An Introduction to Sound and Wind Turbines

Mark Bastasch, PE

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What is Sound?

- A rapid pressure fluctuation above and below the static atmospheric pressure measured in decibels (db)
- Typical sound levels:
  - 70 to 80 dBA – Freeway or trains as heard from 50 feet
  - 30 to 40 dBA – Interior of bedroom or living room
- Typical audible range: 20 Hz to 20,000 Hz
  - Middle C of piano–261 Hz; Lowest C–33 Hz
  - Infrasound – below 20 Hz
  - Low frequency – between 10 and 200 Hz
  - Threshold of hearing is higher for lower frequencies, but all frequencies are audible if level is high enough

Sound Pressure Level

- Atmospheric pressure is approximately 14.7psi (about 100,000 Pascals (Pa) = 34 feet water)
- 94 decibels sound pressure level (4-hr OSHA limit) = pressure fluctuations of 1 Pa = 0.000145 psi = 0.004 inch of water
- The pressure fluctuations above and below atmospheric pressure are very small

Sound Pressure Levels (Lp or SPL)

Noise Source at a Given Distance	A-Weighted Sound Level in Decibels	Relative Energy
Carrier deck jet operation	140	100,000,000
	130	10,000,000
Jet takeoff (200 feet)	120	1,000,000
Auto horn (3 feet)	110	100,000
Jet takeoff (1000 feet) Shout (0.5 foot)	100	10,000
N.Y. subway station Heavy truck (50 feet)	90	1,000
Pneumatic drill (50 feet)	80	100
Freight train (50 feet) Freeway traffic (50 feet)	70 to 80	10
	70	1
Air conditioning unit (20 feet)	60	.1
Light auto traffic (50 feet)	50	.01
Living room Bedroom	40	.001
Library Soft whisper (5 feet)	30	.0001
Broadcasting/Recording studio	20	.00001
	10	.000001

Decibel Math

- 50 dB + 50 dB = 53 dB
- 50 dB + 60 dB = 60 dB
- Must convert back to pressure before doing math:
  - Lp1 + Lp2 = 10*Log(10Lp1/10+10Lp2/10)
  - Lp1 – Lp2 = 10*Log(10Lp1/10-10Lp2/10)

Decibel Math

- Combination of Sources of Same Level Lp1+10*Log(#)
- 10*Log(2) = 3
- 10*Log(10)=10
- 10*Log(100)=20
- 10*Log(1000)=30

Sound Power Levels (PWL or Lw)

- Lw (dB) =10*log(W/Wref)
- Wref=10^{-12}=0.00000000001 Watt
- 1 Watt of acoustical energy = 120 dB Lw
  0.1 Watt of acoustical energy = 110 dB Lw

Sound Power & Pressure Levels

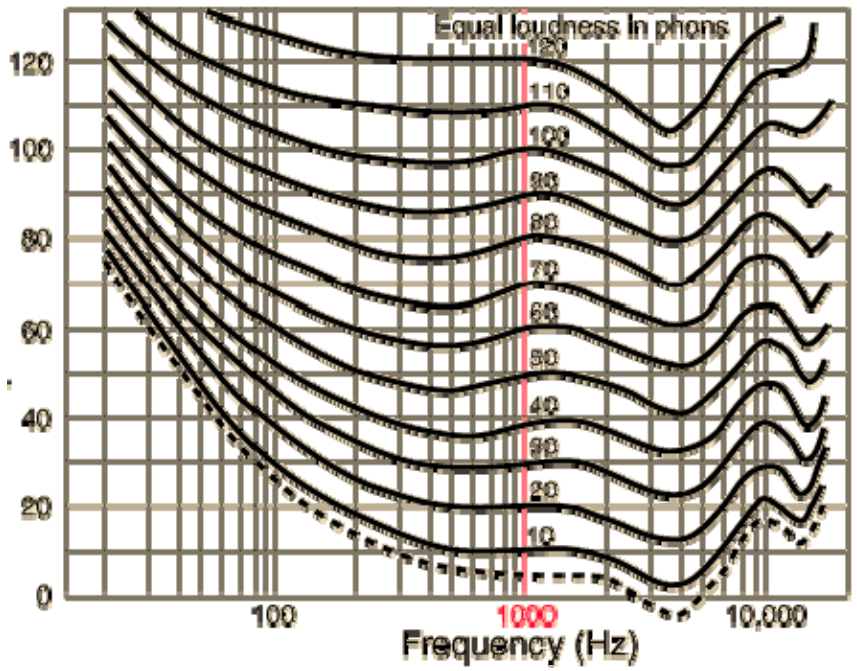
- Sound power level is INDEPENDENT of distance from the source (wattage of light bulb)
- Sound pressure level varies with distance (brightness or intensity of light bulb)
- Sound pressure levels should always specify distance if characterizing a source

Sound Power & Pressure Levels

- Though interrelated, sound power level and pressure level cannot be directly compared
- Sound power level takes into consideration the size of the source (Lw=Lp + 10*log [area in m2])
- Sound pressure level (Lp or SPL):
  85 dBA at 3ft from a 5hp and a 500hp pump
- Sound power level (Lw or PWL):
  500 hp pump >5 hp pump

Fundamentals of Perception

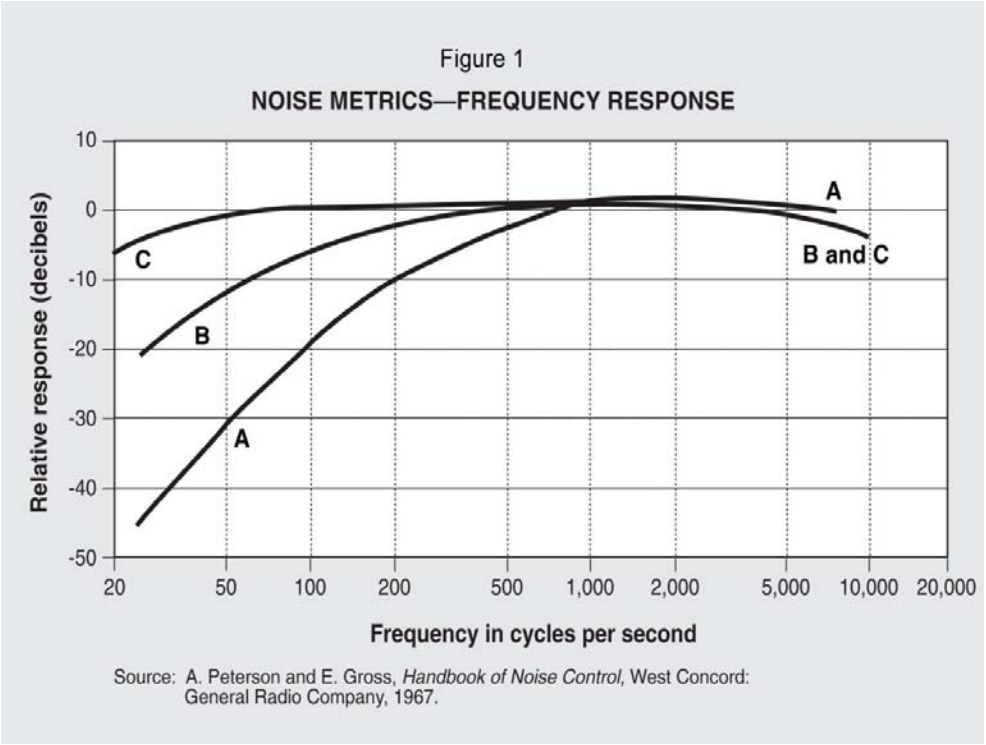
Pure Tone



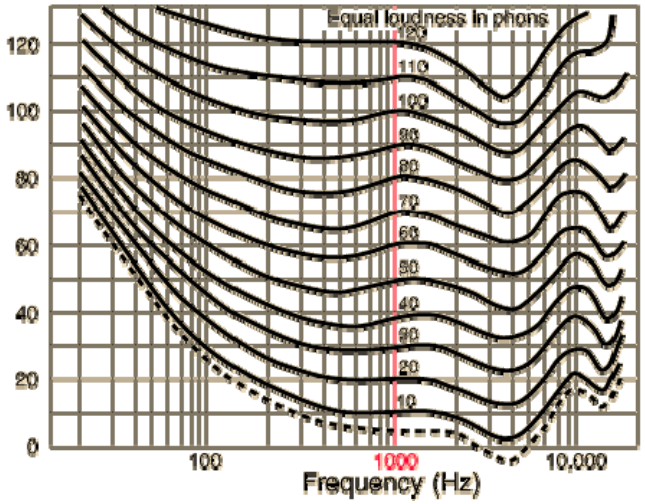
Middle C of piano – 261 Hz
Lowest C – 33 Hz

- Threshold of hearing is higher for lower frequencies
- All frequencies are audible if level is high enough
- 30 dB @ 1000 Hz is equally loud as 65 dB @ 40 Hz

Fundamentals of Perception



- A-weighting (dBA) - reflects hearing threshold
- Low levels are audible if frequency varies from background level



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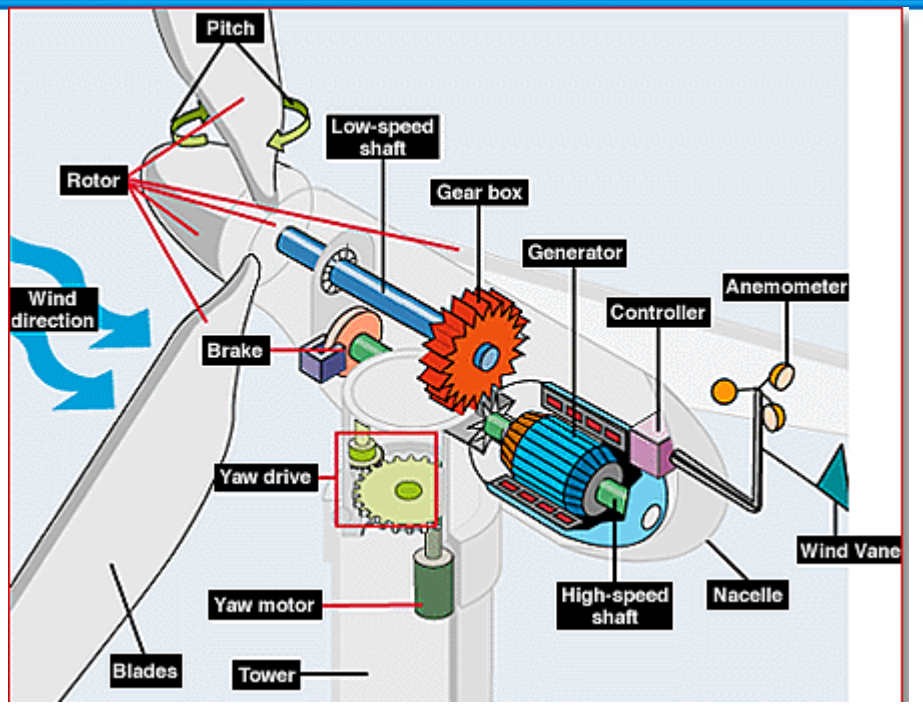
Noise Generating Mechanisms

- Aerodynamic
  - Trailing edge noted to be most important
  - Noise level generally proportional to tip speed[5]
    - *Tip vortex noise is not typically significant source*
  - Complex mechanisms at work
  - Typical noise control solutions (enclosures, barriers, silencers, vibration isolation, etc.) are not applicable

Noise Generating Mechanisms

- Mechanical Sources
  - Gearbox
  - Generator
  - Yaw Drives
  - Cooling Fans



- Standard noise control measures are used to minimize mechanical noise
  - Yet still requires detailed analysis and engineering
  - Aerodynamic noise remains likely dominate source

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Acoustic Array

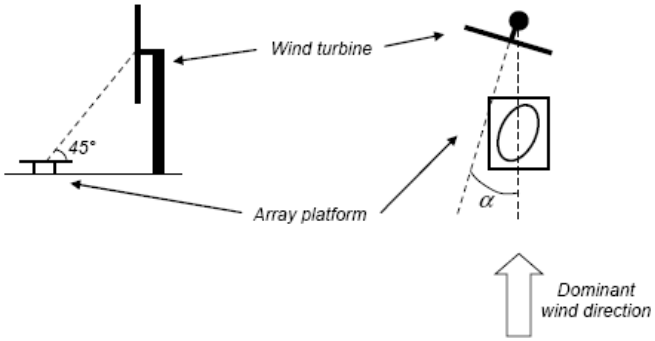

Figure 2: GE 2.3 MW turbine (left) and GAMESA 850 kW turbine (right) with typical noise source distribution in the rotor plane.

Source: Oerlemans & Schepers, 2007 (SIROCCO)

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Outdoor Sound Emissions

- IEC 61400-11
  - Wind Turbine Generator Systems Part 11: Acoustic noise measurement techniques
- Microphone mounted on ground board(Hub Height + ½ Rotor Dia.)
- Wind speed measurements with and without wind turbine operating

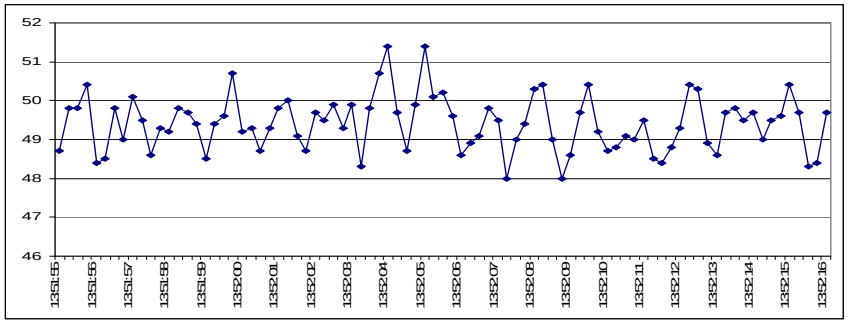
- Sound power levels calculated (1/3 octave bands from 20 Hz to 10 kHz to be incorporated in update)
- Update to change reference wind speed height from 10-meter to hub height to avoid confusion

Adverse Effects of Sound

- Noise-Induced Hearing Loss > 80-85 dBA
- Task Interference > 70 dBA
- Speech Interference
  - *Above 80 dBA, shouting often required*
  - *Above 50 to 55 dBA, voices begin to raise*
- Sleep Disturbance – guidance varies and is often based on transportation sources
- Annoyance

Characteristics That May Increase Annoyance

- Tonal
- "Impulsive" or excessively amplitude-modulated (AM)
  - Confusion between infrasound, low frequency, and AM noise (swish, swish)
  - "A time varying sound is more annoying than a steady sound of the same average level." – *Dr. Geoff Leventhall*
  - Study in the UK identified limited instances of excessive AM and noted additional study was unwarranted.



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Infrasound and Low Frequency Sound

- Infrasound from wind turbines is not perceptible and does not exceed levels produced by natural sources.
- Low frequency sounds from wind turbines are not distinguishable from background sounds for frequencies less than 40 Hz.
  - Perceptible levels of low frequency sound may be produced under certain conditions
- The audible swooshing sound is typically in the 500-1000 Hz range; it is neither infrasound nor low frequency sound.

(Colby, et al 2009)

- *Differences in Atmospheric Absorption:*

  1 dB @ 250 Hz; 8 dB @ 2000 Hz (at 3300 ft)

Wind Shear and Potential for Masking

- Increases in wind speed typically yields increases in background sound levels; at the same time sound emissions from wind turbines also increase with increased wind speed.
- Wind shear is a measure of how wind speed increases with height. The ratio between wind speed at ground level and elevation will vary on a number of factors.
- When potential for wind shear is not evaluated, turbines may reach maximum sound power under low ground level wind speed (particularly when turbines are located on ridgelines)
- Consider evaluating a project at its maximum sound power irrespective of wind speed
- Important to avoid implying the project will be silent or completely masked

Federal Environmental Noise Policy

- Varies by Agency

Summary of Federal Guidelines/Regulations for Exterior Noise (dBA)

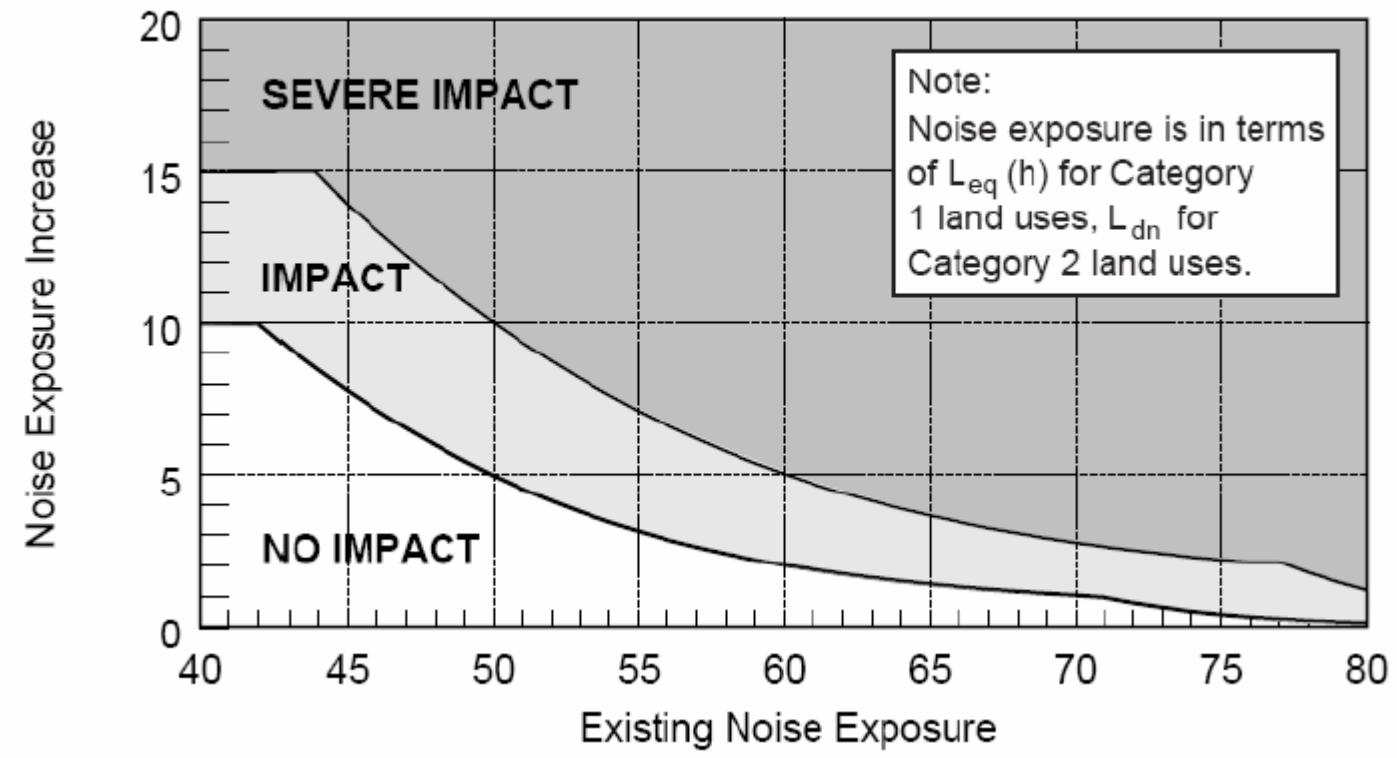
Agency	L_{eq}	DNL
Federal Energy Regulatory Commission (FERC)	[49]	55
Federal Highway Administration (FHWA)	67	[67]
Federal Aviation Administration (FAA)	[59]	65
U.S. Department of Transportation—Federal Rail and Transit Authorities (FRA & FTA)[5,6]	Sliding scale, refer to Figure	Sliding scale, refer to Figure
U.S. Environmental Protection Agency (EPA)[7]	[49]	55
U.S. Department of Housing and Urban Development (HUD)[8]	[59]	65

Note: Brackets [59] indicate calculated equivalent standard. Because FHWA regulates peak noise level, the DNL is assumed equivalent to the peak noise hour.

"Allowable Increase" from Federal Railroad and Transit Administrations

- L_{dn} based for residences

(Note: Residential uses are included in Category 2)



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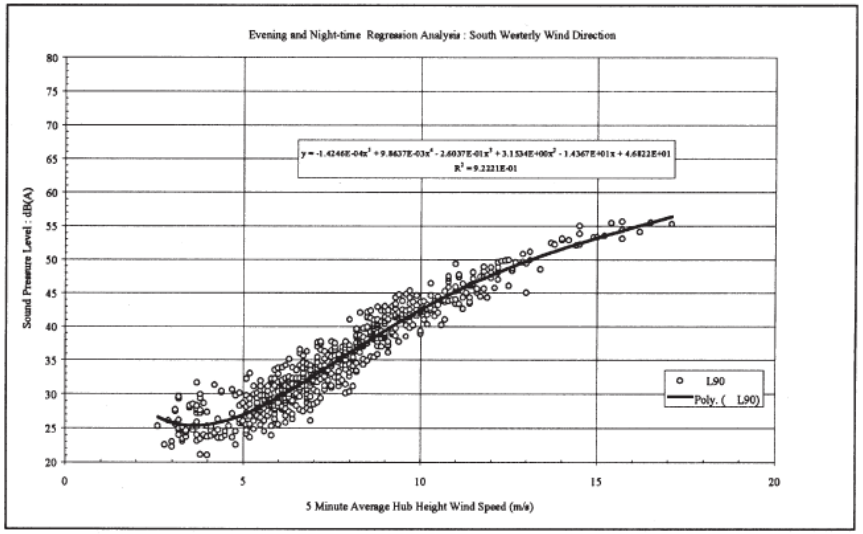
Relative and Absolute Criteria

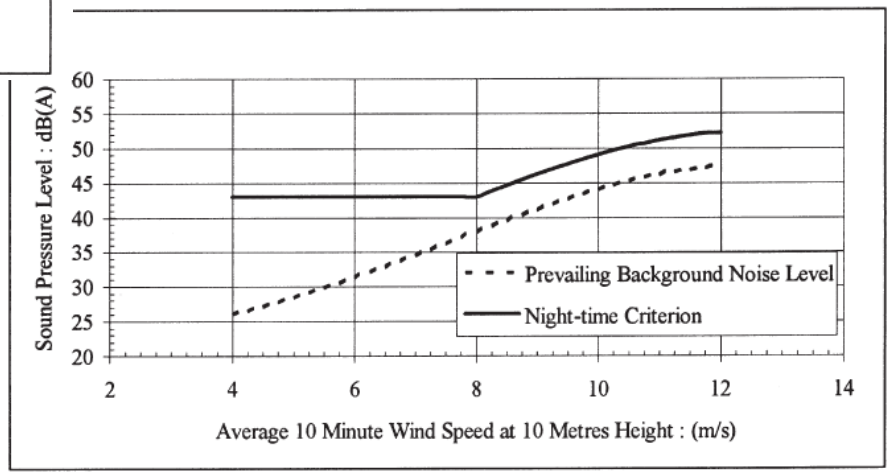


Increase over what? Need to define existing level.

(scatter may be more significant than depicted here)

Is 15-dB increase acceptable when result is less than 45 dBA? How should a maximum level be established? How is variability or probability to be addressed?

Is wind to be evaluated differently than other sources?



Example of night-time noise criterion

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Wind Farm Sound Planning

- Non-acoustic factors may be as important as acoustic factors
  - Visibility, attitude and understanding of necessity of the source
  - Good public relations and outreach imperative
  - Field trips to operating facilities likely reasonable given increased development (silence is not a reasonable goal *nor* should it be implied)
  - Coordinate construction and start-up activities to avoid conflicts with neighbors
  - Ensure local community and land owners understand benefits
  - Respond to concerns, they may indicated maintenance issue