Part 1: Water Tunnel Velocity Calibration and Drag Measurement on a Cylinder From Pressure Measurements

Objectives:

a) Calibrate the velocity of the water tunnel as a function of impeller motor rpm for use in subsequent hydrodynamic experiments using static pressure from pitot tubes
b) Make measurements of the drag coefficient of a circular cylinder at three different flow velocities (0.6, 1.0 & 1.4 m/s). Both the velocity calibration and drag measurements are based on pressure measurements.

Discussion:

A circular cylinder is located vertically in a water tunnel. A pressure sampling system provides measurements of the pressure different across a pitot static probe and the pressure distribution around the 1-inch diameter (2.54 cm) cylinder.

The drag $D_p$ due to the pressure distribution on the cylinder can be calculated by integrating the pressure $p$ around the cylinder:

$$D_p = \int p \times \cos \theta \times da$$

The pressure Drag can be rewritten in terms of the pressure drag coefficient $C_{DP}$,

$$C_{DP} = \frac{D_p}{\frac{1}{2}\rho U^2 A} = \frac{\int p \cos \theta da}{\frac{1}{2}\rho U^2 A} = \frac{\int C_p \cos \theta da}{A}$$

Where $A$ is the reference area and $C_p$ is the pressure coefficient,

$$C_p = \frac{p - p_{ref}}{\frac{1}{2}\rho U^2}$$

To perform the integration in eq.(1) around the cylinder we integrate in terms of the angular coordinate $\theta$ from 0 to $2\pi$. The angular coordinate $\theta$, is taken to be zero at the leading edge stagnation point. The reference area is $A = D \times b$ where $D$ is the diameter of the cylinder and $b$ is a unit length along the cylinder, giving the incremental area $da = (D/2) \times b \, d\theta$. The pressure drag coefficient can then be calculated from the following integral.
\[ C_{Dp} = \frac{1}{bD} \int_0^{2\pi} C_p \cos\theta \left( \frac{D}{2} \right) d\theta = \int_0^{2\pi} C_p \cos\theta d\theta \]

(4)

**Experimental Setup:**

The Water Tunnel is 6 Feet long. It has a square cross section with width being 10 Inches. The pressure distribution system consists of a 1” cylindrical test specimen that has been configured with 13 pressure ports. A pitot tube at the inlet of the tunnel monitors the dynamic pressure of the flow. A computer that has an analog to digital converter, digital input and output ports and Lab-view software installed controls the system. The 13 cylinder pressure ports and the pitot stagnation port are routed to 14 solid-state pressure transducers that convert the mechanical pressure to an analog electrical signal. A multiplexer selects one port under computer control and routes the pressure value to the computer’s A to D converter input. The signal is then converted by the analog to digital converter into a digital value. All the ports are scanned and the pressures are shown on a manometer type display to visualize pressure distribution around 180 degrees of the cylinder. The port pressure samples are then recorded to disk when the operator selects record data for post processing.

![Pitot Tube: Measurement of Fluid Velocity](image)

\[ P_a + \frac{1}{2} \rho_a U_a^2 = P_b + \frac{1}{2} \rho_b U_b^2 \]

\[ U_a = 0 \& U_b = U_\infty \]

\[ P_a - P_b = \frac{1}{2} \rho_a U_a^2 = q_\infty \]

\[ \therefore P_a - P_b = \rho_1gh \]

\[ U_\infty = \left( \frac{2(P_a - P_b)}{\rho} \right)^{1/2} \]

\[ \therefore U_\infty = \left( \frac{2\rho_1\Delta hg}{\rho_\infty} \right)^{1/2} \]

**Experimental Procedure:**

1. Calibrate the water tunnel test section by generating a plot of velocity versus motor frequency using the upstream pitot-static tube and Bernoulli’s equation. Calibrate the operation of the water tunnel for motor frequencies from 5 to 45 Hz in 5 Hz increments.
2. Turn the power to the computer on and allow the system to boot into windows.
3. Turn on the power to the Toshiba power inverter for the motor.
4. Ensure the power indicator is lit on the aluminum box with the red neon lamp (located on the lower shelf beneath the bench).
5. Follow the instructions below to run the calibration and cylinder pressure distribution measurement experiment.

   a. **Calibration**
   
   I. In the PressureDistribution folder on the desktop, double click on WatChanPressNew.vi.

   II. Run the VI by clicking the right arrow at the top of the screen. For the calibration portion of the experiment, with the flow stopped, click the 'Zero' button on the vi. It will take 2 additional scans to zero the sensor offset. Save the zero pressure scan data to use in correcting for offset error later in your analysis.

   III. Dial in the desired frequency using the Frequency Adjust knob on the inverter while monitoring the Frequency indicator. Wait for 60 seconds for the flow to stabilize. Dial frequencies from 5 Hz – 45 Hz going up by 5 Hz increments.

   IV. Run the VI and record the values for Static Pressure (in m of water).

   V. Use the formulas in the lab write-up to determine the velocities for the frequencies from steps 4 and 5 and plot the velocities as a function of frequency. Repeat steps 4 and 5 until pressure values for all the frequencies have been recorded.

   VI. Determine the frequencies that are required to operate the flow at the desired velocities (0.6, 1.0 & 1.4 m/s) for the experiment by interpolation of your data.

   b. **Cylinder Pressure Distribution.**

   I. Start the VI

   II. Enter your Zero offset values to correct for the system errors

   III. Adjust the flow velocity to the speed desired by rotating the Frequency Adjust knob on the inverter to the frequencies found in step V & VI of the calibration section.

   IV. Allow the flow to stabilize for 60 seconds and run the VI. The values on the display may be stored to disk by entering a file name when prompted.

   V. Repeat steps III and IV until data for all three flow velocities.

6. For velocities plot the pressure coefficient as a function of angle around the cylinder on a single graph. The pressure measurements are located at the following angular positions.

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<td>12</td>
<td>157.5</td>
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<td>13</td>
<td>180</td>
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7. Compare the measured pressure coefficient distributions to that for the idealize flow around the cylinder $C_p = 1 - 4 \sin^2 \theta$, by plotting it along with the measured pressure coefficient.

8. Using the analysis given in the discussion section, calculate the drag coefficient for each of the three measured pressure coefficient distributions. To check your integration procedure, also integrate the idealized in viscid pressure coefficient distribution for a cylinder $C_p = 1 - 4 \sin^2 \theta$. The resulting integral should give $C_{DP} = 0$.

9. Based on the error in the pressure measurements and the other uncertainties in the parameters in the experiment calculate the error in the calculated drag coefficients.
Part 2: Water Tunnel Velocity Calibration and Drag Measurement on a Cylinder From Laser Doppler Velocity Measurements

Objectives:

a) Re-Calibrate the velocity of the water tunnel as a function of impeller motor rpm for use in subsequent hydrodynamic experiments using Laser Doppler velocity measurements
b) Make measurements of the drag coefficient of a circular cylinder at three (0.6, 1.0 & 1.4 m/s) different flow velocities. Both velocity calibration and drag measurements are based on velocity measurements from a laser-Doppler Velocimeter.

Discussion:

Laser Particle Velocimetry:
An understanding of the simplified theory of the operation of a laser-Doppler velocimeter is necessary for performing the water tunnel velocity measurements.

When two monochromatic Laser beams cross, a fringe (interference) pattern is formed.

Due to the Gaussian intensity distribution of the Laser beam, the fringes at the center of the focal volume will be brighter than at the edges. As a particle crosses the fringes, the scattered light will have the following intensity signal:
The faster the particle moves through the focal volume, the higher the frequency of modulation of intensity.

The velocity of the particle can be determined from the frequency times the fringe spacing.

The Fringe Spacing can thus be calculated in terms of wavelength of Laser \( \lambda \) and angle between the two beams \( \Theta \) as

\[
\Delta = \frac{\lambda}{2 \sin \left( \frac{\Theta}{2} \right)}
\]

For the Argon-ion Laser system used in this experiment,

\[
\lambda_1 = 488.0 \text{nm} = 4.88 \times 10^{-7} \text{cm}
\]
\[
\lambda_2 = 514.5 \text{nm} = 5.145 \times 10^{-7} \text{cm}
\]

For a 50 cm focal length lens,

\[
\Theta = 2.32^\circ
\]

If the velocity in the direction of the flow is \( U_x \), the frequency from a particle crossing the fringe volume is

\[
f = \frac{U_x}{\Delta} = \frac{2U_x}{\lambda} \sin \left( \frac{\Theta}{2} \right)
\]

The Laser-Doppler velocimeter instrument detects the optical signal scattered from particles in the flow and determines the velocity from the measured frequency. By traversing the Laser/detector head and the crossed laser beams across the water channel, velocity profiles can be measured.
Finding the drag from the measured velocity:

The calculation of the drag coefficient of a cylinder examined the momentum loss in the wake from the velocity measured with the LDV apparatus. The analysis is based on a control volume analysis using the geometry shown in the figure below.

The integral form of the mass conservation equation is given as:

$$\oint \rho \vec{U} \cdot d\vec{A} = 0$$

Since there is no fluid flow through the top and bottom surfaces of the control volume shown above, the integral becomes

$$\int_{1}^{2} \rho U_{1} dy - \int_{4}^{3} \rho U_{2} dy = 0$$

Using the geometry above, this integral can be rewritten as

$$\int_{0}^{h} U_{1} dy - \int_{0}^{h} U_{2} dy = 0$$

And, since the upstream flow velocity is uniform this simplifies to give

$$U_{1}h - \int_{0}^{h} U_{2} dy = 0$$

Add and subtract $U_{2}h$ where $U_{2}$ is the free stream flow located downstream of the cylinder.

$$U_{1}h - U_{2}h + \int_{0}^{h} (U_{2} - U_{2}) dy = 0$$

A little algebra then gives
\[(U_{1\infty} - U_{2\infty})h + U_{2\infty} \int_{0}^{b} \left(1 - \frac{U_{2}}{U_{2\infty}}\right) dy = 0\]

If we define the displacement thickness, \(\Delta\) as
\[\Delta = \int_{0}^{b} \left(1 - \frac{U_{2}}{U_{2\infty}}\right) dy\]

We can then write a relationship between the free stream velocities upstream and downstream of the object, the displacement thickness, and the height of the apparatus as
\[U_{1\infty} = U_{2\infty} \left(1 - \frac{\Delta}{h}\right)\] (1)

Eq. (1) can be used to calculate the change in the free stream velocity from state 1 ahead of the cylinder to state 2 in the wake of the cylinder. However, unless boundary layer effects at the water tunnel walls are taken into effect, this relationship will not be very accurate.

The Drag force on the cylinder can be calculated from the momentum loss of the fluid entering and exiting the control volume.

In general for a flow with uniform loss in flow velocity the drag would be given as
\[Drag = m \Delta U\] (2)

Where \(m\) is the mass flow rate around an object and \(U\) is the change in free stream flow speed around this object. Again, this form assumes that the flow field is uniform in the direction transverse to the mean flow vector.

Our situation is more complex, in that the flow magnitude does vary in the transverse direction. In this case, the drag is given by momentum-balance arguments in terms of an integral
\[Drag = \iint \rho U_{2} da (U_{1} - U_{2})\]

The drag per length \(b\) of the cylinder is given by
\[Drag = b \int_{0}^{b} \rho U_{2} (U_{1} - U_{2}) dy\] (3)

Assuming the velocity ahead of the cylinder is uniform \(U_{1} = U_{1}\), and setting \(b=1\), the Drag per unit length of cylinder is
\[Drag = \frac{1}{2} \rho U_{1\infty}^{2} \int_{0}^{b} 2 \left( \frac{U_{2}}{U_{1\infty}} - \left( \frac{U_{2}}{U_{1\infty}} \right)^{2}\right) dy\] (4)
With the assumption that \( U_{2,\infty} = U_{1,\infty} \),

\[
\text{Drag} = \frac{1}{2} \rho U_{1,\infty}^2 \int_0^L \frac{U_2(y)}{U_{2,\infty}} \left( 1 - \left( \frac{U_2(y)}{U_{2,\infty}} \right) \right) dy 
\]

(5)

The Drag coefficient \( C_D \) is defined by normalizing the drag by the dynamic pressure \( \frac{1}{2} \rho U_{1,\infty}^2 \) and the projected area of the cylinder \( A_p = D \cdot b \) where \( D \) is the diameter of the cylinder and \( b = 1 \) is the unit length of the cylinder. The Drag coefficient per unit length of cylinder is:

\[
C_D = \frac{\text{Drag}}{\frac{1}{2} \rho U_{1,\infty}^2 A_p} = \frac{\text{Drag}}{\frac{1}{2} \rho U_{1,\infty}^2 D} 
\]

(6)
Experimental Setup:

The Laser Doppler system is used to make non-intrusive velocity measurements in a fluid flow.

The system consists of an Solid State laser, a beam separator/shifter and splitter, a fiber optics and lens system, a photomultiplier receiver, digital signal processors and a computer system with the Flowsizer program installed. Flowsizer is the program that performs numerical analysis on the received data from the signal processors and then displays the results on the screen in addition to saving velocity information to disk. The program also allows the selection of operating parameters for the hardware and software for the system.
**Experimental Procedure:**

1. Turn the power to the computer on and click on the Flowsizer icon.
2. Turn the power on to the Unidex indexer that controls the traversing table.
3. Adjust the flow velocity to the speed desired by rotating the Frequency Adjust knob on the inverter to the frequencies found in Part 1 for the desired Velocities.
4. Ensure the curtain around the experiment is closed such that a stray beam or reflection from the laser cannot escape and pose a hazard to other personnel in the laboratory. Ensure also that all members of the group are wearing their safety glasses.

5. Turn on the FSA 3500 (Power switch is located on the rear panel)
6. Turn on the Powersight laser system. (Power switch is located on the rear panel)
   - Wait 1 minute to let the power supply energize the laser
   - Turn the laser key to the on position.
   - Press the silver button to output the laser beam, a red light should illuminate around the button.

7. Make sure the aperture on the laser is in the fully open position and particles are injected into the channel.

8. Follow the instructions below to run the calibration and the velocity measurement experiment.
   a. **Calibration**
      i. At the FlowSizer console, under Home category -> Run management panel, select MAE in the Current drop down box.
      ii. Hardware category -> Traverse panel -> Start Traveses Manager
      iii. In Manual tab, press on Abs Home to move the traverse to its hardware zero reference point. Wait until the hardware finish moving, verify visually that it is at the home position (the laser should be at a location downstream of the cylinder). This puts the traverse at a known reference location, indicated as 0,0,0. All future indicated positions are displacements from this point.
      iv. The top lines in X, Y, Z, group boxes show the current positions of the x,y, and z axies of the traverse (z axis is not used in this experiment). The boxes next to the Move button allow you to enter a new position for each axis.
         Enter 23.5 and 5.25 to the X and Y boxes next to the Move button correspondingly and press Move.
   b. **Dial in the desired frequency using the Frequency Adjust knob on the inverter while monitoring the Frequency indicator. Wait for 60 seconds for the flow to stabilize. Dial frequencies from 5 Hz - 45 Hz going up by 5 Hz increments.**

   c. **Home** category -> Run Capture panel -> press Begin.
      This will start the data capturing process.
   d. Continue to increment the Frequency on the motor inverter and repeat step VI and VII until the velocity for the maximum frequency has been recorded.
   e. **Home category -> Run Management panel -> press Save.**
      Enter a name for the run and save it.
   f. **To play back or export the data:**
      Home category -> Run management panel -> select the name you entered in step VI in the Current drop down box -> Hit Playback in Run Capture panel -> Press Data Sets to CSV file to export data (Notice: the X & Y position can't be read).
   g. **Continue to increment the Frequency on the motor inverter and repeat step VI and VII until the velocity for the maximum frequency has been recorded.**
IX. Plot the frequencies and velocities. Determine the frequencies that correspond to the three velocities (0.6, 1.0 & 1.4 m/s) that will be used to take actual data for determining drag of the cylinder.

X. Use the calibration values of Frequency that correspond to the desired velocities for the remainder of the experiment.

b. **Velocity Measurements**

   I. There are four sets of data that will be taken at three different velocities for this experiment. There is one axial set that provides velocity information for various centerline positions in the tunnel 6 inches upstream and 8 and 16 inches downstream of the cylinder. In addition, there are three sets of data that provide velocity information across the water tunnel (transverse) at 6 inches upstream and 8 and 16 inches downstream of the cylinder.

   II. To begin taking data, dial the Frequency that corresponds to the velocity desired into the inverter. Allow 60 seconds for the flow to stabilize.

   III. At the FlowSizer console, under **Home** category -> **Run management** panel, select MAE in the **Current** drop down box.

IV. **Hardware** category -> **Traverse** panel -> **Start Traverse Manager**

   V. In **Manual** tab, press on **Abs Home** to move the traverse to its hardware zero reference point. Wait until the hardware finish moving, verify visually that it is at the home position (the laser should be at a location downstream of the cylinder). This puts the traverse at a known reference location, indicated as 0,0,0. All future indicated positions are displacements from this point.

   VI. In **Matrix** tab, press **Open** and select Traverse 1.TRV. It is the transverse position matrix for location X = 6 inches upstream of the cylinder. Make sure the "MAE" is used under **Run Setup** column.

   VII. **Hardware** category -> **Traverse** panel -> **Start Scan Capture**. A window will pop up and shows the current location of data capture. The data is saved to **Location0000xx**. Wait few minutes for the whole process to finish.

   VIII. To play back or export the data:

       **Home** category -> **Run management** panel -> select **Location0000xx** in the **Current** drop down box -> Hit **Playback** in **Run Capture** panel -> Press **Data Sets to CSV file** to export data (Notice: the X & Y position can't be export, but you have it in your position matrix in step VI). Repeat this step until all your data captured in VII is exported.

    VII. Repeat step III to VIII and using Traverse 2.TRV, Traverse 3.TRV and Axial.TRV in step VI. Repeat this step with a different desired flow velocity

XII. Turn the Frequency knob fully CCW at the end of the experiment. The laboratory assistant or TA will power the system down at the end of the lab session

10. Plot the velocity and the RMS velocity for each flow condition as a function of distance from the cylinder on separate graphs and compare with the velocity from the pitot probe calibration. Also, on a separate graph plot the RMS velocity normalized by the absolute value of the local mean velocity as a function of distance from the cylinder. Is there an upstream influence of the flow around the cylinder?
11. Calculate the drag coefficient for the cylinder for 3 velocities using the velocity profiles obtained in the earlier steps and equation 5 given in the Discussion session. Compare the measured ratio of $U_2 / U_1$, with that calculated from Eq. 1. You are required to calculate the error in the Drag coefficient based on the error in the velocity measurements.

12. Compare the drag coefficient $C_D$ determined from the wake velocity measurements with the pressure drag coefficient $C_{DP}$, in a table as a function of the Reynolds number of the flow based on the diameter of the cylinder.

13. Compare these drag coefficient results with those obtained using the pressure distribution method used in part 1, and also compare both sets of results with those found in any fluid mechanics textbook.

- Chi Wai Chow
January - 2014

References: