Lab #3  
Similitude: Vertical Axis Wind Turbines – in Water and Air!  
CEE 3310 Fall 2015

Safety
The major safety hazard in this laboratory is a shock hazard. Given that you will be working with water and items running on standard line voltages (the pump and the computer) you should pay attention to the possibility of electric shock. If water spills on the desktop, please clean it up if there is no risk of shock. If water gets near a 110 Volt electrical connection (i.e. a wall outlet or anything connected to it) DO NOT clean it up. Seek a TA, Cowen, or one of the CEE technicians (Tim Brock, Paul Charles, or Cameron Willkens, who have offices across from the lab) for help.

The lab has many research tools that are potentially dangerous in un-trained hands. We implore you to not touch anything that you have not been invited to use in the CEE 3310 labs.

Particularly important, if you are about to enter the lab and you notice that the “Laser in use” sign is illuminated. DO NOT ENTER. Knock loudly and see what is going on or find a TA, one of the CEE technicians, or Cowen.

If you enter and you see a cyan blue or greenish laser beam light DO NOT LOOK AT IT. Turn away and ask loudly if it is O.K. to enter or leave and seek out a TA, one of the CEE technicians, or Cowen. This should not occur but if it does follow the above procedures.

Always work with a minimum of two people.

Objectives
In this laboratory you will investigate the power produced by a vertical axis wind turbine (VAWT) mounted in our teaching flume – so in a water current. Your goal is to find the non-dimensional relationship between power and current velocity. We will measure the water velocity with an acoustic Doppler velocimeter or ADV, which was introduced in Lab #2. You will also get a chance to explore turbulent water flows and get a sense of their unsteadiness with the ADV.

Theory

The Flow
The power, $P_w$, produced by a VAWT can be expressed dimensionally as

$$P_w = \phi(U, D, L, \omega, \rho, \mu)$$

where $\phi$ is a function of the variables in parenthesis and $U$ is the mean water velocity away from the VAWT, $D$ is the diameter of the VAWT, $L$ is the height of the VAWT, and $\omega$ is the angular rotation rate in radians per second ($2\pi/T$ where $T$ is the rotation period, i.e., the time for the VAWT to make one complete rotation). Now, we have 7 variables and 3 physical dimensions so there must be 4 dimensionless parameters that define the problem. We immediately recognize the
Reynolds number and the aspect ratio of the VAWT \((L/D)\), leaving us Power \((P_w)\) and angular velocity \((\omega)\) to nondimensionalize. Demonstrate for yourself that you can get \(C_p = \frac{P_w}{0.5 \rho U^3 DL}\), which is known as the coefficient of power, \(TSR = \frac{\omega R}{U}\), the tip speed ratio. Obviously \(R = D/2\) and recall that \(P_w = \omega T_q\) where \(T_q\) is the torque (which is actually what we will measure to calculate the power). Hence we have the following non-dimensional relationship:

\[
C_p = \psi(TSR, Re_D, \frac{L}{D})
\]

3.2

This suggests that to understand the power produced by a given turbine we need to hold the aspect ratio constant and vary \(Re_D\) and \(TSR\). Aha, as we have seen if the flow is sufficiently turbulent the problem often becomes independent of Reynolds number so let’s make that assumption and study \(C_p\) by varying \(TSR\) and tracking \(Re_D\) and seeing how things look.

Now the dimensional analysis we have just conducted does make some assumptions – namely that for our VAWT, which when being tested in water will sit just below the free surface and you will see surface wake signatures, surface tension and surface wave (gravity) effects, which are typically important for free surface flows, are not important here. This is a reasonable starting point (trust the instructor!) for our purposes (accuracy of 1 or 2 significant figures). Had we included these additional parameters we would have found two additional \(\Pi\)’s – the Froude number and the Weber number and a systematic study of VAWTs near a free surface would investigate their effects – particularly Froude number as for VAWTs of any appreciable size the Weber number will be very large suggesting that surface tension is not important.

**Experimental Apparatus**

The experiment will be conducted in the teaching flume – the same flume used in Lab #2. The sluice gate has been raised all the way so as not to interfere with the water flows you will generate. As in lab #2, a weir will force the water outlet flow to be supercritical, which ensures that surface wave energy will be forced out of the test section and cannot propagate back into the test section.

We will measure the local water velocity vector using an Acoustic Doppler Velocimeter (ADV). We will work with an ADV manufactured by Nortek known as a Vector ADV – same as you used in Lab #2, shown in figure 1. More details about the ADV at [http://www.nortekusa.com/en/products/velocimeters/vectrino](http://www.nortekusa.com/en/products/velocimeters/vectrino). The ADV measures velocity by detecting the Doppler shift in an acoustic pulse transmitted into the water column. The acoustic pulse is transmitted from the center of the metal probe (the three-pronged thing in the lower left of Figure 1). The ADV detects the sound scattered by particles and air bubbles in the water column a fixed distance from the probe. It detects the velocity component normal to the bisector between three probe tip faces and the vertical. Through trigonometry the velocity vector in an
orthogonal coordinate system can be determined. The four arms are bent at an angle of about 30 degrees to the perpendicular plane of the probe shaft. The result is the 4 acoustic ‘listeners’ are focused to listen at a point about 5 cm below the center of the probe end (where the acoustic ‘speaker’ is located). Hence the ADV measures the velocity at a point 5 cm below the probe end in a cylindrical volume of water that is only about 1.2 cm in length and 0.6 cm in diameter. We will use the probe to determine the $x$, $y$ and $z$ components of velocity. The ADV software defines $z$ to point upward into the ADV probe head, $x$ to point in the radial direction towards one of the four probe tips (with the red tape wrapped around it) in the direction perpendicular to $z$, and $y$ by the right hand rule. We have mounted the ADV on a U-channel you can lay across the flume such that the $+x$ arm (with the red band) is in the downstream channel direction, $y$ is the transverse (cross-channel) direction, and $z$ is the vertical direction. More details of the principles of operation for the ADV can be found at the above web site in case you are interested, or consider taking CEE 4370/6370 – Experimental Methods in Fluid Dynamics in spring 2017!

To repeat the experiment in air, we will simply place a fan inside the drained flume and upstream of the turbine. This is a bit crude as we cannot control the quality of the flow, but it will yield sufficient results. To measure the flow speed, we will use an ultrasonic anemometer. The turbine will spin much faster in air, so we will not be able to count rotations. Instead, we will use an optical encoder that sends signals to a Matlab script via a Data Acquisition System. The TAs will show you how to use this.

**Experimental Methods**

1) If the flume is full of water when you begin the lab, proceed to step two. Otherwise, begin with the air measurements by skipping to step 11 and coming back to step two when you’re finished with the air measurements.

2) Verify that there is approximately 25 cm of water in the flume when the pumps are off – there is a mark near the ruler just before the outlet on the right side of the test section at the downstream end. DO NOT OVER FILL THE FLUME or you will flood the lab! Should you add too much water there is a drain valve located below the ruler on a panel.

3) You will work with three different mean current velocities. Work from lowest to highest.

4) Turn on the pumps. The master power switch is on the upstream end of the flume on the left-hand side looking downstream. Just hit start on one of the controllers on the right hand side of the flume. You can change the flow rate by changing the frequency, using the up and down arrows on the controller of the pump you are running. 60 Hz is full speed for a given pump and due to the head difference between the inlet of the pump and the upstream flume inlet (headbox) it will take a minimum setting of around 25-28 to get the flow to rise up and over the downstream weir and achieve the target flow depth – 30 cm. Your goal is to test at least 3 flow rates. The first case with 30 Hz for all the three pumps should provide you with around 30 cm/s. And the second one with 45 Hz for all the three pumps should give you close to 40 cm/s. The third case with 60 Hz for all the three pumps should give you close to 50 cm/s. Don’t worry too much about the exact velocity, just take what you get
and record the value measured by the ADV. You may try additional flow rates if you are interested and have time. DO NOT RUN THE PUMPS OVER 60Hz.

5) To operate the ADV software, follow this procedure:
   a. Double-click on the ‘Vector’ icon on the desktop to start the software.
   b. The instructor has chosen an optimal ADV configuration for this lab. To load this configuration, go to the menu at the top of the screen and select File > 331Configuration.
   c. To start the ADV, select On-line > Start Data Collection from the menu. The ADV will begin measuring velocity and plot the x, y, and z-components to the screen in real-time. We have set a time constant to 30 seconds so the values you see in the table on the top left are the 30 s average velocities.

6) There is a power supply on the opposite side of the flume from the ruler. It is used to apply a current to a hysteresis brake – basically a device to apply a known torque to the VAWT axis magnetically. Think of this brake as the load – i.e., how hard it is to turn the turbine. You can think of it as varying the type of generator you are using to convert the flow into electricity. You will start with the power supply off and then add increasing torques. Make sure the power supply is off and the current knob is turned all the way down (to the left). Do not touch the voltage knob.

7) With the flume running the VAWT should be spinning. If it is not, give it a tap to get it going.

8) Looking at the top of the VAWT you will see a cylinder with a single piece of white tape vertically. You will count the number of rotations of this white tape over 1 minute to measure the rotation rate of the VAWT (you will get number of revolutions in 60 s, which you need to convert to $\omega$). You may also use the optical encoder (see step 15 for instructions).

9) Repeat steps 1-7 by applying increasing currents to the hysteresis brake – use approximately $\{0 25 50 60 70 80 90 100 110\}$ mA. You can increase the current with the current knob on the power supply (turn it on after the 0 mA test) and read an accurate value on the multimeter, which is connected in series with the hysteresis brake. For the lower flow speeds the VAWT will stop rotating before you get to 110 mA. That will be the end of your set of experiments at that flume velocity. Refer to Figure 2 for the calibration curve for the hysteresis brake.
10) Repeat steps 1-9 at two additional flume velocities (45 Hz and 60 Hz).

11) Have the TA unmount the ADV so it is not in the way. Drain the flume by opening the drain with the switch located on the panel on the right side (facing downstream) near the weir end. Only drain until the channel is empty and then close the drain.

12) Use the squeegee to create a relatively dry area one panel upstream of the turbine (it may help to tilt the flume toward the weir while squeegeeing). Using a piece a plastic to prop it up in front about one inch, place the fan in the flume centered, pointing at the turbine, with the exit approximately even with the beginning of the upstream flume panel.

13) Start with the fan on “High” and give the turbine a good push to get it moving (it will accelerate to a much higher speed than in the water).

14) Hold the anemometer about half way between the fan and turbine in the middle of the flume and wait for a steady reading.

15) When the turbine appears to have reached a constant rate of rotation, run the Matlab script (the TA will demonstrate). A plot will appear showing the frequency spectrum measured over 60 seconds. If the turbine has been at a fairly constant rate of rotation, there will be a clear highest peak. If the rate of rotation was changing over the sample period, there will be more of a flat region. In this case, repeat the measurement. Use the cursor to determine the

![Calibration Curve](image)

Figure 2. Calibration curve for the histeresis brake.
peak value. The encoder sends 1024 signals per revolution, so, to find the revolutions per second, you must divide the maximum frequency by 1024.

16) Repeat step 12 by applying increasing currents to the hysteresis brake (refer to step six). With the fan on “High”, use 6-8 values between 0 and about 80 mA (see Figure 2 for the calibration curve). Note: in air, the turbine decelerates much more slowly. If the current is high and the turbine is still spinning, but the frequency spectrum does not have clear maximum, the turbine may be slowly decelerating and the current is too high to continue.

17) Turn off the brake by turning the power supply off and turn the fan to “Medium”. Give the turbine a minute or two to reach its new speed. Repeat steps 12 and 13 using 5-7 values between about 0 and 65 mA.

18) If you began with the air measurement, remove the fan and fill the flume using the switch on the same panel as the drain. Have the TA mount the ADV and proceed to step one.

**Data Collection/Analysis**

Your goal is to determine the function $\psi$ relating $C_p$ to TSR while monitoring $Re_D$ (equation 4.2). The ADV and anemometer measure the water and air temperatures ($\theta$), respectively, so that you can get a good estimate of $\nu$ (especially important in water, as it varies by almost a factor of 2 over the temperature range 5 °C – 25 °C). For the VAWT in the channel $D = 0.180$ m and $L = 0.220$ m. Note, when no current is applied to the hysteresis brake it still applies a torque of 0.0014 Nm. Also note that we have estimated the frictional torque of the bearings to be 0.0020 Nm so you should add 0.0034 Nm to your applied torque to get the total.

<table>
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<tr>
<th>$U$ (m/s)</th>
<th>Applied Current (mA)</th>
<th>Applied Torque (Nm)</th>
<th>Total Torque (Nm)</th>
<th>Measured RPM</th>
<th>$\omega$ (rad/s)</th>
<th>TSR</th>
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Check-Out
Prepare the following plots to show the TA's:

1. A plot that shows your measured $C_p$ as a function of TSR, hence a plot of $\psi$. That’s a total of five specific data sets (two in air and three in water). Use different symbols/line types and/or colors for each.
2. What is the effect of $Re_D$ over the range you measured?
3. Is it reasonably to study a VAWT in water if the prototype application is in air?