Aerodynamic analysis of aircraft model using indigenously developed wind tunnel facility

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Abstract. This paper presents a design of force balance setup that can measure lift force acting on the aircraft model. The setup was developed indigenously and installed in an open circuit low-speed wind tunnel. It mainly consists of two components viz. a traverse mechanism that can hold the model in the test section at different angles of attack and air speeds and a supporting frame to hold the traverse mechanism over it. The spring balances are used to obtain lift force readings at different angles and air speeds. The experimental and numerical investigations were done in the wide range of Reynolds number (range: 0.55 to 1.12 lakh) and angle of attack (range: -6º to 20º). The results are presented in terms of pressure contours, velocity contours, pressure coefficient and lift coefficient. From the experiments it was found that value of lift coefficient increases with angle of attack and stalling occurs at 18º for all the air speeds. However, in the numerical results the stalling was observed little earlier than 18º angle of attack. The experimental results were compared with CFD results and an average relative error of 18% was observed which may be due to assumption of 2-D airfoil in CFD analysis.

Keywords: aerodynamics, aircraft, airfoil, CFD, lift, wind tunnel

1. Introduction

Wind tunnels are large cross-section tubes of various shapes with air moving inside them. Air is blown around an object in the wind tunnel, which can be considered as the moving object in the stagnant air as there is a relative motion between the object and air. These tunnels are used to mimic the conditions of an object in flight. Aero-dynamists, engineers, and scientists use wind tunnels to study the aerodynamic characteristics of different objects, from jet wings to car windshields. By getting a better understanding of the way air moves around or through objects under test, designers and manufacturers can devise and create faster, more reliable, safer, and more efficient products. Low-speed wind tunnels move air inside at a very low Mach number (M), with speeds of air in the test section up to 480 km/h (~ 134 m/s i.e., M = 0.4) [1].

In wind tunnels, test scale models of aircraft and spacecraft can be tested while some wind tunnels are large enough to accommodate full-size versions of vehicles. Considering the case for testing an aircraft model, the main motive is to test the wings of the aircraft because wings are responsible to generate the lift force required by the aircraft to fly. The magnitude of lift will depend on the kind of airfoil used in the wing and most commonly National Advisory Committee for Aeronautics (NACA) airfoils are used and its nomenclature is based on the numbering that decides the quality and performance of that airfoil.
Li et al. [2] used a low speed closed circuit wind tunnel for experimentation in which a support system was used to hold the model. For force measurement, a six-component sting-type strain gauge balance in conjunction with a signal amplifier was used. Mizoguchi et al. [3] used an open-circuit wind tunnel to test wings of different aspect ratios. In order to measure aerodynamic coefficients three-component balance was used. A strut was used to hold the model in the inverted position at different angles of attack (AoA). Laitone [4] tested the performance of different wings at low Reynolds number by measuring lift and drag forces and for this purpose, a sensitive two-component beam balance was designed. The wing was hung vertically from the beam balance mounted on the top of the tunnel.

Mueller and Batill [5] conducted experiments to study the separation characteristics for two-dimensional (2-D) airfoil at different Reynolds number (Re) between 40,000 to 400,000. A highly sensitive external strain gauge platform balance was used, and it was mounted with an aircraft model in the tunnel. Saleh et al. [6] proposed a design of multi-component strain-gauge external balance with trial-and-error method using finite-element simulations. This gauge was manufactured, and calibration was done for lift, drag, and pitching moment and interference error was found to be less than 2%.

Sahin and Acir [7] performed a numerical analysis of NACA 0015 airfoil in ANSYS Fluent to determine lift and drag coefficients. A semi-circular-rectangular shaped flow domain was selected and Spalart Allmaras viscous model was used. Muftah [8] used similar shaped domain for analysis of NACA 2414 airfoil in COMSOL Multiphasic Design modeler. Spalart Allmaras viscous model was used to obtain contours for velocity and pressure. Kulshreshtha et al. [9] carried out the numerical study for three airfoils i.e., NACA 2412, NACA 2414, and NACA 2415 using the k-epsilon viscous method and compared their lift and drag coefficients. Sharma [10] investigated four airfoils numerically in Fluent at low Reynolds number to calculate force coefficients and compared them to find the airfoil with the best performance. Spalart Allmaras viscous model was chosen for the analysis.

2. Experimental work
In the present study, the experiments were performed in an open-circuit low-speed wind tunnel with an aircraft model in the Reynolds numbers range of 55413 to 112505 and angles of attack range of -6º to 20º.

2.1. Wind tunnel
The experiments were performed in the subsonic open circuit wind tunnel (suction type) which was indigenously developed at Mechanical Engineering Department, Nirma University and it is shown in figure 1. The wind tunnel consists of an entry section, settling chamber, convergent section, test section, diffuser section, and fan at end of the wind tunnel. To minimize the turbulence level, a honeycomb structure is provided at starting of the settling chamber. The size of the test section is 381 mm × 254 mm (15” × 10”). The fan is incorporated with a variable frequency drive (VFD) to generate different air speeds corresponding to the frequency given. The calibration of the wind tunnel was carried out by using pitot-tube and micro manometer to measure air speeds at different locations inside the test section at various fan speeds. In the present study, experiments were carried out at four different air speeds i.e., 11.88 m/s, 16.4 m/s, 20 m/s, and 24.12 m/s and corresponding Reynolds number.
All the measuring instruments were calibrated before putting in use. The experimental uncertainty in the lift coefficient was estimated in accordance with the procedure given by Kline and McClintock [11] and the relative uncertainty in the lift coefficient was found to be in the range of $\pm 5\%$.

### 2.2. Aircraft model

In order to perform the experiments, three dimensional (3-D) aircraft model was developed as shown in figure 2.

![Figure 2. Aircraft model used for experimentation.](image)

It was fabricated using mild steel and teak wood and to hang the model strings were attached to the wings and fuselage. The details of the wing profile are provided in table 1.

**Table 1. Wing specifications**

| Wing     | Details          |
|----------|------------------|
| Profile  | NACA 2414        |
| Material | Teak wood        |
| Wingspan | 340 mm           |
| Chord length | 72 mm         |
| Planform area | 23800 mm$^2$ |
2.3. Traverse Mechanism
The traverse mechanism consists of a stainless-steel tube of 1 x 1 inch\(^2\) cross-section and bolts. It was required to move the wing of the model, keeping the tail at constant height, so that the angle of attack of the wing can be varied. Two holes were drilled on the front and top faces which were at the same distance as of string on the aircraft wing. Holes on the top face accommodate bigger bolts having a slot along their length. Smaller bolts were added perpendicularly in these slots from the front face, and this will restrict the rotational motion of the bigger bolt and allows only vertical translational motion. With this arrangement angle of attack of the aircraft model in the wind tunnel test section could be changed. Apart from this, two bolts were welded at the end of the bigger bolt to hold spring balance using a nut. Figures 3 and 4 show a 3-D CAD model and photograph of the traverse mechanism respectively.

![Figure 3. 3-D CAD model of traverse mechanism.](image3.png)

![Figure 4. Traverse mechanism.](image4.png)

2.4. Supporting frame
Supporting frame was required to hold the traverse mechanism and it can accommodate the mechanism when placed over the wind tunnel roof. The dimensions of the stand were decided based on the dimensions of the test section of the wind tunnel and aircraft model wing. Figure 5 shows the supporting frame used for the experimentation.
2.5. Experimental setup
A 3-D CAD model of the complete assembly comprised of the aircraft model in the test section, traverse mechanism, and frame is shown in figure 6.

It can be observed that the aircraft model is hanged upside-down because in this arrangement lift force will be generated downwards and it will create tension force in the strings. This tension force was measured using the spring balance. Figure 7 shows the test section of the wind tunnel.
When air blows in the tunnel it tends to push the model backward and this will include a drag component in the force readings. In order to overcome this and to prevent the backward motion of the aircraft model, a C-section was attached behind the aircraft model with the tunnel roof as shown in figure 8.

**Figure 8.** C-section in test section.

### 2.6. Experimentation

Experiments were performed to obtain the lift force (L) generated by the aircraft model when it was in the wind tunnel at a different angle of attack and air speeds. Air speed in the tunnel depends on the speed of the fan installed at end of the tunnel. Fan speed depends on the frequency of the Variable Frequency Drive (VFD) and this frequency was already calibrated with the air speed in the wind tunnel.

Experiments were performed for angle of attack varying from -6° to 20° with a step of 2° each. At each angle, the wind tunnel was operated at four different speeds viz. 11.88 m/s, 16.4 m/s, 20 m/s, 24.12 m/s and based on these speeds, Reynolds number (Re) was found as 55413, 76496, 93288 and 112505 respectively. Three force scales are used to measure the force acting on the aircraft model when the tunnel is running, and readings are added to get the total force for the wing. This sum also includes the
weight of the model which is subtracted from this sum to obtain the net lift force. The lift coefficient and pressure coefficient were calculated using equations (1) and (2).

\[
C_L = \frac{L}{\frac{1}{2} \rho A v^2} \tag{1}
\]

\[
C_p = \frac{p - p_\infty}{\frac{1}{2} \rho A v^2} \tag{2}
\]

where, \( \rho \) is density of air (kg/m\(^3\)), \( A \) is area (m\(^2\)), \( v \) is air speed (m/s), \( p \) is static pressure (N/m\(^2\)), \( p_\infty \) is free stream pressure (N/m\(^2\)).

2.7. Experimental results
The lift force acting on the model was obtained at different angles of attack and air speeds and calculations were carried out to obtain the value of the lift coefficient (\( C_L \)). Values of \( C_L \) are plotted against AoA at different Re as shown in figure 9.

![Figure 9. Variation of lift coefficient with angle of attack at different Re.](image)

From figure 9, it can be observed that \( C_L \) increases with Re and it also increases with AoA up to a point called stall angle and reduces after this. It was found that the stall occurs at around 17º AoA for all the Reynolds numbers. At 0º AoA value of \( C_L \) is greater than zero and it becomes zero at negative AoA, this is one of the characteristics of the cambered airfoil profile. Among the previous studies, similar results were also reported by Sahin and Acir [7] for NACA 0015 profile, by Muftah [8] for NACA 2414 airfoil profile and by Kulshreshtha et al. [9] for NACA 2412 profile.

3. Numerical investigations
The two-dimensional numerical investigations of NACA 2414 airfoil were carried out by computational fluid dynamics (CFD) analysis software ANSYS Fluent to obtain lift coefficient at different AoA and Re. These results will be comparable to the experimental results because the wing used for the experimental work is of uniform cross-section throughout its span. CFD analysis is performed for 2-D NACA 2414 from AoA -4º to 16º with a step of 4º each to obtain the value of lift Coefficient (\( C_L \)) at four different Re corresponding to the experimentation.

3.1. Computational domain and grid generation
For the analysis, a semi-circular rectangular 2-D domain was selected which had a radius of 15C (C is chord length) and a rectangular portion length of 20C. The computational domain was discretized using the hexahedral grid. In order to study the effect of grid size, a grid independence test was performed by varying the edge sizing of the mesh from 0.0035 m to 0.05 m and it was found that total grid elements of around 250,000 were appropriate and results do not vary on the further grid refinement. Based on the
grid independence test, edge sizing of 0.005 m was chosen for the further simulations and corresponding number of grid elements were 258664. The computational domain and the mesh are shown in figure 10 (a) and (b).

![Figure 10](image)

**Figure 10.** (a) 2-D computational domain and (b) mesh used for CFD analysis.

### 3.2. Solution methodology

In order to capture the turbulence, realizable k-epsilon viscous model was selected for the numerical analysis because it can give solution convergence even at higher AoA and it is quite accurate method for flows involving boundary layers and separation. The semi-circular portion was chosen as velocity inlet boundary condition whereas airfoil was given no-slip shear condition. The coupled scheme was selected for pressure-velocity coupling and default settings for spatial discretization were kept. An absolute criterion for residual monitors was considered as $10^{-6}$ and initial values for calculation were defined based on the velocity input.

### 3.3. Results and discussion

A comparison is made between the values of lift coefficient obtained from CFD analysis and experimental values for different values of Reynolds number to check for the error and deviation in the results. Figures 11 and 12 show plot of comparison corresponds to $\text{Re} = 55413$ and $\text{Re} = 93288$ respectively. It is observed that in CFD results stall occurs earlier i.e., at 9° as compared to experimental results i.e., at 16°. Also, the experimental values of lift coefficient are found to be greater than CFD values at both the Re with an average relative error of 18%. This error can be due to the fact that the experiments were performed for a 3-D aircraft model whereas CFD analysis was carried out for a 2-D airfoil profile. Moreover, turbulence in the wind tunnel, the least count error of the force balance device, swaying motion of the model, etc. may also lead to some error.
From the CFD analysis, velocity and pressure contours were obtained for the airfoil at different angles of attack for a given Reynolds number. Figure 13 depicts velocity contours at \( Re = 93288 \) at different AoA. It can be observed that velocity is relatively higher at the top edge of the airfoil as compared to the bottom edge except at \( \alpha = 4^\circ \). This created low pressure at the top edge and high pressure at the bottom edge. According to Bernoulli’s theorem, as a result of this pressure difference, an upward lift force is generated. At \( \alpha = -4^\circ \), the situation gets reversed, velocity is higher at the bottom edge and lower at the upper edge. This creates a low-pressure zone at the bottom and produces a downward lift force.
Figure 13. Velocity contours at different angles of attack at Re = 93288.

It can be seen that the flow separation starts after \( \alpha = 8^\circ \) and as the angle increases the separation point starts shifting towards the upper edge. When \( \alpha \) reaches \( 16^\circ \), the flow is separated from around 50% of the chord length of the airfoil and due to this lift force reduces significantly.

The pressure contours were obtained at different angles of attack at Re = 93288 as shown in figure 14. As discussed, in all the contours (except \( \alpha = -4^\circ \)), velocity is found higher at the top edge, and this forms a low-pressure zone near the top region. Due to this an upwards lift force is generated. After \( \alpha = 8^\circ \), as AoA is increased the pressure difference across the airfoil is reduced and this resulted in decreases in the magnitude of the lift force. In case of \( \alpha = -4^\circ \), there is a low-pressure zone at the bottom edge and because of this direction of the lift force gets reversed (i.e., downwards).
Figure 14. Pressure contours at different angles of attack at Re = 93288.

The variation of pressure coefficient \( (C_p) \) obtained from the numerical analysis along the upper and lower surfaces of the airfoil at Re = 93288 for different AoA is shown in figure 15. The direction of the y-axis is reversed so that the upper edge remains up in the plot as it will be subjected to the negative value of \( C_p \). Higher the difference in the value of \( C_p \) between upper and lower edges, higher will be the value of lift force acting on the airfoil and this can be observed from these plots.

Figure 15. Pressure contours at different angles of attack at Re = 93288.

Among the previous works, similar results were also reported by Kamas and Omar [12] for NACA 2414 airfoil at different speeds and by Madhavan [13] for NACA 2414 airfoil.
4. Conclusions

In the present study, a design and development of force balance setup were presented that can measure lift force acting on the aircraft model. The setup was developed indigenously and installed in an open circuit low-speed wind tunnel facility. It consists of a traverse mechanism that can vary the angle of attack of the model and supports the model in the wind tunnel with help of strings with the force balance. The experimental and numerical investigations were done in the Reynolds number range of 0.55 to 1.12 lacks and angle of attack range of -6° to 20°. The major conclusions drawn from the study are as under:

- From the grid independence test, it was found that an edge size of 0.005 m and the corresponding number of grid elements of 258664 were appropriate for the computational analysis.
- From the velocity contours correspond to Re = 93288, it was observed that flow gets detached from the airfoil surface after 8°, i.e., stall occurs after this point.
- From pressure contours correspond to Re = 93288, it was observed that there was higher pressure at the upper surface and low pressure at the lower surface for AoA = -4°, which created a negative lift. However, for positive AoA, there was lower pressure on the upper surface and higher pressure on the lower surface which induces positive lift. Moreover, the magnitude of pressure difference and hence the lift force increased with AoA up to stall condition.
- Comparison between experimental and CFD results for C_L at Re = 55,413 and Re = 93288, showed that stall occurs a little early in case of CFD analysis and the relative average error of 18% was observed. This error can be due to the fact that the experiments were performed for a 3-D aircraft model whereas CFD analysis was carried out for a 2-D airfoil profile.
- The average relative uncertainty for the lift coefficient was found to be in the range ±5%.

5. References

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