ENGR 1181 | Lab 7: Wind Turbine

- Preparation Material (Lab 7A)
- Lab Procedure (Lab 7A)
- Preparation Material (Lab 7B)
- Lab Procedure (Lab 7B)
- Report Guidelines (Combined)
Preparation Material (7A)
Learning Objectives:
The Wind Turbine labs introduce students to basic concepts in fluid flow, including the relationship between pressure, velocity, and generated power and efficiency of wind energy. Students will review this document and then take the Carmen quiz before arrive at lab.

1. Overview of the Wind Turbine Lab (7A):
The Wind Turbine Lab introduces basic concepts that engineers use to design and build wind turbines. In the Wind Turbine Lab, you will:

1. Be introduced to fluid mechanics and Bernoulli’s equation
2. Associate wind velocity to the pressure changes inside the tunnel
3. Observe the conversion of wind energy to electrical energy
4. Explore the characteristics of the wind tunnel and turbine

2. The First Wind Turbine
Utilizing wind’s kinetic energy, windmills have been used to crush things like grain and pulp, machine saw wood, or pump water since as early as 7th century. However nowadays wind’s kinetic energy is mainly transformed into electrical power through wind turbines. Figure 1 shows the first wind turbine to generate electricity in the United States built in Cleveland, Ohio in 1888.

Figure 1: The first automatically operated electricity-generating wind turbine in the USA\textsuperscript{1,2}
3. Harvesting Energy from Wind

Along with solar energy, harvesting energy from the wind has proven to be another avenue for an alternative energy source. Different technologies have been developed to collect the energy from the wind for a given purpose. Windmills which have been around for centuries and sail boats are technologies that have been around for centuries and have harvested the energy in wind to perform a specified function. In this lab and the arena of alternative energy, wind energy is converted to electricity. As the wind blows, the wind turbine rotates a generator and so produces electricity. The power output ranges between types of turbines. Turbines used in residential areas vary from ten to one hundred kilowatts while turbines used on farms range from 0.1 to higher than six megawatts. As an example, the city of Bowling Green, Ohio, uses half of generating capacity of the American Municipal Power Wind Farm of 7.2 MW.

4. Wind Energy is a Form of Solar Energy

Wind is mainly caused by solar energy. Three factors together cause wind: the atmosphere heating non-uniformly, earth's uneven surface, and the earth's rotation. Wind Energy in general refers to the kinetic energy present in the wind. According to Figure 2, the force diagram shows that wind push against the blade (the blue bar) and causes the blade to rotate.

![Figure 2: Force Diagram of wind and the wind turbine blade](image)

This kinetic energy in wind is converted to mechanical energy of rotating rotors. The generator in the wind turbine can then convert this mechanical power into electricity.

Wind energy is a popular form of alternative energy because the source of the energy is free. However, there are several costs involved in developing and running a wind farm, including manufacture of the wind turbines, land, infrastructure (transmission lines), and maintenance. In Ohio, the most promising area for developing wind farms is off-shore in Lake Erie.
5. The Components of a Wind Turbine

A wind turbine as shown in Figure 3 mainly consists of a generator, controller, blades and a tower as shown in figure one.

The wind turns the blade which in turn rotates the shaft which turns the gears in the generator to create electricity. The largest component of the turbine is the rotor which consists of the blades and their point of connection. Gear boxes are necessary to increase the speed of rotations at the generator. Without these gears, the shaft would not rotate as fast as required by generator to produce electricity. In general based on the size of the rotor, wind turbines can produce power ranging from kilowatts to megawatts.

Changing different aspects of the blades such as whether or not the blades are perpendicular or parallel to the wind can affect the amount of power produced. Due to the existence of various components, companies such as GE and Siemens use engineers from different disciplines such as electrical, mechanical, and material science to design wind turbines.
6. Fluid Mechanics Principles and Equations
The design of the wind blade indicates principles of fluid mechanics. This airfoil shape (Figure 4) causes a pressure difference. As velocity of a body of gas increases, its pressure decreases. This concept is realized in the Bernoulli principle. As a result, the blade is lifted and it enhances the rotation of modern wind turbines as shown in Figure 4.

![Diagram of an airfoil](image)

Figure 4: Diagram of an airfoil

Common applications of the airfoil shape are configured for both stationary and dynamic use such as fans, rudders, compressors, propellers, and rotors.

For any two points in the path of incompressible liquid flow, Bernoulli’s equation is expressed as

\[
\frac{v_1^2}{2} + \frac{p_1}{\rho} + gz_1 = \frac{v_2^2}{2} + \frac{p_2}{\rho} + gz_2
\]

(1)

where \(v, p, z\) are velocity, pressure, and height of different points respectively. In this lab, point one is a point outside of the tunnel and point two is inside. So \(v_1\) is the velocity of air outside the tunnel. \(v_2\) is the velocity of air inside the tunnel. \(p_1\) is the pressure of air outside the tunnel. \(p_2\) is the pressure of air inside the tunnel. \(g\) is the gravity acceleration. \(z_1\) is the height where pressure is measured outside the tunnel. \(z_2\) is the height where pressure is measured inside the tunnel.

If \(z_1=z_2\) and \(v_1=0\)

\[
\frac{p_1}{\rho} = \frac{v_2^2}{2} + \frac{p_2}{\rho}
\]

(2)
This is a reasonable assumption in this lab because velocity outside can be considered as the reference velocity (zero) and the two heights can be set equal. In the lab, the arduino board is equipped with a port for reading the voltage at the generator (wind turbine) and two pressure sensors to measure air pressure. Therefore the wind speed is determined by using the Bernoulli’s equation.

Rearranging terms and solving for \( v_2 \),

\[
v_2 = \sqrt{\frac{2(p_1 - p_2)}{\rho}} = \sqrt{\frac{2\Delta p}{\rho}}
\]

where \( \rho \) is the density of air at standard temperature and pressure, 1.29 kg/m\(^3\)

The Power available in the wind is defined as

\[
P = \frac{1}{2} \rho Av^3
\]

where \( \rho \) is the density of air at standard temperature and pressure (1.29 kg/m\(^3\)), \( A \) is the area swept by the turning turbine blades in m\(^2\), \( v \) is the wind speed in m/s.

\textit{Volumetric flow rate} \quad Q = vA

Where \( Q \) is the volumetric flow rate in m\(^3\)/s. \( v \) is the velocity in m/s. \( A \) is the cross-sectional area in m\(^2\).

\textit{Mass flow} \quad \dot{m} = \rho Q

Where \( \dot{m} \) is the mass flow rate in kg/s. \( Q \) is the volumetric flow rate in m\(^3\)/s. \( \rho \) is air’s density in kg/m\(^3\).

\textbf{7. Lab Preparation Assignment}

In order to finish your preparation for Wind Turbine Lab, students are required to:

1. Take the Wind Turbine Lab quiz (on Carmen)
2. Preview the following Wind Turbine Lab Procedure
3. Optional Reading: Sustainable Energy - Without the Hot Air
REFERENCES:


Lab Procedure (Lab 7A)
Introduction and Background
A residential complex with 40 houses is looking to power its energy needs using wind energy.

As an engineer in a power supply consulting company, you are to pick a location of your choice from the map provided at the Report Guidelines of this document. At this location, determine the amount of power that can be produced by a 77 m diameter turbine with a 25% efficiency. The blades have a length of 32 m and the overall height of the turbine is 80 m.

The amount of energy needed for a house in this complex is 50 KWH/Day. Can this wind turbine power the entire residential complex? If not, what percentage of the needed power can be supplied by the wind turbine?

Assume that the wind turbine operates all day and the wind speed is a constant.

Data based on: GE 1.5 -77 Wind Turbine.

In order to answer the question, you have to do some lab experiments to understand the relationships between wind speed, pressure, and power along with wind turbine efficiency range.

This lab is divided into two parts. In Week One you will explore the characteristics of the wind and the wind turbine. This includes using the tunnel apparatus to understand how pressure relates to speed, the power available and other physical characteristics of the wind. Following this, you will explore how a wind turbine reacts to the changes in the wind speed. In Week Two, you will determine which turbine blade arrangement gives the most power for specific conditions. This will shed light on the manner in which wind turbines are designed.
ENGR 1181 Lab 7: Wind Turbine  
Lab Procedure 7A

Task 1. Observe equipment, worksheet, and understand the scope of the lab
In this task you will observe the worksheet and familiarize yourself with the equipment being used in the lab procedure. Be sure to check all pictures and to follow all steps before moving on to Task 2.

![Wind Turbine Lab Setup](image)

Figure 6: Wind Turbine Lab Setup

1. Check to see that there is a “+” shaped wind vane resting against the Fan Motor. It must be in the “+” orientation as shown in Figure 7.
Figure 7: The vane inside the tunnel with “+” orientation up against the Fan Motor

a. Electrical connections from the 18V DC Power Supply to the Fan Motor. The red and black wires should be connected from the corresponding connectors (red to positive and black to negative/ground) on the 18V DC Power to the Fan motor as shown in Figures 8 and 9 below. The remaining yellow wire should be left unconnected.

Figure 8: Electrical Connectors on the 18 VDC Power Supply
Figure 9: Connections from the 18V DC Power Supply to the Fan Motor

Figure 10: The Arduino board and the Display Panel
2. One plastic tube should be connected from the Pitot Tube on the Wind Tunnel to its corresponding connector on the Pressure Sensor. A second plastic tube should be connected from the Static Port on the Wind Tunnel to its corresponding connector on the Pressure Sensor as shown in Figures 10 and 11.

   a. Connect the 9V DC power module to the Arduino Board as shown in Figure 11.
   b. Make sure the circular tube extension is locked in place with the “click” sound.

The Arduino Board must be plugged in for 5 minutes before calibration is performed. This will allow the pressure transducer to heat up and reach a steady state.

3. Press and release the Reset Button on the Display Panel. The Arduino Board now starts calibrating. Wait for the calibration to be completed. This will be indicated on the Display Panel. The other buttons will not be used in this lab and so only press the reset button if required.

4. Once calibration is finished, you should notice that both Speed 1 should equal zero when the Voltage knob is fully counter clockwise (the 0.0 V position) and the Fan Motor is not running. See Figure 12.

5. Notice the two knobs on the DC Power supply. The Current Control (CC) knob should be turned fully clockwise. The Voltage Control (CV) knob should be turned fully counter clockwise (the zero Volts output position).

   IMPORTANT NOTE: The Fan Motor in the Wind Tunnel has a MAXIMUM voltage rating of 12 Volts. But the 18V DC Power Supply can supply up to 18 Volts. Therefore, NEVER beyond 12 Volts from the DC Power Supply. Exceeding 12 Volts can damage the Fan Motor permanently.
6. After all electrical connections have been made, turn on the DC Power Supply.

**IMPORTANT NOTE:** Ensure that there is always sufficient clearance for free air flow at both ends of the Wind Tunnel. Nothing (books, backpacks, computers, etc.) should block the air path of at either end of the Wind Tunnel.

7. Briefly familiarize yourself with the lab equipment. The Wind Turbine (the DC Motor and Propeller) is not used for this task, so it should not be in the Wind Tunnel for this Task.
   a. Turn on the power switch on the 18V DC Power Supply and gradually move the Voltage knob from 0 up to 12 Volts. Observe how the wind speed varies on the Arduino Board Display Panel. Note the voltage value at which the fan begins to move. Enter this value in the place provided in the Worksheet.

   b. With the DC power source voltage set at 9 Volts, rotate the Pitot tube towards and away from the center of the tunnel. Note that the wind speed value on the Display Panel changes. Now, move the Pitot tube to the center and slowly rotate the Pitot tube. Note that the wind speed shown on the display panel changes.

   c. Rotate the Voltage knob fully counterclockwise back to 0 Volts. Place the Pitot tube in the correct orientation (parallel to the airflow with the opening facing the wind source). Do not worry about the position as long as orientation is correct.

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**Figure 12:** Display panel at 0 V (Recalibrate if any speed value is not zero)
**ENGR 1181 Lab 7: Wind Turbine**  
Lab Procedure 7A

**TASK 2. Calibrate the wind source using the Arduino Board**

This task uses the Arduino Board to calibrate the wind source, by measuring the wind speed along the profile at all of the radial positions specified in **Table 1. Wind Velocity vs. Radial Position of the Pitot Tube.**

In order to complete Task 2, complete the following steps:

1. Ensure that the equipment is set up properly, as per Task 1. Use Figure 6 as your guide. If the wind turbine and propeller blade is in place, remove it.

2. Set the 18V DC Power Supply to 6.0 Volts.

3. Move the Pitot tube to the specified radial positions (per the excel spreadsheet) and record the wind speed displayed on the Display Panel in **Table 1** (radius 0 is when the pitot tube head is at the center of the wind tunnel). There will be a slight fluctuation in values and so use your best judgment to pick an approximate average value. The Pitot tube is graded at 1 cm gradations. This will be helpful in positioning the Pitot tube.

4. You can measure the radial position of the Pitot tube with the outside of the large diameter plastic wind tunnel cylinder as the registration point for reading the centimeter marks that are sketched on the Pitot tube.

5. Repeat Step 3 for 9V and 12 V and record the data in **Table 1**.

6. The Graph automatically plots Wind Velocity versus Radial Position of the Pitot tube from the data as it is entered into **Table 1**.

7. Complete **Table 1** by entering and replicating the formula for pressure difference for each voltage and radial position. The pressure difference $\Delta P$ can be calculated using the formula

$$\Delta P = \frac{\rho_{(air)}v_2^2}{2}$$

where,

- $\Delta P$ is the pressure difference in Pascals (Pa)
- $v_2$ is the air speed inside the tunnel (m/s)
- $\rho_{(air)}$ = density of air at standard temperature and pressure (1.29 kg/m$^3$)

8. In **Table 2**, and the Plot next to it, estimate $r_{average}$ for 6V, 9V and 12V. This value is estimated by matching the average wind speed values (automatically calculated in **Table 2**) to the corresponding Radial Positions on the Graph.

9. Make a plot of the pressure difference versus radial location (This can be done after lab).

10. Check that speed values read zero when the **Voltage knob** is set to the 0.0 V. If not, press the reset button on the Arduino Board.
TASK 3. Measure Wind Velocity and calculate Wind Power in the Wind Tunnel (1 Volt increments)

In this task you will measure the power of the wind source as a function of wind speed. In order to do this, you will use the average wind speed radial positions \( r_{\text{average}} \) from Table 2.

For the 6, 7 and 8 Volt settings, use the \( r_{\text{average}} \) from Table 2 that you estimated at 6 V. For the 9, 10 and 11 Volt settings, use the \( r_{\text{average}} \) at 9 V. For 12 V, use \( r_{\text{average}} \) at 12 V.

1. Place the Pitot tube at the average radial location for 6V (recorded in the cells just below Table 2).
2. Set the DC Power Supply to 6 V.
3. Record the wind speed (from the Arduino Board) in Table 3.
4. Increment the DC Power Supply by 1 V until 12 V is reached. At each value, record the wind speed.

**REMEMBER: Place the Pitot tube in the correct position for each voltage (refer to the note above)**
5. For each voltage, enter formulas in Table 3 to calculate the power produced from the wind source using \( P = \frac{1}{2} \rho A v^3 \).
6. Make a plot of Wind Power vs. Wind Velocity (can be done after lab).
7. Calculate the volumetric flow rate \( Q \) in cubic meters per second (\( \text{m}^3/\text{s} \)) and the mass flow, \( m \)-dot rate (\( \text{kg/s} \)) at each voltage using the following formulas:

\[
\text{Volumetric flow rate, } Q \quad Q = vA \quad \text{m}^3/\text{s}
\]

\( Q \) is the volumetric flow rate in \( \text{m}^3/\text{s} \), \( v \) is wind speed in \( \text{m/s} \) and \( A \) is area in \( \text{m}^2 \) – shown at the bottom of Table 2.

\[
\text{Mass flow rate, } m\text{-dot} \quad \dot{m} = \rho Q \quad \text{kg/s}
\]

and \( \dot{m} \) is the mass flow rate in \( \text{kg/s} \). \( Q \) is volume air flow rate in \( \text{m}^3/\text{s} \) and \( \rho \) is air density \( \text{kg/m}^3 \).
TASK 4. Measure the Wind Turbine Power Output as a function of WindVelocity (for the wind turbine with 2 and 3 Blades)

1. Install the 2-blade propeller on the Wind Turbine Generator as shown in Figure 13. Plug the wire connector from the Wind Turbine into the Arduino Board as shown in Figures 13 and 14. Make sure that the side with the black mark on the connector wire goes into the positive terminal on the Arduino Board. This wire is polarity dependent (the Display Board will show zero power output if the wire is not installed correctly).
2. Push and release the button marked "B2" on the Display Panel to display the Wind Turbine Power Output. Note that this power is displayed in mW on the Display Panel. Convert the values to watts as you enter data into Table 4.

3. Set the DC Power Supply to 6 Volts.

4. Record the Wind Turbine Power Output for the 2-Blade turbine shown on the Display Panel in Table 4.

5. Increment the Voltage by 1 Volt until 12 Volts is reached, recording the Wind Turbine Power Output at each voltage.

6. Replace the 2-blade propeller with the 3-blade propeller. First, locate the embossed letters on one blade of the 3-blade propeller. Orient the 3-blade propeller so the embossed letters face toward the wind turbine motor body. Carefully push the propeller hub onto the wind turbine motor shaft.

7. Repeat steps 3 to 5 with the 3-Blade propeller installed.

8. On one graph, plot the Wind Turbine Power Output vs. Wind Velocity for both propellers and add a polynomial trendline to each curve on the graph. (You can graph this plot after lab).
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Lab Procedure 7A

TASK 5. Clean-Up Procedure
1. Clean and organize the equipment
2. Leave all items below on the table.

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Item Description</th>
<th>Qty.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The tunnel apparatus</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>18 Volt Power Supply</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>12 Volt Wind Source Fan</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>DC propeller motor</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Pitot Tube (s)</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>Arduino Board with Display</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>Manufactured Wind Turbine Blades</td>
<td>2</td>
</tr>
</tbody>
</table>

Task 6. Check-Out Policy
After you have finished the lab and the clean-up procedure, have your instructor or GTA sign the "End-of-Lab Signoff" line at the end of the rubric. You will lose 5 points if this is not signed by your Instructor/TA.

Preparation for next week
1. Research different Turbine Blade Geometries.
   
   

2. Decide what Turbine Blade Designs you will use in Week 2.

3. Bring a camera to class to take a photo of each design proposed.
Learning Objectives

In Lab 7B, students will:
1. Determine the influence of wind turbine blade design on power generated.
2. Investigate optimum number of blades and possible blade orientations.
3. Measure the influence of the pitch angle in a Wind turbine design on power generated.

TASK 1. Build your own wind turbine blade set. (Your kit should contain at least one-30˚ pitch hubs and one 45˚ pitch hub.)

1. Each student should create a SINGLE turbine blade with any geometry of your choosing. Each team member should have different blade geometry. (The number of blades your team creates will depend on team size.)
   a. To create a blade, cut out your design on the provided balsawood.
   b. Obtain a hub from your kit with a 30˚ pitch.
   c. Insert the blade inside a groove on the hub.
2. Test each blade design at 12V.
3. Record the power produced from each design in Table 5: Power output of the design turbine versus the wind velocity.
4. Select the turbine blade design that produces the greatest power at 12 V.
5. If you receive a 0.0 V reading, turn the polarity of the wind turbine’s motor wire around and test again.
6. Take a photo(s) of all the designs tested.
ENGR 1181 Lab 7: Wind Turbine
Lab Procedure 7B

TASK 2. Test the power produced by the wind turbine while varying the number of blades

1. Using the selected turbine blade design (Task 5 above), build five more balsawood turbine blades.
2. Add another blade in the opposite groove (on the hub) to the blade chosen from the Task 5 and record the power produced from the turbine in Table 6.
3. Use one of the 30° degree hubs to create a three blade system. This arrangement should look similar to a ‘Y’. (Be very careful NOT to break the hubs – they are expensive)
4. Test the three blade turbine and record the power produced in Table 6.

NOTE: In each set, the blade shape should be the same, only change the number of blades.

5. 30° pitch hub, create a six blade turbine and record the power. Determine the arrangement/number of blades that produces the maximum amount of power.
6. Produce the selected arrangement (the one that produces maximum power) on the hub with a 45° pitch. Test the 45° pitch hub and record the power in Table 7.

TASK 3. Clean-Up Procedure

1. Remove the hub from the motor shaft.
2. Leave unused balsawood pieces on the table.
3. Clean and organize the equipment
4. Leave all items below on the table.

<table>
<thead>
<tr>
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<tr>
<td>3</td>
<td>12 Volt Wind Source Fan</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>DC propeller motor</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Pitot Tube (s)</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>Arduino Board with Display</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>Blade Hubs</td>
<td>2</td>
</tr>
</tbody>
</table>

Task 4. Check-Out Policy

After you have finished the lab and the clean-up procedure, have your instructor or GTA sign the “End-of-Lab Signoff” line at the end of the rubric. You will lose 5 points if this is not signed by your Instructor/TA.
Report Guidelines
ENGR 1181 Lab 7: Wind Turbine
Report Guidelines

ENGR 1181  |  Lab Report
General Guidelines

Write a Lab Report
For details on content and formatting, see the Technical Communications Guide on Lab Report specifications.

Lab Specific Directions

Executive Summary
• Write this section last. After completing your individual conclusions, provide the client with specific recommendations agreed upon by each of the engineers in your group.

Discussion
• In addition to requirements listed in the Technical Communications Guide, be sure to briefly address the following questions within the discussion.
  o Based on the Introduction and Background scenario:
    ▪ Pick a location from the map in Figure 15 on the next page and determine the power produced by a single turbine and answer the questions.
  o Calculate the wind speed if the change in pressure measured by the Pitot tube is 100 Pascals and the density of air at that time was 1.29 kg/m³. Your solution must show the equation you used and all the steps to arrive at your answer. State your answer at the end.

Conclusion & Recommendations (Individual)
• Now that you’ve gained some knowledge about wind energy, discuss the applications and importance of wind energy, using specific advantages and disadvantages (3 of each).
  o Support your answers with data from the lab and properly cited outside sources.
Figure 15: Map of the current winds in Ohio