An Experimental Validation of Numerical Post-Stall Aerodynamic Characteristics of a Wing

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ABSTRACT

Experiments are conducted on a 3D wing with section NACA4415 at four different Reynolds numbers for a range of angles of attack spanning both pre and post-stall regimes of flow. The results are compared with literature and output from an in-house code, which predicts post-stall aerodynamic characteristics. Comparison is sought primarily for the post-stall data.

**Keywords:** experiment, post-stall, aerodynamics, numerical, VLM3D

1. INTRODUCTION

The interest in extending linear methods to include post-stall regimes of flow has existed since Prandtl’s Lifting Line Theory. A vortex-lattice method algorithm based on a novel decambering approach\textsuperscript{1} uses an estimate of the reduction in camber at post-stall angles of attack to account for the change in the coefficients of lift, $C_l$ and pitching moment, $C_m$ from the inviscid case. In a more recent approach, a numerical iterative vortex lattice method\textsuperscript{2} is developed to study flow past wing(s) at high angles of attack where the separated flow is modelled using nascent vortex filaments distributed along wing-span. Researchers have also used different ways of estimating the effective angle of attack to account for the loss in lift at high angles of attack.

Earlier investigations were made at lower Reynolds numbers in the small atmospheric wind tunnels and extrapolated to compare with the full scale actual flight conditions. Due to scale effect, the aerodynamic coefficients vary with the change in Reynolds numbers that leads to the practical necessity of requiring the flow around the model aerodynamically similar to the full-scale prototype. Eastman and Sherman\textsuperscript{3} made attempts to provide section characteristics at any free air value of Reynolds numbers and discussed influence of scale effect on airfoil section characteristics incorporating various corrections for length and turbulence.

In a similar work, Naik and Ostowari\textsuperscript{4} performed a number of experiments to study the stalling...
aerodynamic characteristics as a function of aspect ratio, airfoil thickness and Reynolds numbers. They emphasised the insensitivity of lift and drag coefficient in the post stall region after studying the variation of these aerodynamic coefficients in a wide range of aspect ratios and Reynold numbers. To investigate the contamination effects on airfoil performance in horizontal axis wind turbine, Hoffman conducted experiments with the application of leading edge grit roughness (LEGR). After subjecting a NACA4415 airfoil model to various Reynolds numbers in a subsonic wind tunnel under steady and unsteady conditions, they observed 16% reduction in maximum lift coefficient and 67% increase in drag coefficient after the application of LEGR.

The investigation carried out in the present study identifies aerodynamic characteristics of NACA 4415 wing section at multiple Reynolds numbers in the post stall region. The primary objective of this paper is to get experimental corroboration of the numerical post-stall predictive algorithms developed. It is also expected to use the ‘decambering’ technique as a physical tool to control boundary layer behavior.

2. EXPERIMENTAL SETUP

2.1 Wind Tunnel Facility

In this paper, results are reported from experiments conducted in the Transition and Flow Control Laboratory, Aerospace Engineering Department, IIT Madras. All tests were conducted in a medium size, subsonic, open circuit wind tunnel having a test-section area of 0.5m × 0.5m × 2m as shown in Fig.1. A six bladed fan installed downstream of the test section is rotated by a 5 HP motor. This being a suction-type wind tunnel, the gauge pressures inside the test section may be negative. The Reynolds numbers were varied by changing the tunnel speed with the same set of model, since the tunnel operates on atmospheric pressure only. The minimum and maximum wind speeds obtained in the test section were 5 m/s and 32 m/s respectively.

![Fig. 1: Schematic diagram of Test Section and Wind Tunnel Setup at IIT Madras](image-url)
2.2 Wing Model Specification

The wing models used have a NACA4415 airfoil section and a chord length, \( c=6.3 \text{cm} \) and a span, \( b=40 \text{cm} \). Separate models with the same dimensions have been used for pressure and force measurement. The material used for wing model is carbon fibre. The rotation of the wing model was controlled by a turning table through an opening on the tunnel floor. The pressure distribution over the wing was obtained by using a wing model with pressure tappings on its mid-span on the upper and lower surfaces along the chord. Total of 22 pressure taps were placed around the wing (12 and 10 pressure taps are placed over the upper and lower surface respectively) to have a good assessment of pressure distribution in the chordwise direction. The second wing model is fabricated to directly acquire the wind forces and moments through load balance.

2.3 Measurement Techniques

Measurement of Pressure and force have been carried out separately with separate models and measuring instrument.

2.3.1 Pressure Measurement

Data was acquired and processed from 22 surface pressure taps using transducer called scanivalve, one individual tunnel pressure transducer and an angle of attack potentiometer. The scanivalve was first calibrated by subjecting the pressure taps with a known pressure through a pressure pump. Pressure data is acquired in a 50x150 matrix form using a Lab view interface after connecting the wing model pressure taps to scanicalve. The further post-processing of pressure data is done after converting the gauge pressures into absolute pressures allowing for the residual pressure in each port.

The filtered pressure data is used to evaluate coefficients of pressure, lift and drag using the following empirical relations.

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

\[
C_l = \frac{L}{\frac{1}{2} \rho A V^2} 
\]

\[
C_d = \frac{D}{\frac{1}{2} \rho A V^2} 
\]

The lift and drag forces on the airfoil have been calculated by integration of measured pressure distribution over the airfoil surface using MATLAB.
2.3.2 Force Measurement

A three-component load balance consisting a balance mechanism, strain gauge instrumentation amplifiers and Microcontroller based measuring system have been used for measuring lift and drag forces on the wing model. The balance mechanism is designed as a floor balance. The model is mounted on the stem that protrudes into the test-section and fixed on a metric plate, which transfers the loads on to 4 strain elements. The outputs from the strain gauge mounted on the strain elements are then amplified. The calibration coefficients were first calculated by a relationship between the measured outputs and the physical parameters to which the instrument is subjected. The strain gauge instrumentation is designed in the linear range of sensitivities. The calibration coefficients were then calculated from the slope of these linear variations and expressed in the following equation

The Calibration coefficients used are \( D_{ij} = \begin{bmatrix} -1.8978 & -1.8964 & -0.21153 \\ -19.9898 & 13.1284 & -30.9883 \\ 0.14817 & -0.07042 & 0.85827 \end{bmatrix} \) (4)

The load balance system with the wing model is mounted on the wind tunnel after calibrating the instrument. Voltages measured by the microcontroller were converted into forces using the following conversion equation.

Lift \( L = \left( \frac{D_{11}V_1 + D_{12}V_2 + D_{13}V_3}{G} \right) \times 1000 \)

Drag \( D = \left( \frac{D_{21}V_1 + D_{22}V_2 + D_{23}V_3}{G} \right) \times 1000 \)

Pitching Moment \( PM = \left( \frac{D_{31}V_1 + D_{32}V_2 + D_{33}V_3}{G} \right) \times 1000 \) (5)

Raw data points of each individual observation are demonstrated in an I-Chart as shown in Fig. 2, which exemplifies the variation of lift and drag raw data points with respect to the mean line.

![I-Chart of Lift](image1)

![I-Chart of Drag](image2)

Fig. 2: Statistical representation and filtering of raw data points measured by microcontroller
The Control limits and variation from the mean value is calculated from the following statistical relation

\[ UCL = \bar{x} \pm 3\sigma \]  

(6)

The standard deviation is set in a way that all the data points lying under \( \pm20\% \) from mean line have being considered. The data points not falling in the prescribed limit are outliers and have been discarded.

3. NUMERICAL ANALYSIS

The numerical code used for analysis is VLM3D, which is an in-house 3D code developed to implement the post-stall predicting tool based on ‘decambering’. The chordwise camber distribution at each section of the wing is reduced to account for the viscous effects at high angles of attack. This approach is somewhat similar to that developed by Tseng, J. B. and Lan\(^6\), but differs in its capability to use both the \( C_l \) and the \( C_m \) data for the section and in the use of a two-variable function for the decambering. In addition, unlike all of the earlier methods, the current approach uses a multi-dimensional Newton iteration that accounts for the cross-coupling effects between the sections in predicting the decambering for each step in the iteration. Vortex Lattice Method (VLM) is used and the values of decambering at each section of a wing(s) are evaluated in an iterative fashion. The lifting surface is divided into several spanwise and chordwise lattices. Each spanwise section \( j \) (composed of a row of chordwise lattices) has two variables, \( \delta_{1j} \) and \( \delta_{2j} \), for defining the local decambered geometry at that section. Unlike in the two-dimensional case, where the \( \delta_{1} \) and \( \delta_{2} \) as shown in Fig. 3 selected to match the differences between the potential-flow and the viscous-flow results, in the three-dimensional case, changing a \( \delta \) on one section is likely to have a significant effect on the neighboring sections and on the sections of the downstream.

![Decambering functions](image)

(a) Decambering function \( \delta_{1} \)  
(b) Decambering function \( \delta_{2} \)

Fig. 3: Linear decambering functions used in current method

To account for these effects, a \( 2N \)-dimensional Newton iteration is used to predict the \( \delta_{1} \) and \( \delta_{2} \) at each of the \( N \) sections of all the wings so that the residuals, \( \Delta C_l \) and \( \Delta C_m \) at these sections
approach zero as the iteration progresses. A $2N \times 2N$ matrix equation is solved for each step of the Newton iteration.

4. RESULTS

The current wind-tunnel results are compared with the output from the in-house code, VLM3D as shown in Fig. 4(a). VLM3D required the input 2D, i.e. airfoil characteristics. The numerical data from XFOIL, experimental data from Abbott and Von Doenhoff\textsuperscript{5} and Naik and Ostowari\textsuperscript{4} have being used as the input for VLM3D at their respective Reynolds number as shown in Fig.4 (a). The current wind-tunnel results for drag are compared with literature as shown in Fig. 4 (b) since VLM3D does not predict viscous drag but only induced drag, which is not used here.

A comparison between coefficients of lift and drag is represented in Fig. at different Reynolds numbers recorded in the wind tunnel. The Reynolds numbers and their respective wind speed are mentioned in the Table 1. It is observed from Fig. 5 that the coefficient of drag becomes more dominant after increasing the Reynolds number from $Re = 0.093 \times 10^6$ to $Re = 0.123 \times 10^6$ resulting in a gentle decrease in the lift coefficient in the post stall region compared to other two Reynolds numbers.

![Graphs showing comparison](image_url)

(a) $C_l - \alpha$ comparison with VLM3D
(b) $C_d - \alpha$ comparison with literature

Aerodynamic Characteristics from wind-tunnel compared with numerical analysis and Literature

Table 1. Wing model experimental parameters

<table>
<thead>
<tr>
<th>Wind Speed (m/s)</th>
<th>Reynolds Number</th>
<th>Mach Number</th>
<th>Free Stream Pressure (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.92</td>
<td>$0.093 \times 10^6$</td>
<td>0.069</td>
<td>53</td>
</tr>
<tr>
<td>28.48</td>
<td>$0.114 \times 10^6$</td>
<td>0.082</td>
<td>68</td>
</tr>
<tr>
<td>30.5</td>
<td>$0.123 \times 10^6$</td>
<td>0.088</td>
<td>78</td>
</tr>
</tbody>
</table>
To study the scale effects between model and prototype Eastman and Sherman\(^3\) have recorded airfoil data at various values of Reynolds number between values as low as few hundred thousand to thirty million. One such airfoil data at very low Reynolds number has been used here as an input to VLM3D. The present experimental results at \(Re = 0.044 \times 10^6\) are compared with Eastman and Sherman at \(Re = 0.043 \times 10^6\).

As observed from Fig. 6, the experimental data and VLM3D are in good accord with each other for lower angles of attack. The stall angle and post-stall aerodynamic characteristics demonstrate a similar arrangement due to the contiguity of Reynolds numbers.

The present experimental results for \(C_l\) are plotted along with experimental 2D results at \(Re = 3 \times 10^6\) from Abbott and Doenhoff\(^7\) and XFOIL at the same Reynolds number as shown in Fig. 7. The present experimental results for both \(C_l\) and \(C_d\) shown in Figures 7 and 4 (b) respectively are compared with experimental 3D results for a wing of aspect ratio, AR=6 at \(Re = 0.25 \times 10^6\) from Naik and Ostowari\(^4\).

The coefficients of lift from the current wind-tunnel are compared with experiments in literature and plotted along with 2D airfoil data as shown in Fig. 7. Although the Reynolds numbers are not comparable, it clearly shows that airfoil data is greater than 3D data as expected.

It is also to be noted that results at each angle of attack have been obtained as a single run and not as part of a sequence due to the restriction in the experimental set-up. It is expected that the latter will have different aerodynamic implications.
The size of the test-section is a limitation in this work, so that the Reynolds Number that can be achieved is $0.12 \times 10^6$.

5. CONCLUSIONS

Pressure and force data are presented for a NACA4415 wing model with aspect ratio 6.35 for Reynolds numbers $Re = 0.044 \times 10^6$, $Re = 0.093 \times 10^6$, $Re = 0.114 \times 10^6$, $Re = 0.123 \times 10^6$. The experimental results are compared with an in house post stall predicting tool VLM3D based on decambering.

At lower Reynolds number, the experimental data and VLM3D are in good accord and demonstrates similar aerodynamic characteristics at Stall angle and post stall region with a maximum deviation of 20%, which could be considered as a well predicted result in the post stall region by VLM3D. The similar assessments are made at other ranges of wind speeds and Reynold numbers.

Even though some of the comparisons made in this work have not been at comparable Reynolds numbers, the results seem to corroborate each other exhibiting similar stalling characteristics and arrangement in post stall region.

In the experimental data sets, a gentle decrease in lift coefficient in the post stall region was recoded due to an increase in drag force after a slight change in Reynolds number from $Re = 0.093 \times 10^6$ to $Re = 0.123 \times 10^6$. Both pressures and loads have been measured and compared with literature. The experimental investigation is carried out at steady state.
REFERENCES
3. Eastman N. Jacobs and Albert Sherman, “Airfoil section characteristics as affected by variation of the Reynolds number”, NACA Report number 586