Analysis of Aerodynamic Hysteresis in Echelon formation

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Abstract. This work is based on the vortex lattice method using a “decambering” approach, which accounts for flow separation and makes the separated flow to follow viscous flow condition at high angles of attack over the airfoil and 3D wings. This method used to study the aerodynamic hysteresis of two wings configuration at near stall and post-stall flow conditions. The hysteresis of different data and their effect have been studied. The effect of shifting stall due to presence of hysteresis for forward and backward flow regimes also has been reported.

1. Introduction
Aerodynamic hysteresis of wings is of practical importance because it results in widely different values of $C_L$ and $L/D$ ratio for the wing at a given angle of attack since the angle of attack at which the flow reattaches on top of the wing is lower than the angle of attack at which the flow separates. It also affects the recovery from stall and/or from a spin. Hysteresis effects are encountered in both Horizontal-axis and Vertical-axis wind turbines.

Ching-Huei Lin[1] stated that the best operation to get the maximum output power is to rotate with a large external resistance (more than $R_2$) to achieve a high level angular speed and then decreases the external resistance to slow down the angular speed to enter the hysteresis region.

Dosaev Marat[2] explained how hysteresis phenomenon occurred in the operation of an H-type stand-alone Darrieus wind turbine system. He also shown that hysteresis effect has registered for the range of external resistances of 10 Ohm to prove theoretical results for turbine angular speed, current and voltage but they measured for different wind speeds and different values of external resistance.

Selig et al. [3] attempted to increase the $C_{l_{max}}$ of the S1223 because it has tested with vortex generators (VGs) on the upper surface at 0.17c and, separately, with a 0.01c Gurney flap. Also, they showed the VGs produced a $C_{l_{max}}$ of 2.3 for increasing angles of attack followed by an abrupt stall and a hysteresis loop between 16 - 20 deg.

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The aim of this paper is to study the occurrence of hysteresis in the fixed wing configuration when multiple wings are in operation. The method used in this analysis is to predict post-stall aerodynamic characteristics of wing(s) [4].

2. Numerical Procedure
A vortex-lattice method algorithm based on the decambering approach [4] is used for predicting aerodynamics hysteresis of wings using known section data. Although the numerical code, VLM3D based on this approach was originally developed with a view to predict post-stall aerodynamics of single wings or their configurations, it has been found to be robust and powerful in the analysis of formation flight as well with some modifications.

The unique feature of formation flight is the interaction between the vortices and aircraft (both leading and trailing), which is captured well by the modified VLM3D [5]. Post-stall results provide enhanced understanding of formation flight aerodynamics.

This overall objective was achieved by finding the effective reduction in the camber distribution for each section along the span. The typical flow past an airfoil at small angles of attack consists of a thin boundary layer that remains attached to the surfaces of the airfoil. For these conditions, the $C_l$ and $C_m$ predicted using potential flow analysis of the airfoil camberline agrees closely with the computational and experimental results that account for viscosity as shown for $\alpha < 12^\circ$ in Figs. 1 & 2.

![Figure 1. Residuals in Coefficient of Lift.](image1)

With increasing angles of attack, the boundary layer thickens on the upper surface and finally separates, as shown in Figs. 3 & 4 using both experiment and computation. It is this flow separation that causes the viscous results for $C_l$ and $C_m$ to deviate from the predictions using potential flow theory for $\alpha > 12^\circ$ as shown in Fig. 4. The reason for the deviation can be related to the effective change in the airfoil camber distribution due to the boundary-layer separation. If the decambering could be accounted for, then a potential-flow prediction for the decambered airfoil would closely match the viscous $C_l$ and $C_m$ for the high-$\alpha$ flow past the original airfoil shape. This decambering idea served as the basis for the formulation of the current approach for the three-dimensional flow problem.

The effects of $\delta_1$ and $\delta_2$ on the change in $C_l$ and $C_m$ for a given $\alpha$ can be computed reasonably well using thin airfoil theory and a three-term Fourier series approximation for a flat plate with a flap deflection [6]. These values of $\delta_1$ and $\delta_2$ in radians for given $\Delta C_l$ and $\Delta C_m$ are presented in Eqs. 1 and 2.
Figure 3. Flow separation over an airfoil - Flow Visualisation with Experiment

\[
\delta_2 = \frac{\Delta C_m}{\frac{1}{4} \sin 2\theta_2 - \frac{1}{2} \sin \theta_2} \quad (1)
\]

\[
\delta_2 = \frac{\Delta l - [2(\pi - \theta_2) + 2\sin \theta_2] \delta_2}{2\delta_2} \quad (2)
\]

\[
\theta_2 = \cos^{-1}(1 - 2x_2); x_2 = 0.8 \quad (3)
\]

While the camber reduction due to the flow separation can be determined from computational flows, no such detailed information is available from wind tunnel results that typically provide only the \( C_l - \alpha \) and \( C_m - \alpha \) curves.

3. Results & discussion
Results presented in this paper are of rectangular planform for Echelon formation. In this study, the wings with aspect ratio of 7 have been used and analyzed the impact of aerodynamic hysteresis. Figure 5 shows the typical echelon formation used in hysteresis analysis.

Figure 4. Flow separation past an airfoil - Flow Visualisation with Numerical Analysis

Figure 5. Typical Echelon form
3.1. Hysteresis with Echelon formation
We carried the analysis of hysteresis on Echelon formation for different airfoil data and for the same aspect ratio. Three cases of airfoil data have examined, and these data are from Bangash[7] and William[8]. Analyzing the hysteresis in trailing wing is to show how the trailing wing performs for various offsets, how leading wing influences the performance of trailing wing particularly near stall & post-stall regions and how active in governing the aerodynamic characteristics of the particular wing.

The dimension of the wings in all cases are of rectangular planform having the aspect ratio, AR = 7 & and unit chord. The offsets between the leading and trailing wings are, $dx = 0$, $dy = 0$ & $dz = -0.11$.

The first case has been studied for the airfoil data of 2D Selig and Fig. 6 shows the graphical representation of $C_L - \alpha_{tw}$ & $C_Di - \alpha_{tw}$ curves. The plots show the clockwise hysteresis loop in both the cases. The loop has the zig-zag path at the end, but shows the significant changes in the forward and backward curves. The stalling angles($\alpha_{stall}$) are $19^o$ and $18^o$ for forward and backward flow directions. Since the 2D data of this model is not highly non-linear in pre-stall region, the current method also do not show any non linearity.

The second case has been studied for the airfoil data of Wortmann FX63-137 and Fig. 7 shows the graphical representation of $C_L - \alpha_{tw}$ & $C_Di - \alpha_{tw}$ curves. Here the hysteresis loops seems to be small but, plots show the clockwise hysteresis loop in both the cases. The stalling angles($\alpha_{stall}$) are $24^o$ and $23^o$. The 2D data of this model does not impose any nonlinearity in its characteristics and in the similar manner 3D model from the current method also not having any non-linearity. The smooth stall region before the sudden drop has been observed.

The third case has been studied for the airfoil data of 2D Bangash and Fig. 8 shows the graphical representation of $C_L - \alpha_{tw}$ & $C_Di - \alpha_{tw}$ curves. Here also, there is a hysteresis loop but very small in size and looks like a triangle in shape. In hysteresis loop, the forward curve has sudden stalling region whereas backward curve avoids the sharp region near stall. The stalling angles of forward and backward curves are $20^o$ and $19^o$. Here too the clockwise hysteresis loop in
Figure 7. wing $C_L - \alpha_{tw}$ & $C_{Di} - \alpha_{tw}$ curves for AR = 7 & Wortmann FX63-137 as input

both the cases. Since the 2D data of this model is linear in its characteristics therefore current method also do not have linearity and have smooth regions in both pre and post-stall conditions. Unlike previous results in this paper using other data, trailing wing in formation does not have long range hysteresis.

Figure 8. wing $C_L - \alpha_{tw}$ & $C_{Di} - \alpha_{tw}$ curves for AR = 7 & 2DBangash as input
4. Conclusion
A numerical analysis on Echelon formation has been studied to get insights into the behaviour of aerodynamic hysteresis. The main observation in the analysis of two wing configurations using VLM3D is the formation of a considerable loop in post-stall flow regions of both $C_L - \alpha \& C_{Di} - \alpha$ curves & a good observation from the hysteresis study is the fall and rise of lift and drag coefficients in forward and backward loop of near stall & post-stall regions. Post - stall results based on hysteresis gives the idea to recover from a stall with minimum loss.

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