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ESTIMATION OF CLARK Y-14 AIRFOIL'S LIFT HYSTERESIS IN LOW-SPEED FLOW

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ABSTRACT

A phenomenon called hysteresis is responsible for the difference in the separation and the reattachment angles of an airfoil which is seen within the vicinity of the stalling angle of attack. The reason for this is the difference in the expected lift distribution of an airfoil for a particular angle of attack when recovery from stall is achieved. This leads to asymmetric flow parameters around a body even when the boundaries remain symmetric. Empirical results were obtained for a two-dimensional Clark Y-14 airfoil by varying the angle of attack for different Reynold's numbers in order to estimate how lift characteristics are affected by the formation of hysteresis loops at different Reynolds numbers. It was seen that the extent of the clockwise hysteresis loops of the Clark Y-14 increased with the increase of the Reynolds number up to the Reynolds number of 134072 before starting to decrease again. The stalling angles followed a similar pattern before starting to decrease at a Reynolds number of 164543. These trends observed for the Clark Y-14 airfoil is similar to that of the Eppler 591 and NACA 0018 by Lance W.Traub and W.A Timmer respectively (Timmer, 2008), (Traub, 2016). *When analyzing the coefficient of pressure variation for the Clark Y-14 airfoil at a particular Reynolds number, it was seen that a laminar separation bubble was formed for the forward stroke which shifted towards the leading edge of the airfoil which was common for all the Reynolds numbers. In the forward stroke, it could be seen that a laminar separation bubble was formed whereas for the backward stroke no such laminar separation bubble was formed for the same angle of attack which gave rise to the hysteresis loops of the Clark Y-`14 airfoil. It was observed that the laminar separation bubble had a direct impact on the formation of the hysteresis loops giving rise to static stall hysteresis as mentioned in previous research published by various authors. The empirical results obtained were further validated using Computation Fluid Dynamics.*

KEYWORDS: Coefficient of pressure, Lift hysteresis, Lift curve, Flow separation, Stall

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1. INTRODUCTION

Aerodynamic hysteresis can be defined as the change in aerodynamic properties as they become history dependent. Put into simple words, it is the existence of multiple values of coefficient of lift, drag and moment instead of a single value depending on the sense of the angle of attack. Hysteresis is mainly of two types, namely conventional (static hysteresis) and dynamic hysteresis (Williams, et al., 2015). Conventional hysteresis is seen when the airfoil is pitched very slowly above the stalled condition and slowly pitching it back down. If we consider the coefficient of lift, here we could observe two distinct values for this aerodynamic property for the same angle of attack depending on whether the angle of attack was increasing or decreasing giving rise to a hysteresis loop. Dynamic hysteresis on the other hand is seen when an airfoil is in motion. Conventional hysteresis need not be present for dynamic hysteresis to occur in aerodynamic coefficients when the flow is separated.

The most common type of hysteresis that is seen in airfoils is the static stall hysteresis which is seen near classic stall. It is necessary to reduce the angle of attack significantly below the pre catastrophic stalling angle of attack in order to reattach the flow and recover the lost lift during stall. Depending on the hysteresis loop formed hysteresis loop could either be clockwise or anticlockwise (Traub, 2016).

Various factors affect this so formed Hysteresis loops in the aerodynamic coefficients such as the Reynold's number (Brunner, et al., 2021), Turbulence intensity (Hoffmann, 1991), type of separation bubble formed (Marchman, 1987), effective body of the airfoil (Landman, 2001) and the boundary layer separation and the separation on the airfoil (Landman, 2001), (Timmer, 2008), (Traub, 2016). Even though various research has been conducted regarding static stall hysteresis on various types of airfoil, very few have been conducted on a Clary Y airfoil. These do not sufficiently discuss the hysteresis effects of this particular airfoil and its behaviour at different Reynolds numbers. This research was conducted with the intention of providing a detailed idea about how the Clark Y-14 airfoil behaves in the said Reynolds number range and how lift characteristics are affected due to the presence of hysteresis in the said airfoil. Clear understanding of lift characteristics of an airfoil under hysteresis is of utmost importance as it would be extremely dangerous since stall recovery requires a large decrease in angle of attack contrary to a simple reduction of back pressure on the controls. The nature of the stall becomes much more complicated in low Reynolds numbers due to laminar separation bubbles which may form before full stall and various other factors that might influence it. Hence having a better understanding of how the Clark Y-14 airfoil reacts to hysteresis will be much beneficial. A component of this research was done previously which gave rise to some interesting facts regarding the relationship of the Reynold's number with the formation of the hysteresis loops and the continuation of the research further gave rise to some more insight on how the laminar separation bubble plays a role in the formation of the hysteresis loop in the Clark Y-14 airfoil and the validation of the empirical results through CFD simulations which is discussed in this paper.

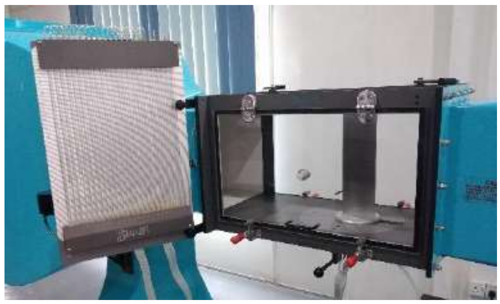

Figure 1. Wind Tunnel Apparatus

2. METHODOLOGY

The initial stage included carrying out of wind tunnel experiments in order to find the relationship of the Reynold's number on the extent of the hysteresis loop. The Reynolds number range was selected by considering the limitations of the AEROLAB Educational Wind tunnel at Kotelawala Defence University which was used for conducting of the test. The wind tunnel has a test section of 30.5 cm × 30.5 cm × 30.5cm and a speed range of 4.5 m/s to 64 m/s. The AEROLAB pressure wing resembling a Clark Y-

14 airfoil with a chord of 8.9cm having 18 flush mounted taps was mounted on the test section and pressure readings via a multi tube manometer was obtained.

The experiment was conducted by varying the angle of attack of the pressure wing by multiples of 1 degree for the forward (increasing the angle of attack until the airfoil stalls) and the backward stroke (decreasing the angle of attack back from stall). MATLAB was used in order to calculate the coefficient of lift by integrating the area between the upper and lower surface of the airfoil of Cp Vs X/C graph.

The next stage of the research consisted of carrying out of CFD simulations in order to validate the obtained wind tunnel results. The simulations were carried out for a Reynolds number of 134072 corresponding to wind tunnel RPM of 800 using ANSYS 2021 R1 software.

The Computational flow domain used to analyse the Clark Y-14 airfoil of non-dimensional chord length of 1m is a C type mesh consisting of a frozen layer which radiates 3 times the chord from trailing edge towards the forward and 5 times the chord towards the aft. The entire grid extends 10 times the chord from the trailing edge and 60 times the chord behind the airfoil. Inflation layers were used in order to better capture the effects near the boundary layer.

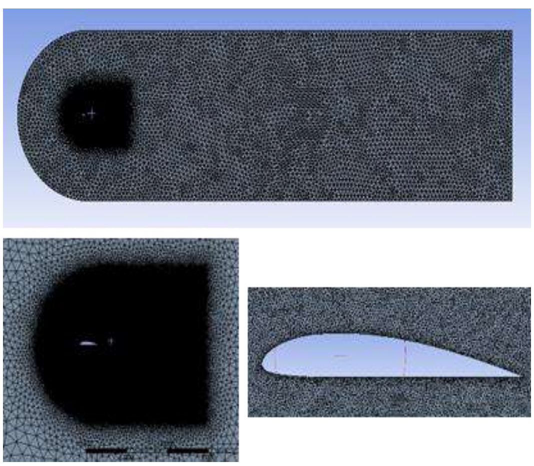

Figure 2. CFD Mesh

The Kω SST turbulence model was used with a velocity inlet and a pressure outlet for the domain. The lower and upper boundaries of the domain was set to wall and the convergence criteria was set to 1e-06.

3. RESULTS AND DISCUSSION

The coefficient of pressure variation and the relationship of the extent of the hysteresis loop with Reynold's number was discussed earlier. It was seen that the extent of the clockwise hysteresis loops increased with the Reynold's number up until a Reynold's number of 134072 before starting to decrease again for the Clark Y-14 airfoil.

The stalling angle too followed a similar pattern. The stalling angle continued to increase until a Reynolds number of 146260 before starting to decrease again. The summarised results from the Research paper are given below. These trends shown by the Clark Y-14 airfoil is similar to that of the findings by Lance W. Traub and W.A. Timmer for the Eppler 591 and NACA 0018 airfoils, respectively.

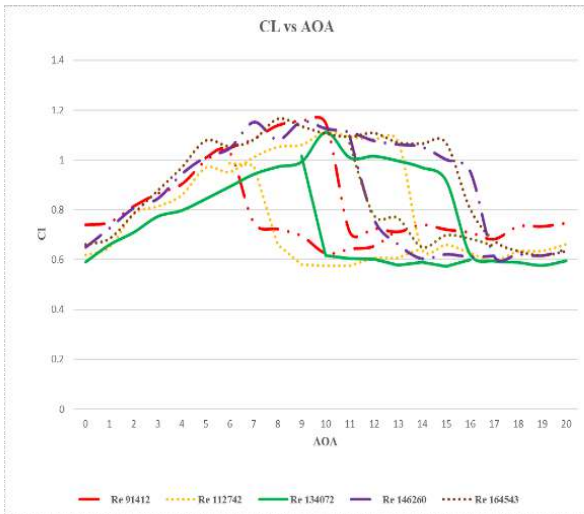

Figure 3. Hysteresis Curves for different Reynold's numbers

Table 1: Extent of hysteresis loop with Reynold's number

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

Table 2. Stalling angle variation with Reynold's number

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

Furthermore, by studying the coefficient of pressure variations, it was discovered that a laminar separation bubble was formed. By considering a particular Reynold's number and looking at the coefficient of pressure graphs, it was seen that a nearly constant pressure region (plateau region) was found at a certain location and a sudden increase in the surface pressure following the plateau region. It was further observed that the surface pressure recovered gradually and smoothly downstream of this region. These features characterize the formation of a laminar separation bubble where the laminar boundary layer separates followed by transition and reattachment creating a bubble (Traub, 2016).

By considering a particular Reynold's number of 146260 and looking at the coefficient of pressure variation for different angles of attack, it was observed that the laminar separation bubble is formed at locations of X/C of 0.5, 0.3 and 0.05 for angles of attack of 0,5 and 15 degrees respectively. This shows that the laminar separation bubble has continued to move upstream of the airfoil towards the leading edge with the increase of the angle of attack. This phenomenon was common to all the Reynold's numbers for which the experiments were conducted on.

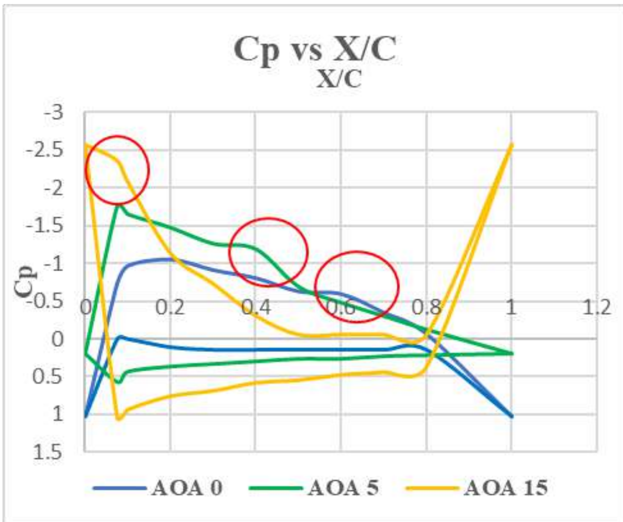

Figure 4. Coefficient of pressure variation at Reynold's number of 146260 for different angles of attack

It was seen that for the Reynold's number of 134072 at 15 degrees, for the forward stroke a separation bubble was formed at a location of X/C nearly equal to 0.05 which is evident from the pressure plateau and the flow separates at a location of X/C nearly equal to 0.5 from the upper surface. But when it comes to the backward stroke, there is no evidence for a formation of a laminar separation bubble and instead the flow over the upper surface is seen to separate closer to the leading edge with no reattachment to be seen leading to a great loss of lift which was observed by looking at the coefficient of lift curve corresponding to the particular Reynold's number. For the angle of 18 degrees the separation bubble had burst in the forward stroke and the flow does not reattach after separation and the coefficient of lift has drastically decreased with almost identical behaviour seen in the backward stroke as well.

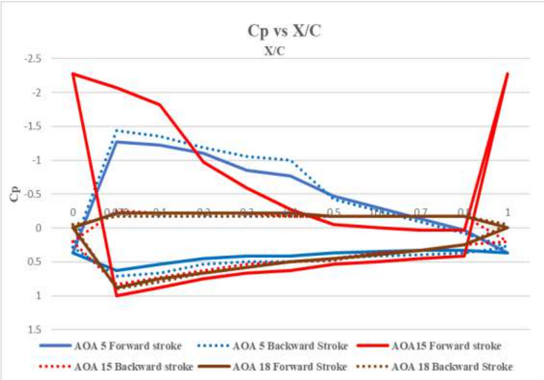

Figure 5. Cp variation for different angles of attack for Re of 134072

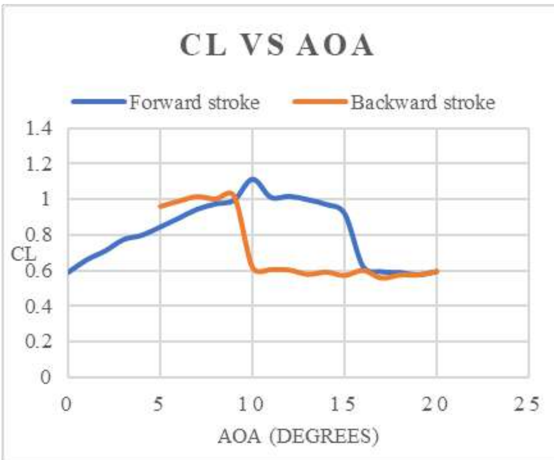

Figure 6. Cl variation for forward and backward stroke at Reynolds number of 134072

During the forward process it is seen that the flow separates and reattaches forming a laminar separation bubble which results in a higher lift while for the backward stroke the separated flow does not reattach and form a bubble and the flow continues to stay separated for the same angle of attack range diminishing the lift characteristics of the Clark Y-14 airfoil resulting in a clockwise hysteresis loop (Traub, 2016). Hence it can be seen that the formation of the clockwise hysteresis loops for the lift characteristics of the Clark Y-14 airfoil has a strong relationship to the formation of the laminar separation bubble which is in agreement with previous research that has been published on various other airfoil types (Marchman, 1987), (Sarlak et al., 2018), (Traub, 2016).

The CFD simulations that were run in order to validate the experimental results are given in Table 3.

Table 3. Comparison of wind tunnel and experimental results

AOA	CL simulation (KW SST)	Cl experimental	Error	Error %
0	0.53176	0.5899	0.05814	10%
2	0.6957	0.7087	0.013	2%
4	0.8339	0.7969	0.037	5%
6	0.91764	0.8924	0.02524	3%
8	0.96831	0.9724	0.00409	0%
10	0.807883075	1.1103	0.30242	27%
12	0.683735777	1.015	0.33126	33%
14	0.64579816	0.9694	0.3236	33%
16	0.65	0.6216	0.0284	5%
18	0.5974	0.5883	0.0091	2%
20	0.59685	0.5947	0.00215	0%

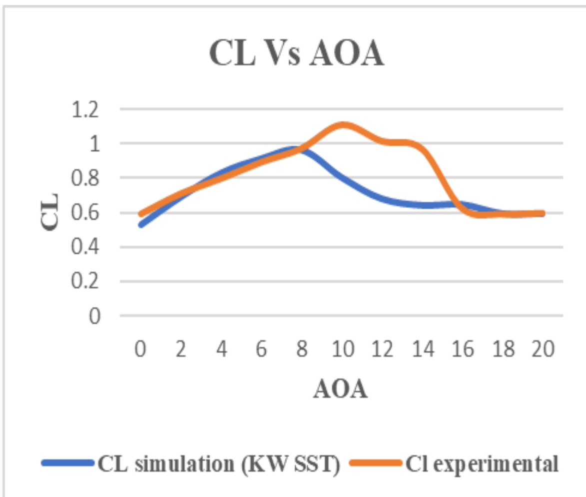

Figure 7. Cl vs AOA for Wind tunnel and CFD results

The wind tunnel results and the CFD results are almost identical for low angles of attack and very high angles of attack above 16 degrees with an error percentage of less than 10%. The results within the region of 10-14 degrees shows a very high deviation from the experimental results. The turbulence model has interpreted flow separation prior to that of the experimental results which gave rise to this deviation. The model has been unable to predict the stalling point of the airfoil accurately. This could be because of the high amount of randomness and turbulence within the stalling vicinity and the lesser amount of refinement of the CFD mesh due to the lack of computational power to further refine the mesh in order to capture these phenomena and the time constraints available. It is safe to say that the CFD results has validated the experimental results up to a certain extent but was not able to predict the flow behaviour near the stalling region, hence it is not appropriate to come to conclusions based on the values obtained within this region.

The pressure contours and the streamlines at different angles of attack was analysed in order to get a better understanding regarding the flow over the airfoil. By looking at the dynamic pressure contours it was seen that the flow over the airfoil was initially fully attached and with the increase of the angle of attack the wake behind the airfoil continued to increase. It was also seen that the path followed by the flow field is not that of the physical body of the airfoil and instead it is of a different shape. The path followed by the flow might be the effective body of the stalled airfoil rather than its physical body which might have been the reason for the occurrence of hysteresis loop and why a stalled flow persists even when the angle of attack is reduced below the staling angle. The angle of attack of the stalled airfoil needs to be reduced to an angle lower than that of the effective body's stalling angle in order to reattach the flow as stated by Morris II et al. for a symmetric airfoil (Morris, et al., 2020). This is to be further studied by conducting experiments on an effective body of the stalled Clark Y 14 airfoil.

4. CONCLUSION

A two-dimensional asymmetric Clark Y 14 airfoil was observed in low-speed flows by varying the parameters of angle of attack and Reynold's number.
It was observed that the Reynold's number and angle of attack are primary parameters that have an impact on the occurrence of hysteresis loops in static stall hysteresis of the Clark Y-14 airfoil and the size of the so formed hysteresis

It was observed that a clockwise hysteresis loop was formed for the lift characteristics of the Clark Y-14 airfoil where the extent of the Hysteresis loop increased with the Reynolds number where the maximum could be seen at Reynolds number of 134072 before starting to decrease again. The stalling angle of attack of the said airfoil too followed a similar pattern where the stalling angle increased with the Reynolds number before starting to decrease at a Reynolds number of 146260. These patterns observed are similar to the hysteresis loops observed for the Eppler 591 and NACA 0018 airfoils by Lance W. Traub and W.A. Timmer respectively.

The coefficient of pressure curves of the Clark Y-14 airfoil showed a laminar separation bubble forming which shifted towards the leading edge of the airfoil with the increase of the angle of attack for all the Reynolds numbers for which the experiment was conducted. For the forward stroke it was seen that a laminar separation bubble was formed, but for the backward stroke no such laminar separation bubble was formed, which led to a drastic decrease in the lift characteristics of the backward stroke giving rise to a clockwise hysteresis curve for the Clark Y-14 airfoil.

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