Introduction
Colin Kestell

- Senior Lecturer
  School of Mechanical Engineering
  The University of Adelaide
- Engineering Manager until 1997
- PhD (Active control of sound in a small single engine aircraft cabin with virtual error sensors) in 2000
- Teach Engineering Design

Noise, Where does it come from?
- An audible vibration transported to the observer through an elastic solid or fluid

Sound – Our perception of sound

For a point source radiating into a free field, where the object is small relative to the distance

\[
\begin{align*}
L_p &= L_W - 20\log(r) - 8\, \text{dB} \\
L_W &= L_p + 20\log(r) + 8\, \text{dB} \\
L_{p2} &= L_{p1} - 20\log\left(\frac{r_2}{r_1}\right) \\
L_{p2} &= L_{p1} - 6\, \text{dB} \quad \text{if } r_2 = 2r_1
\end{align*}
\]

Measuring Sound

Log LL
Log L
ref
5
meas

Sound

\[
dB = 10\log\left(\frac{p^2}{P_{ref}}\right)
\]

\[
= 20\log\left(\frac{p}{P_{ref}}\right)
\]

\[
P_{ref} = 2 \times 10^{-12} \, \text{Pa}
\]

\[
u\text{Pascals}
\]

<table>
<thead>
<tr>
<th>dB</th>
<th>0</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
<th>110</th>
<th>120</th>
<th>130</th>
<th>140</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>µPa</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>60</td>
<td>70</td>
<td>80</td>
<td>90</td>
<td>100</td>
<td>110</td>
<td>120</td>
<td>130</td>
<td>140</td>
<td>150</td>
<td>160</td>
<td>170</td>
</tr>
</tbody>
</table>

Hearing threshold

\[
W_p = 20\mu\text{Pascals}
\]

\[
W_{ref} = 1 \times 10^{-12} \, \text{Watts}
\]

9/05/2008
Wind Turbine Noise and Vibration

**Measuring Sound**

For a line source radiating into a free field, where the object is small relative to the distance:

\[
L_p = L_w - 10\log(r) - 5dB
\]

\[
L_w = L_p + 10\log(r) + 5dB
\]

\[
L_{p2} = L_{p1} - 10\log\left(\frac{r_2}{r_1}\right)
\]

\[
L_{p2} = L_{p1} - 3dB \quad \text{if} \quad r_2 = 2r_1
\]

\[
W_{aw} = 1 \times 10^{-16} \text{Watts}
\]

\[
\rho_{aw} = 20 \mu\text{Pa}
\]

**Fundamentals of Noise and Vibration. M.P.Norton**

---

**Types of noise**

- **Tonal Noise**
  - 440Hz
  - 1000Hz
  - 10000 Hz

- **Random Noise**
  - White Noise
  - Pink Noise

**Vibration**

- Structure-borne vibration transmits energy throughout the entire system.
- The displacement of a surface is the combined contribution of all of its modes. Which mode is excited the most is dependent on the source.
- Each and every exterior surface will radiate sound energy.
- The effectiveness of this radiation is known as the 'radiation efficiency'
Wind Turbine Noise and Vibration

Measuring Vibration

Vibration
- Measured in terms of:
  - Displacement
  - Velocity
  - Acceleration – sometimes in terms of ‘g’ (gravity)
- dB also used ... or
- absolute units on either a logarithmic or linear scale

Be careful of units!

All this and more covered in Part IIA 3C6 Vibration and Part IIB 4C6 Advanced Linear Vibration

Measuring sound and vibration

Instrumentation - vibration
- Conditioning amplifier
- Laser vibrometer
- Accelerometer
- Strain gauge
- Spectrum Analyser

Measuring sound and vibration

Calibration

Wind Turbine Noise

Wind turbines produce noise because of:
1. Blades
2. Rotor
3. Pitch
4. Brake
5. Low speed shaft
6. Gear box
7. Generator
8. Controller
9. Anemometer
10. Wind Vane
11. Nacelle
12. High speed shaft
13. Yaw drive
14. Yaw Motor
15. Tower

What generates the noise in wind turbines?
Wind Turbine Noise and Vibration

Aerodynamic Noise
- Blade passes through turbulent, often gusty flow
- Blade motion causes turbulence
- Wing tip vortices cause turbulence
- Turbulence creates sound (broadband audible pressure perturbations)
- Turbulence higher as each blade passes tower
- Consider a 3 blade, 26 RPM rotor will have a BPF of 1.3 Hz

Shaft noise
- unbalanced
- bent shafts
- non-concentric alignment
- \[ \text{frequency(Hz)} = \frac{\text{RPM}}{60} \]
Wind Turbine Noise and Vibration

**Shaft noise**
- Varies with shaft speed
- Frequency (Hz) = \( \frac{\text{RPM}}{60} \)

**Gear Noise**
- Shaft frequency (Hz) = \( \frac{\text{RPM}}{60} \)
- Mesh frequency (Hz) = \( N \times \frac{\text{RPM}}{60} \)

**Gear Noise**
- Consider gear pairs with a simple ratio: 2:1, 3:1 etc
  - Periodically the same teeth will mesh
  - At a frequency equal to the shaft frequency of the larger gear
  - One full revolution of the large gear, also returns the small gear to the same place

**Gear Noise**
- Gears that share common multiples also mesh the same two teeth periodically.
  - Consider: a 40 tooth pinion and a 60 tooth sprocket,
  - Turn the sprocket TWO FULL turns, moving 120 teeth past a point.
  - This moves 120 teeth on the pinion, driving it THREE FULL turns.

**Gear Noise**
- This cyclic nature is known as the HUNTING TOOTH.
- The frequency is equal to:
  \[ \text{Gear mesh frequency} = \frac{\text{Lowest Common Tooth Multiple}}{\text{Shaft frequency}} \]
- This causes uneven wear
- Choose tooth numbers that result in a high 'lowest common multiple' to keep this frequency as low as possible
- This is why gears have apparently strange teeth numbers
Wind Turbine Noise and Vibration

Gear Noise
- Probable 14 tooth gear issue
- Drive speed

Gear Box Failure

Bearing Noise

Generator Noise
- A typical 3-phase generator will have
- 3 pairs of (6) opposing wound coils
- 4 rotating permanent magnets
- Producing 12 pulses per revolution

Normal spur gears – cost effective
- Helical gears – smoother mesh, more expensive, produce an axial force component as well as a tangential
- Herring bone gears (far more expensive) realign the resultant force
Vibration isolation

\[ \omega = \sqrt{\frac{k}{m}} \]

- Increase mass or decreased stiffness
- Increased damping

Acoustic resonance

- The large tower will act like an organ pipe
- Broadband and tonal noise will propagate through the duct and excite standing wave resonances

Examples

- Vesta V52-850 kW, 3 Blade, 26 RPM

Examples

- WindWorld 600kW, Enecon 500kW

Examples

- Canadian 1.5 MW Wind Turbine Spectrogram

Psycho-acoustic characters of relevance for annoyance of wind turbine noise.
Wind Turbine Noise and Vibration

Examples
- Acoustic model of typical wind turbine sound propagation

Noisy or quiet?
- Normal conditions

Machinery health monitoring
- In-situ microphones, strain gauges and accelerometers on
  - Rotating machinery
  - Critical structures

Noisy or quiet?
- Many claim that the noise is worse at night or in the early hours of the morning.
  - Less masking (other noises covering it up)
  - Physiological issues
  - Meteorological effects

Noisy or quiet?
- One of a few meteorological effects

---

Image 1: Illustration of acoustic model of typical wind turbine sound propagation.

Image 2: Chart showing the relationship between decibels (dB) and pascals (Pa).

Image 3: Diagram illustrating machinery health monitoring.

Image 4: Diagram showing noisy or quiet conditions.

Image 5: Diagram depicting noisy or quiet conditions due to meteorological effects.

9/05/2008