OBJECT

The aim of this experiment is to obtain the pressure distribution around an airfoil, and to determine the lift, drag and pitching moment variations with different angles of attack.

THEORY

The drag force, $F_D$ is the component of force on a body acting parallel to the direction of motion.

The drag coefficient $C_D$ is defined as

$$C_D = \frac{F_D}{\frac{1}{2} \rho \, v^2 \, A_P}$$

$A_P$ is selected as maximum projected wing area and $1/2 \, \rho \, v^2$ is dynamic pressure in terms of free stream velocity $v$. (for other objects projected frontal area is used)

If compressibility and free surface effects are neglected drag coefficient is a function of Reynolds number only, for a given configuration. ($Re = \rho \, v \, t / \mu$, $t$ is the maximum thickness of the airfoil section)
The total drag force, \( F_D \) is the sum of the friction drag and pressure drag. Fig 1 illustrates the two extremes.

\[
F_D = \int \tau_w \, dA
\]

Fig. 1 Flow Over a Flat Plate at Different Orientations

In Fig 2 Drag coefficients for a few selected objects are given. This experimental data is for single objects immersed in an unbounded fluid stream. Wind tunnel tests require corrections to simulate the condition of an unbounded flow.
By streamlining, the separated flow region can be reduced, thus pressure drag decreases. However since surface area also increases so as the friction drag, in Fig 3, there is an optimum streamline shape which gives minimum total drag.

Lift force $F_L$, acts on an immersed body normal to the relative motion between fluid and the body. Fig 4 illustrates the production of dynamic lift on a cambered airfoil at angle of attack ($\alpha = 8.6^o$)

![streamlines and pressure distribution](image)

Fig. 4 Streamlines and pressure distribution about a cambered airfoil, at angle of attack $\alpha = 8.6^o$

The lift coefficient $C_L$ is defined as

$$C_L = \frac{F_L}{\frac{1}{2} \rho \, \alpha^2 \, A_p}$$

where $A_p$ is projected wing area and it is equal to chord times span (see Fig. 8)

*Lift Coefficient From Pressure Distribution:*
The lift coefficient may be calculated from the pressure distributions on the upper and lower surfaces such as shown in Fig 4b.

Referring to Fig. 5 and Fig. 6, pressure coefficient $C_P$, and the components of the resultant force, $C_Z$ and $C_X$ in respective directions are defined as follows,

$$C_Z = \int_{\text{surface}} C_P d\left(\frac{x}{c}\right)$$

where

$$C_P = \frac{P_a - P_i}{\frac{1}{2} \rho v^2}$$

$$C_X = \int_{\text{surface}} C_P d\left(\frac{z}{c}\right)$$

$(P_a)$ is the pressure on airfoil surface and $P_i$ inlet pressure (reference pressure)

The ordinates of the highest and lowest points on the section are $z_2$ and $z_1$ respectively. From geometry

$$C_L = C_Z \cos \alpha - C_X \sin \alpha$$

$$C_D = C_Z \sin \alpha + C_X \cos \alpha$$

For numerical integration of $C_X$ and $C_Z$ please refer to Appendix.
Pitching moment $M$, is the moment acting in the plane containing the lift and the drag. It is positive when it tends to increase the incidence. The moment coefficient $C_M$ (with respect to 0.25$c$) is defined as

$$C_M = \frac{M}{\frac{1}{2} \rho \text{v}^2 \text{A}_c c}$$

To complement the theory presented in this section references can be used, following keywords may guide you:

- Laminar-flow and Conventional Airfoil Sections.
- Optimum Shapes for Low Drag
- Designation of Airfoil Section Shapes
- Stall
- Polar Plots (plots of $C_L$ vs $C_D$)
- Lift and Drag in Automotive Applications
- Induced Drag
- Effect of Flaps on Aerodynamic Characteristics of Airfoil Sections.
- Lift and Circulation
EXPERIMENTAL SET UP

300 mm x 300 mm Suction Wind Tunnel :

For better understanding refer to Fig 7

![Diagram of 300 mm x 300 mm Suction Wind Tunnel](image)

The tunnel, of the open circuit type, is constructed mainly in aluminium, and supported by a tubular steel framework. The air enters the tunnel through a carefully shaped inlet, the entrance being covered by a protective screen. The working section is of perplex giving full visibility and the various models are supported from one of the side walls or by means the three component balance. At the upstream end of the working section there is a static tapping and a total head tube. While at the downstream end there is a pitot static tube which may be traversed over the full height of the working section. (Fig 8)
After the working section a diffuser leads to the axial flow fan unit and the air velocity is controlled by means of a double butterfly valve on the fan outlet. The fan discharges by way of a silencer. Maximum air velocity is such that pressure differences of the order of 300 mm water are developed and these may be read with suitable accuracy by the simple manometer provided.

As an airfoil model NACA 0012 profile is used. In Fig. 9 the locations of pressure tappings and dimensions of the model are given.

**Fig. 8 Dimensions of the Test Section**

**Fig. 9 Pressure Tapping Locations of the Airfoil Model**

*Three Component Balance:*
The balance is mounted on the side wall of the test section of the tunnel, and it will be used to measure lift and drag forces acting on the model.

Referring to Fig 10 its main framework comprises a mounting plate which is secured to the wind tunnel working section and carries a triangular force plate. The force plate and mounting plate are connected by three supporting legs, disposed at the corners of the force plate. Each leg is attached to the force plate and mounting plate by spherical universal joints. The effect of this is to constrain the force plate to move in a plane parallel to the mounting plate, while leaving it free rotate about a horizontal axis. The necessary three degrees of freedom are thus provided.

The model support is free to rotate in the force plate for adjustment of the angle of incidence (attack) of the model while its position may be locked by means of an incidence clamp.

The force plate may be locked in position by two centring clamps, and these should always be tightened when the balance is not in use, or when changing models.

The forces acting on the force plate are transmitted by way of flexible cables to strain gauge load cells which measure respectively the fore and aft lift forces and the drag force. The drag cable which lines horizontally, acts on a line through the centre of the model support, while the two lift cables act vertically through points disposed equidistant from the centre of the model support and in the same horizontal plane as the support.
The sum of the forces on the fore and aft lift tapes thus gives the lift on the model, while the difference when multiplied by 0.127 gives the pitching moment in Newton-meters.

A drag balance spring acts on the force plate to apply pre-load to the drag load cell.

The output from each load cell is taken to a strain gauge amplifier carried on the mounting plate and thence via a flexible cable to a display unit comprising a set of three electronic voltmeters, showing the output from the respective load cell circuits (Fig. 10 Lower right).

*Computer Control With The Wind Tunnel*

The software COMPEND W which runs on a PC is interfaced with three component balance and the 20 way scanning valve which constrains also the pressure transducers and single axis traverse mechanism.

When the Equipment interface for computer control and data acquisition, COMPEND W, is used with the wind tunnel it is possible to present experimental results rapidly and clearly on the video display unit, with copies available for analysis from the printer.

Each data point recorded by COMPEND W is the mean of several separate readings taken over a specified time period. Hence high frequency fluctuations can be averaged.

Setting up the system and running COMPEND will be demonstrated by your lab assistant during experiment.

*20 way scanning valve :*

The 20 way scanning valve provides a method of performing 20 pressure measurements in sequence automatically. Tubes are connected to 20 solenoid valves on a common manifold. These valves are appeared in turn to allow the pressure to act on a
sensitive differential pressure transducer with a full scale range of 500 mm H₂O. The opening of the valves can be manually stepped using the up and down buttons, automatically stepped at a present time interval or controlled by COMPEND W when the scanning valve is set to PULSE mode. Thus data from any pressure port on the airfoil model can be obtained by selecting the pressure port number.

The two additional pressure transducers, (PRESSURE 2 [P2] and PRESSURE 3 [P3]) have a full scale range of 700 mm H₂O. These transducers are used to measure dynamic pressure at inlet and exit of the test section. Thus connected to total and static tubes differentially at these locations. (See Fig 8)

TEST PROCEDURE

1. Read Fluid Mechanics Laboratory Rules and Regulations before starting which is posted in technicians room.

2. Check whether the centring clamps are tight, set the airfoil support at zero incidence and tighten the incidence clamp.

3. Switch on the mains supply in the force display unit. It is desirable to allow a warm-up time of fifteen minutes for the load cells before taking any readings. During this time record atmospheric pressure and temperature.

4. Release the centring clamps. Record zero readings of aft lift, fore lift and drag.

5. Start the electric motor which drives the wind tunnel. Set the tunnel speed using the butterfly valve. Record inlet dynamic pressure as a difference of inlet static and total pressure manometer readings. Use this value to calculate wind velocity.

6. Press "Hold Display" button on the display unit Record the readings of the digital voltmeter.

7. By 3° degree increments increase the angle of attack and make a series of measurements of lift and drag up to 18 degree of attack. This angle may be set by releasing the incidence clamp, and rotating the model support to the desired angle and re tightening the clamp.

THE CENTRING CLAMP MUST BE LOCKED BEFORE RELEASING THE INCIDENCE CLAMP OR HANDLING THE FORCE PLATE IN ANY
WAY OTHERWISE THERE IS A RISK OF DAMAGING THE LOAD CELLS.

Due to blockage of the airfoil at high angles of attack, tunnel velocity may change, make the experiment at fixed tunnel speed by regulating with the butterfly-valve.

*Pressure distribution on the airfoil.*

8. Set the airfoil to an angle selected by your lab assistant.

9. Record pressure from [P1] cell on the COMPEND main screen at the displayed scanning positions. The scanning will continue manually until the pressure at all twenty points on the airfoil have been measured and recorded.

10. Record Dynamic pressure for the calculation of free stream velocity from PRESSURE 2 cell on the COMPEND main screen.

**CALCULATIONS**

1. Free stream velocity

\[
\nu = \sqrt{\frac{2 \Delta P_l \cdot \rho_{\text{water}}}{\rho_{\text{air}}}}
\]

where \(\Delta P_l\) is the upstream dynamic pressure in m H\(_2\)O.

2. Drag, lift forces and pitching moment at each angle of attack

\[
F_D = D
\]

\[
F_L = (A + F)
\]

\[
M = 0.127 (F - A)
\]
where A, F and D are obtained after correcting the readings by zero readings

A: Lift force from aft load cell in Newtons
F: Lift force from fore load cell in Newtons
D: Drag force from drag load cell in Newtons


4. Calculate pressure coefficients:

$$C_p = \frac{P_s - P_i}{\frac{1}{2} \rho u^2}$$

where

$P_s$: Static pressure on the surface of the airfoil in Pa.
$P_i$: inlet static pressure
$u$: free stream velocity

and complete Table 1. in Appendix.

5. After obtaining pressure distribution around the airfoil, using Table 1. and the expressions given in Theory and Appendix calculate lift and drag coefficients.

COMPARE them with the ones you measured directly from the balance.
GRAPHS

Draw the following curves

a) On the same graph plot $C_l$, $C_d$ and $C_m$ vs. the angle of incidence label the curve with the Reynolds number of the flow.

b) Plot $C_p$ vs $x/c$ - along the chord direction at the selected angle of attack

UNCERTAINTY ANALYSIS

1. INTRODUCTION

As the second part of the experiment, you will perform an uncertainty analysis for the Wind Tunnel Experiment.

The term uncertainty is used for refer to a "possible value that an error may have". It is necessary to make a distinction between single sample and multiple sample uncertainty analysis. The distinction hinges on whether or not a "large" or "small" number of independent data points are taken at each test point and on how the data are handled.

2. THEORY

2.1 Describing a variable

Consider a variable $X_i$ which has a known uncertainty $\delta X_i$. The form of representation of this variable and its uncertainty is
\[ X_i = X_i( \text{measured}) \pm \delta X_i \ (20:1) \]

This statement should be interpreted to mean the following:

- The best estimate of \( X_i \) is \( X_i( \text{measured}) \),
- There is an uncertainty in \( X_i \) that may be as large as \( \pm \delta X_i \),
- The odds are 20 to 1 against the uncertainty of \( X_i \) being larger than \( \pm \delta X_i \).

The value of \( \delta X_i \) represents \( 2\sigma \) for a single sample analysis where \( \sigma \) is the standard deviation of population of a possible data set.

2.2 *The Root Sum Square (RSS)*

The results \( R \) of the experiment is assumed to be calculated as a function of a number of independent parameters represented by

\[ R = R \ (X_1, X_2, X_3, \ldots, X_m) \]

The effect of the uncertainty in a single measurement on the calculated results, if only that measurement were in error, would be

\[ \delta R X_i = \frac{\delta R}{\delta X_i} \delta X_i \]

The partial derivative of \( R \) with respect to \( X_i \) is the sensitivity coefficient for the results \( R \) with respect to measurement \( X_i \). When several independent variables are used in the function of \( R \), the individual terms are combined by RSS method.

\[ \delta R = \left( \sum_{i=1}^{m} \left( \frac{\delta R}{\delta X_i} \delta X_i \right)^2 \right)^{\frac{1}{2}} \]
2.3 *Single sample analysis*

Unlike a multiple sample experiment, in which the variable error in a set of measurements can be determined from variance of the set of itself, simple sample experiments require an auxiliary experiment in order to estimate the variable component of the uncertainty.

This usually takes the form of a set of independent observations of the process at a representative test condition over a representative interval of time. The principal difficulty here is finding $\sigma$, the standard deviation of the population from a smaller than infinite set of observations. $\sigma$ is different from the standard deviation of the set of observations made in the auxiliary experiment, but can be estimated from it.

In single sample uncertainty analysis, each measurement is assigned three uncertainty value; its zeroth, first and $N_{th}$ order uncertainties.

* The zeroth order uncertainty of a measurement is the RSS combination of all the fixed and random uncertainty components introduced by the measuring system.
* The first order uncertainty of a measurement describes the scatter that would be expected in a set of observation using the given apparatus and instrumentation system, while the observed process is running. The first order uncertainty includes all effects of process unsteadiness as well as the variable error effects from the measuring system. The first order uncertainty interval must be measured in an auxiliary experiment.
* The $N_{th}$ order uncertainty of a result is a measure of its overall uncertainty, accounting for all sources of fixed and variable errors. This is the value that should be reported as the overall uncertainty. The NT order uncertainty is calculated as the RSS combination of the first order uncertainty $\delta X_{i,1}$ and the fixed errors from every source.

3. **PROCEDURE**

Make a single sample analysis by performing an auxiliary experiment at a certain airfoil position (with fixed incidence and fixed tunnel speed).

i) Take the necessary data after disturbing the system and returning back to the fixed operating point. You can disturb the system in various ways like by playing with the butterfly-valve, angle of attack or their combination, but make sure that you take the disturbance back so that you are at fixed operating point again, just then you can take your readings.
ii) Referring to the above terminology and to the lecture notes make an uncertainty analysis for the following terms and report their Nth order uncertainty:

* inlet dynamic pressure readings, 

\[ \Delta P_i \]

* display unit readings,

\[ A,F,D \]

Assume that all the fixed error on display unit readings are corrected by subtracting zero values. Also assume that there is no fixed error on \( \Delta h \) (inlet dynamic pressure manometer).

iii) Find out the uncertainty for \( R_e, C_l, C_D \)

iv) Use inlet dynamic pressure manometer to find the fixed error of the inlet pressure transducer.

DISCUSSION AND CONCLUSION

Discuss what have you observed during the experiment, NOT what you done. Also discuss the results (do you think they are reasonable, why or why not, compare the behaviour of the curves and relate them to each other, etc.). Write about the shortcomings of the experiment and your recommendations. Note that the originality of the discussions is for your benefit. Remember what is graded is the degree to which you can correctly comment on the experiment and the results.

REFERENCES

1. Moffat, R. J.; "Describing The Uncertainties in Experimental Results"; Experimental Thermal and Fluid Science no:1 pp. 3 - 17; 1988.


5. Lecture notes by Orhan Kural.


7. Fox, Robert W.; "Introduction to Fluid Mechanics"; 1985