Barotrauma in bats from wind turbines.

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Outline

Introduction

Barotrauma:

- Physical damage caused by pressure differences between internal and external environments.
- Wind turbines create rapid pressure drops that can harm bats, [1].

Mechanism of Barotrauma

- Turbine blades create low-pressure zones.
- Rapid decompression damages bats' lungs and other organs.

Why Are Bats Vulnerable?

- **Physiological Traits:**
  - Thin lung tissue.
  - High metabolic rates.
- **Behavioral Traits:**
  - Attraction to turbines due to insect concentration or roosting behavior [3].
  - Response to airflow patterns similar to trees.

Facts About Bat Fatalities

- Wind turbines are causing unprecedented bat fatalities worldwide.
  - Collisions
  - Barotrauma
- Hypothesized fatalities range into tens to hundreds of thousands annually, [2, 3].
- Fatalities peak in late summer and autumn during migratory periods, [2, 3].
- Species affected in North America, [2]:
  - Hoary bats (*Lasiurus cinereus*)
  - Eastern red bats (*Lasiurus borealis*)
  - Silver-haired bats (*Lasionycteris noctivagans*).

Significance of Bat Survival

- Bats are vital for ecosystem services:
  - Pest control: consume large quantities of insects.
  - Pollination and seed dispersal.
- Low reproductive rates make populations vulnerable to declines, [3].
- Long-term population effects could disrupt ecosystems and agriculture.

Causes of Bat Fatalities at Wind Turbines

- **Barotrauma**
  - Postmortem analysis indicates Barotrauma, [2].
- **Research Motivation**
  - Explore the interplay of bad behaviour and turbine design.
  - Address risks and environmental impacts of wind energy.
- **Significance**
  - Understanding these behaviour aids in developing mitigation strategies.

Fluid Dynamics

- For an incompressible fluid, the continuity equation is given by:

$$\nabla \cdot \mathbf{u} = 0$$

- Define the potential function (ϕ), such that

$$\mathbf{u} = \nabla\phi$$

- Substituting $\mathbf{u} = \nabla\phi$ into the continuity equation.

$$\nabla^2\phi = 0, \quad \text{where} \quad \phi \longrightarrow u_x \quad \text{as} \quad (x, y) \longrightarrow \infty \quad \text{and} \quad \nabla\phi \cdot n = 0$$

- Define the stream function ψ such that,

$$\frac{\partial\phi}{\partial x} = \frac{\partial\psi}{\partial y} \quad \text{and} \quad \frac{\partial\phi}{\partial y} = -\frac{\partial\psi}{\partial x}.$$

- It can be shown that ψ also satisfy the Laplacian.
- The complex potential $f(Z)$ combines these:

$$f(Z) = \phi + i\psi \quad \text{where} \quad Z = x + iy$$

Complex Potential Function

- Components:
  - Potential function: $\phi = \text{Re}(f)$.
  - Stream function: $\psi = \text{Im}(f)$.
- For flow past a cylinder of radius a, the complex potential is:

$$f(Z) = U\left(Z + \frac{a^2}{Z}\right)$$

- Derivative of $f(Z)$ gives the velocity field:

$$f'(Z) = U\left(1 - \frac{a^2}{Z^2}\right)$$

Bernoulli Equation

- Bernoulli's equation for steady, inviscid, incompressible, irrotational fluid flow is:

$$\frac{P}{\rho} + \frac{1}{2}|f'(Z)|^2 + gy = C$$

- The streamline is horizontal, y can be ignored.
- The constant C is determined by the free-stream velocity U:

$$C = \frac{1}{2}U^2$$

Pressure Distribution

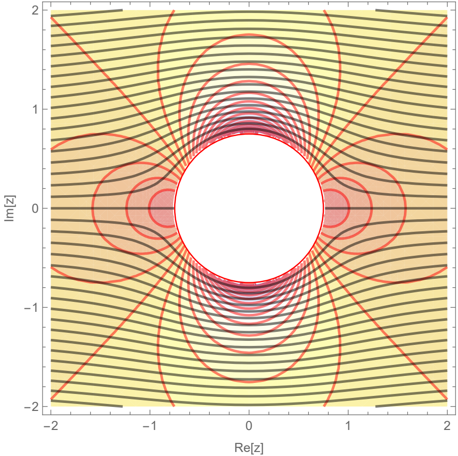
- Rearranging Bernoulli's equation:

$$P = \left[\frac{1}{2}U^2 - \frac{1}{2}|f'(Z)|^2\right]\rho$$

- Pressure is highest at the stagnation points (front and rear).
- Pressure decreases along the sides due to flow acceleration.

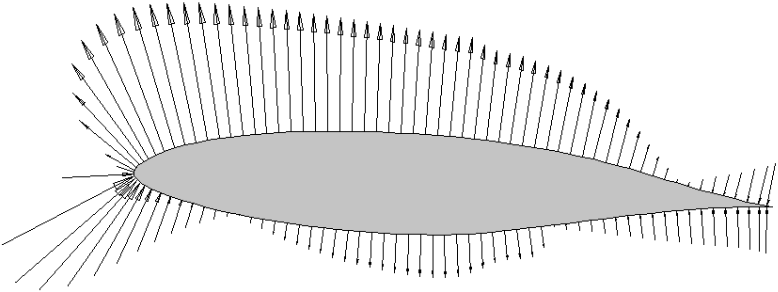
Pressure and Streamline Contour Plot

- Visualization of pressure distribution around the cylinder.
- Contour plot highlights regions of high and low pressure.



Joukowski Airfoil

- **Pressure Distribution around airfoil**, adapted from Aviation StockExchange by P. Kampf (https://aviation.stackexchange.com/questions/5230/how-to-plot-the-pressure-distribution-over-an-airfoil)

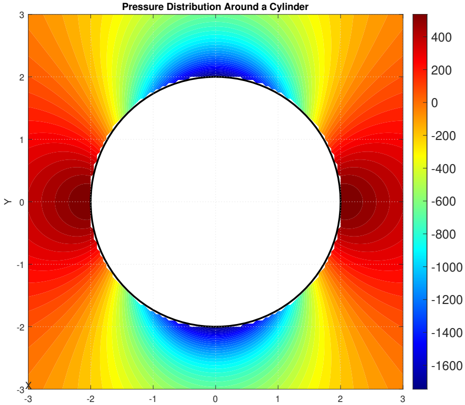


Pressure Difference

- For Baratrauma, [1]

$$\Delta P \in [5, 10] kpa$$

- Change in pressure $\approx 2000pa = 2kpa$
- Not enough to cause Barotrauma.



Direct Collision and Nearby Passage

- Angular velocity of blades (ω) in Rev/sec.

$$\omega = \frac{V_{Blade}}{r}$$

- Let W_B be the blade width. Then time for bat to pass through blade zone.

$$\tau = \frac{W_{Blade}}{V_{Bat}}$$

- Time taken for blade to cover separation arc.

$$T_{Blade} = \frac{2\pi}{\omega n}$$

- Thus collision criterion:

$$\text{if } \tau \geq T_{Blade} \implies Collision$$

Collision Example

Given:

- Bat Speed (V_{Bat}): 8 m/s
- Blade Radius (r): 40 m
- Blade Width (W_{Blade}): 2 m
- Turbine Speed (Rev/Sec): 0.20
- Number of Blades (n): 3

Steps:

1. $\omega = 2\pi \cdot 0.20 = \frac{2\pi}{5}$ rad/s
2. $V_{\text{Blade}} = \omega \cdot r = \frac{2\pi}{5} \cdot 40 = 16\pi \approx 50.27$ m/s
3. $\tau = \frac{W_{Blade}}{V_{Bat}} = \frac{2}{8} = 0.25$ s
4. $T_{\text{Blade}} = \frac{2\pi}{\omega n} = \frac{2\pi}{\frac{2\pi}{5} \cdot 3} = 1.67$ s

Hit or Miss?

Collision Criterion:

- $\tau = 0.25\,\mathrm{s}$
- $T_{\text{Blade}} = 1.67\,\mathrm{s}$

Probability of collision:

$$Pr = \frac{\tau}{T_{\text{Blade}}} \approx 15\%$$

Simulation:

Vortex Problem

- **Vortex Dynamics**
  - **Roll-Up of Vortexes:** Created by merging or interacting vortices in fluid dynamics, where smaller vortices combine to form a larger one, often due to turbulence or instabilities.
  - **Maximum Velocity and Travel Distance:** Vortexes impact airspace navigability [4].

Bat Perception and Behavior

  - Misleading sensory cues from turbulent airflows [5].
  - Increased collision risk during insect migrations [3].
  - Vortex flows

$$F(\xi) = \sum_{j=1}^{N} \left[\frac{i\Gamma_j}{2\pi} \ln\left(\xi - \xi_j\right) \right], \quad \text{and} \quad F'(\xi) = \sum_{h=1}^{N} \left[\frac{dx_h}{dt} - i \frac{dy_h}{dt} \right]$$

Each blade of the turbine generates a vortex at its tip.

- Vortex 1

$$\frac{dx_1}{dt} = Re\left[\frac{i\Gamma_2}{2\pi(\xi - \xi_2)} + \frac{i\Gamma_3}{2\pi(\xi - \xi_3)}\right]$$
$$\frac{dy_1}{dt} = -Im\left[\frac{i\Gamma_2}{2\pi(\xi - \xi_2)} + \frac{i\Gamma_3}{2\pi(\xi - \xi_3)}\right]$$

- Vortex 2

$$\frac{dx_1}{dt} = Re\left[\frac{i\Gamma_1}{2\pi(\xi - \xi_1)} + \frac{i\Gamma_3}{2\pi(\xi - \xi_3)}\right]$$
$$\frac{dy_1}{dt} = -Im\left[\frac{i\Gamma_1}{2\pi(\xi - \xi_1)} + \frac{i\Gamma_3}{2\pi(\xi - \xi_3)}\right]$$

- Vortex 3

$$\frac{dx_1}{dt} = Re\left[\frac{i\Gamma_1}{2\pi(\xi - \xi_1)} + \frac{i\Gamma_2}{2\pi(\xi - \xi_2)}\right]$$
$$\frac{dy_1}{dt} = -Im\left[\frac{i\Gamma_1}{2\pi(\xi - \xi_1)} + \frac{i\Gamma_2}{2\pi(\xi - \xi_2)}\right]$$

3-Vortex problem

3-Vortex simulation

Vortex Sheet equation

The vorticity profile shed from the back of the blades can be simulated by the following gamma equation.

Elliptic blade profile: $\gamma(x) = 2Ux\left(a^2 - x^2\right)^{-\frac{1}{2}}$ where $-a \leq x \leq a$

Approximation of Circulation (Γ) is given by:

$$\begin{aligned}\Gamma &= \int_0^a \gamma(x)\, dx \\ &= \int_0^a 2Ux\left(a^2 - x^2\right)^{-\frac{1}{2}}\, dx\end{aligned}$$

Therefore,

$$\Gamma = 2Ua.$$

Tangential Velocity V_θ

The tangential velocity V_θ through the Lamb-Oseen approximation,

$$V_\theta = \frac{\Gamma}{2\pi r}\left(1 - \exp\left(\frac{-r^2}{4\nu t}\right)\right).$$

We find the Maximum velocity(V_{Max}) by optimizing V_θ with respect to r. Therefore,

$$\begin{aligned}
V_\theta &= \frac{\Gamma}{2\pi r}\left(1 - \exp\left(\frac{-r^2}{4\nu t}\right)\right) \\
\frac{d}{dr}V_\theta &= \frac{d}{dr}\left(\frac{\Gamma}{2\pi r}\left(1 - \exp\left(\frac{-r^2}{4\nu t}\right)\right)\right) \\
&= \frac{\Gamma}{2\pi}\left[-\frac{1}{r^2}\left(1 - \exp\left(\frac{-r^2}{4\nu t}\right)\right) + \frac{1}{2\nu t}\exp\left(\frac{-r^2}{4\nu t}\right)\right]
\end{aligned}$$

Maximum Tangential Velocity V_θ

To find the maximum Tangential velocity we let:

$$\frac{d}{dr} V_\theta = 0$$

this implies that:

$$\begin{aligned}
0 &= \frac{\Gamma}{2\pi}\left[-\frac{1}{r^2}\left(1-\exp\left(\frac{-r^2}{4\nu t}\right)\right)+\frac{1}{2\nu t}\exp\left(\frac{-r^2}{4\nu t}\right)\right] \\
&= \frac{1}{r^2}\left(\exp\left(\frac{-r^2}{4\nu t}\right)-1\right)+\frac{1}{2\nu t}\exp\left(\frac{-r^2}{4\nu t}\right) \\
&= \left(\exp\left(\frac{-r^2}{4\nu t}\right)-1\right)+\frac{r^2}{2\nu t}\exp\left(\frac{-r^2}{4\nu t}\right)
\end{aligned}$$

Maximum Tangential Velocity V_θ continued...

$$\exp\left(\frac{-r^2}{4\nu t}\right) + \frac{r^2}{2\nu t}\exp\left(\frac{-r^2}{4\nu t}\right) = 1$$

$$\ln\left[\exp\left(\frac{-r^2}{4\nu t}\right)\left(1 + \frac{r^2}{2\nu t}\right)\right] = \ln(1)$$

$$1 + \frac{r^2}{2\nu t} - \exp\left(\frac{r^2}{4\nu t}\right) = 0$$

Roots at $r = 0$ and $r = 2\sqrt{\nu \cdot t \cdot 1.256}$. But $r \neq 0$

Maximum Tangential Velocity V_θ continued...

$$V_\theta = \frac{\Gamma}{2\pi r}\left(1 - \exp\left(\frac{-r^2}{4\nu t}\right)\right)$$

Substituting, $r = 2\sqrt{\nu \cdot t \cdot 1.256}$:

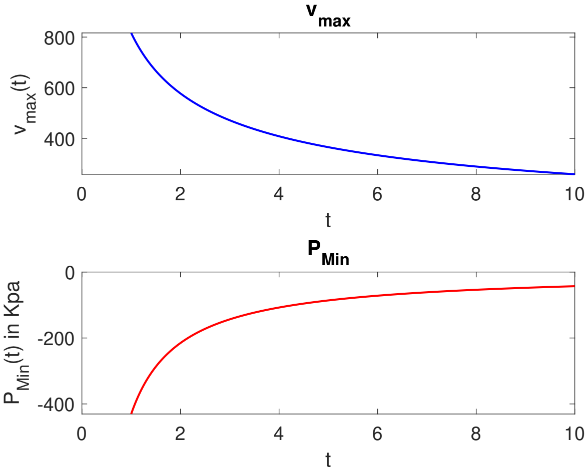
$$V_{max} = \frac{Ua}{2\pi\sqrt{\nu \cdot t \cdot 1.256}}[1 - \exp(1.256)]$$

Therefore,

$$P_{min} = \left[\frac{1}{2}U^2 - \frac{1}{2}(V_{max})^2\right]\rho$$

Graphical Representation

- We can now plot V_{max} *vs* t and P_{min} *vs* t.



Example..

- Taking $U = 5$, $a = 30$ and $\nu = 1.8$ x 10^{-5}
- We obtain pressure drops on the order of magnitude of 100 kPa.
- This is more than sufficient to cause Barotrauma in Bats.

Conclusions

- Bat death is an important issue in wind turbines.
- Deaths are caused by both collisions and Barotrauma, with Barotrauma being the primary cause .
- Direct collision probability $\approx 15\%$.
- A near-miss pressure drop is not sufficient to cause Barotrauma.
- Wingtip vortex Barotrauma is highly likely.

Thank You!, Questions?

References I

Erin F Baerwald, Genevieve H D'Amours, Brandon J Klug, and Robert MR Barclay.
Barotrauma is a significant cause of bat fatalities at wind turbines.
Current biology, 18(16):R695–R696, 2008.

Paul M. Cryan and Robert M. R. Barclay.
Causes of bat fatalities at wind turbines: Hypotheses and predictions.
Journal of Mammalogy, 90(6):1330–1340, 2009.

Paul M. Cryan, P. Marcos Gorresen, Cris D. Hein, Michael R. Schirmacher, Robert H. Diehl, Manuela M. Huso, David T. S. Hayman, Paul D. Fricker, Frank J. Bonaccorso, Douglas H. Johnson, Kevin Heist, and David C. Dalton.
Behavior of bats at wind turbines.
Proceedings of the National Academy of Sciences (PNAS), 111(42):15126–15131, 2014.

References II

M. Soultanzadeh and A. Moradi.
Numerical simulation and experimental study of blade pitch effect on darrieus straight-bladed wind turbine with high solidity: a case study under realistic conditions.
2020.

G. Tóth and G. Házi.
Merging of shielded gaussian vortices and formation of a tripole at low reynolds numbers.
Physics of Fluids, 22, 2010.