Aerodynamics of Wind Turbine Blades

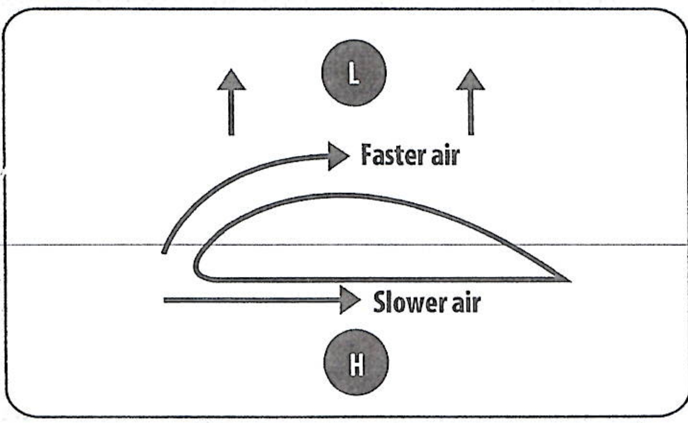
Why Turbine Blades Move

There are two important reasons why wind turbine blades are able to spin in the wind: Newton's Third Law and the Bernoulli Effect.

Newton's Third Law states that for every action, there is an equal and opposite reaction. In the case of a wind turbine blade, the action of the wind pushing air against the blade causes the reaction of the blade being deflected, or pushed. If the blade has no **pitch** (or angle), the blade will simply be pushed backwards (downhill). But since wind turbine blades are set at an angle, the wind is deflected at an opposite angle, pushing the blades away from the deflected wind. This phenomenon can be viewed on a simple, flat blade set at an angle. If you push the blade with your finger from the direction of the oncoming wind, the blade will deflect away from your finger.

Bernoulli's Principle, or the Bernoulli Effect, tells us that faster moving air has lower pressure. Wind turbine blades are shaped so that the air molecules moving around the blade travel faster on the downwind side of the blade than those moving across the upwind side of the blade. This shape, known as an **airfoil**, is like an uneven teardrop. The downwind side of the blade has a large curve, while the upwind side is relatively flat. Since the air is moving faster on the curved, downwind side of the blade, there is low pressure on this side of the blade. This difference in pressure on the opposite sides of the blade causes the blade to be "lifted" towards the curve of the airfoil.

AIRFOIL SHAPE: A CROSS-SECTION



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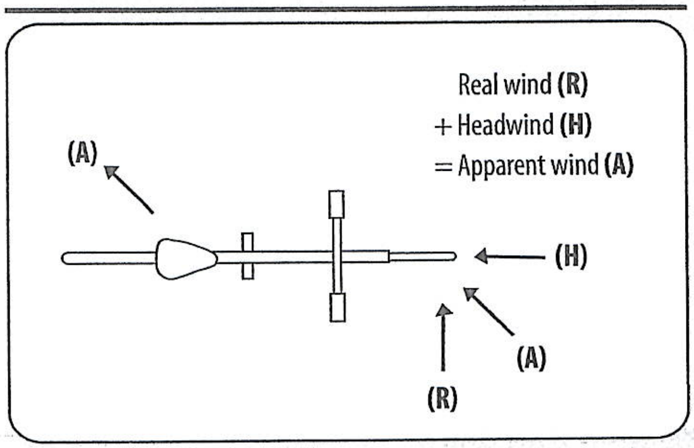
Understanding Wind

Wind turbine blades must be optimized to efficiently convert oncoming winds into motion energy to rotate the main driveshaft. But when designing turbine blades, the real wind is only one part of a larger equation. Good blades must also account for the apparent wind that is experienced as the blade passes through the air.

Imagine riding your bike on a day with a fresh breeze at your side. As you begin to ride and pick up speed, you feel this wind from the side, but also wind pushing back at you from the direction you are moving. When you stop riding, there is just the wind from the side again. This wind that is "created" as you are moving is known as headwind. The headwind, combined with the real wind, is known as apparent wind. A wind turbine blade experiences apparent wind as it passes through the air. This apparent wind is from a different direction than the "real" wind that has caused the blade to begin moving. Since the tips of large turbine blades may be moving through the air at speeds up to 322 km/h (200 mph), this apparent wind can be very significant!

APPARENT WIND



Aerodynamics

Efficient blades are a key part of generating power from a wind turbine. The efficiency of a wind turbine blade depends on the drag, lift, and torque produced by the blade. These factors are affected by the size and shape of the blades, the number of blades, and the blade pitch.

Drag

Drag is defined as the force on an object that resists its motion through a fluid. When the fluid is a gas such as air, the force is called aerodynamic drag, or air resistance. Drag is a force that is working against the blades, causing them to slow down. Drag is always important when an object moves rapidly through the air or water. Airplanes, race cars, rockets, submarines, and wind turbine blades are all designed to have as little drag as possible.

Imagine riding your bike down a big hill. To go faster, you might tuck your body to expose as little of it to the apparent wind as possible. This is a trick to reduce drag. Now imagine you have a big parachute strapped to your back when you ride down the hill. The parachute increases the drag significantly and this drag force slows you down.

Drag increases with the area facing the wind. A large truck has a lot more drag than a motorcycle moving at the same speed. Wind turbine blades have to be streamlined so they can efficiently pass through the air. Changing the angle of the blades will change the area facing the apparent wind. This is why blade pitch angles of 10-20 degrees tend to have much less drag than greater angles.

Drag also increases with wind speed. The faster an object moves through the air, the more drag it experiences. This is especially important for wind turbine blades, since the blade tips are moving through the air much faster than the base of the blade. The shape and angle of wind turbine blades changes along the length of the blade to reduce drag at the blade tips.

Reducing Drag on Wind Turbine Blades:

1. Change the pitch—the angle of the blades dramatically affects the amount of drag.
2. Use fewer blades—each blade is affected by drag.
3. Use light-weight materials—reduce the mass of the blades by using less material or lighter material.
4. Use smooth surfaces—rough surfaces, especially on the edges, can increase drag.
5. Optimize blade shape—the tip of a blade moves faster than the base. Wide, heavy tips increase drag.

Lift

Lift is the aerodynamic force that allows airplanes and helicopters to fly. The same force applies to the blades of wind turbines as they rotate through the air. Lift opposes the force of drag, helping a turbine blade pass efficiently through air molecules. The main goal of a well-designed wind turbine blade is to generate as much lift as possible while minimizing drag.

The amount of lift a blade or wing can generate is determined by several factors—the shape of the blade, the speed of the air passing around the blade, and the angle of the blade relative to the apparent wind.

Shape

The airfoil shape of the blade helps to generate lift by taking advantage of the Bernoulli Effect. Wind turbine blade designers have experimented with many different airfoil shapes over the years in an effort to find the perfect shape that will perform well in a range of wind speeds. Even minor changes in this blade shape can dramatically affect the power output and noise produced by a wind turbine.

The airfoil profile (shape) of a turbine blade will actually change as you move down the length of the blade, generally getting flatter and narrower toward the tips of the blades. This is to optimize the lift and minimize drag.

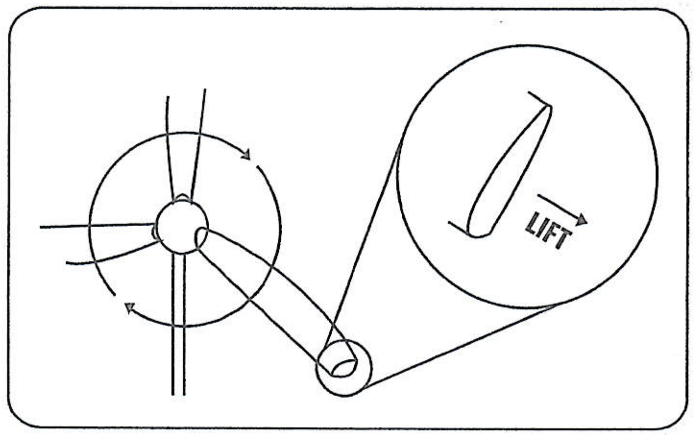
Speed

Remember that the speed of air passing around the blade is a combination of the real wind and the headwind as the blade moves. The faster the blade is moving, the more drag/headwind it experiences, but the lift force will also increase as the blades move faster.

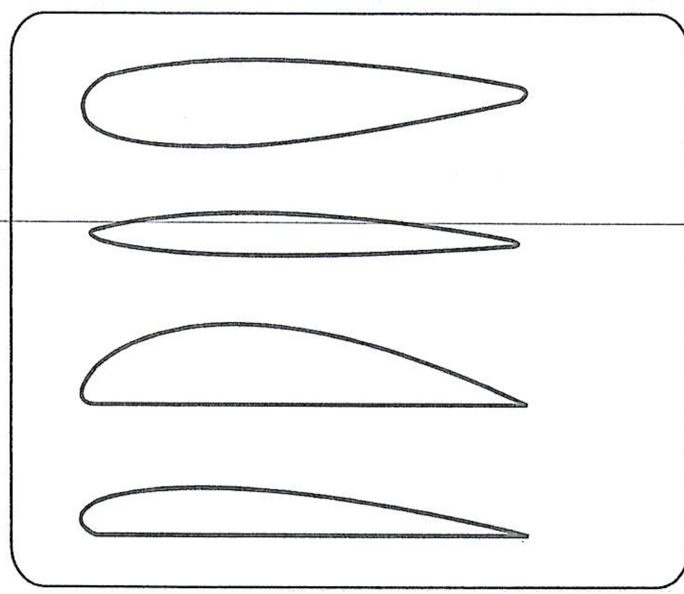
The tips of wind turbine blades travel much further with each rotation of the blades, and therefore move through the air much faster than the roots of the blades. Since they are traveling the furthest distance with each rotation (distance/time = speed), the tips of turbine blades experience more headwind. The roots, or base, of the blades do not experience as much headwind since they are passing through the air much more slowly.

The faster the air molecules are passing over a blade or wing, the more lift can be generated. So the tips of real turbine blades generate much more lift than the roots. Some large wind turbines have blade tip speeds over 322 km/h (200 mph).

LIFT



AIRFOIL SHAPES

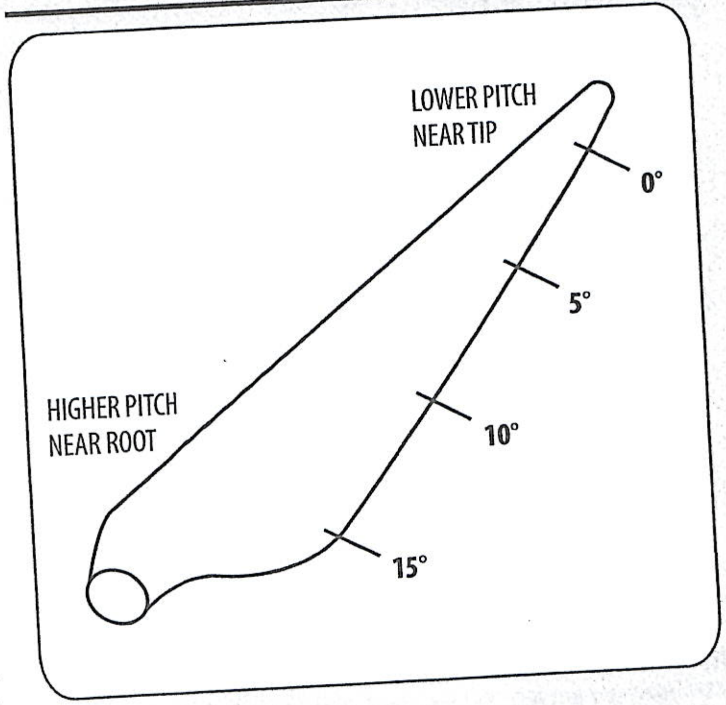


Angle

The angle of the blades also greatly impacts how much lift is generated. On large wind turbines, the blade angle is constantly adjusted to give the blades the optimal angle into the apparent wind. The angle of the blade relative to the plane of rotation is known as the pitch angle. The angle of the blade relative to the apparent wind is called the angle of attack. The angle of attack is very important, but also complicated since it will change as the real wind speed changes and the speed of the blade (headwind) changes. On most airfoil blade shapes, an angle of attack of 10-15 degrees creates the most lift with the least drag.

Real wind turbine blades typically have a twisted pitch — meaning the blade angle is steeper at the root of the blade and flatter further away from the hub. Once again, this is due to the fact that the tips move so much faster through the air. By twisting the pitch, the blades are able to take advantage of a more ideal angle of attack down the length of each blade. The tips of a real turbine blade may have close to a 0 degree pitch angle, but this section of the blade generates a great deal of lift.

BLADE PITCH

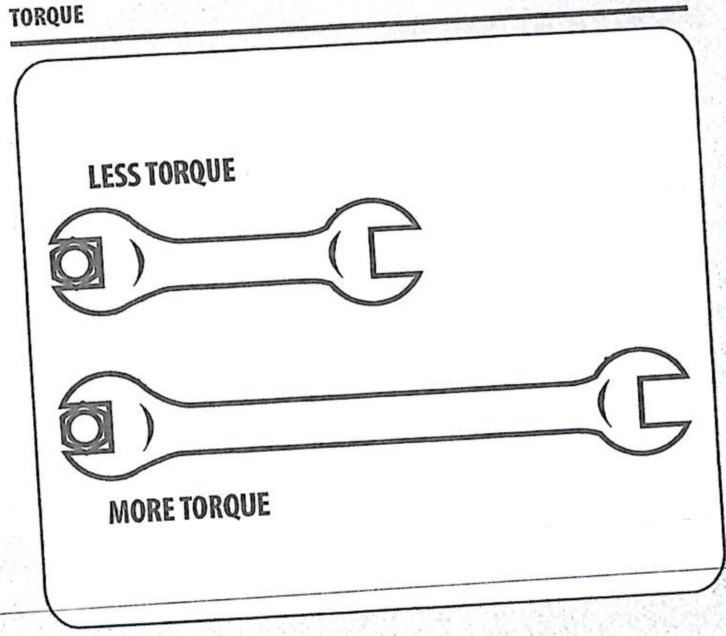


Torque

Torque is a force that turns or rotates something. When you use a wrench on a bolt or twist a screw loose with a screwdriver, you are generating torque. Torque is a lot like leverage. If you are trying to turn a wrench, sometimes you need a lot of leverage to loosen a tight bolt. Wind turbine blades are like big levers, but instead of your muscle turning them they use the force of the wind.

Torque is equal to the force multiplied by distance. This means that the longer your blades are, the more torque you can generate. For example, imagine someone trying to loosen a tight bolt. Pushing with all his might, he can exert 100 pounds of force. If his wrench was 1 foot long, he would be exerting 100 foot-pounds of torque. If he applied the same force to a 2 foot long wrench, he would be exerting 200 foot-pounds of torque on the bolt. This additional leverage makes it much easier to loosen the bolt.

TORQUE



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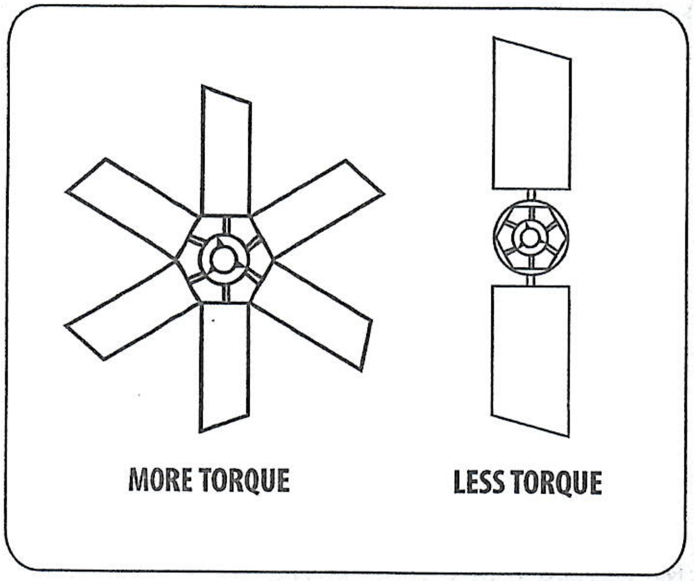
Gearing Up For More Power

On a real wind turbine, the long blades give the turbine a lot of leverage to provide power to the generator. Utility scale large turbines often have large gear boxes that increase the revolutions per minute of the rotor by 80 or 100 times. This big gear reduction demands a lot of leverage from the blades. Think about riding your bicycle—when you shift into high gear it may be harder to pedal. A higher gear demands more torque.

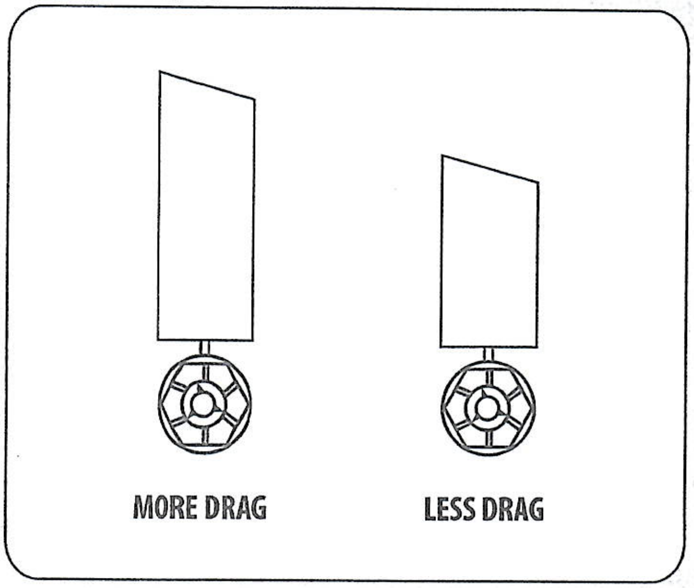
Power output is directly related to the speed of the spinning drive shaft (revolutions per minute or rpm) and how forcefully it turns. A large wind turbine has a rotor with blades, a gear box, and a generator. As the blades spin, the rotor rotates slowly with heavy torque. The generator has to spin much faster to generate power, but it cannot use all the turning force, or torque, that is on the main shaft. This is why a large wind turbine has a gear box.

Inside the gear box, there is at least one pair of gears, one large and one small. The large gear, attached to the main shaft, rotates at about 20 revolutions per minute with a lot of torque. This large gear spins a smaller gear, with less torque, at about 1,500 revolutions per minute. The small gear is attached to a small shaft that spins the generator at high speed, generating power. The relationship between the large and small gears is called the **gear ratio**. The gear ratio between a 1,500 rpm gear and a 20 rpm gear is 75:1.



Putting It All Together

Increasing the torque generated by the blades often increases the drag they experience as they rotate. For example, longer blades will generate more torque and more drag. Increasing the blade pitch will generally increase the torque and increase the drag. Increasing the number of blades will generally give you more torque and more drag. For this reason, it is important to design blades to match the load application. If you are using a windmill to lift a bucket of weights, a slowly spinning rotor that generates lots of torque will be best. If you are using a turbine to light a string of LED bulbs wired in series, you will need a rotor that spins very rapidly with very little drag.



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1. Exploring Blade Pitch

Question

How does the blade's pitch (angle) affect the turbine's electrical output?

Hypothesis

Make a hypothesis to address the question using the following format: "If...then...because..."

Independent Variable: Blade Pitch

Dependent Variable: Electrical Output

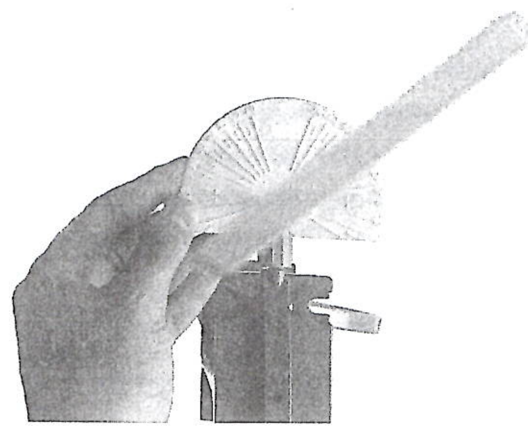
Controlled Variables:

Materials

- Poster board
- Dowels
- Scissors
- Masking tape
- Hub
- Blade pitch protractor
- Turbine testing station (turbine tower, multimeter, fan)
- *Benchmark Blade Template*

Procedure

1. Using the benchmark blade template, make three blades out of poster board. Space them evenly around the hub.
2. Slip the protractor around the dowel. Set the blades to a pitch of 90 degrees.
3. Put your hub on the turbine tower and observe the results. Record the data.
4. Set your blades to a new pitch and test again. This is your second trial. Record your data.
5. Repeat Step 4 at least once more to try to find the pitch that yields the greatest electrical output.



Data Table

	PITCH	ELECTRICAL OUTPUT (VOLTAGE)
TRIAL 1	90 DEGREES	
TRIAL 2		
TRIAL 3		

Graph Data

The manipulated variable is written on the X axis (horizontal) and the responding variable is written on the Y axis (vertical).

Conclusion

Do you accept or reject your hypothesis? Use results from your data table to support your reasoning. Explain which blade pitch you will proceed with for your next investigations and why.

Note: The pitch you found to generate the greatest electrical output will now be a controlled variable. In future explorations you will continue to use this pitch as you investigate.

2. Exploring Number of Blades

Question

How do the number of blades on a turbine affect electrical output?

Hypothesis

Make a hypothesis to address the question using the following format: "If...then...because..."

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Independent Variable: Number of Blades

Dependent Variable: Electrical Output

Controlled Variables: ____

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Materials

- Benchmark blades
- Poster board
- Dowels
- Scissors
- Masking tape
- Hub
- Turbine testing station
- Blade pitch protractor

✔ Procedure

1. Decide how many blades you will be testing and make enough blades for the maximum number you will be testing.
2. In the data table, put down the greatest electrical output from the blade pitch investigation.
3. Put the number of blades you want to test into the hub. They should have the same pitch as in the previous investigation.
4. Put your hub onto the turbine tower and test the number of blades. Record the results as trial 1.
5. Repeat steps 3-4 at least two more times to try to find the ideal number of blades for the greatest electrical output.

Data Table

	NUMBER OF BLADES	ELECTRICAL OUTPUT (VOLTAGE)
BENCHMARK	3 BLADES	
TRIAL 1		
TRIAL 2		
TRIAL 3		

Graph Data

The manipulated variable is written on the X axis (horizontal) and the responding variable is written on the Y axis (vertical).

Conclusion

Do you accept or reject your hypothesis? Use results from your data table to support your reasoning and explain how many blades are ideal for a turbine.

Note: The number of blades with the greatest electrical output should become the benchmark blades for your next investigation.