Wind Turbine Noise, Infrasound and Noise Perception

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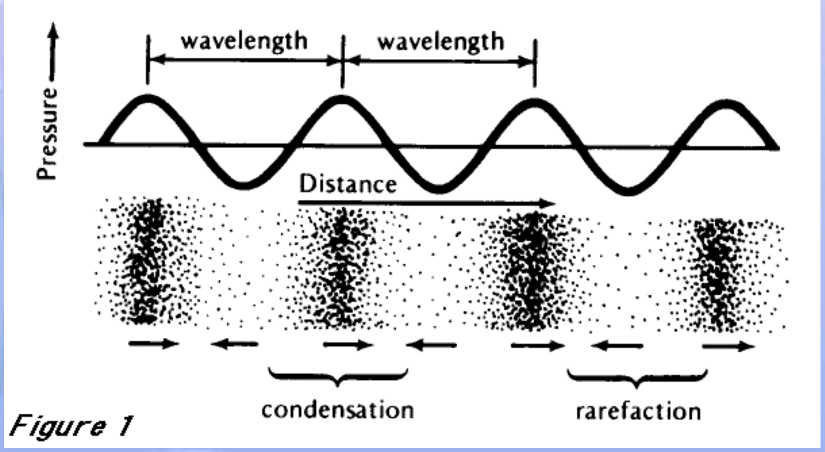
Overview

- Terminology
- Wind Turbine Noise Generation
- Predicting Noise at a Wind Turbine Site
- Noise Regulations
- Infrasound
- Perception of Noise

Terminology

Sound Frequencies

- Sounds are pressure waves



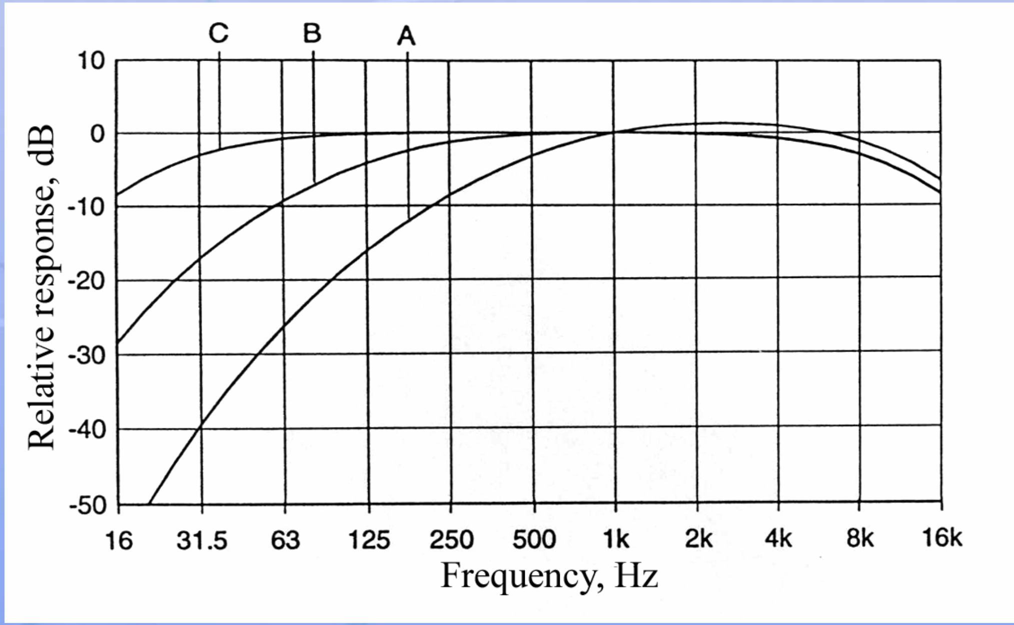
- Sounds have different frequencies:
  - Human hearing: 20 – 20,000 Hz
  - Infrasound less than 20 Hz
- Example
  - Highest piano key – 4186 Hz
  - Middle C – 261 Hz
  - Lowest C on piano – 33 Hz

Measuring Sound: dB Scale

- Sound is measured using units of decibels (dB)
- The dB scale is a logarithmic scale:
  - Doubling distance to turbine reduces sound pressure level 6dB
  - Two turbines produce 3dB more then one turbine.
  - 10dB perceived as a doubling of loudness.
- Examples:
  - 40dB + 40dB = 43dB
  - 40dB + 45dB = 46dB

Measuring Sound: A-weighting

- A-weighting compensates for sensitivity of human ear
- A-weighted levels designated as dB(A)

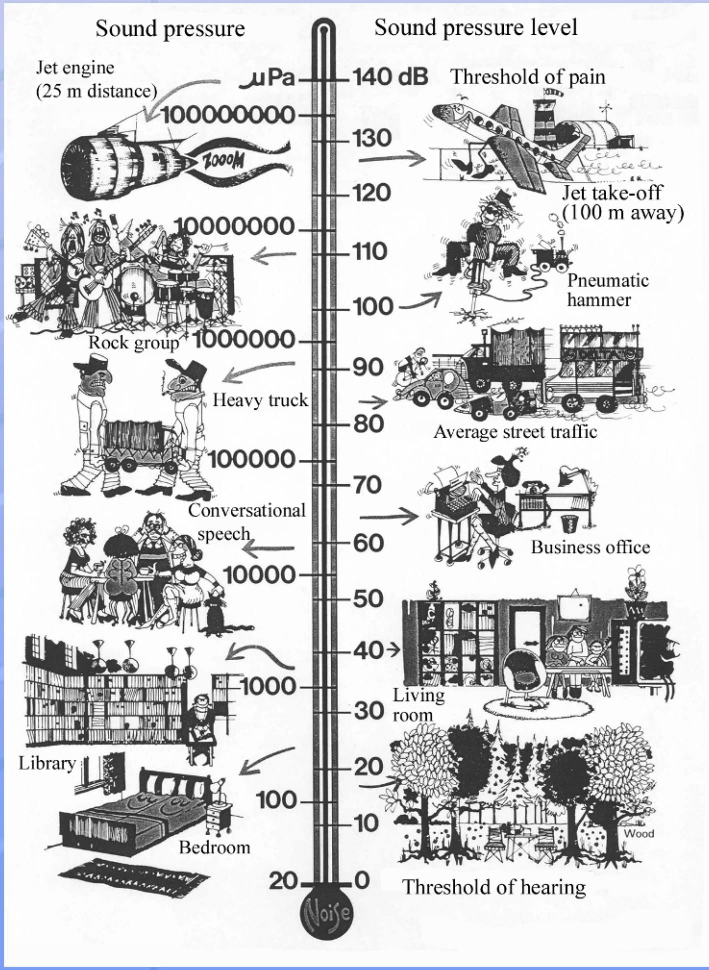


Sound Power vs. Sound Pressure

- Sound power level is a measure of the *source* strength, L_W
  - – Typical values for wind turbines 90-105 dB(A)
- Sound pressure level is a measure of the level at a *receptor* (neighbor, microphone)
  - – Typically < 45dB(A) , L_{Aeq}

Sound Pressure Levels

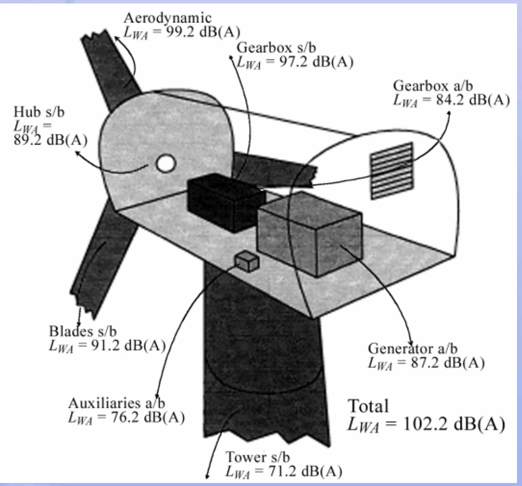
- L_{Aeq}, A weighted equivalent sound levels over a period of time
- L_{90} noise level exceeded 90% of the time
- L_{dn} or DNL, day-night level, night level is weighted more severely

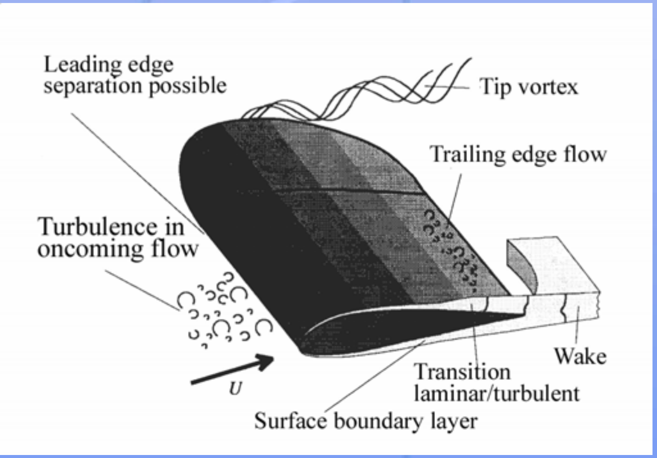


Turbine Noise Generation

Wind Turbine Noise Sources

- Cooling fans
- Generator
- Power converter
- Hydraulic pumps
- Yaw motors
- Bearings
- Blades



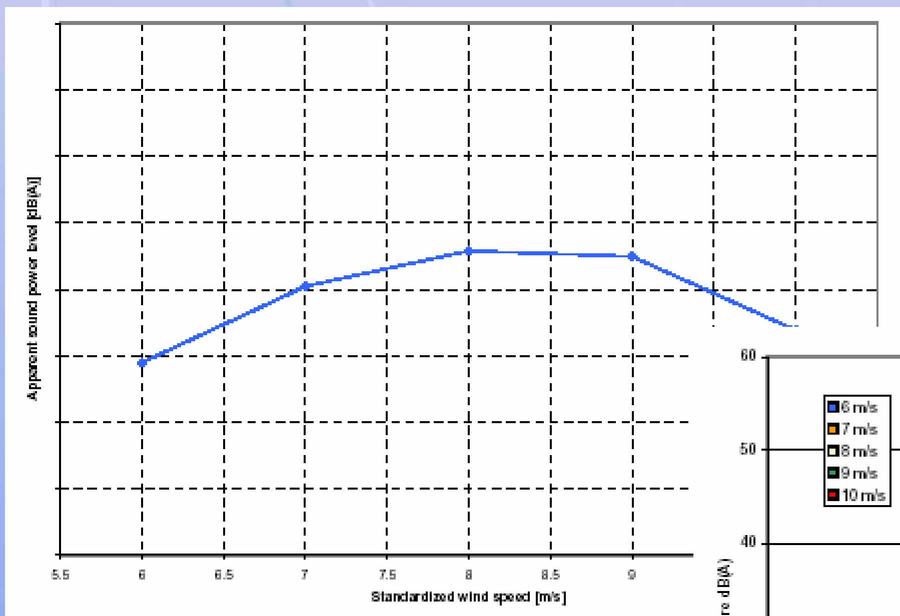


"Wind turbine noise" Wagner, Bareiß, Guidati

Standard for Defining Wind Turbine Sound Power Levels

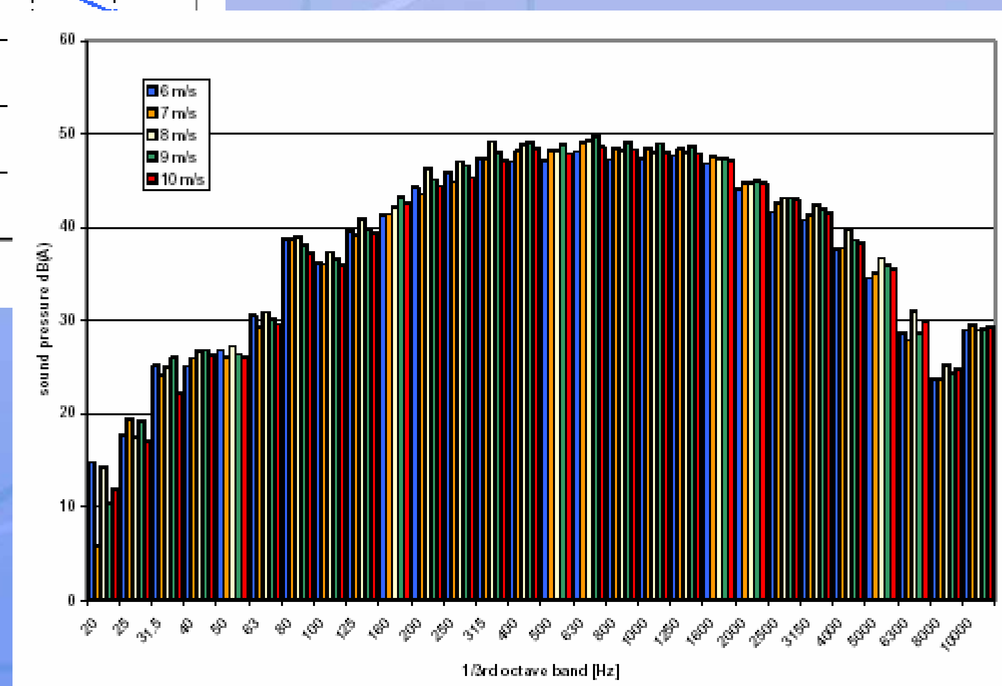
- IEC 61400-11, 2nd edition.
  - Standard for turbine noise measurement techniques
  - Widely accepted
  - High quality reproducible results
  - Used for certification
  - Used by manufacturers to define noise power levels of turbines

Turbine Sound Power Level Data

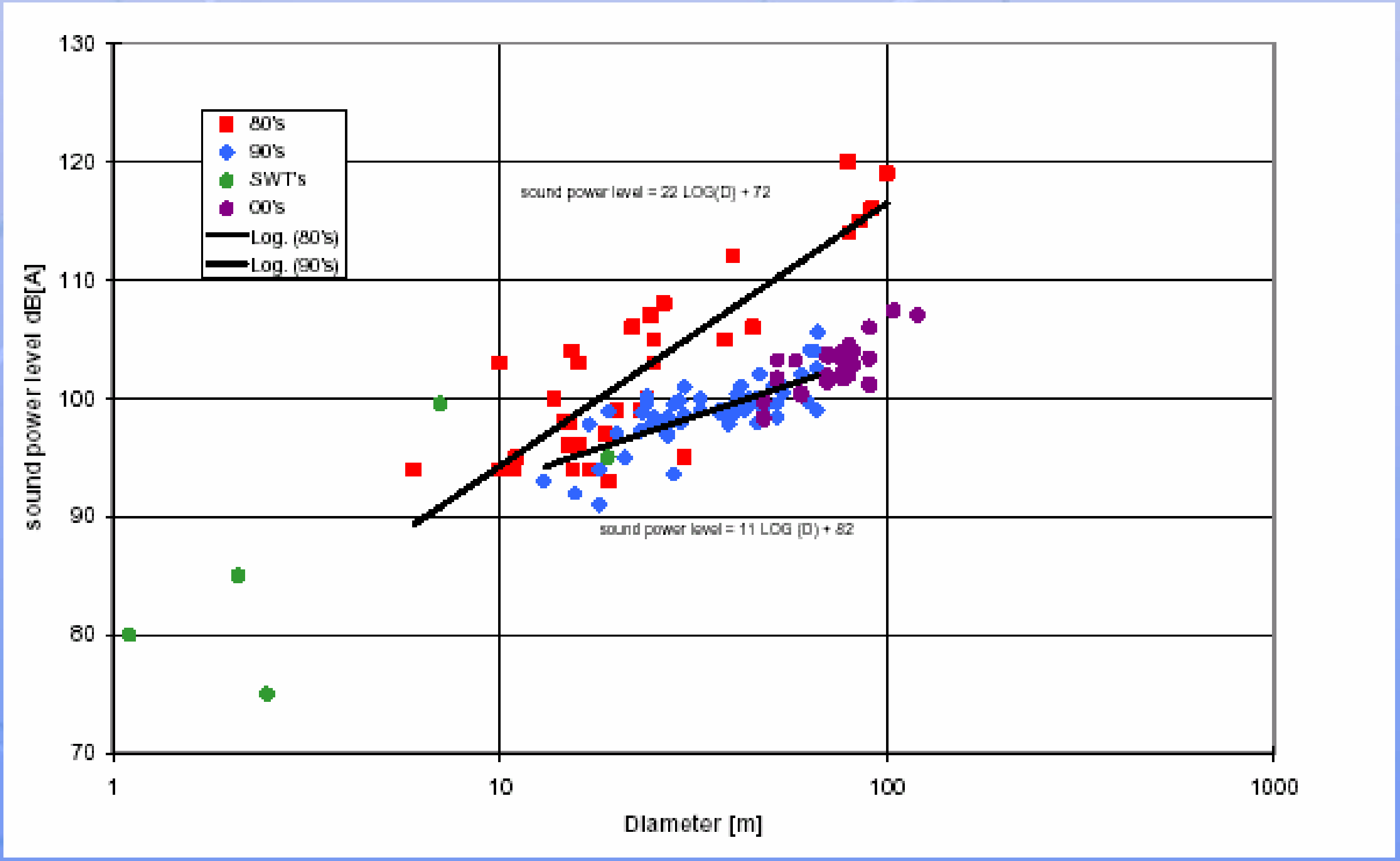


Broadband sound power levels, L_{WA}, vs. wind speed

1/3rd octave spectra

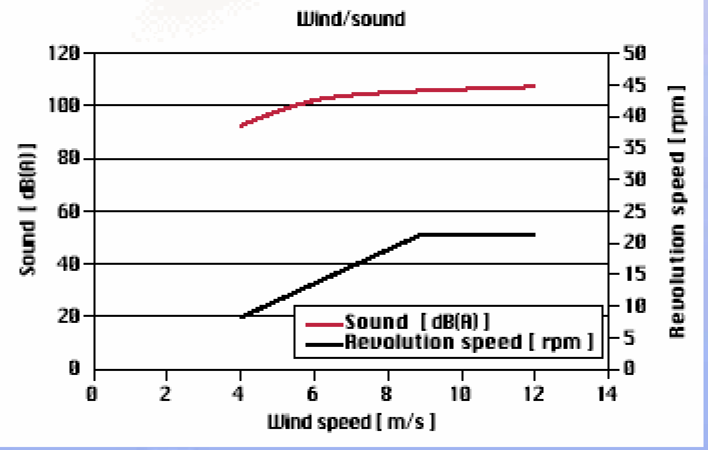


Improvements in Wind Turbine Sound Power Levels



Wind Turbine Sound Data

- Wind turbine sound data should be available from manufacturer



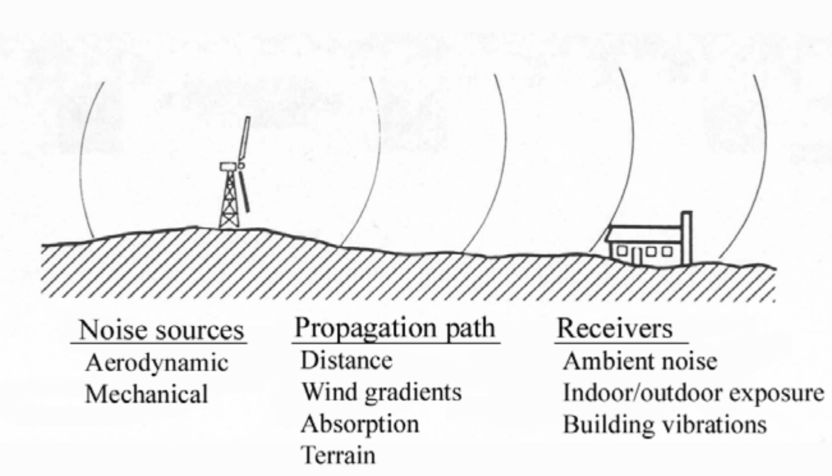
Vestas V66

- Wind turbine sound data from manufacturer should have been measured using international standards for measuring sound from wind turbines
- Data can be used to determine sound levels at a site

Predicting Noise at a Wind Turbine Site

Sound Propagation

- As sound propagates, sound pressure level reduces due to:
  - Sound absorption by ground cover
    - Absorption a function of
      - Ground cover
      - Terrain
      - Frequency content
  - Molecular absorption
    - Less at low frequencies
  - Distance
    - For spherical radiation, -6dB/doubling of distance traveled



Predicting Noise Levels

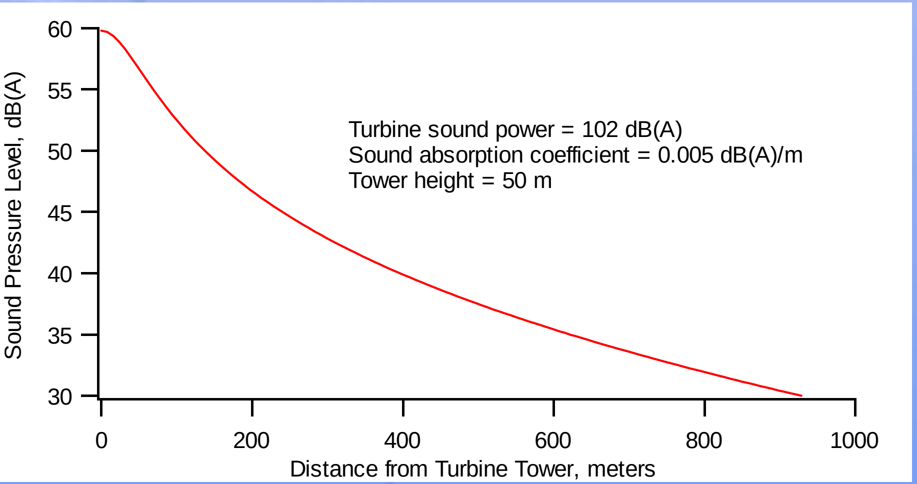
- Rule of thumb
  - Three x blade tip height from turbine to residence
    - acceptable noise levels
- Do the math!
  - Use turbine sound power level and propagation model to calculate sound pressure levels
- Use a computer program to do the math

The Math

- Determine turbine sound power level, say 102 dB(A), turbine tower height
- Use noise propagation model

$$L_p = L_w - 10\log_{10}\left(2\pi R^2\right) - \alpha R$$

  - Determine parameters (air and ground absorption)
  - Use correct model
- Calculate turbine generated noise for various distances from turbine

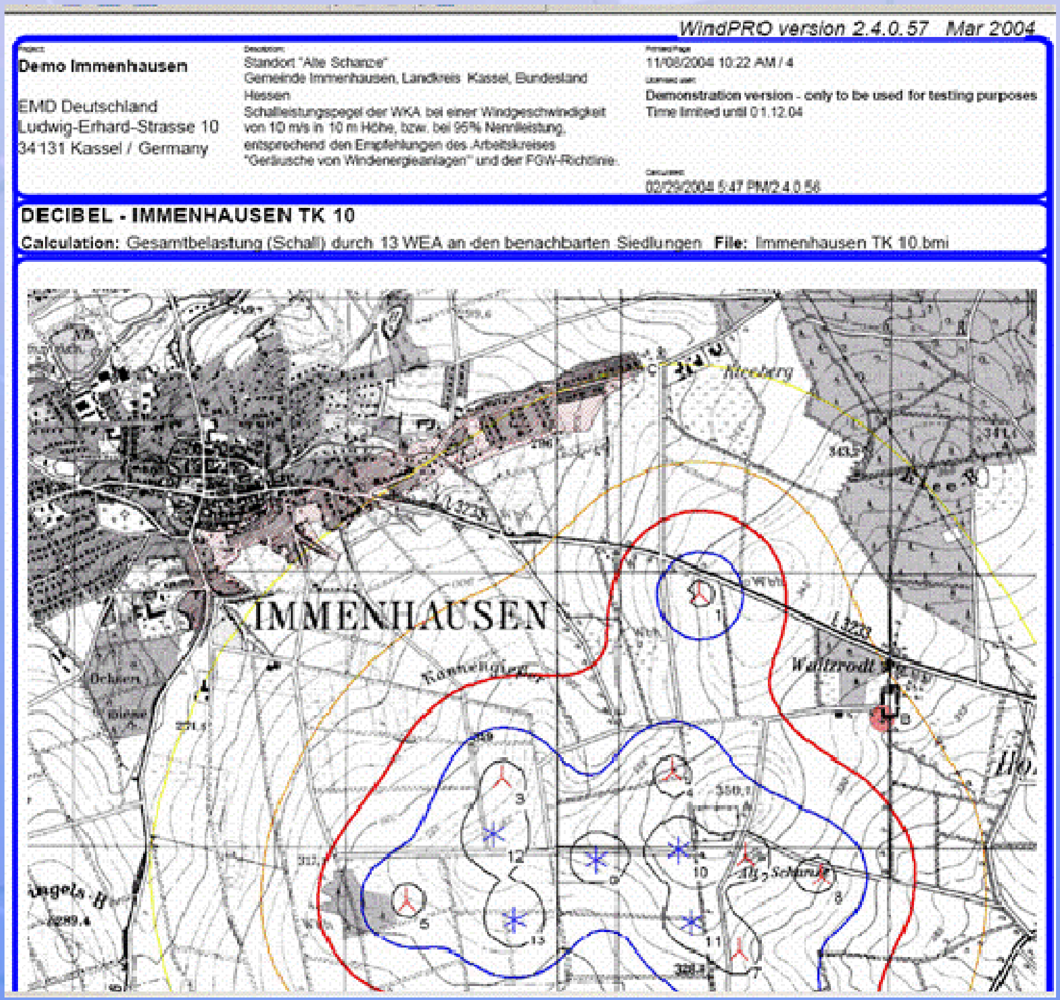


Example noise calculation

Computer Results

- Various computer models are often used to predict noise levels near a wind turbine
- Computer models may consider:
  - Terrain effects
  - Wind direction effects
  - Atmospheric absorption
  - Requirements of different regulatory agencies
  - Background noise
- Computer models often provide
  - Calculated noise pressure levels
  - Maps of equal-noise-level contours

Sample Computer Results



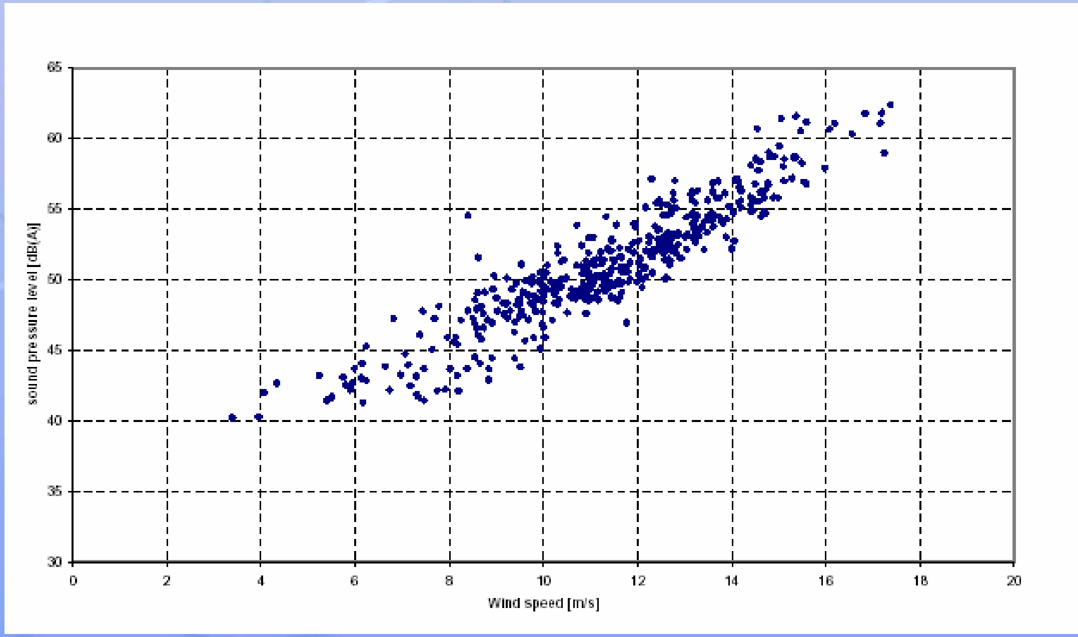
Noise Regulations

MA DEP Noise Regulations

- New broadband source may only raise noise levels 10 dB(A) over L_{90} levels at property line
  - If turbine noise is 9.5 dB(A) over background, together they will be 10 dB(A) over background
- Pure tones, measured in octave bands may only be 3 dB(A) over adjacent bands

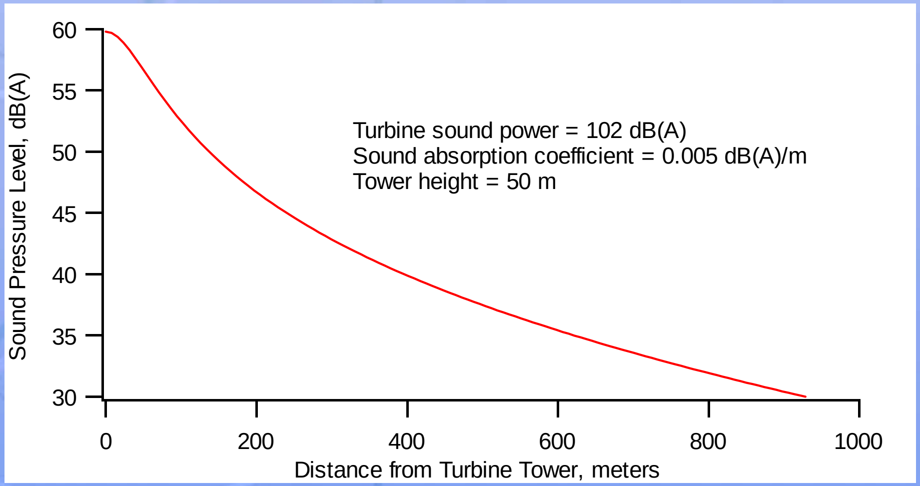
Background Noise

- Masks wind turbine noise
- Increases with wind speed
- Typical levels 30-45dB(A)



Noise Assessment Example

- Measure L90 at site, say 45 dB(A)
- Determine sound pressure levels form turbine
- Compare turbine noise with background
- Noise would be OK at distances over 75 m (250 ft)



Example noise calculation

Noise Assessment
Final Comments

- Various tools are available to predict wind turbine sound levels
- Compliance with regulations many not mean a lack of complaints
- Allowance should be made to account for:
  - Manufacturing/operational variations in sound levels
  - Varying human sensitivity to sounds

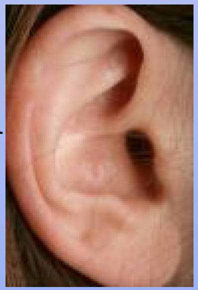
Wind Turbine Infrasound

Ambient Infrasound

- Infrasound: Sounds < 20 Hz
- Natural Sources (.001 Hz to 2 Hz)
  – Air turbulence, distant explosions, waves on the seashore, etc.
- Human activities
  – Road vehicles, aircraft, machinery, artillery, air movement machinery
- Measured with G-weighted value

Human Perception of Infrasound - I

- Infrasound perceived as a mixture of auditory and tactile sensations
  - Primary sensory channel for infrasound is the ear
  - Tonality is lost at 16 – 18 Hz
- No reliable evidence that infrasound below the hearing threshold produces physiological or psychological effects



Human Perception to Infrasound - II

- Perception threshold levels are high
  - Threshold of hearing at 10 Hz ~100dB(G)
- Perception threshold levels ⟶
- Standard deviation of threshold of perception level ~6dB

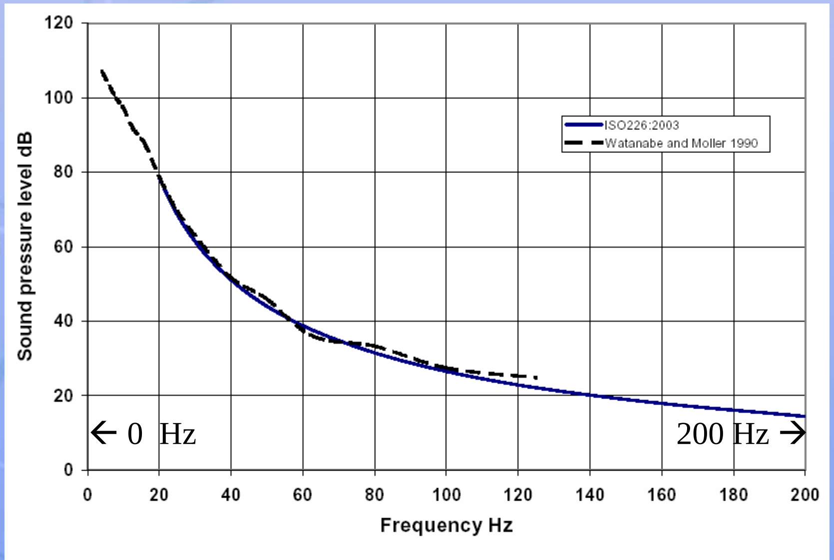


Fig 2. Low frequency threshold

[Levanthall 2005]

Human Perception of Infrasound - III

- Steep rise in sensation of annoyance above perception level
  - At 1000 Hz
    +10 dB appears to be twice as loud
  - At 20 Hz
    +5 dB appears to be twice as loud

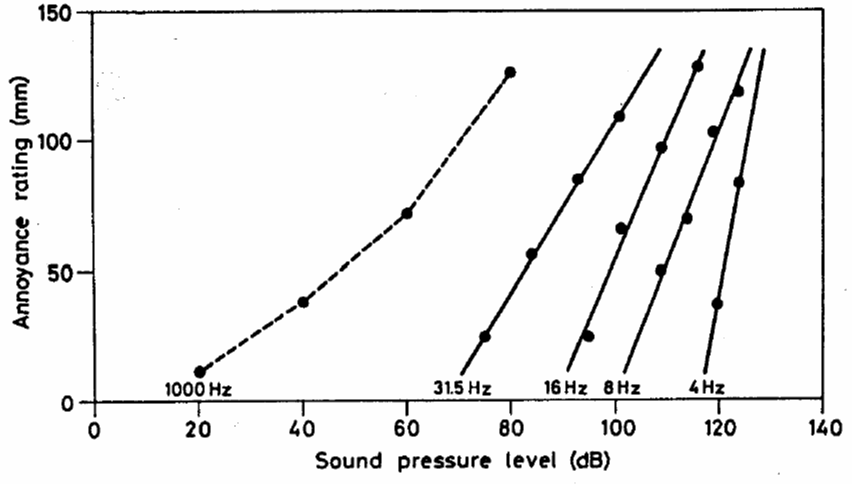
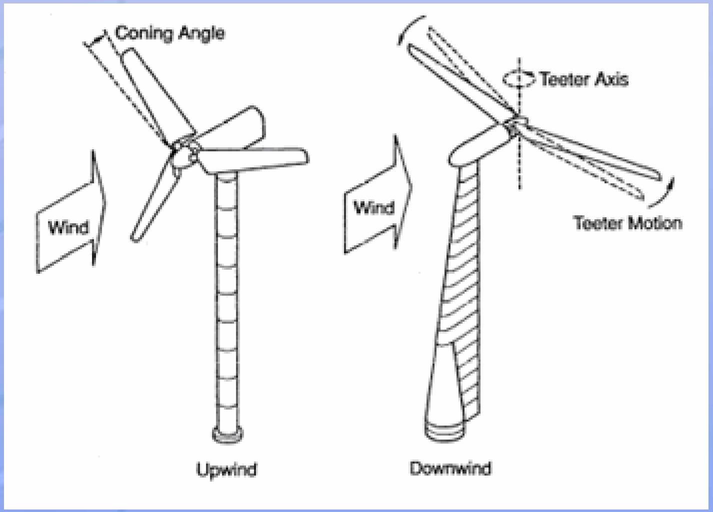


Fig 4 Growth of annoyance at low frequencies

- Variability of perception threshold among humans and steep rise in sensation means some may experience loud noise, others little at all

Overview of Sound Emissions from Wind Turbines

- Upwind rotor emissions
- Downwind rotor emissions
  - Examples



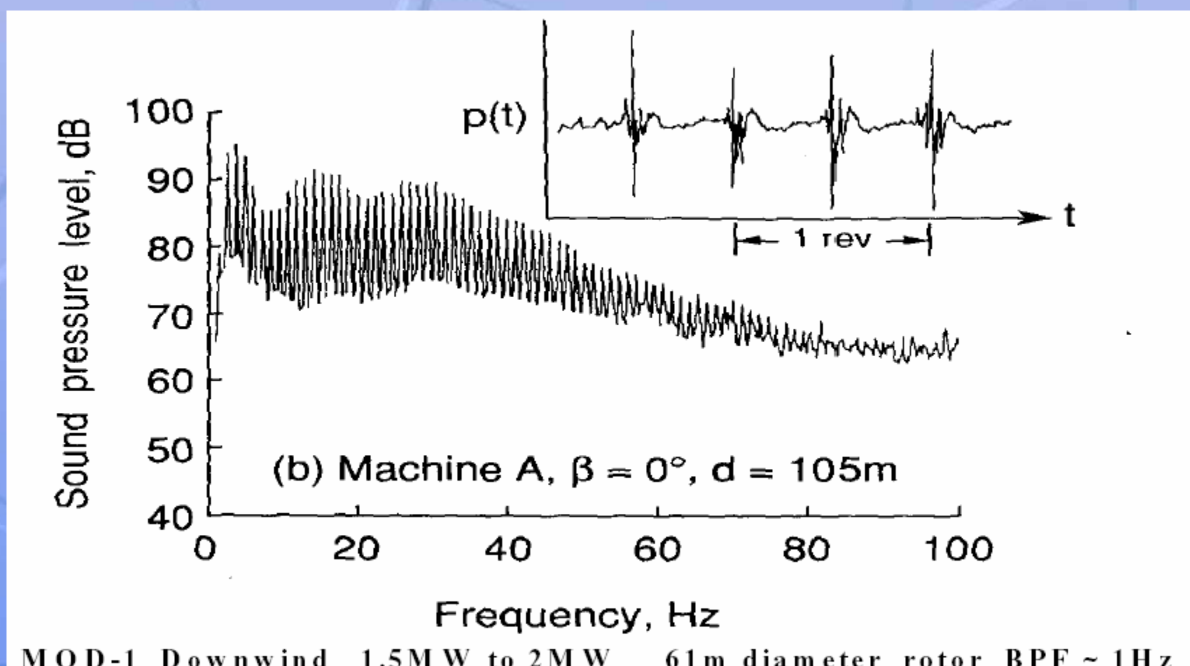
- Example low frequency sound calculation

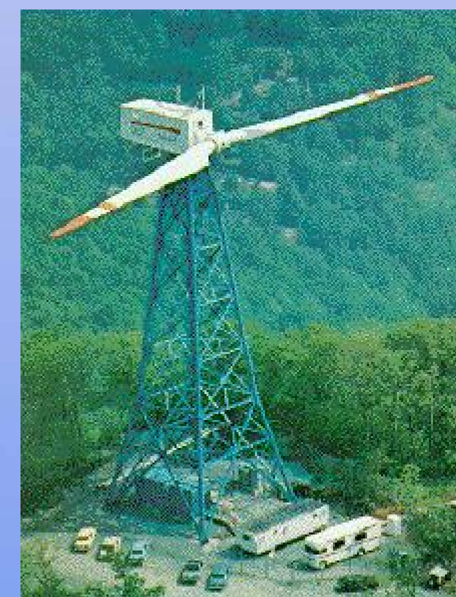
Sound Emissions from Downwind Wind Turbines

- Wind passes tower before blades
- Sudden change in aerodynamics as blades pass behind the tower (tower shadow)
- No modern utility-scale wind turbines employ downwind rotors
- Source of concerns about wind turbines

Sound Emissions from Downwind Wind Turbines

- MOD 1: Pulse each 1 Hz (Blade Passing Frequency)
- Pulse and harmonics seen in spectrum





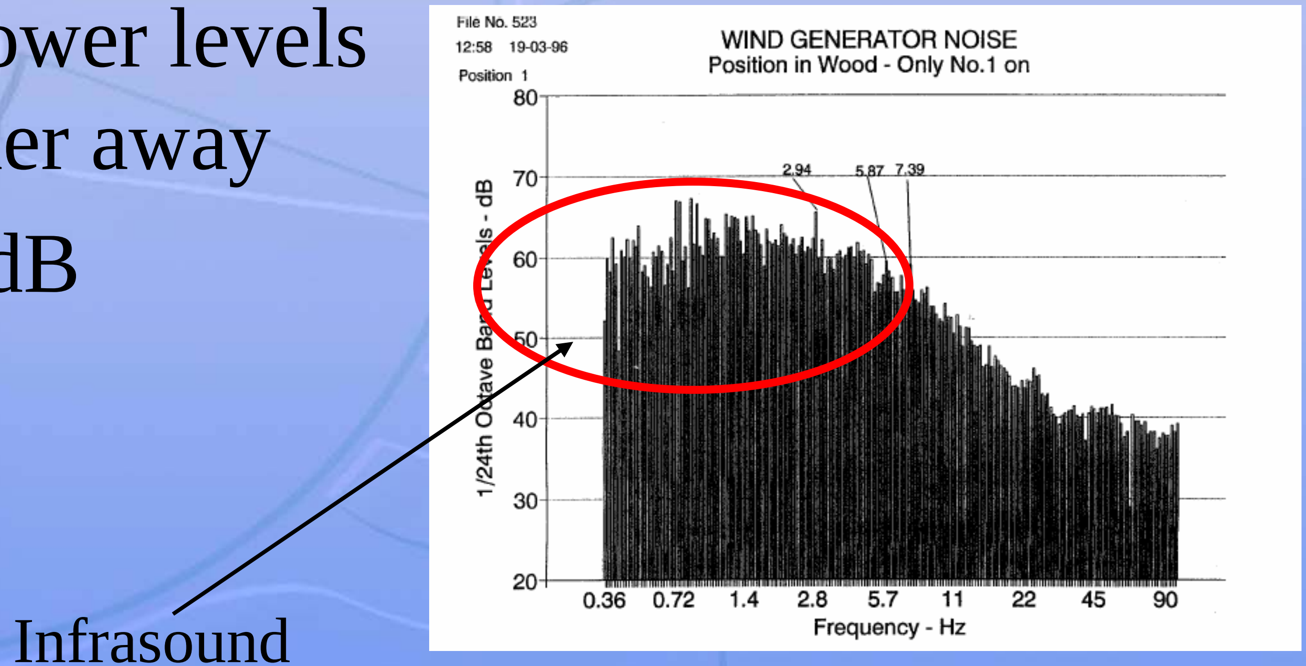
[Levanthall 2005]

Sound Emissions from Upwind Wind Turbine Rotors

- ALL modern utility-scale wind turbines have upwind rotors
- Upwind rotors emit broad band noise emissions, including low frequency sound and infrasound
- Swish-swish sound is amplitude modulation at blade passing frequencies of higher frequency blade tip turbulence and does NOT contain low frequencies
  - Diminishes with distance
  - Blurs with multiple turbines

450 kW Wind Turbine Infrasound

- All infrasound levels below human perception levels 100 m from turbine
  - Even lower levels farther away
- Max: 67 dB

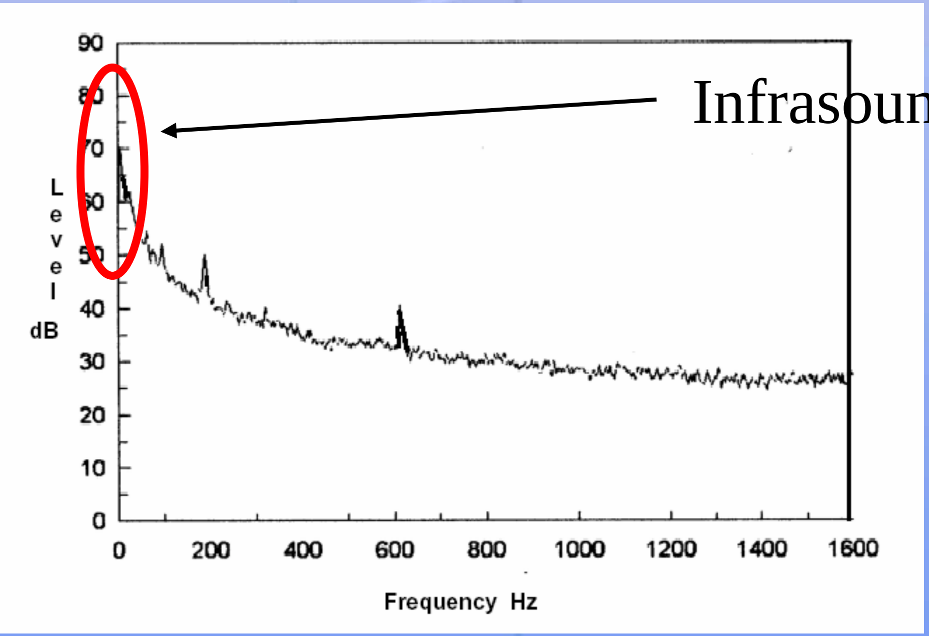


[Snow 1997, as reported in Levanthall 2004]

Vestas V-52, 850 kW

All infrasound levels below human perception levels 80 m from turbine

Max: 70 dB

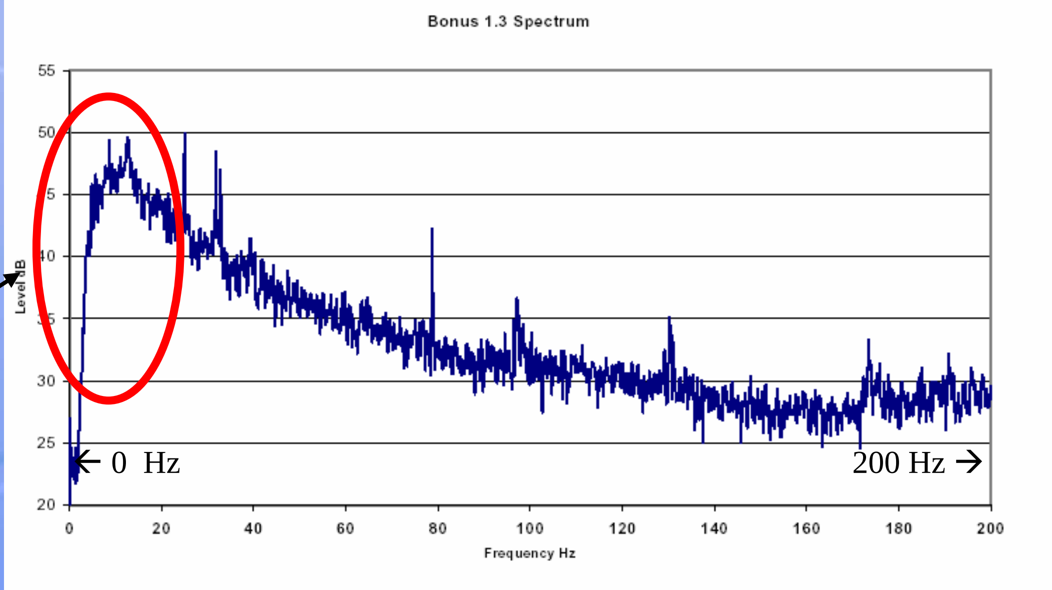


[Windtest 2002, as reported in Leventhall 2004]

Bonus 1.3 MW Sound Spectrum

- All infrasound levels below human perception levels 100 m from turbine
- Max 50 dB

Infrasound



[DELTA, 2003 and Leventhall, 2004]

Vestas V80 – 2 MW

- <u>All infrasound levels below human perception levels 118 m from turbine</u>
- Max < 70 dB

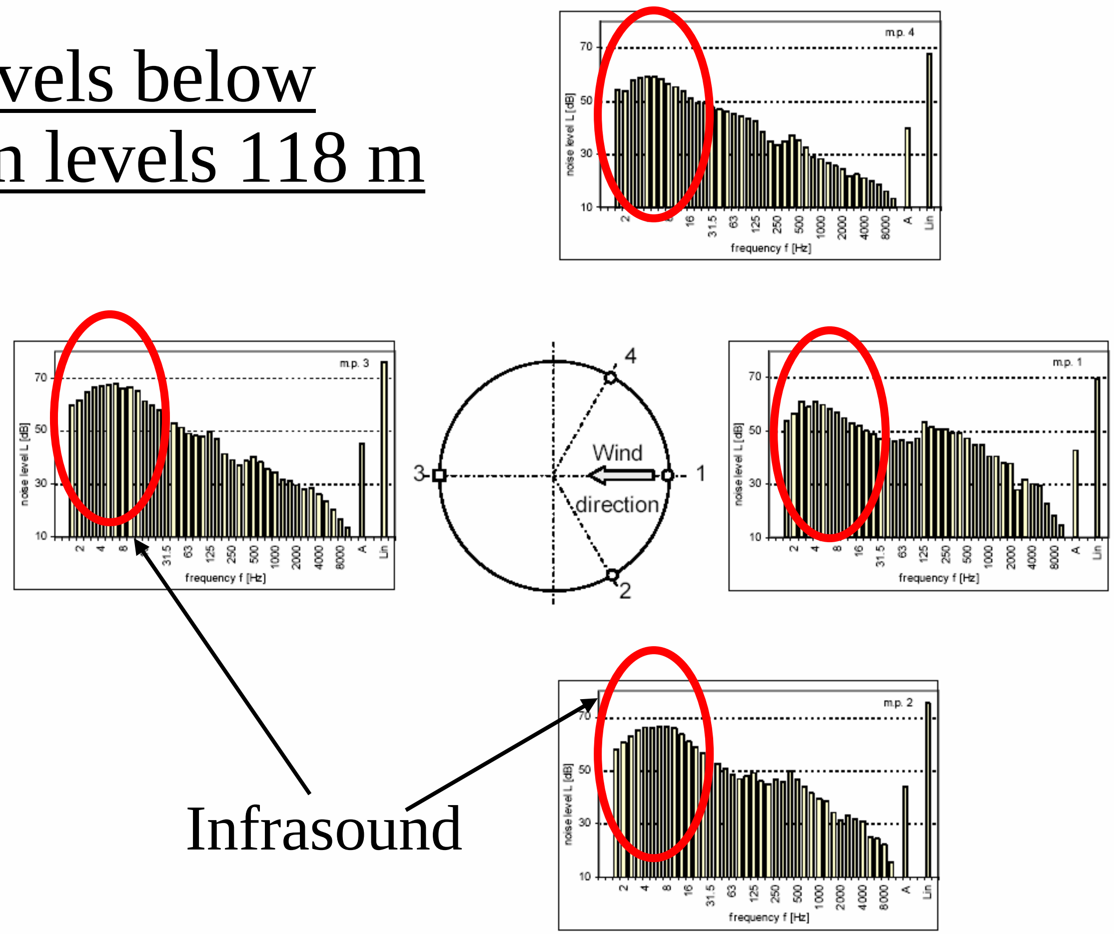
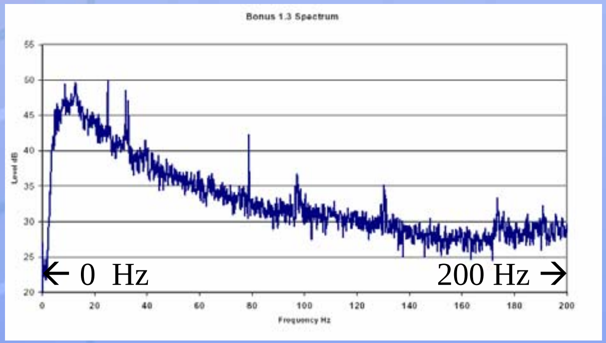


Fig. 6. Averaged 1/3 octave noise spectra of the VESTAS V80 Turbine

[Golec *et al.*, 2005]

Low Frequency Levels Around Wind Farms - Bonus Example

- Calculate low frequency noise at 400 m:
  - Subtract 6 dB from raw data for ground board reflection effect
  - Subtract 6 dB per doubling of distance
  - Add 7 dB for 19 unsynchronized turbines in a wind farm



- Hearing threshold
  - Subtract 12 dB (two standard deviations) from average hearing threshold to characterize minimum threshold of 98% of population

Levanthall 2004

Bonus Results at 400 m

- No one would hear low frequency components below ~ 50 Hz
- Average person would only hear sound above 174 Hz
- No one would hear infrasound
  - Below 20 Hz, little increase in noise, greater increase in threshold
- 19 Turbine wind farm infrasound would also not be detectable by anyone at 400 m

Frequency, Hz	Sound Level at 100 m, dB	Predicted level at 400 m in the open	Average hearing threshold	Min. hearing threshold of 98% of population	400 m level – Min. threshold
25	50	32	69	57	25
31.9	48	30	60	48	18
32.8	47	29	59	47	18
78.8	42	24	31	19	-5
97	37	19	26	14	-5
130	35	13	21	9	-4
174	33	15	16	4	-11

Infrasound Conclusions

- High levels of low frequency sound are required for perception
  - Increases as frequency decreases
- The ear is most sensitive receptor of infrasound
  - If it can't be perceived, it has no effects
- Infrasound is emitted from modern wind turbines, but is NOT a problem

Perception of Sound from Wind Turbines

Older Noise Sensitivity Study

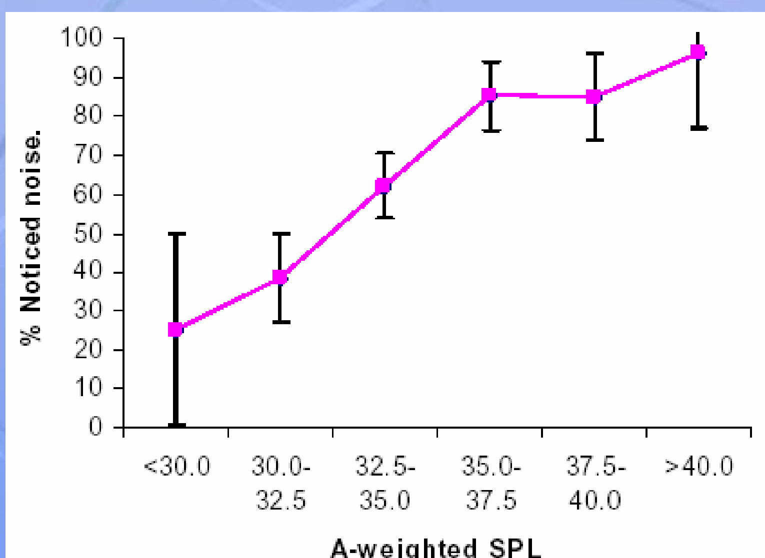
- Wolsink *et al*. 1993
- 574 people exposed to average SPL of 35 dB(A) +/- 5 dB
- Only 6 % annoyed
  - Only a weak relationship between annoyance and A-weighted SPL
- Variables related to annoyance
  - Stress related to turbine noise
  - Daily hassles
  - Visual intrusion of wind turbines in the landscape
  - Age of turbine site
    - The longer the operation, the less the annoyance

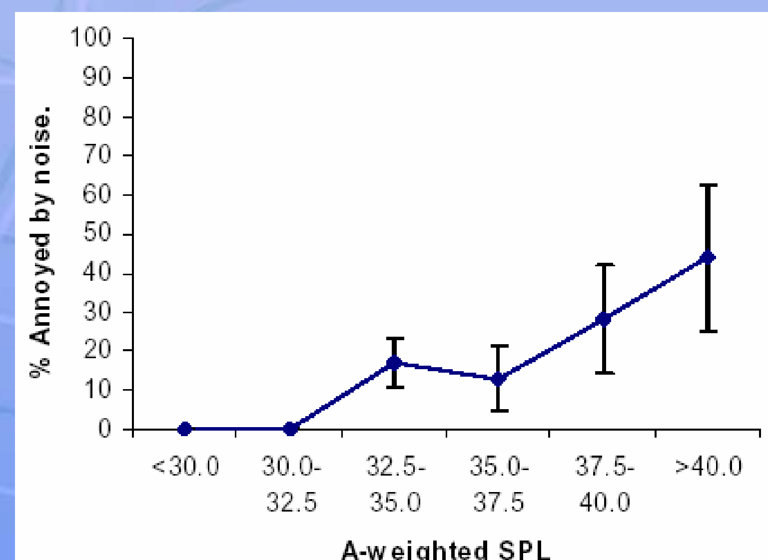
Recent Noise Sensitivity Study

- Pederson and Waye, 2005
- 518 people in rural setting
- A-weighted SPL estimated from Swedish EPA guidelines
- Respondents divided into six SPL levels
- Results
  - Annoyance increases with noise levels
  - Factors other than noise levels also strongly affect annoyance

Perception and Annoyance

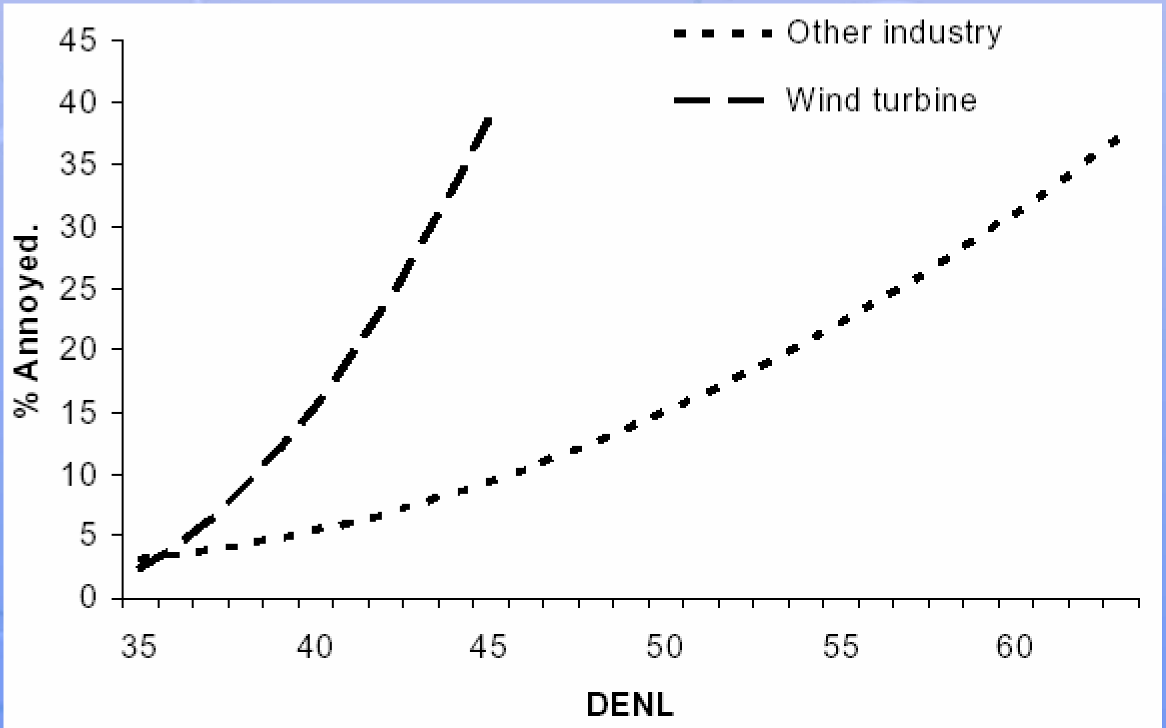
- More noise -> more perception of noise
- More noise -> higher percentage of respondents annoyed





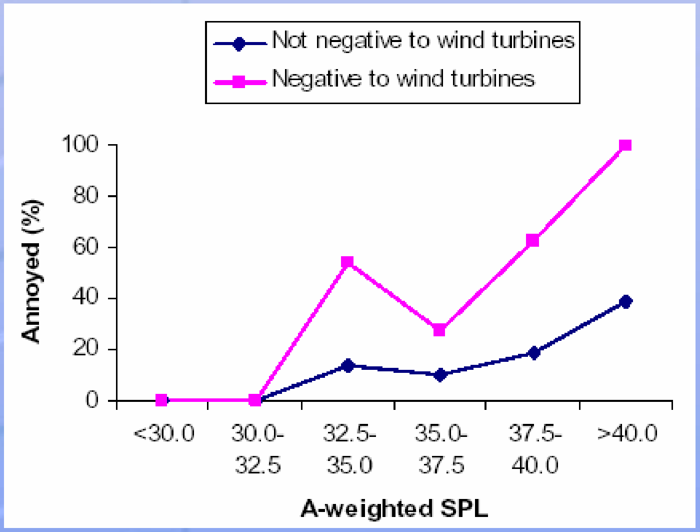
Annoyance Sensitivity

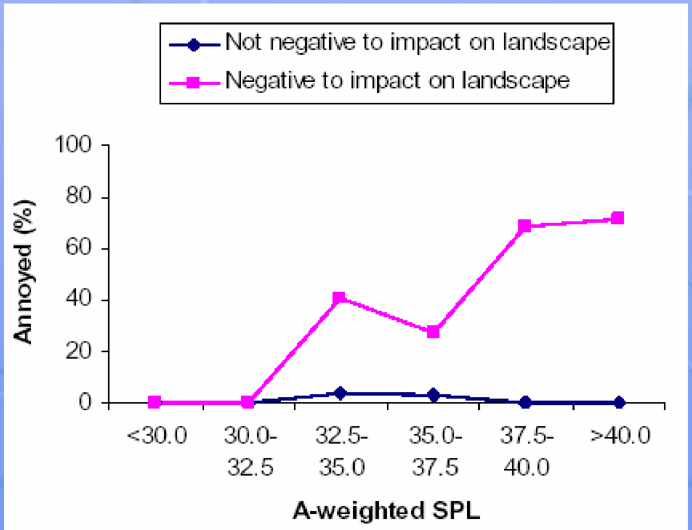
- DENL = metric estimating over-all 24 hour noise levels
- Annoyance increases more rapidly than other stationary industrial noise sources



Attitudes and Annoyance - I

- Annoyance greater when respondents had
  - Increased noise sensitivity
  - Negative attitudes toward turbines
  - Negative attitudes toward turbine impact on landscape





Attitudes and Annoyance - II

- Annoyance greater when respondents:
  - Saw the countryside as a place for peace and quiet as opposed to a place with important economic activities
  - Felt a lack of control over project
  - Felt a sense of being subjected to injustice
- Some of these factors can be influenced in the planning process

Noise Perception Conclusions

- Perceptions of annoyance from wind turbine noise are a function of
  - Noise levels
  - Attitudes toward other aspects of wind power
- Annoyance from wind turbine noise increases more rapidly, as the sound level increases, than for other industrial noise sources
- Careful work at the planning stage may help mitigate some noise concerns

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