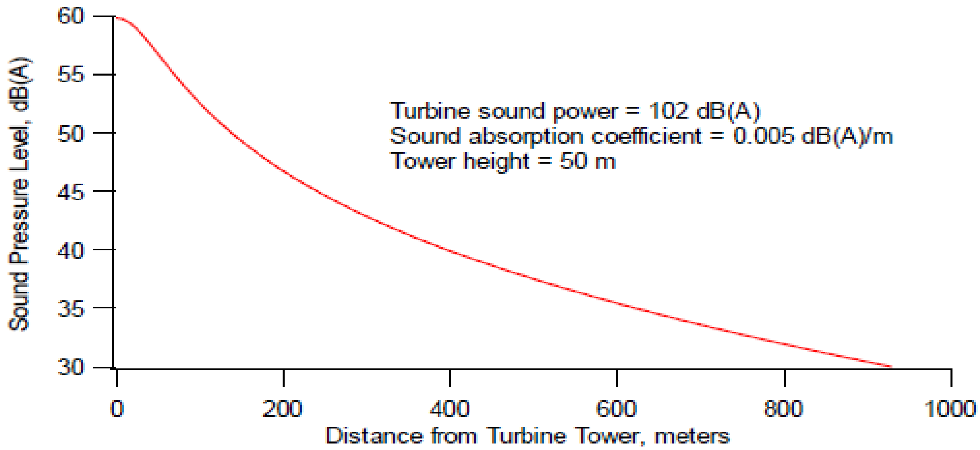


Low frequency noise radiation directivity characteristics in octave bands in the frequency range 100 - 400 Hz by a large turbine with a horizontal axis measured at a distance of 200 m from the turbine.

PROPAGATION OF NOISE EMITTED BY WIND FARMS

Influence of the distance and absorption:

$$L_p = L_W - 10lg(2\pi R^2) - aR$$



Change in the sound pressure level as a function of distance from the turbine with a sound power of LWA = 102 dB and for the sound absorption coefficient a = 0.005 dB / m (5 dB / km). Tower height 50 m.

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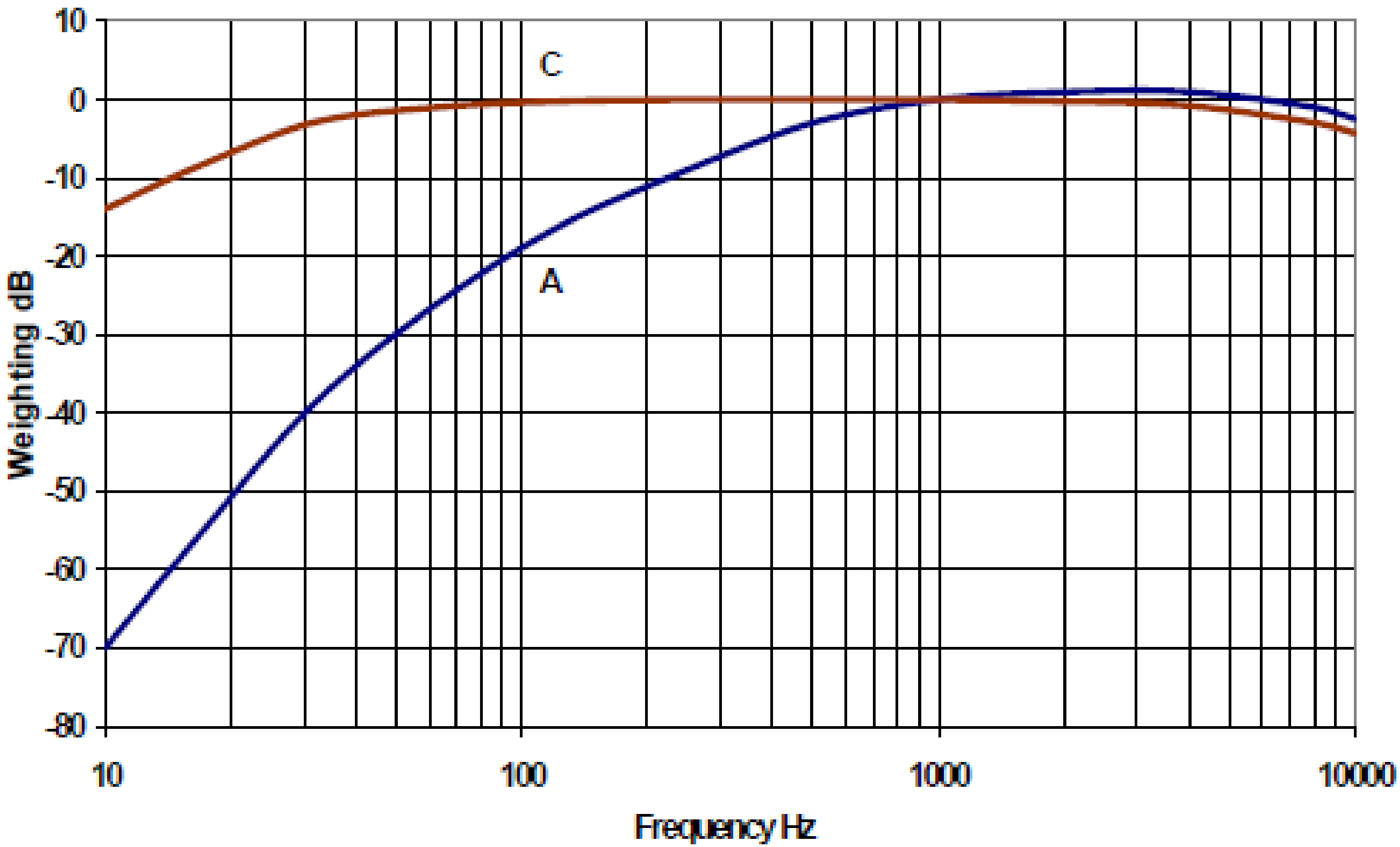
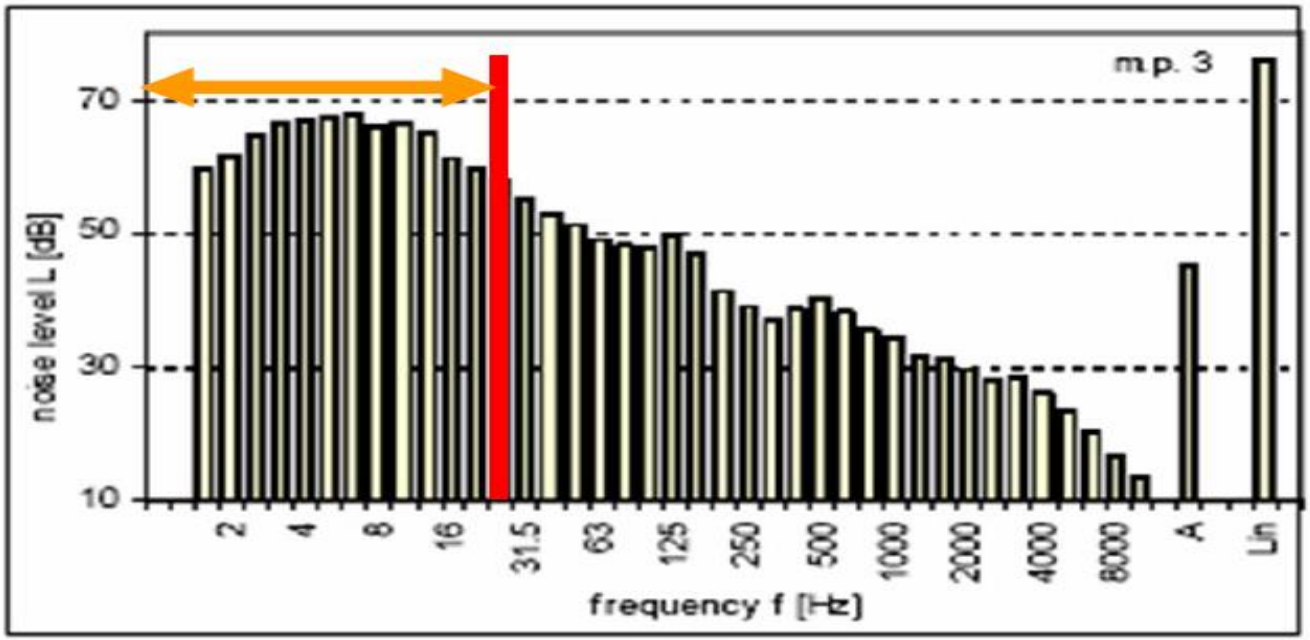
A and C frequency weighting curves

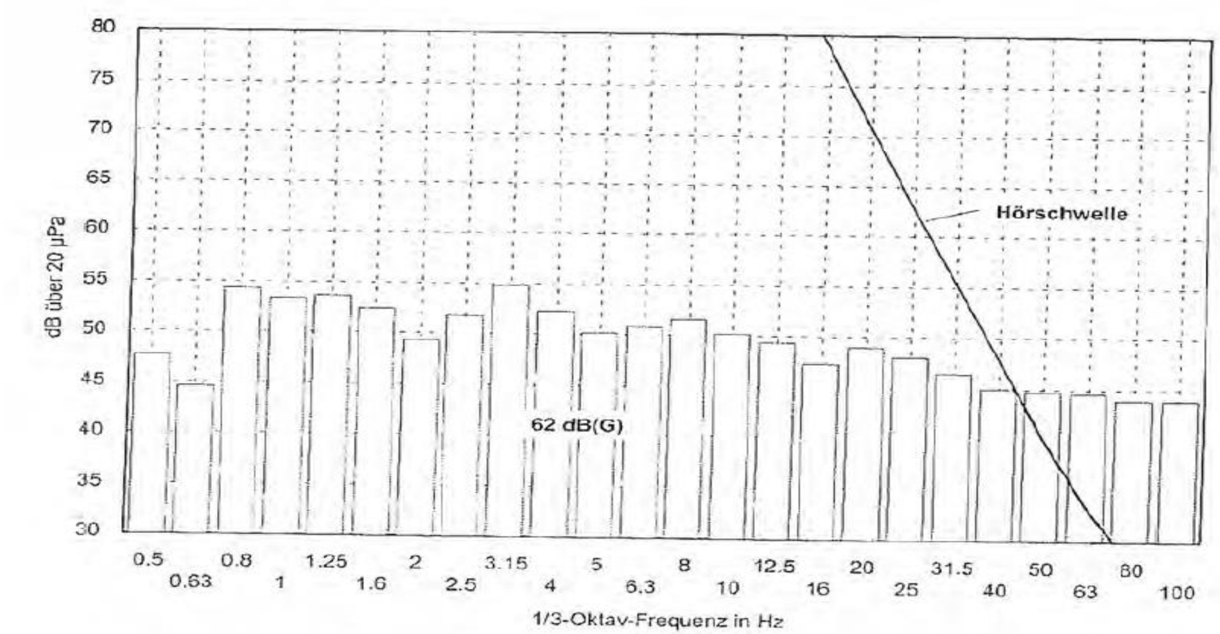


NOISE LEVELS AND SPECTRA OF WIND TURBINES



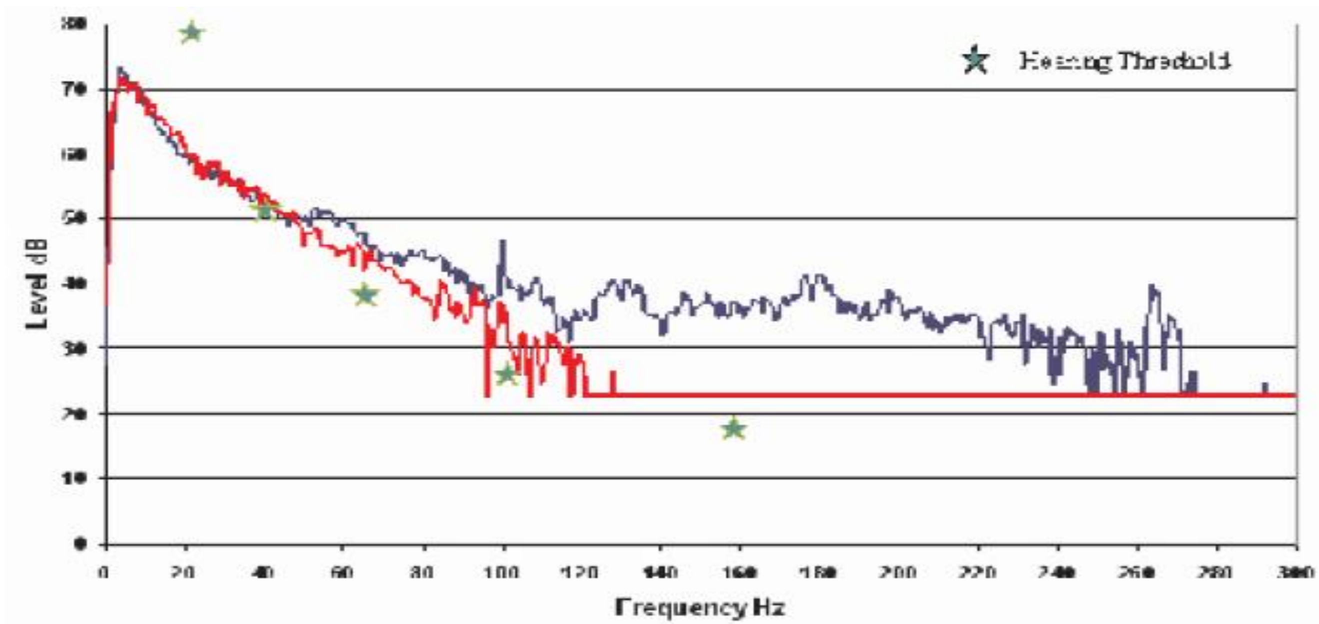
Noise spectrum of a Vestas V80 wind turbine (downwind type) measured in 1/3-octave bands. The levels in the infrasound frequency range (marked by an arrow) are below the hearing threshold levels.

NOISE LEVELS AND SPECTRA OF WIND TURBINES



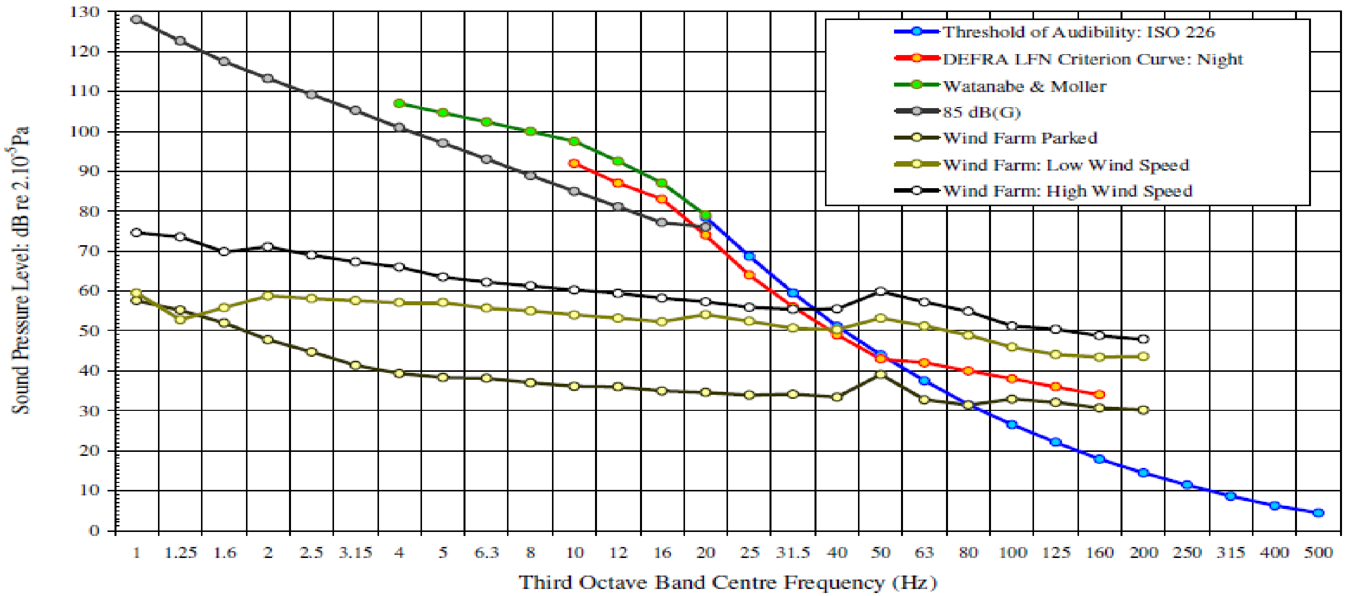
1/3 octave spectrum of infrasound noise and low frequency NORDEX N-80 wind turbine (power 1100 kW, distance 200 m). The hearing threshold has been applied according to DIN 45680

NOISE LEVELS AND SPECTRA OF WIND TURBINES



Noise spectrum of a modern wind turbine (upwind) (blue) with a power of 1.5 MW measured at a distance of 65 m. The acoustic background level is marked in red and the hearing threshold values are marked with stars

NOISE LEVELS AND SPECTRA OF WIND TURBINES



Infrasound and low frequency wind farm noise levels measured at: high wind speed (20 m / s); low wind speed and after turning off the turbine. Hearing thresholds in the range of audible frequencies (ISO 226) and infrasound (Watanabe & Moller) and the night time criterion for the low frequency noise of the British Department of the Environment (DEFRA) have also been drawn.

NOISE LEVELS AND SPECTRA OF WIND TURBINES

Turbine type and power	Distance between measuring point an turbine(s) [m]	Outdoor infrasound level G [dB]	Indoor low-frequency noise level A [dB]	Outdoor background level A [dBA]
Bonus, 450 kW	100-200 (4 turbines)	70	27	54
MOD-1, 2000 kW	1000	74	24	47
WTS-4, 4200 kW	250	84	42	61
USWP-50, 50 kW	500 (14 turbines)	67-79	25	51
WTS-3, 3000 kW	750	68	21	51
WTS-3, 3000 kW	2100	60	12	37
Norma duńska[2)]		85	25	40/45

NOISE LEVELS AND SPECTRA OF WIND TURBINES

Turbine type	Rated power [kW]	Distance between measuring point an turbine(s) [m]	Infrasound level G [dB]	Measuring condition (wind speed, No. of turbines)
Monopteros 50	640	200	84	11 m/s
Enercon E-40	500	200	54 - 64	8 m/s
Vestas V66	1650	100	70	(723 kW)
(Unknown)	2000	200	59	6 m/s
j.w.	2000	200	65	12 m/s
Bonus	450	80	65	9 m/s (4 turb.)
j.w.	450	100	71	8 m/s (1 turb.)
j.w.	450	200	63	10 m/s (1 turb.)
j.w.	450	100 – 200	70	9 m/s (4 turb.)
MOD-1	2000	105	107	
j.w.	2000	1000	73 - 75	
WTS-4	4200	150	92	
j.w.	4200	250	83 - 85	
MOD - 5B	3200	68	71	
USWP-50	50	500	67 - 79	(14 turbin)
Nordex N-80	2500	200	62	(1100 kW)
WTS-3	3000	750	68	
j.w.	3000	2100	60	

CONCLUSIONS

Infrasound affects primarily the hearing organ. The levels of infrasound noise emitted by modern wind turbines (upwind) measured at a distance of 200 m are approx. 25 - 40 dB below the hearing threshold.

As stated in Chapter 7.1.4 of the "Community Noise" report, developed for the World Health Organization (WHO), there is no convincing evidence that infrasound levels below the hearing threshold produce physiological and psychological effects in humans. Infrasound at levels slightly above the hearing threshold may cause perceptual effects, but with the same nature as for audible sounds. Other effects, such as insomnia, fatigue, nausea, etc. occur only at very high levels of infrasound noise.

The levels generated by wind turbines are much lower than these values. Based on research conducted by numerous global centers, it can be concluded that there is no evidence that infrasound noise emitted by modern wind turbines is harmful to the health of people living in their vicinity.

Thank you for your attention !