Wind Tunnel and Aerodynamics

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Abstract

This experiment investigates various aerodynamic principles through multiple setups: a Pitot tube for velocity measurements, a Venturi tube for pressure distribution, a ping pong ball fountain for terminal velocity observation, and airfoil tests for lift analysis. The data collected was compared to theoretical calculations, revealing discrepancies that highlight the limitations of experimental conditions and measurement tools. Notable results include the accuracy limitations of Pitot tube readings at higher speeds, bistable pressure readings in the Venturi tube, and significant deviations in the measured lift on airfoils compared to theoretical predictions. These findings provide insights into practical challenges in aerodynamic experiments and reinforce the importance of precise data collection methods.

Introduction

The study of aerodynamics is crucial in understanding airflow behavior and its impact on objects in motion. This experiment aims to explore fundamental aerodynamic principles using five distinct setups: a Pitot tube to measure airspeed, a Venturi tube to analyze pressure variations, a ping pong ball fountain to observe terminal velocity, a ping pong ball suspended in a wind tunnel to observe drag, and airfoil tests to evaluate lift generation. By comparing experimental results to theoretical models, this lab highlights the practical challenges and considerations encountered in real-world aerodynamic testing. Understanding these principles is essential for applications in engineering, aviation, and physics.

1 Experiment setup and procedures

1.1 Pitot Tube

Following the instructions in the manual [1], we measure the speed of the flow in the center of the wind tunnel both with the meter and the Pitot tube. We place our meter directly next to the Pitot tube to avoid disturbing the flow in front of the Pitot tube opening, while measuring the speed at approximately the same place.

1.2 Venturi Tube

We first mark the height of the manometer liquid at points 1, 2 and 3 (fig. 1) in the Venturi tube with no flow, before using the air supply to blow air into the Venturi tube, placing the outlet of the air supply as close as possible to an opening on the Venturi tube. We set the air supply rate such that the the manometer liquid does not descend into the curve of the manometer. We determine the height of the column in the manometer liquid in each section to get h_1, h_2 and h_3.

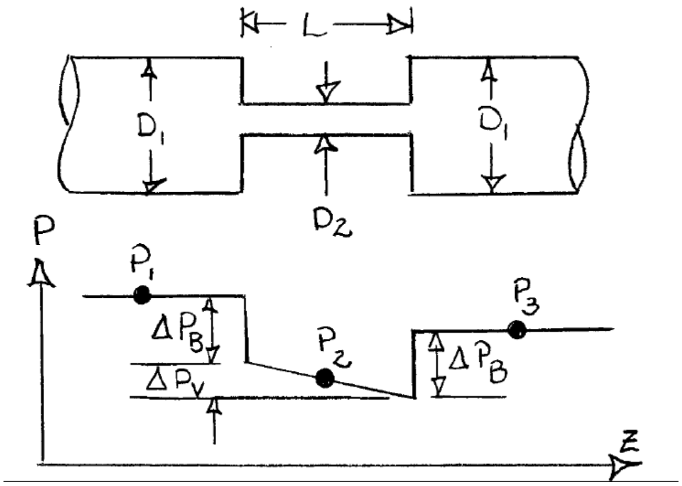

Figure 1: Pressure vs. Distance in a Venturi tube

1.3 Ping Pong Ball on a Fountain

We are trying to find the Reynold's number for which a ping pong ball reaches terminal velocity. Since we are working at high speeds, we use the $Re > 1000$ approximation for the drag force (eq. 1). Our value for $C_D(Re) \approx 0.4$ comes from the lab manual, page 87 [1].

$$F = C_D(Re) \cdot \frac{1}{2}\rho v^2 \cdot \pi R^2 \tag{1}$$

Setting the air supply to a constant output, we measure the air velocity at different heights above the air supply outlet using the Pitot tube. We chose to use the wind speed meter instead of the Pitot tube specified in the lab manual since those measurements are more precise.

We also fix the Pitot tube to the height of the ping pong ball's stable position, and make lateral wind speed measurements.

1.4 Ping Pong Ball in the Wind Tunnel

To create a calibration curve relating power supply voltage and wind speed over the ping pong ball, we place the wind speed meter approximately where the ping pong ball would be and take air velocity measurements for a range of voltages. Then, taping the ping pong ball to a string, we suspend it in the position of the wind speed meter, and measure the angles made by the string for the same range of voltages.

We originally made the calibration curve with air velocity values from the Pitot tube, but decided our results were not accurate, since the Pitot tube measures the speed in the wind tunnel about 6 inches behind where we can place the ping pong ball. However, we still record the height of the Pitot tube to cross-reference our velocity values.

We notice that the ping pong ball oscillates on a plane perpendicular to the flow when trying to measure the angle it makes with the vertical. To prevent this oscillation, we restrict the ball's movement using two protractors - parallel to the flow - caging the string without friction.

1.5 Lift on an Airfoil

Before measuring the lift from the three wings, we measure the lift from the balance and airfoil fixture without any wing attached.

Then, we set the power supply to 16 V, and measure the lift for each airfoil at angles of $0°, 10°, 20°$ and $30°$.

We also obtain theoretical lift values for each airfoil by using the data from the lab manual inside the XFLR5 simulation software [2].

2 Results Measured

2.1 Pitot Tube

The measurements fluctuate at higher speeds. On average, our values on the Pitot tube velocity measurements err by $0.64\,\mathrm{m\,s^{-1}}$, while our velocity meter error is $\pm 0.2\,\mathrm{m\,s^{-1}}$. The pressure difference between the tip of the tube ($v_0 = 0$) and the side of the tube ($v = v_\infty$) is $\rho_a v_\infty^2/2$[1]. Therefore we can write:

$$v_\infty = \sqrt{\frac{2\rho_w g h}{\rho_a}}$$

Using this formula and the wind speed meter, we draw the wind speed vs. fan power supply voltage plots (fig. 2).

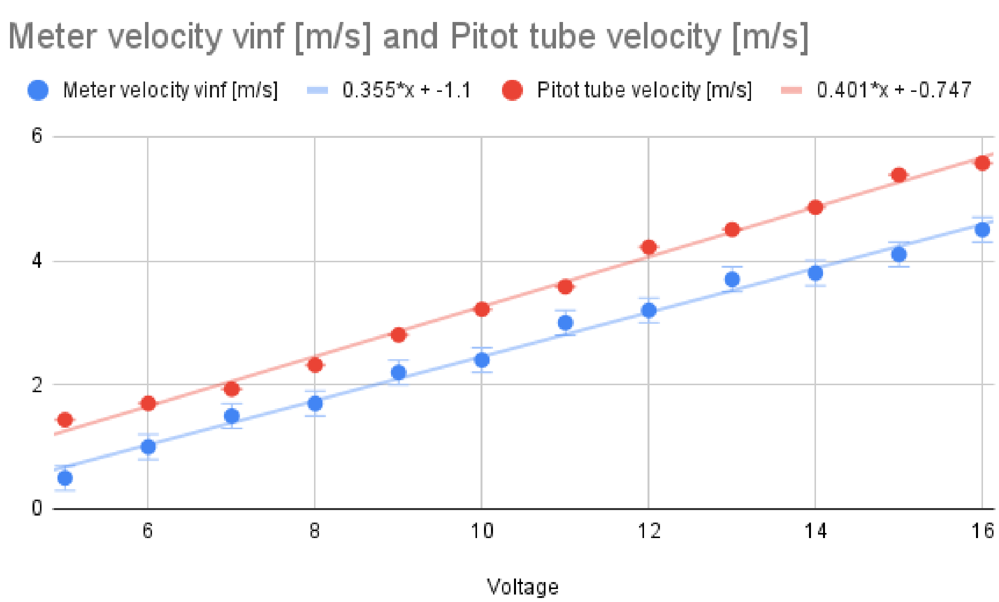

Figure 2: Measuring wind speed with two different sensors

2.2 Venturi Tube

The manometer pressure is bistable. We are not able to obtain substantial height measurements at a low flow rate, where we were expecting a consistent laminar state, and our air supply is not powerful enough to reach a consistently turbulent state. Therefore we measure values with large errors: $h_1 = (-2.2 \pm 0.2)$ cm, $h_2 = (2.1 \pm 0.2)$ cm and $h_3 = (0.5 \pm 0.2)$ cm.

2.3 Ping Pong Ball on a Fountain

We calculate a terminal velocity of $9.36\,\mathrm{m\,s^{-1}}$ and a Reynold's number of 25 313. Since these values were obtained only from data present in the manual with no error figures, we present them as such.

To calculate the velocity of around the ping pong ball at its stable height, we plot our air velocity vs. height measurements and make a line of best fit, knowing our wind speed meter has an error of $\pm 0.3\,\mathrm{m\,s^{-1}}$ (fig. 3).

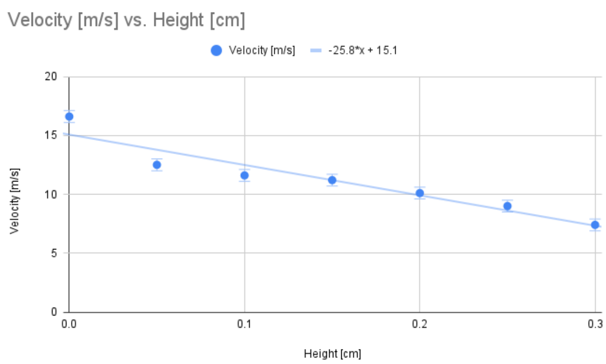

Figure 3: Plotting velocity vs. height allows us to predict the velocity of the air flowing around the ping pong ball when we place it in the stream

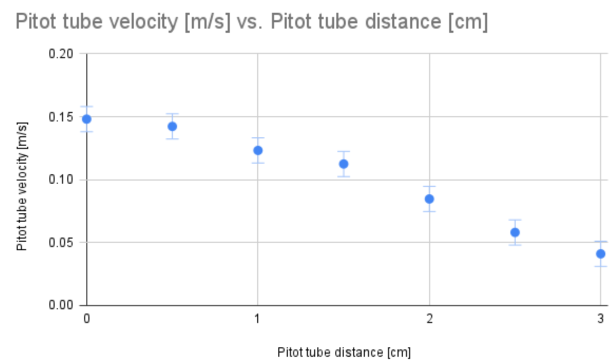

Figure 4: The lateral velocity of the flow above the fountain is inversely proportional to the distance from the center of the fountain

We measure the ball's stable position to be around (22.75 ± 2.00) cm above the fountain.

We measure the lateral air velocity around the ping pong ball's stability height in fig. 4. We use the Pitot tube which has an error of $\pm 0.01\,\mathrm{m\,s^{-1}}$.

2.4 Ping Pong Ball in the Wind Tunnel

At higher voltages, all of our wind speed measurements and derivations have larger errors. Calculating a best fit line for our results in fig. 5 allows us to approximate the velocity of the flow around the ball for any voltage value.

Measuring the angle made by the ping pong ball shows much greater values than both sets of theoretical angles (fig. 6). However, we notice a close relationship between our theoretical angles calculated from two different flow velocity value sources.

2.5 Lift on an Airfoil

We measure the lift generated for each airfoil, and subtract the lift generated by the balance and wing fixture ($L_{\text{offset}} = (4.9 \pm 0.3) \times 10^{-2}$ N. We use the lab manual's lift force equation ($F = KC_l(\alpha)\frac{1}{2}\rho v^2 cw$, with $K = 1 - 0.86c/w$) to plot

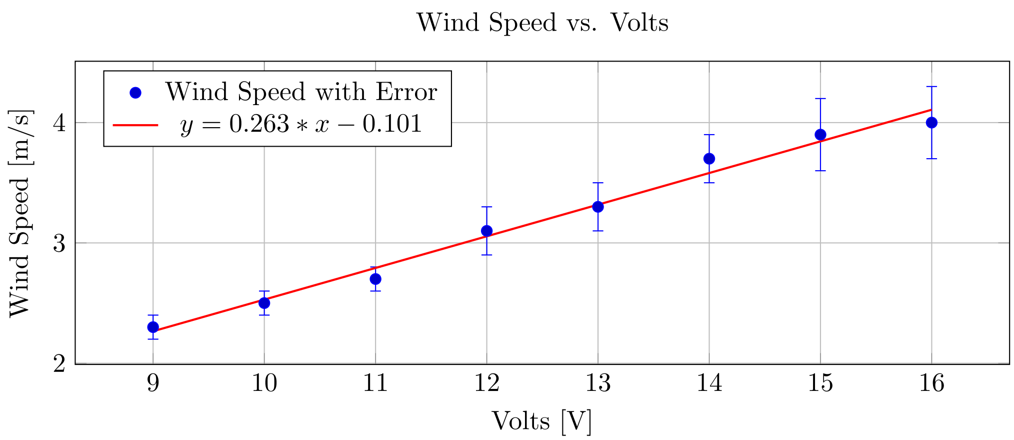

Figure 5: Relating flow velocity in the wind tunnel to the power supply voltage: Wind speed $\approx 0.263 \cdot \text{Voltage} - 0.101$

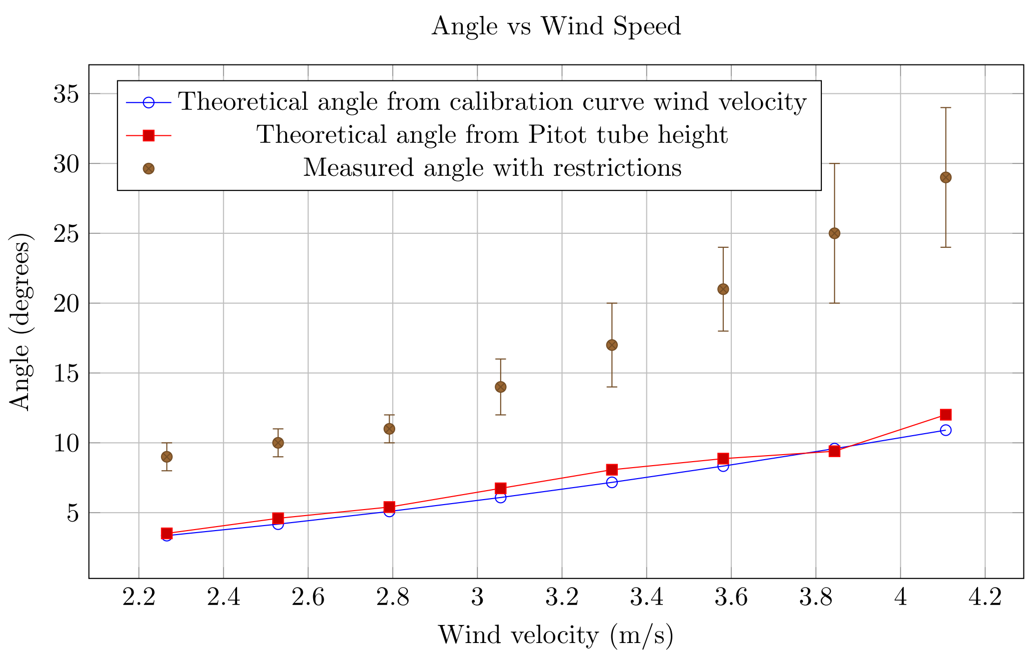

Figure 6: Our measured ball angles were higher than both sets of predicted angles

measured $C_L(\alpha)$ for each airfoil in fig. 7.

We also use the XFLR5 software [2] to simulate the lift coefficients at the angle of attacks we are interested in, and obtained C_l vs. α curves (fig. 7).

3 Data Discussion and Analysis

3.1 Pitot Tube

Since the Pitot tube is positioned at the center of the wind tunnel, while we place the meter closer to the tunnel walls, we observe a slight decrease in wind velocity at the meter. This is due to the boundary layer effect, where air viscosity causes the flow to slow down near the tunnel walls. This behavior aligns with the predictions of the Navier-Stokes equations for viscous flow.

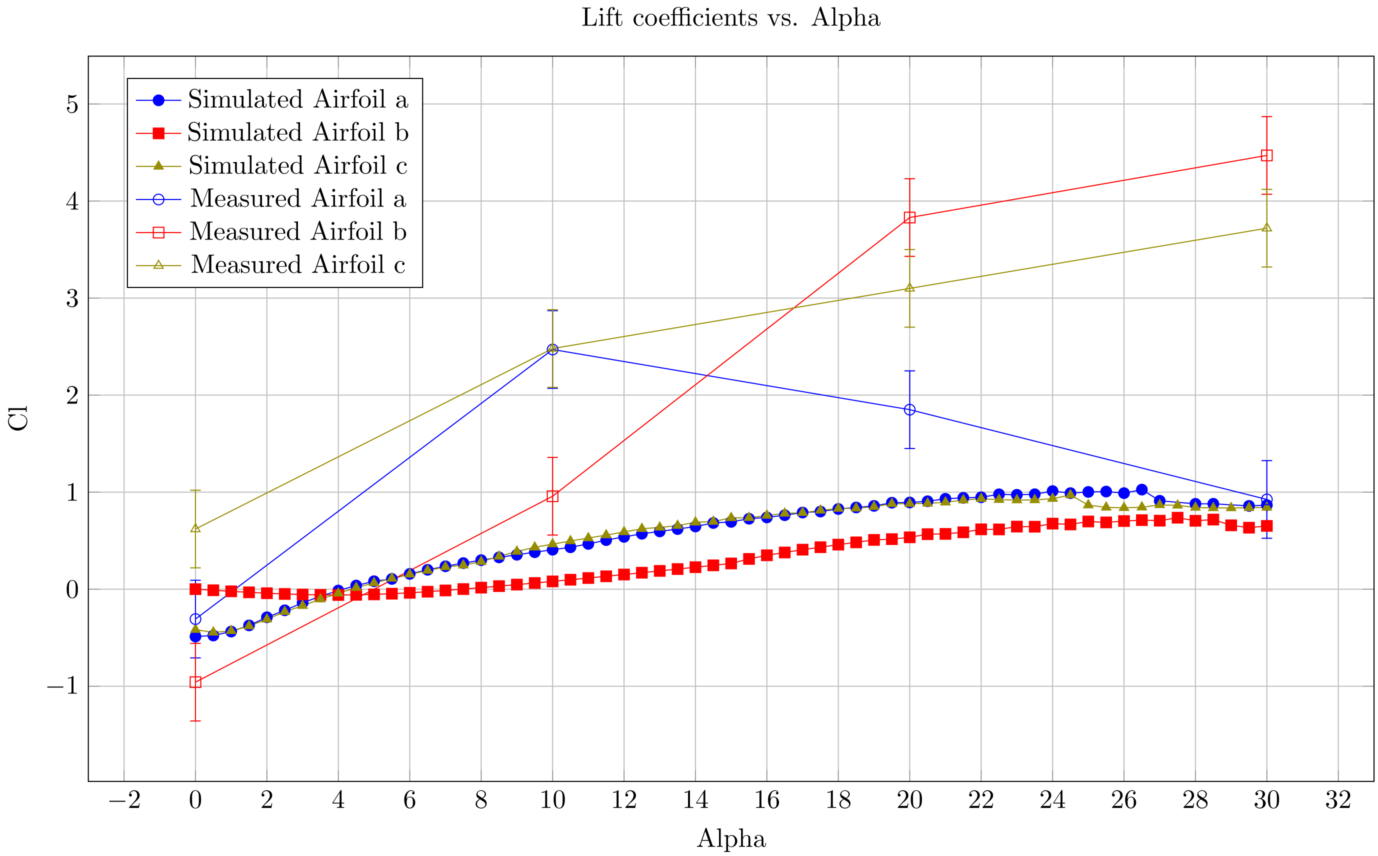

Figure 7: Lift coefficient data obtained from the XFLR5 airfoil simulator [2]

3.2 Venturi Tube

Using the equations describing inviscid flow in a Venturi tube found in the manual (page 85), we are able to calculate a friction coefficient of 1.19×10^{-1} and a Reynold's number of 2058.4, both with 13.48% error. As expected, our Reynold's number is > 1000 and our result for the friction factor is significantly higher than the published value (found in the lab manual, page 88 [1]). This may be because of turbulence introduced by the manometer connection to the Venturi tube. To improve the setup, we would take the smallest possible diameter tube for the manometer to reduce turbulence introduced by the tube's opening into the Venturi tube.

3.3 Ping Pong Ball on a Fountain

From our best fit line equation in fig. 3, our terminal velocity is $-25.8 \cdot 22.75 \cdot 10^{-2} + 15.1 = (9.23 \pm 1.07)\,\mathrm{m\,s^{-1}}$. This is a 1.4% error from our theoretical value calculated from the drag force equation of $9.36\,\mathrm{m\,s^{-1}}$.

We also observe from our lateral air velocity plot (fig. 4) that the air velocity is inversely proportional to distance from the center of the fountain. Since velocity and pressure are inversely proportional, this represents a pressure gradient that increases toward the center, which stabilizes the ping pong ball laterally. If the ball drifts away from the center, it encounters higher velocity flow on the side farther from the center, resulting in a lower pressure on that side due to Bernoulli's principle. The pressure difference generates a restoring force that pushes the ball back toward the center, maintaining its lateral stability.

3.4 Ping Pong Ball in the Wind Tunnel

Since both sources of theoretical angle measurements are so similar, we can infer that our calibration curve would have been equally valid if it had been made based on Pitot tube flow velocity values.

Our measured angles suggest that there is more horizontal force on the ping pong ball than expected, i.e. the drag force on the ping pong ball is more than theoretical. This might be due to the tape on the ball which changes its geometry away from a sphere, increasing the drag on the ball.

Our large error bars also suggest that the flow becomes increasingly turbulent at higher wind velocities, which is supported by the oscillations of the ball we restricted. The turbulent flow might contribute to increasing the drag on the ball, similarly to how it increased the friction coefficient in the Venturi tube.

3.5 Lift on an Airfoil

Several similarities exist between our measured lift and the theoretical lift coefficient curves:

- Airfoil lift increases with α
- The theoretical airfoils' lift coefficients lessen at high α, and airfoil a exhibits a behavior consistent with this, albeit at a lower α

However, this experiment mostly highlights the challenges faced by experimental setups in replicating ideal aerodynamic conditions. Factors such as turbulence, and material imperfections likely contributed to the observed discrepancies between measured and theoretical lift curves.

Conclusion

This experiment provided valuable insights into aerodynamic principles, emphasizing both the strengths and limitations of theoretical models in practical scenarios. The Pitot tube demonstrated reasonable accuracy at lower speeds but introduced errors at higher velocities. The Venturi tube's bistable pressure readings posed challenges in achieving consistent measurements. The ping pong ball experiments revealed deviations in terminal velocity predictions, while the airfoil tests showed higher lift values than anticipated. These results underscore the importance of careful calibration, precise measurement techniques, and recognizing environmental factors when conducting aerodynamic experiments.

References

[1] U.C. Santa Cruz Advanced Physics Laboratory Manual

[2] XFLR5 is an analysis tool for airfoils, wings and planes `https://www.xflr5.tech/xflr5.htm`