APPENDIX B: Example Lab Preparation Guide and Manual

Lab #4 Preparation Guide - Dimensional Analysis of a Scaled Down Wind Turbine

This will be a group report. The report should be about five to seven typed pages plus figures and appendices, and should include the following sections and content:

Introduction (2 points)
- Overview and purpose of the lab.

Background/Theory (4 points)
- Wind turbine theory. What are they, what are the different types, and how is their performance measured (i.e., what are the key performance parameters and what is their significance)?
- Dimensional analysis background. What is it and why is it useful? How does it apply to the wind tunnel measurements you are making for the model wind turbine?

Experimental Setup/Procedure (5 points)
- Overview of the experimental setup. Wind tunnel, wind turbine model type, vane anemometer.
- Wind turbine model wind tunnel electrical power output and cut-in measurements.
- Wind turbine model electrical generator electromechanical efficiency setup, measurements of the input and output parameters.
- Description of the procedure for correlating electromechanical efficiencies between the two measurements conducted above, and how the power coefficient is determined from them.

Results/Discussion (25 points)
- Calculation of the overall efficiency of the wind turbine model for the different flow conditions based on the velocity measurements ahead of the turbine and the electrical power output, and its uncertainty.
- Plot of the overall efficiency for the wind turbine model as a function of wind velocity and comparison of the overall efficiency of the wind turbine model with the GE 1.5 MW prototype wind turbine.
- Show that the power coefficient and its dependence on tip speed ratio can be obtained from dimensional analysis.
- Plot containing electromechanical efficiency setup (EMES) DC motor input voltage ($V_{motor}$) as a function of rotational speed ($n$), including linear regression fit.
- Calculation of the uncertainty of $V_{motor}$ from the above linear regression fit, using the standard error of fit procedure.
Formulation of an equation for the rotor (shaft) power ($P_{\text{rotor}}$) as a function of rotational speed only (n) by substituting the above linear regression fit in Equation 3.

Plot containing electromechanical efficiency setup (EMES) model turbine generator output voltage ($V_{\text{out}}$) as a function of rotational speed (n), including linear regression fit.

Calculation of the uncertainty of the $V_{\text{out}}$ from the above linear regression fit, using the standard error of fit procedure.

Formulation of an equation for the electrical output power ($P_{\text{out}}$) as a function of rotational speed only (n) using the above linear regression fit.

Formulation of an equation for the electromechanical efficiency ($\eta_{\text{em}}$) as a function of rotational speed only (n) by using the two equations above for $P_{\text{out}}$ and $P_{\text{rotor}}$.

Calculation of the electromechanical efficiency uncertainty from the equation above due to propagation of the uncertainties from the two linear regression fits.

Comparison and plotting of the electromechanical efficiencies calculated using the derived equation and those directly computed from the EMES data (without linear regression fits).

Calculation of the tip speed ratio from the wind velocity and rotational speed measurements, including its uncertainty.

Calculation of the wind turbine model power coefficient ($C_p$) based on measured overall efficiencies ($\eta_{\text{overall}}$) and equation calculated electromechanical efficiencies ($\eta_{\text{em}}$), correlating them through the rotational speeds, and its uncertainty.

Plot of the wind turbine model power coefficient as a function of the tip speed ratio and comparison of the power coefficient of the wind turbine model with the GE 1.5 MW prototype wind turbine and/or other representative curves for three blades HAWTs.

Conclusions (8 points)

- Comment on the power coefficients for the wind turbine model.
- Comment on the overall efficiencies for the wind turbine model.
- Comment on the comparison of the model and prototype wind turbine overall efficiencies. How do they compare? Why are they different or similar?
- Comment on the cut-in speed behavior of the wind turbine model.
- Comment on dimensional analysis of wind turbines in comparison to your actual measured results. Do they agree or differ and why?

Overall Quality (6 points)

- Overall quality of the report, including structure and format. The writing is clear and understandable. Proper attention to grammar and spelling. Tables are properly formatted and information is well presented in them (clear to understand). Proper plotting practice, i.e., every figure has a caption and is referred to in the text. Professional looking plots.

Total Points: 50
Extra Points: 10
I. Objectives

This lab involves making wind speed and pressure measurements as well as electrical power output of a model wind turbine and performing dimensional analysis. Electrical power output measurements of the turbine as a function of wind speed will be made in the wind tunnel to assess the turbine’s overall efficiency. An external setup will allow us to assess the electromechanical efficiency of the model wind turbine electrical generator, which in turn will enable us to infer the aerodynamic efficiency and perform dimensional analysis. An extremely useful application of dimensional analysis is in performing experiments using scale models and extrapolating the results to full-size prototypes. In this lab, we will analyze power characteristics of the model wind turbine, and compare the obtained results to the performance of a prototype GE 1.5 MW wind turbine (Figure 1).

The objectives of this lab are to:
1. Gain experience in use of wind tunnels and common measurement instrumentation (vane anemometers, multimeters, dc motors, voltage supply, and tachometers) and procedures (efficiencies characterization).
2. Investigate the effects of rotor blades pitch on the aerodynamic efficiency and cut-in speed.
3. Perform an uncertainty analysis on the velocity measurements.
4. Conduct dimensional analysis on the power generation of the wind turbine.

Figure 1: Image of a model wind turbine in a wind tunnel. GE 1.5 MW wind turbines arranged in a wind farm. (Source: http://www.gepower.com)
II. Background

Wind turbines are devices that extract power from the wind and convert it to electrical power (as opposed to a windmill, which is used for mechanical power generation). Wind power is a renewable energy source, which is the primary reason it is becoming increasingly popular around the world as a means to keep up with the global energy demand. Although very promising with regard to energy production, wind turbines do suffer from a number of setbacks, such as production costs and the obvious constraint that they depend on the wind behavior and must be located in a region where wind blows, that is, far from traditional power grids. Despite these and other setbacks, wind turbines are expected to play a major role in meeting the global energy demands for many years to come.

Wind turbines are typically characterized by the orientation of their axis of rotation, which results in two primary categories: vertical axis wind turbines (VAWT) and horizontal axis wind turbines (HAWT). Both types of wind turbines have advantages and disadvantages. HAWT are the more commonly used type, mainly because no VAWT to date has matched the efficiency of the HAWT. VAWT, however, are typically more space-efficient, which is why many are used in urban settings, such as on rooftops. Wind turbine performance is presented with a power performance curve; a typical one is shown in Figure 2.

![Typical wind-turbine power performance curve](image)

Figure 2: Typical wind-turbine power performance curve. *(Source: Fluid Mechanics: Fundamentals and Applications, Cengel, 2010)*

The cut-in speed is simply the wind speed that is required to produce useful power. The rated speed is the wind speed at which the turbine produces the rated power, which is typically the maximum power. The cut-out speed is the maximum speed for which the turbine is designed to produce power. Typically, the turbine blades are stopped by some braking mechanism when the wind speed reaches this cut-out speed, and this is done for safety purposes. In this lab, we will create power performance curves for the model wind turbine and compare it to a characteristic curve for a prototype GE 1.5 MW wind turbine.
When comparing the performance between different wind turbines, it is useful to apply a dimensional analysis in order to obtain the relevant non-dimensional parameters related to power output. To this end, we introduce the aerodynamic efficiency of a wind turbine, often referred to as the power coefficient, $C_p$. The power coefficient is defined as the ratio of the mechanical power output at the rotor shaft to the total power available in the wind, and is given by

$$C_p = \frac{P_{\text{rotor}}}{P_{\text{wind}}} = \frac{P_{\text{rotor}}}{\frac{1}{2} \rho U_\infty^3 A_{\text{rotor}}}$$

where $P_{\text{rotor}}$ is the rotor power output of the wind turbine (i.e. the power output at the shaft of the rotor), $A_{\text{rotor}}$ is the swept area by the blades and rotor (which is simply the area that the approaching wind “sees”), and $U_\infty$ is the free-stream velocity of the wind. Albert Betz (1885 – 1968) was the first to show that the maximum possible value of the power coefficient for any wind turbine is $C_{p,\text{max}} = 0.5926$, known as the Betz limit. For a detailed explanation of the Betz limit, refer to “Wind Energy Explained: Theory, Design and Application” by James F. Manwell, Jon G. McGowan, and Anthony L. Rogers. The $C_p$ is highly dependent on wind turbine design (HAWT, VAWT, number of blades, etc.) but across all varieties it is a function of the tip speed ratio, $\lambda$. This is the ratio of the rotor furthestmost point from the rotation axis speed (this is the blade tip speed for most HAWT) to the free stream wind speed, such that:

$$\lambda = \frac{\omega R_{\text{rotor}}}{U_\infty}$$

where $\omega$ and $R_{\text{rotor}}$ are the wind turbine rotational speed and radius, respectively.

In addition to the aerodynamic efficiency of the wind turbine, it is also important to consider its electromechanical efficiency defined as the ratio of the electrical power output to the rotor power input ($\eta_{\text{em}} = P_{\text{out}}/P_{\text{rotor}}$). This efficiency captures the losses associated with the gear train of the wind turbine and the electromechanical conversion process. The overall efficiency of the wind turbine is defined as the ratio of the electrical power output to the available power in the wind ($\eta_{\text{overall}} = P_{\text{out}}/P_{\text{wind}}$) and is therefore equal to the product of the power coefficient and mechanical efficiency ($\eta_{\text{overall}} = \eta_{\text{em}} C_p$).

In this lab you will conduct overall wind turbine efficiency measurements in the wind tunnel and perform electromechanical efficiency measurements of the turbine generator in an ex-situ calibration setup. These two measurements would allow you to determine and plot the power coefficient as a function of tip speed ratio for comparison with a large scale prototype turbine.
III. Experiments

This lab entails making measurements on two testing stations providing setups for measurements of the overall performance of a model wind turbine with a rotor diameter of $D_{\text{rotor}}=36\text{cm}$ and its electromechanical efficiency characteristics, respectively. These two sets of measurement data will be used to determine the aerodynamic efficiency of the wind turbine. Correlation between the two sets of data for a given operating condition is done by matching the rotor speed, which is measured with a handheld tachometer.

LARGE WIND TUNNEL STATION:

1. Wind speed measurements

Velocity measurements in fluid flows can be obtained by a variety of instruments that use different physical principles. During your last laboratory you learned how to utilize the Bernoulli principle by pressure measurements from a Pitot-static probe. This lab deals with much lower wind speeds and measurement results are very sensitive to errors. In order to sense the velocity in the wind tunnel accurately you will be using a vane anemometer. This is essentially just another but smaller turbine wheel assembly you will find mounted inside the test section, now called vane anemometer since it is not used to produce a power output. The anemometer is connected to a hand-held meter outside the wind tunnel on which you can directly read the measured wind velocity. The device is pre-calibrated and ready to use.

Before you start taking measurements make sure that the units are set to meter per second (m/s). After you have changed the wind tunnel setting you can take a reading as soon as the displayed speed has settled at a constant value. Within its range of 0.50 – 35.0 m/s the accuracy of the vane anemometer is $\pm (2\% + 0.2\text{m/s})$.

2. Set the angle of attack of the model wind turbine blades to high aerodynamic efficiency.

Set the model wind turbine rotor assembly to the 2 mark. YOUR TA WILL DO THIS FOR YOU!

3. Measure the air velocity and the model wind turbine power output at different wind tunnel free stream velocity settings
Turn on the wind tunnel fan motor frequency at 15 Hz by using the thumb wheel and the arrow buttons on the wind tunnel control panel. The thumb wheel is very sensitive, so be careful and do NOT overshoot. This will be the highest speed of your measurements and you need to allow the speed to even out for at least 30 seconds. Measure the wind velocity using the vane anemometer. These values are essential for calculating the power coefficient, $C_p$. The wind turbine is attached to a voltage meter. At each wind speed, it will display the voltage associated with the power generation. This is the voltage drop over a 220 Ohms resistor. Record both the measured freestream velocity and the voltage produced by the wind turbine. For your analysis you will also need to know the rotor speed. It is the crucial parameter for the data matching with the electromechanical efficiency station. Record the tachometer reading and continue with the next speed setting.

Now decrease the speed by steps of 1 Hz and wait for at least 10s before you decrease further. You have to make sure that both the value of the vane anemometer and the rotor speed of the wind turbine have settle to give a fairly constant reading. Both readings are independent from another and have a different dead time to the changing in wind speed, in contrast to the output voltage reading, which adjusts instantaneously. In doing so, follow the procedure as outlined in Appendix A.1. As you approach the cut-in speed (when the turbine rotor ceases to rotate) from higher velocities take readings in smaller step size of 0.2 Hz until you reach the cut-in.

Take readings of all parameters at every speed. Note: Do not increase speed above 16 Hz! This will damage the wind turbine and make it unavailable for future labs.

4. Set the angle of attack of the model wind turbine blades to low aerodynamic efficiency.

Set the model wind turbine rotor assembly to the 2.5 mark. YOUR TA WILL DO THIS FOR YOU!

5. Repeat wind tunnel station measurements for the model wind turbine at the low aerodynamic efficiency setting.

Repeat steps 3 and 4 above at the new model wind turbine aerodynamic settings.

**ELECTROMECANICAL EFFICIENCY STATION:**

The overall efficiency $\eta_{overall}$ measured in the wind tunnel tests encompasses a chain of losses. The total available wind power cannot be entirely converted into mechanical shaft rotational power. The Betz limit establishes limits on the maximum amount of power that can be extracted from the wind (this is similar to the Carnot efficiency for heat engines). In actual implementation, aerodynamic viscous losses reduce the actual amount of rotational shaft power
that can be extracted from the wind power below this limit. This power conversion efficiency represents the aerodynamic efficiency or power coefficient. Besides the aerodynamic losses, not all the available rotational power in the shaft can be converted into electrical power.

Commonly known losses in electro-mechanical systems occur due to mechanical friction and electrical heat dissipation through the entire electric circuit of the generator. These overall losses are captured in the electromechanical efficiency $\eta_{em}$. In order to assess the aerodynamic characteristics of the wind turbine model for comparison with a real world wind turbine, we need to evaluate the electromechanical efficiency for the turbine generator in order to extract the power coefficient from our overall efficiency measurements.

In this portion of the lab, $\eta_{em}$ for the wind turbine generator is measured as a function of operating conditions, namely the rotational speed. For these purposes, the wind turbine generator is connected and driven by a DC motor through a coupler. The power output of the DC motor (which is the power input to the turbine generator) is varied by adjusting the DC motor driving voltage using an adjustable power supply, such that

$$P_{\text{rotor}}[\text{W}] = \frac{1}{146000 \frac{\text{RPM}}{\text{Vols}}} \left(1283 \frac{\text{RPM}}{\text{Vols}} \times V_{\text{motor}} - 96.6 \text{[RPM]} - N \text{[RPM]} \right) \frac{2\pi N \text{[RPM]}}{60} \quad (3)$$

where $V_{\text{motor}}$ is the input DC motor voltage in Volts and $N$ is the shaft rotational speed in RPMs.

6. Setting the voltage of the DC motor

The rotational speed of the system is again measured with a tachometer that is pointed towards the coupler, where the reflection mark has been attached. For all DC motor input voltages and rotor speeds, measurements have to be taken as described below; follow the procedure according to Appendix A.2.

7. Take readings of the motor input power

After the rotor speed is adjusted through the power supply, take readings of the input voltage of the DC motor for this rotational speed. Always make sure to also take notes of the rotor speed.

8. Measure the power output from the wind turbine generator

The generator side of the assembly is equipped with exactly the same electrical power output setup as in the wind tunnel experiments. It is attached to a voltage meter. At each rotor speed, they will display the current and the voltage associated with the power generation. This current is passing through a 220 Ohms resistor. Record the voltage produced by the wind turbine generator at all preset rotor speeds.
A. Wind Tunnel Station and Electromechanical Efficiency Station Settings

1. Wind Tunnel Station

Set the wind tunnel motor speed to 15 Hz and take the first reading of the wind turbine rotational speed, the wind velocity, and the output voltage of the turbine generator. Decrease the tunnel speed and take readings in steps of 1 Hz down to 7 Hz. Finally, decrease the wind tunnel setting by increments of 0.2 Hz until the turbine rotor stops spinning. This procedure is tabulated below:

<table>
<thead>
<tr>
<th>Tunnel setting (Hz)</th>
<th>N [RPM]</th>
<th>$U_\infty$ [m/s]</th>
<th>$V_{out}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2. Electromechanical Efficiency Station

Set the voltage supply to 3.0 Volts, then decrease the voltage supply setting in increments of 0.5 Volts until the generator is spinning at about 600 RPM (measured using the handheld tachometer). Then, decrease the voltage supply setting by 0.1 Volts until the rotor stops spinning. This procedure is exemplified by the following table:

<table>
<thead>
<tr>
<th>Motor setting (Volts)</th>
<th>N (RPM)</th>
<th>V_in</th>
<th>V_out</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>~ 600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>