Wind Turbine Blade Design

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How does a wind turbine work?

1. Inflow of wind

2. Inflow of wind activates rotor (A) & blades (B)

3. Rotor & blades spin the main shaft (C) and gearbox (D), which spins the generator (G), resulting in electrical output
Calculation of Wind Power

Power in the Wind = \( \frac{1}{2} \rho AV^3 \)

- Effect of swept area, A
- Effect of wind speed, V
- Effect of air density, \( \rho \)

Swept Area: \( A = \pi R^2 \) Area of the circle swept by the rotor (m\(^2\)).
Many Different Rotors...
Blade Composition
Wood

Wood
- Strong, light weight, cheap, abundant, flexible
- Popular on do-it yourself turbines

- Solid plank
- Laminates
- Veneers
- Composites
Blade Composition

Metal

- Steel
  - Heavy & expensive
- Aluminum
  - Lighter-weight and easy to work with
  - Expensive
  - Subject to metal fatigue
Blade Construction
Fiberglass

• Lightweight, strong, inexpensive, good fatigue characteristics
• Variety of manufacturing processes
  – Cloth over frame
  – Pultrusion
  – Filament winding to produce spars
• Most modern large turbines use fiberglass
Airfoil Shape

Just like the wings of an airplane, wind turbine blades use the airfoil shape to create lift and maximize efficiency.

The Bernoulli Effect
Twist & Taper

- Speed through the air of a point on the blade changes with distance from hub
- Therefore, tip speed ratio varies as well
- To optimize angle of attack all along blade, it must twist from root to tip
Tip-Speed Ratio

Tip-speed ratio is the ratio of the speed of the rotating blade tip to the speed of the free stream wind.

There is an optimum angle of attack which creates the highest lift to drag ratio.

Because angle of attack is dependant on wind speed, there is an optimum tip-speed ratio

\[ TSR = \frac{\Omega R}{V} \]

Where,
\[ \Omega = \text{rotational speed in radians/sec} \]
\[ R = \text{Rotor Radius} \]
\[ V = \text{Wind “Free Stream” Velocity} \]
Performance Over Range of Tip Speed Ratios

- Power Coefficient Varies with Tip Speed Ratio
- Characterized by $C_p$ vs Tip Speed Ratio Curve
Betz Limit

All wind power cannot be captured by rotor or air would be completely still behind rotor and not allow more wind to pass through.

Theoretical limit of rotor efficiency is 59%

Most modern wind turbines are in the 35 – 45% range
Rotor Solidity

**Solidity** is the ratio of total rotor planform area to total swept area

Low solidity (0.10) = high speed, low torque

High solidity (>0.80) = low speed, high torque

Solidity = \( \frac{3a}{A} \)
Manufacturing Blades

The blade mold (left) is lined with layers of fiberglass, then injected with epoxy resin. To enhance stiffness, a layer of wood is placed between the fiberglass layers. The two molds are joined and adhered together using a special liquid epoxy, which evenly joins the two sides of the blade.

Finally, the whole mold is baked like a cake! 8 hours at 70 degrees C.
Before delivery, samples of the rotor blades have to go through a variety of static and dynamic tests. First, they are subjected to 1.3 times the maximum operating load. To simulate 20 years of material fatigue, the blades are then mounted on special test beds and made to vibrate around two million times, before the endurance of the material is again tested with a final static test.

The blades are painted white, then shipped to wind farms all over the world.
Wind Turbine Blade Challenge

• Students perform experiments and design different wind turbine blades

• Use simple wind turbine models

• Test one variable while holding others constant

• Record performance with a multimeter or other load device

• Goals: Produce the most voltage, pump the most water, lift the most weight
  – Minimize Drag
  – Maximize LIFT
  – Harness the POWER of the wind!
Advanced Classroom Blades

Airfoil Blades

Cardboard Tube for twisted blades
Questions?

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Wind Turbine Number and Pitch of Blades Design

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Number of Blades – One

• Rotor must move more rapidly to capture same amount of wind
  – Gearbox ratio reduced
  – Added weight of counterbalance negates some benefits of lighter design
  – Higher speed means more noise, visual, and wildlife impacts

• Blades easier to install because entire rotor can be assembled on ground

• Captures 10% less energy than two blade design

• Ultimately provide no cost savings
Number of Blades - Two

- Advantages & disadvantages similar to one blade
- Need teetering hub and or shock absorbers because of gyroscopic imbalances
- Capture 5% less energy than three blade designs
Number of Blades - Three

- Balance of gyroscopic forces
- Slower rotation
  - increases gearbox & transmission costs
  - More aesthetic, less noise, fewer bird strikes
Lift & Drag Forces

- The **Lift Force** is perpendicular to the direction of motion. We want to make this force BIG.

- The **Drag Force** is parallel to the direction of motion. We want to make this force small.

\[ \alpha = \text{low} \quad \alpha = \text{medium} < 10 \text{ degrees} \quad \alpha = \text{High Stall!!} \]
Lift/Drag Forces Experienced by Turbine Blades
Pitch Control Mechanisms
Some Wacky Ideas...