Estimation of Lift Hysteresis of an Airfoil in low speed flow

WARD Jayathilake[1] and JI Abeygoonewardene[1#]

[1]Kotelawala Defence University, Ratmalana, Sri Lanka

#jabeygoonewardene@kdu.ac.lk

***Abstract**: A phenomenon called hysteresis leads to a difference in separation and reattachment angles of an airfoil at angles of attack near and above stall. This an airfoil than expected for a given angle of attack when recovering from a stall. This leads to asymmetric flow parameters around a body even when the boundaries remain symmetric. Empirical results for lift and pressure coefficients were obtained for a two-dimensional Clark Y-14 at low speeds. The lift characteristics of the airfoil was observed while varying angle of attack and Reynold's number. It was seen that the extent of the lift hysteresis largely depends on Reynold's number. Further experiments and Computational Fluid Dynamics (CFD) simulations will be conducted in order to determine occurs when there is a difference in the lift distribution of the relationship of the effective body of the stalled airfoil and the presence of hysteresis loops.*

***Keywords:** Coefficient of pressure, Lift hysteresis, Lift curve, Flow separation, Stall*

1. Introduction

It is commonly assumed that symmetric boundary conditions produce symmetric flows. However, this is often far from the real case. A flow that has large regions of separation will result in asymmetries in the instantaneous as well as mean flow, even when the boundaries remain symmetric. This leads to hysteresis, in which the forces and moments on a body depend on the time history of the attitude. This phenomenon is often observed during flow visualization of bodies such as aircraft models in wind tunnels (Barlow, et al., 1999). In case of airfoils, this is due to the fact that when the angle of attack is increased beyond its stalling angle, the flow does not reattach at the same angle when the angle of attack is lowered again. In other words, an airfoil does not recover from a stall following the same variation of flow parameters it underwent before it was stalled. The difference between the separation and reattachment angles is defined as the size of the hysteresis loop (Morris, et al., 2020). From an aerodynamic point of view, hysteresis is the existence of multiple values for lift, drag and moment coefficients for a given angle of attack instead of a single value. Aerodynamic hysteresis is of two types: namely, static and dynamic hysteresis (Williams, et al., 2015). Static hysteresis also termed as conventional hysteresis is the results that are obtained when the readings are taken under quasi static conditions which is by slowly pitching the airfoil until stalled and pitching it back down slowly while dynamic hysteresis is seen when the airfoil is under motion. There are various factors that affect the extent and the formation of the hysteresis loops in the aerodynamic coefficients such as the Reynolds number (Brunner, et al., 2021), Turbulence intensity (Hoffmann, 1991), effective body of the airfoil (Landman, 2001) ,type of separation formed (Marchman, 1987) and the boundary layer transition (Mueller, 1985) and/or separation on the airfoil (Timmer, 2008), (Traub, 2016). In a study conducted on a symmetrical NACA 0012 airfoil at a Reynolds number (Re) of 475000, Morris et al found an agreement with the hypothesis that the reattachment angle of the stalled airfoil is the stalling angle of the associated effective body.

A majority of the available work has concentrated on analysing the static and dynamic hysteresis on symmetric airfoils. The present study aims at estimating the extent of static lift hysteresis on an asymmetric Clark Y-14 airfoil in low-speed flows, while analysing the parameters affecting the same and determining relationship of the effective body of the airfoil and the occurrence of hysteresis loops in stall hysteresis.

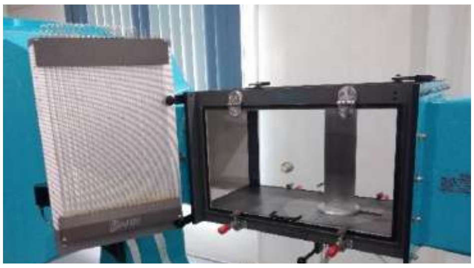

Figure 1. Wind tunnel apparatus

2. Methodology and Experimental Design

The preliminary stage of the methodology consists of deriving experimental results for a Clark Y-14 airfoil. The experiment is conducted in the Aerolab educational wind tunnel at Kotelawala Defence University which is capable of simulating low speed flows in the range of 4.5 to 64 m/s, having a test section dimension of 30.5 cm × 30.5 cm × 30.5 cm. The pressure wing, resembling a Clark Y-14 airfoil having a chord of 8.9 cm, has 18 flush mounted taps which render pressure readings via a multi-tube liquid manometer.

Appropriate range of Reynold's number (Re) was selected for the experiment considering the limitations of the wind tunnel ranging from 60941 to 204155. The experiments were carried out by varying the fan speed of the wind tunnel from 400 to 1200 rpm (revolutions per minute) in increments of 100 rpm to bring about the change in the Reynold's number as depicted in table 1.

Table 1. Corresponding Reynolds number for fan speed

Fan speed, rpm	Reynolds number
400	60941
500	79224
600	91412
700	112742
800	134072
900	146260
1000	164543
1100	182825
1200	204155

The experiment was conducted at standard sea level conditions. The pressure readings for the upper and the lower surface was tabulated by varying the angle of attack (AoA) in 1degree intervals and the lift coefficient (C_L) for the pitch up and the pitch down was calculated using the student version of MATLAB software. Thereby the lift curve and coefficient of pressure (Cp) variations for each setting were obtained.

3. Results

The variation of the coefficient of pressure (Cp) for some angles of attack for the forward and backward stroke (pitch up and pitch down) for different flow speeds are given below. Since the flow speed is the only parameter varied, it therefore shows the dependence with change in Reynold's number. Figures 2 to 10 depict the Cp plotted against x/c (the distance along the chord/length of the chord).

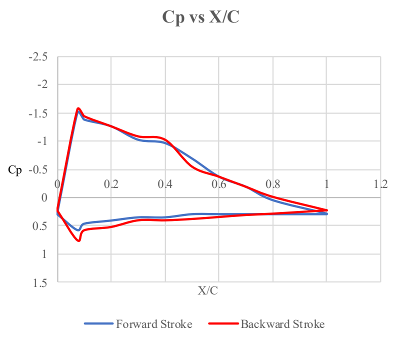

Figure 2. Cp vs x/c for Re = 112742 at 5°

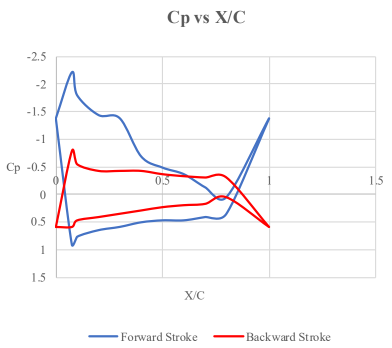

Figure 3. Cp vs X/C for Re = 112742 at 10°

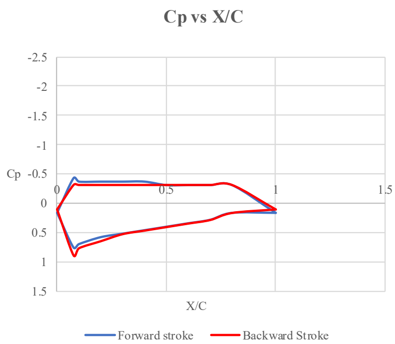

Figure 4. Cp vs x/c at Re = 112742 at 15°

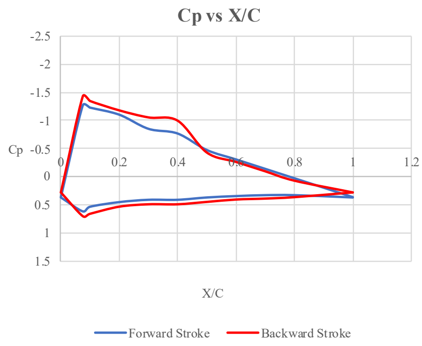

Figure 5. Cp vs x/c fort Re = 134072 at 5°

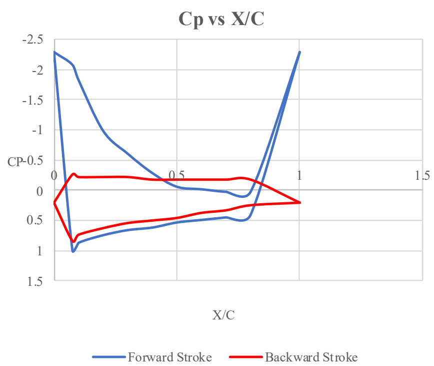

Figure 6. Cp vs x/c for Re = 134072 at 15°

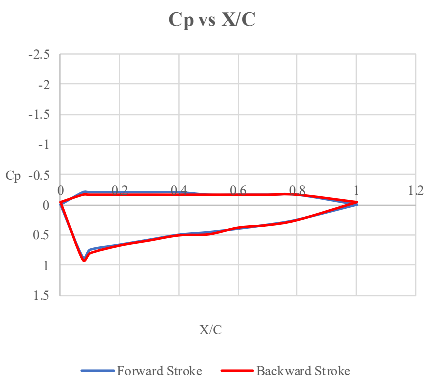

Figure 7. Cp vs x/c for Re = 134072 at 18°

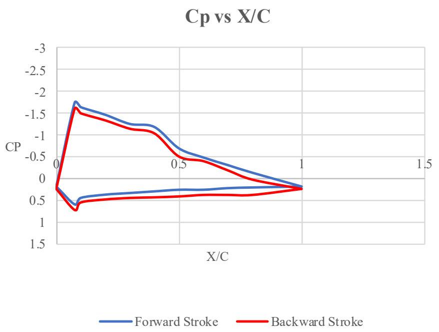

Figure 8. Cp vs x/c for Re = 146260 at 5°

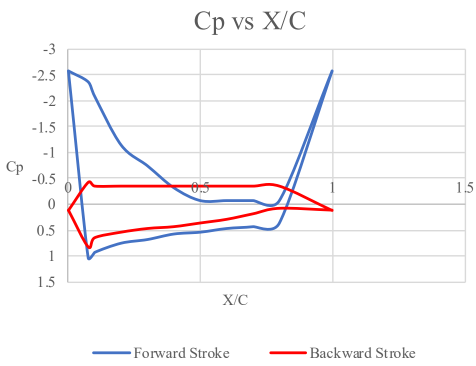

Figure 9. Cp vs x/c for Re = 146260 at 15°

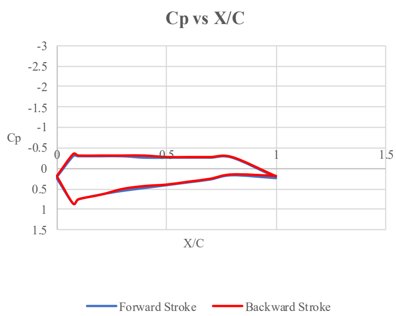

Figure 10. Cp vs x/c for Re = 146260 at 18 °

The plotted lift curves (lift coefficients vs the AOA) with the aid of the MATLAB software for different Reynolds numbers are given in figures 11 to 15.

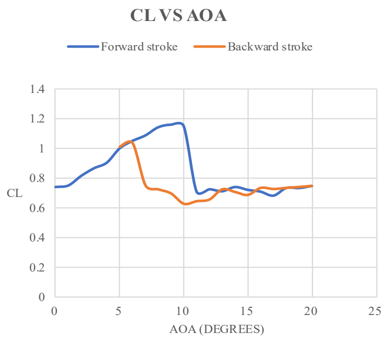

Figure 11. Figure Lift curve for Re = 91412 for forward and backward stroke

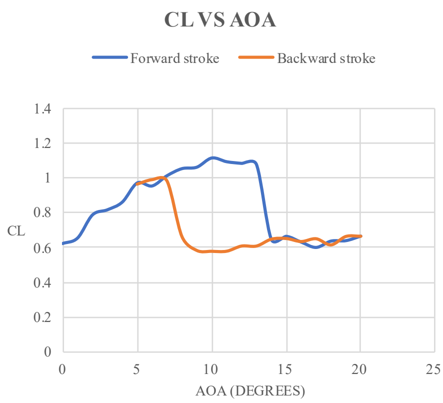

Figure 12. Lift curve for Re = 112742 for forward and backward stroke

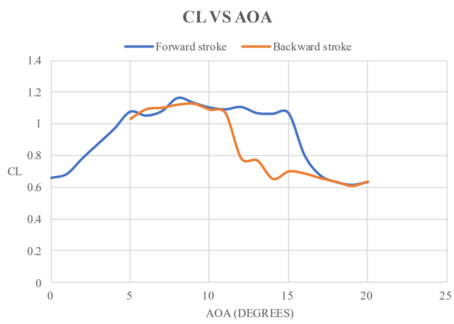

Figure 13. Lift curve for Re = 134072 for forward and backward stroke

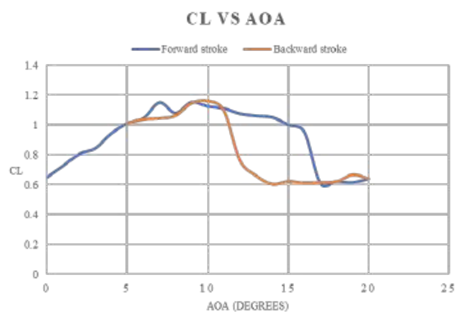

Figure 14. Lift curve for Re = 146260 for forward and backward stroke

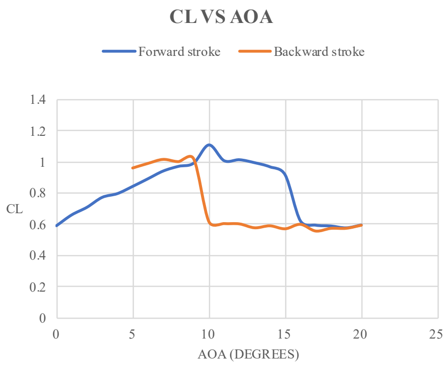

Figure 15. Lift curve for Re= 164543 for forward and backward stroke

4. Discussion

The present study focused on the experimental results derived via a two-dimensional airfoil for low speeds. It was observed that at very low speeds, no significant hysteresis loop is created. The lift coefficient variations at low angles of attack (5 degrees) for varied Reynold's numbers are almost identical for the forward and backward strokes. Further, there are no signs of flow separation.

As angle of attack and Reynold's number increases (as shown in figures 3, 6 and 9), it is evident that the presence of a significant hysteresis loop as the difference between separation and reattachment are more prominent. Further, the lower surface of the airfoil displays a rather similar trend in its pressure coefficient variation for both the forward and backward stroke. The upper surface on the other hand, shows significant deviations. This maybe a result of the higher level of separation on the upper surface due to increased camber. The upper surface pressure coefficient reaches a maximum closer to the leading edge during the forward stroke, while it drastically decreases during the backward stroke. The pressure distribution on the upper surface during the backward stroke also shows a constant value, indicating that large scale flow separation has occurred (Russel, 1979).

Considering the variation of lift coefficient, the clockwise hysteresis loop is observed (figures 11 to 15) . The extent of the loop increases with Reynolds number before it starts to decrease again. Table 2 depicts the extent of the hysteresis loops obtained for different Reynolds numbers.

Table 2. Extent of the hysteresis loop with Reynolds number

Reynolds number	Extent of hysteresis loop	Presence of hysteresis loop
60941	negligible	-
79224	negligible	-
91412	6° - 11°	4°
112742	7° -14°	6°
134072	9° -16°	7°
146260	11° -17°	5°
164543	11° -17°	5°

The results render that the hysteresis loop is prominent at an angle of attack of 7° at a Reynold's number 134072. The stalling angles of attack of the Clark Y-14 airfoil derived through experimental results are given in table 3. The stalling angle of attack peaks around 16°.

Table 3. Variation of stalling angle with Reynolds number

Reynolds number	stalling angle
91412	above 10°
112742	above 13°
134072	above 15°
146260	above 16°
164543	above 16°

From the above results it can be concluded that the Reynold's number plays an important part in determining the existence of hysteresis loop of an airfoil. At very low Reynolds numbers, no significant hysteresis loops were detected. With the increase of the Reynolds numbers the extent of the hysteresis loops continued to increase until 134072 and slightly decrease for Reynolds number of 146260 and 164543. Also, the stalling angle also has a positive relationship with the Reynolds number. When the Reynold's number was increased the stalling angle continued to rise with an exception at Reynolds number of 164543.

The accuracy of the empirical results derived maybe compromised to a certain extent due to common factors affecting results obtained during wind tunnel testing. Buoyancy effect, solid and wake blockage in the test section and errors associated with reading liquid heights of the manometer tubes cannot be neglected. Thus, a comprehensive validation of the results through numerical simulations is necessary.

5. Future Work

The second intended stage of the methodology to be followed will involve validating of the experimental results using computational fluid dynamic simulations. Further the effective body of the stalled Clark Y-14 airfoil will be isolated and modelled in order to obtain its lift curve, so as to investigate the relationship between the effective body and hysteresis loop of the airfoil.

The work will be continued to examine the lift hysteresis of a three-dimensional airfoil to better understand the parameters affecting the phenomenon. The experimental results will be validated using CFD simulations considering both the two dimensional and three-dimensional airfoils. The effective body of the stalled Clark Y-14 airfoil is to be modelled in order to determine the relationship between the effective body and the hysteresis loops present. While the work here li. mited only to low-speed flows, further examination can be made in flows in the higher subsonic or even transonic regimes.

6. Conclusion

The hysteresis loop of a two-dimensional asymmetric airfoil was observed in low-speed flows by varying parameters of angle of attack and Reynold's number. It was found that Reynold's number and angle of attack are primary parameters that have an impact on the occurrence of static lift hysteresis and the size of the hysteresis loop is significant at particular Reynolds number at low speeds for the Clark Y 14 airfoil.

References

Brunner, C., Kiefer, J., Hansen, M., Hultmark, M., (2021). Study of Reynolds number effects on the aerodynamics of a moderately thick airfoil using a high-pressure wind tunnel. *Experiments in Fluids*, 62(8).

Hoffmann, J., (1991). Effects of freestream turbulence on the performance characteristics of an airfoil. *AIAA Journal*, 29(9), pp.1353-1354.

Landman, D., Britcher, C., (2001). Experimental Investigation of Multielement Airfoil Lift Hysteresis due to Flap Rigging. *Journal of Aircraft*, 38(4), pp.703-708.

Marchman, J., Sumantran, V., Schaefer, C., (1987). Acoustic and turbulence influences on stall hysteresis. *AIAA Journal*, 25(1), pp.50-51.

Morris, W., Zenker, C., Ingraham, J., Wolfenbarger, T., (2020). A Theory of Stall Hysteresis – Why the reattachment angle is less than the separation stall angle. *AIAA Scitech 2020 Forum*,.

Mueller, T., (1985). The influence of laminar separation and transition on low Reynolds number airfoil hysteresis. *Journal of Aircraft*, 22(9), pp.763-770.

Rae, W., Pope, A., Barlow, J., (1999). *Low speed wind tunnel testing*. New York: Wiley.

Timmer, W., (2008). Two-Dimensional Low-Reynolds Number Wind Tunnel Results for Airfoil NACA 0018. *Wind Engineering*, 32(6), pp.525-537.

Traub, L., (2016). Semi-Empirical Prediction of Airfoil Hysteresis. *Aerospace*, 3(2), p.9.

Williams, D., An, X., Iliev, S., King, R., Reißner, F., (2015). Dynamic hysteresis control of lift on a pitching wing. *Experiments in Fluids*, 56(5).

Author Biography

WARD Jayathilake is an undergraduate at the Department of Aeronautical Engineering at the Faculty of Engineering of General Sir John Kotelawala Defence University, Sri Lanka.

JI Abeygoonewardene is a Senior Lecturer in Aeronautical Engineering at the Faculty of Engineering of General Sir John Kotelawala Defence University, Sri Lanka.