ME 207: Fluid Dynamics

Project 12 - Lift measurement for external flow over aircraft wing

Group 7

Anuj Manoj Joshi	23110033
Jatin Agarwal	23110147
Tanushka Anand Sonde	23110332
Vardayini Agrawal	23110353
Yug Mitulkumar Desai	23110370

Contents:

Objective:

The primary objective of this experiment is to **investigate the lift characteristics of an airfoil** under varying flow conditions. Specifically, the experiment aims to:

1. **Measure the lift force** on an airfoil at different **angles of attack** and **freestream velocities** (corresponding to different Reynolds numbers).

2. **Determine the lift coefficient (Cl)** for each test condition and observe its variation with respect to angle of attack and Reynolds number.

3. **Compare the experimentally obtained lift coefficients** with **theoretical or computational predictions**, evaluating deviations and underlying causes.

4. **Quantify experimental errors and uncertainties** in all measured parameters, including lift force, velocity, and angle of attack, to assess the reliability and accuracy of the results.

Theoretical Discussion and Background:

The generation of lift on an airfoil is a fundamental concept in aerodynamics, resulting from the interaction between the airfoil surface and the surrounding airflow. It arises mainly due to the **pressure difference** between the upper and lower surfaces of the wing, and to a smaller extent from the shear (friction) forces along the surface.

When air flows over a wing-shaped body, it moves faster over the curved upper surface and slower underneath. This difference creates lower pressure on the top and higher pressure underneath, resulting in a net upward force. The components of the pressure and wall shear forces in the direction normal to the flow tend to move the body in that direction, and their sum is called lift.

1. Lift Force and Lift Coefficient

The lift force L acting on an airfoil can be expressed as:

$$L = C_L \frac{1}{2} \rho V^2 A$$

Where:

- L: Lift force (N)

- C_L: Lift coefficient (dimensionless)
- ρ: Density of air (kg/m³)
- V: Freestream velocity (m/s)
- A: Planform area of the airfoil (m²)

The lift coefficient C_L is a non-dimensional parameter that quantifies the lift produced relative to the dynamic pressure and area. It depends on the angle of attack, Reynolds number, and airfoil geometry.

2. Angle of Attack and Thin Airfoil Theory:

For a symmetric thin airfoil in inviscid, incompressible flow, Thin Airfoil Theory provides a linear relationship between lift coefficient and angle of attack α (in radians):

$$C_L = 2\pi\alpha$$

This relation holds well for small angles of attack (typically less than 10°) and under ideal flow conditions. As α increases, C_L increases linearly until the stall point.

Beyond a critical angle of attack, flow separation occurs over the upper surface of the airfoil, leading to a sudden drop in lift—a phenomenon known as stall.

3. Reynolds Number and Flow Regimes

The Reynolds number Re is a dimensionless quantity used to predict flow patterns in different fluid flow situations. It is given by:

$$R_e = \frac{\rho V L}{\mu}$$

Where:

- L: Length (Here chord length of the airfoil (m))
- μ: Dynamic viscosity of air (Pa·s)

The Reynolds number influences the nature of the boundary layer (laminar or turbulent), which in turn affects the lift and drag characteristics. Higher Re generally results in thinner boundary layers, delayed flow separation, and improved lift performance.

4.Lift Force from Pressure Distribution:

When detailed pressure measurements are available over the surface of a wing, the lift force can be determined by integrating the pressure and shear stress contributions:

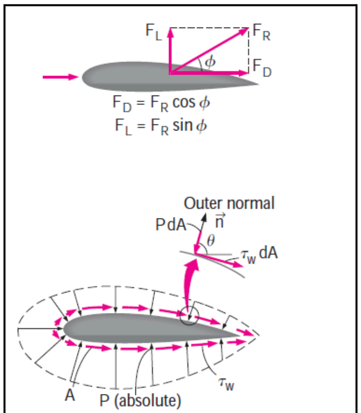
$$dF_L = - P\sin\theta dA + \tau_w \cos\theta dA$$

Where:

- P = Local pressure on the surface
- τ_w = Wall shear stress
- θ = Angle between the local surface normal and the freestream direction
- dA = Differential surface area

By integrating over the entire surface of the wing:

$$F_L = \int_A (- P\sin\theta dA + \tau_w \cos\theta)\, dA$$



The pressure and viscous forces acting on a two-dimensional body and the resultant lift and drag forces.

In many practical cases, especially at low angles of attack and moderate Reynolds numbers, the shear contribution is small, and the lift force is dominated by the pressure difference between the top and bottom surfaces.

In real experimental conditions, several factors can cause deviations from ideal theoretical predictions:

- **Viscous effects** lead to boundary layer development, flow separation, and wake formation.
- **Three-dimensional effects** (especially in finite wings) introduce induced drag and modify lift distribution.
- **Wind tunnel wall interference**, surface roughness, and instrumentation limitations contribute to measurement errors.

Thus, experimental results are often compared with theoretical curves and error analysis is essential for interpreting the accuracy of findings.

- Description of the set up including a schematic and an actual photograph.
- Detailed measurements in the format of tables (if applicable).
- Interpretation/Explanation of the results, including comparison with the literature, if applicable.
- Uncertainty analysis of the results obtained.

References

- Anderson, J. D. (2017). *Fundamentals of Aerodynamics* (6th ed.). McGraw-Hill Education.
- Çengel, Y. A., & Cimbala, J. M. (2018). *Fluid Mechanics: Fundamentals and Applications* (4th ed.). McGraw-Hill Education.
- White, F. M. (2011). *Fluid Mechanics* (7th ed.). McGraw-Hill Education.

Acknowledgement:

We would like to express our sincere gratitude to IIT Gandhinagar for offering the course ME207: Fluid Dynamics, which has allowed us to learn and practically apply several fundamental concepts of fluid dynamics.

We extend our heartfelt thanks to Prof. Dilip Srinivas Sundaram for his invaluable instruction in the theoretical aspects of the course and to Prof. Uddipta Ghosh for designing the laboratory experiments, which allowed us to engage with various practical setups.

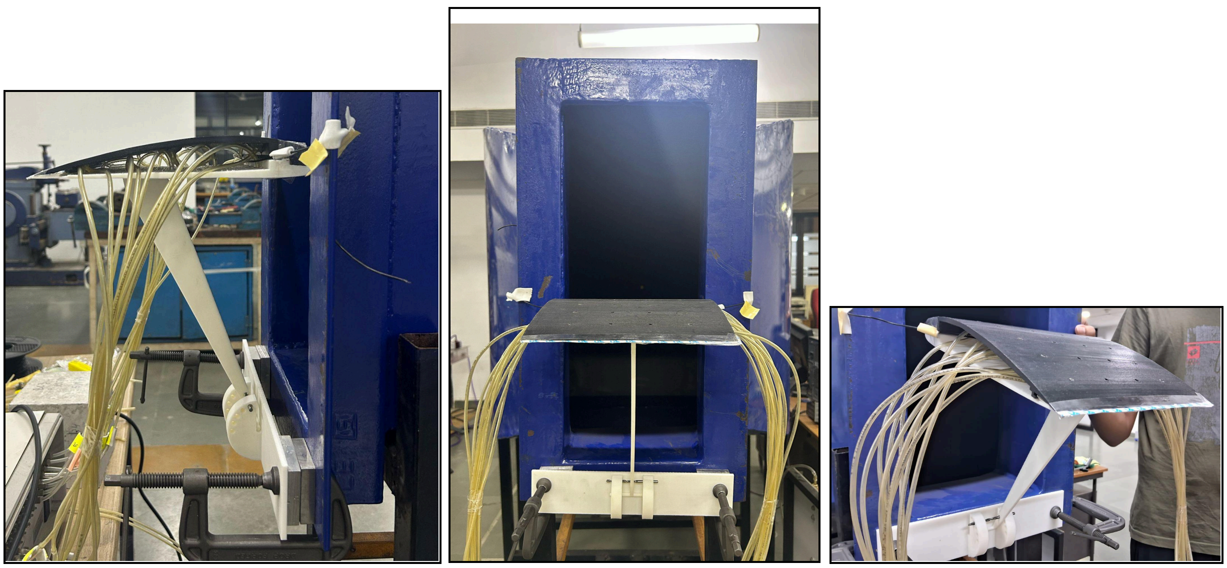
Lastly, we sincerely appreciate the guidance and support of the teaching assistants for clarifying doubts and helping us whenever we encountered challenges during the lab.

Experimental Setup:

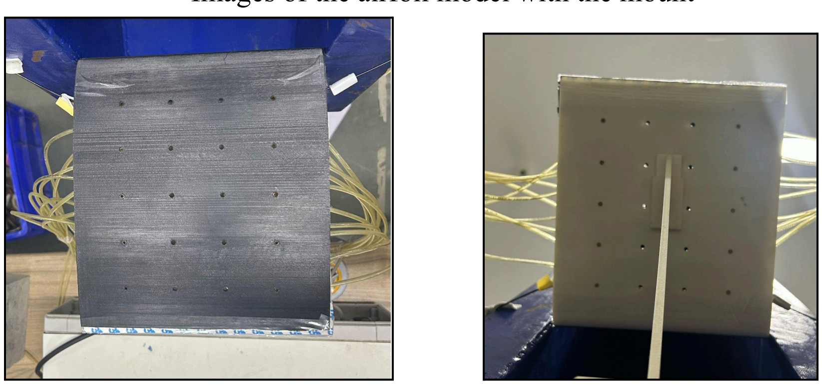
To investigate the lift generated by an airfoil, we devised an experimental setup aimed at determining the pressure distribution over the wing surface. By measuring the gauge pressure at multiple points above and below the airfoil, we aimed to quantify the pressure differential responsible for lift. This setup enabled us to evaluate the aerodynamic behaviour of the airfoil under controlled wind tunnel conditions.

- Airfoil Model and Mounting Mechanism:

- NACA 4412 airfoil was fabricated using 3D printing for aerodynamic testing.
- The airfoil surface was embedded with 20 pressure tap holes:
  - 10 on the upper surface
  - 10 on the lower surface
- The airfoil was hollow and open from both ends, allowing easy access to the internal pressure tubes from either side.
- The airfoil was mounted onto a custom-designed 3-D printed stand, which slides into a socket located at the base of the airfoil for secure fitting.
- This stand was clamped to the entrance of the wind tunnel to ensure stability during the experiment and to ensure that the airfoil was properly aligned to face the oncoming airflow.
- The base of the stand featured a rotational mechanism, allowing it to rotate even after being clamped, thereby enabling adjustable control over the angle of attack (AoA).
- To prevent wobbling of the airfoil at higher wind speeds, a string was passed through the airfoil from one side to the other, and its ends were tied to the walls of the wind tunnel for lateral stabilisation.



Images of the airfoil model with the mount



Images of the pressure taps created on the top and bottom surfaces of the airfoil

- Pressure Measurement System: Pressure Scanner and Digital Manometer

- A pressure scanner and a digital manometer were used to measure the gauge pressure at various pressure taps embedded in the airfoil.
- Flexible pressure tubes were properly labelled and inserted into the respective holes on the airfoil surface:
    - Care was taken to ensure that the tubes fit securely without protruding from the surface, so as not to disrupt the pressure reading or airflow.
    - Tubes were routed carefully to avoid interfering with the airflow, particularly beneath the lower surface of the airfoil.
- Each pressure tube was systematically connected to individual channels on the pressure scanner, ensuring organised and reliable mapping of pressure tap positions to scanner inputs.
- The digital manometer had two ports:
    - One port was connected to the output of the pressure scanner.
    - The other port was left open to the atmosphere, allowing for gauge pressure measurement (i.e., pressure relative to ambient atmospheric pressure).
- The pressure scanner allowed for channel selection via a digital interface. By selecting a channel on the scanner's display, the corresponding pressure tap could be monitored.
- The digital manometer displayed the gauge pressure corresponding to the currently selected channel, enabling accurate and sequential recording of pressure values at all 20 tap locations.

Image: Pressure scanner

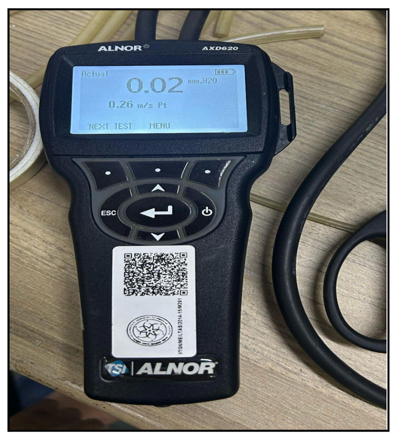


Image: Digital Manometer


Image: Pressure tubes connected to the pressure taps on the airfoil

- Wind Tunnel setup:

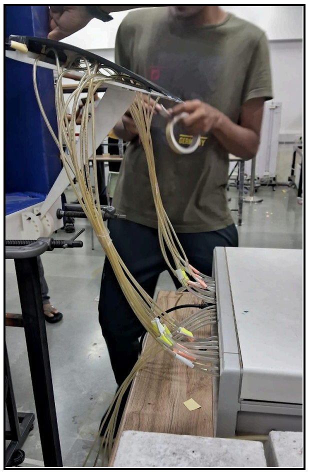
- The experiment was performed in a closed-circuit wind tunnel, allowing controlled and consistent airflow for aerodynamic testing.
- Air velocity inside the tunnel could be adjusted by varying the fan frequency using a control meter. An increase in frequency resulted in a corresponding increase in airflow velocity across the airfoil.
- To ensure consistency throughout the experiment, the specific frequencies corresponding to desired velocities were noted and used during all measurements.

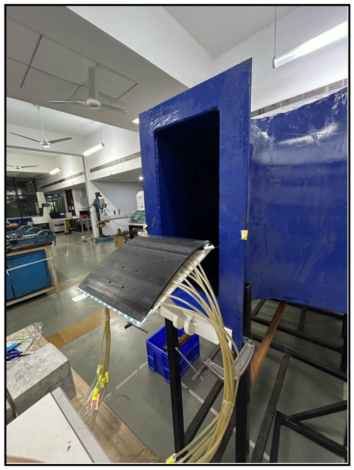
- Pitot Tube and Velocity Measurement
    - A Pitot-static tube was placed in the test section of the wind tunnel to measure airflow velocity.
    - The Pitot tube provided both total pressure and static pressure, with their difference indicating dynamic pressure.
    - This pressure difference was measured using a digital manometer, connected to the Pitot tube and it gave us the velocity for each wind speed setting.

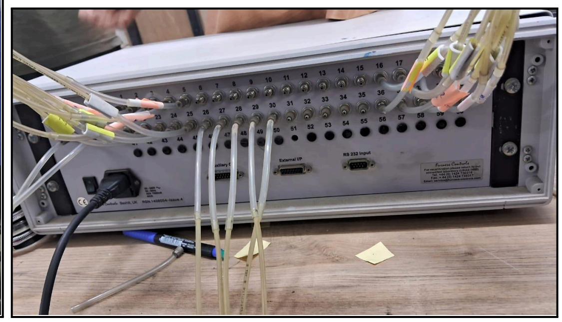
Image of a pitot tube

Readings were taken for three different angles of attack (AoA), and for each AoA, the airfoil was tested at three distinct wind speeds.

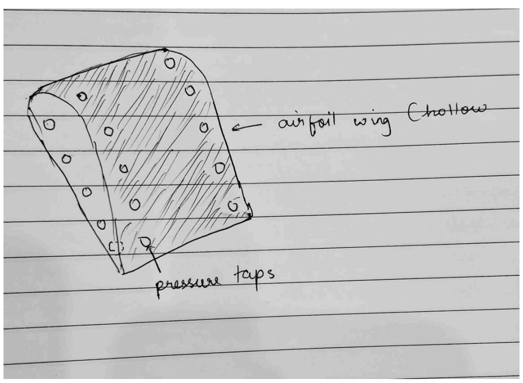
Final setup:

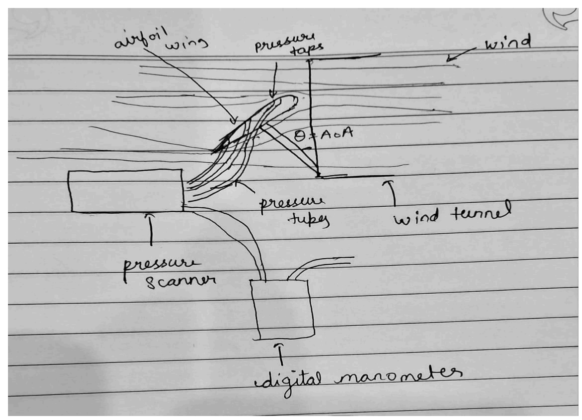






Schematic Diagram:





Conclusion

This experiment explored the lift characteristics of a cambered airfoil (NACA 4412) at various wind speeds and angles of attack. By measuring surface pressures, we calculated the lift force and the corresponding lift coefficient (C_L) under different flow conditions.

As expected, lift increased with both freestream velocity and angle of attack. Interestingly, the airfoil produced positive lift even at 0°, which confirms the behavior of cambered airfoils. At higher angles like 35.78°, the C_L continued to rise without signs of stall, which is unusual and likely due to the low Reynolds numbers and laminar flow conditions in our setup. These findings highlighted how experimental conditions such as surface finish, pressure tap resolution, and Reynolds number can significantly affect aerodynamic performance.

The experiment successfully fulfilled its primary objective of measuring lift forces at different angles of attack. It also provided us with meaningful hands-on experience in aerodynamic testing and data analysis. Through this process, we gained a better understanding of the relationship between pressure distribution and lift generation, and learned the importance of experimental design and uncertainty analysis in fluid dynamics studies.