FORWARD FACING FLAP FOR DELTA WING PERFORMANCE IMPROVEMENT

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Abstract – *In the present study, the concept of forward facing flap mounted on a slender delta wing, originally proposed by Hurley is considered. The test model resulted in surfaces that deflected from the basic delta to form a simple X-configuration. With this configuration, force balance measurements were conducted at low speed in a low speed open circuit wind tunnel. The lift produced was found to be dependent on both the flap deflection angle and thickness. Overall, the results obtained are very promising as they show definitive trends in the lift performance improvement of the X-configuration over conventional base delta wing at low angles of attack.*

Keywords: *Delta wing, vortical flow, forward facing flap*

Nomenclature

c	chord length (in mm)
t	thickness of flap (in mm)
S	area of base wing (in mm2)
u	wind tunnel velocity (m/s)
Re	Reynolds number (=ρuc/μ)
C_L	coefficient of lift
C_D	coefficient of drag
ΔC_L	changes in lift coefficient
ΔC_D	changes in drag coefficient
α	angle of incidence (degree)
β	angle of flap (degree)
ρ	density of fluid (kg/m^3)
ʌ	sweep angle of delta wing (degree)
μ	dynamic viscosity (kg/(m.s))

I. Introduction

Study of lifting bodies in various flow conditions of subsonic [1-3], transonic [4, 5] or supersonic [6-8] speed ranges is an area of continued research in aerodynamics.

The NACA four- and five- digit airfoils have evolved mainly from considerations where density changes are small and flow encountered can be considered incompressible. In order to produce high lift that is required during the take-off and landing phases of an aircraft flight, the angle of incidence of the wing is increased.

However, there is a limit to the maximum lift that a wing can produce, which generally happens at a critical angle of 12 to 16 degree angle of incidence, depending on the type of wing cross section used. If the angle of incidence is increased beyond this critical angle, the wing stalls or loses its ability to produce lift accompanied by a large increase in drag. Generally, this phenomenon is caused by the separation of boundary layer on the wing surface that is a major concern in incompressible flow.

In high-speed flows, where density changes can no longer be ignored, the compressibility effects can become the dominant consideration and give rise to a new form of flow breakdown that manifests in the formation of shock waves.

The flow discontinuity arising from shock waves produces sudden and abrupt changes in the density, pressure, velocity and temperature with subsequent drop in lift and dramatic increase in drag. Under such circumstance, avoiding or managing shock wave and its detrimental effects becomes of greater priority.

Some modifications to the top and bottom surfaces of the subsonic incompressible airfoils have been attempted to push the location of the shock waves towards the trailing edge of the airfoil resulting in what are often called the transonic airfoils.

In addition, the use of forward or backward sweep has also been incorporated on subsonic airfoils. The sweep makes an airfoil experience a reduced component of the free stream velocity hitting its leading edge. This has the effect of delaying the occurrence of the formation of shock waves.

With increasing demand to fly faster and moving into supersonic speed range, it became clear that a new type of lifting body that operated that could handle shock wave effects but was still capable of producing lift was required. This is the background against which delta wing with sharp edges have been developed for high-speed flow.

Delta wing, however, has poor aerodynamic efficiency at low speed that is not desirable during aircraft take-off or landing. Consequently, lot of efforts have been devoted towards the performance enhancement of delta wing at low speed.

The goal of the present paper is to contribute to these efforts by investigating the use of forward facing flap on delta wing to achieve its performance enhancement at low speed.

II. Literature review

Although the concept of lifting delta wing originated during the First World War from works in Germany, it was Jones who provided the theoretical formulation for supersonic delta wing [9].

In some sense, Jones work was an extension of Prandtl's lifting line theory for high aspect ratio wings. With low aspect ratio, high taper and high sweep, delta wing is able to delay or mitigate the effects of shock wave. This makes particular attribute of delta wing makes it an attractive lifting device for high speed or supersonic flight.

The lift is generated on a delta wing involves the combination of two separate mechanisms or modes of lift production. The first mechanism involves the conventional method of using angle of inclination to an oncoming flow to produce pressure differences on the top and bottom surfaces of the delta thereby generating lift. The lifting or the top surface of the delta wing does not generally have any curvature and the lift produced is akin to that produced by a flat plate.

In the second instance, the delta wing, instead of preventing flow separation, it induces separation of flow but in a controlled manner along a separation line defined by its sharp leading edges. The separated flow from the edges roll up and form vortices that then re-attach back onto the top surface on a line called the re-attachment line. The vortices energize the flow on the upper surface of the delta wing and the flow remains attached to the wing for much higher angle of incidence, often as high as 40 degrees.

The vortices on the delta wing top surface are composed of two types of vortices, the primary and secondary vortices and the combined effect is the generation of additional lift, called vortex lift, for the delta wing.

With increasing angle of incidence, the strength of the vortices increases but unlike conventional subsonic wing, the total lift produced is not linear.

Overall, the ensuing flow field on a delta wing is quite complex and the lift generated for a particular angle of incidence is much lower than for a conventional subsonic wing at the same angle. With further increases in the angle of incidence, the delta wing eventually loses its ability to produce lift by a mechanism called vortex bursting.

In a supersonic flow, the sharp leading edges on either side of the delta wing also fix the location of the shock waves. This allows the shock waves to remain attached to the delta wing and the flow downstream of the shock wave is able to produce lift on the delta wing during supersonic flight.

Additional features such as the long root chord and short span make the delta wing structurally efficient. Thus, compared to a swept wing of similar lifting capability, the delta wing is stronger, stiffer and lighter.

Furthermore, its long root chord facilitates larger internal volume to an airfoil section that can be used for fuel and storage. The light yet robust structure of delta wing have been a major factor in the success of many supersonic aircraft that have used it such as the MiG-21 or the Mirage aircraft.

Various passive and active means of flow control have been explored to study and improve the performance of a wing at low speed and high speed flows. These have included geometry changes, rotating cylinder [10], vortex trapping or maintaining two-dimensional flow with end plates [11], blowing [12], using discrete Coanda jet [13], adding energy to energise boundary layer with sound [14] or synthetic jet [15], air tabs for jet control [16] and so forth. These methods may be suitable for conventional subsonic airfoil but are either unsuitable for use on delta wing or have had little or limited success.

One of the approach that has shown much promise is the deployment of a leading edge vortex flap on a delta wing [17]. This was a study by Marchman. He placed an additional section on the leading edge that was deflected downward preserving the vortex flow and increasing lift. However, this increase in lift was accompanied by an increase in drag.

Marchman's studies found that although a 70% lift increase was achieved at a 5-degree angle of attack, the additional drag produced was the much higher of order of 300%. This suggested that the design is not suitable for take-off but may be useful for the landing.

Other studies on the effect of leading edge flaps found the flap deflection to cause large changes in the size and location of the vortex core, as well as in the axial and swirl velocity profiles. The effect of the flaps on vortex breakdown was also considered, but attempts to predict the variation in breakdown location with flap deflection was not successful.

Rao and Johnson [18] investigated the relative merits of a number of leading edge devices on lift dependent drag reduction at high angles of attack, of which three were designed to maintain attached leading edge flow over the wing span while the fourth (a vortex plate) forced separation to generate a span wise vortex.

The vortex plate was found to be the most promising, providing drag reduction at angles of attack above 10 degrees. This suggested that the use of flow separation to establish vortices offers a promising technique to increase both lift and drag and hence the aerodynamic efficiency of a delta wing.

Earlier works by Hurley in 1961 [19] had also suggested that instead of suppressing separation, it should be exploited.

Hurley carried out experiments on a two-dimensional, rectangular wing. He allowed flow to separate from the leading edge and made to attach to the upper surface of a forward facing flap as shown in Fig. 1. Increases in lift were observed. At the same time, it was found that a blowing slot was required at the leading edge of the flap to establish the free streamline flow.

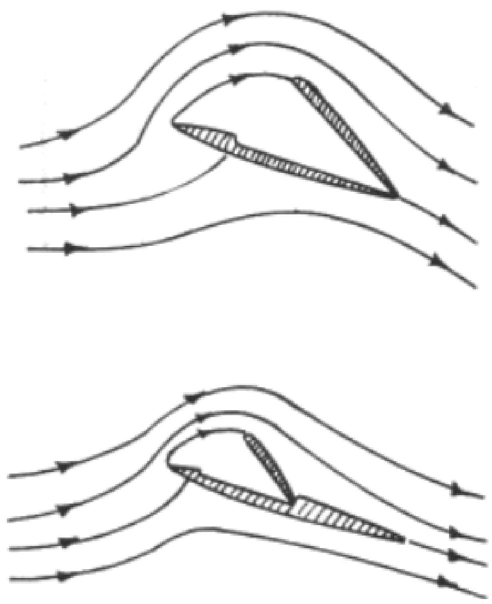

Fig.1 Hurley's proposed configurations of a free streamline flap [19]

Based on his results, Hurley remarked that a forward facing flap if introduced onto a delta wing as shown in Fig.2 might improve lift and decrease drag, without the need for boundary layer control. The present study was conducted to explore this delta wing flap as a 'proof of concept' for lift enhancement.

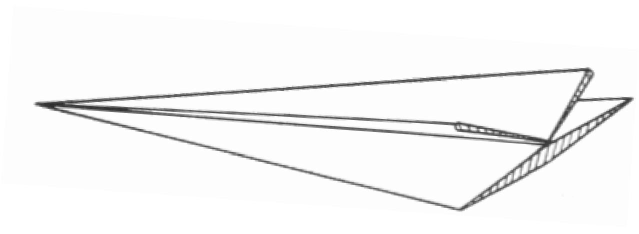

Fig.2 A three-dimensional view of the Hurley's concept of a delta wing with flap [24].

III. Experiment

Investigation of delta wing flow is fraught with difficulties. Numerical investigation using computational fluid dynamics and or experimental investigation using wind tunnel and associated instrumentation have their limitations. In the absence of reliable data for validation of the numerical data necessary for computational fluid dynamic investigation, it was decided to perform wind tunnel experimentation as a better option.

Following Hurley's concept as depicted in Fig. 2, delta wing and flaps were constructed for testing which resulted in what looks like an X configuration.

The base of the wing and flaps were made of separate pieces to allow for flexibility in flap deflection angle. For ease of manufacture, the base of the wing was simply an aluminum triangular plate. The flaps were also made of aluminum plates and were attached to the base wing at various flap angles.

The flap deflection angle was taken to be the angle between the upper surface of the base wing and lower surface of the flap.All edges of the base wing and flaps were left square.

The configuration of the base wing was kept fixed with 2 mm thickness and 60 degrees leading edge sweep angle. Four flap plates were made with sweep angles of 60 and 75 degrees and thicknesses of 1.2 mm and 5 mm.

Some thoughts were also given as to how the data from wind tunnel experiments would be obtained. Any measurement method that would be intrusive in nature, such as hot wire [19] or pitot probe [20] could only be deployed with partial success, as they have the potential to produce vortex bursting and thereby render the flow useless.

Non-intrusive methods such as laser velocimetry or PIV [21] would also require introducing seeding particles, the presence of which also could result in vortex breakdown. Since the present study was more of a proof of concept nature, it was felt force balance measurements would be quite useful to get the overall trend and broad indications of the performance potential of the forward facing flap.

Experiments were conducted in a 760 mm diameter open test section, open circuit, subsonic wind tunnel at a Reynolds number, based on root chord, of 2.7×10^5. The model was mounted on a cylindrical metal post. The load cell used was located under the post. A digital protractor was used to measure the angle of attack during experiments. A FCO510 micro-manometer with a measurement resolution of 0.01 Pa was use for velocity measurement.

The force balance results obtained for lift and drag were normalised by $\frac{1}{2} \rho u^2 S$, where ρ was density of air, u was velocity of wind tunnel and S was the area of the base wing.

The load cell accuracy was estimated to be $\Delta C_L = 0.18$ and $\Delta C_D = 0.18$.

IV. Results and discussions

The effect of varying flap deflection angle, size, and sweep angle were studied.

First, the results for the base wing without the flaps (control case) were obtained followed by incorporating flaps of varying sweep angles and thickness at various flap angles.

IV.a Effect of flap defection angle

Fig. 3 show the results for a 60^0 sweep angle flap of 2 mm thickness. Five flap angles of 4^0, 13^0, 21^0, 43^0 and 30^0 were used.

The results obtained for lift coefficient for angle of attack ranging between 0^0 and 40^0 were then compared with the result obtained for the base wing.

It can be seen from this figure that at low angles of incidence, the coefficient of lift variation is linear. The lift curve slope is, however, slightly higher for larger flap angles. The stall angle, however, is lower for the base wing.

It appears that for the different flap angle tested, the case of 43-degree flap angle appears to have higher lift curve slope and stall angle. Another feature worth noting is that the stall angle drop is less severe for all flap angles compared to the base wing.

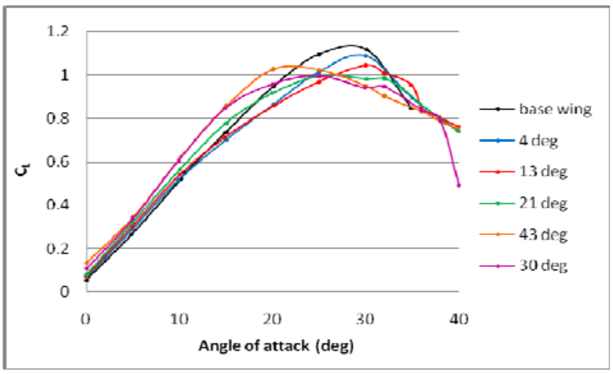

Fig. 3 lift coefficient versus angle of attack with flap deflection for the 60 degree swept flap

In Fig. 4, the drag coefficient versus angle of attack for the same flap angle variations obtained for lift coefficient presented in Fig.3 are presented.

The drag behaviour of flaps with different flap angles as observed in Fig. 4 shows somewhat of a nonlinear behaviour with angle of incidence changes.

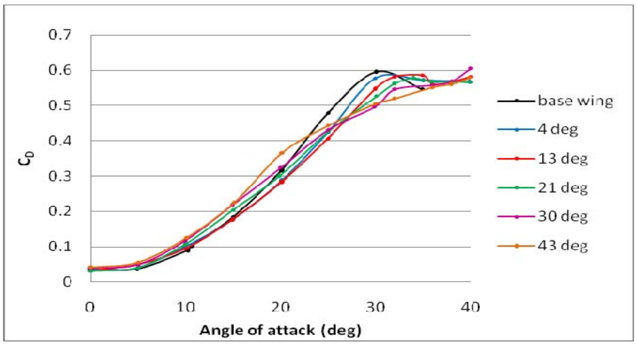

Fig. 4 Drag coefficient versus angle of attack with flap deflection for the 60 degree swept flap

While the base wing exhibits lower drag at lower angle of incidence, but higher drag at higher angle of incidence. The drag appears to be lower with higher angle of incidence for flaps placed at higher angle in relation to the base wing.

To provide additional insight, the model was inverted so the flaps became downward deflecting. Fig.5 provides the effect on lift generated for the inverted 60-degree swept flap.

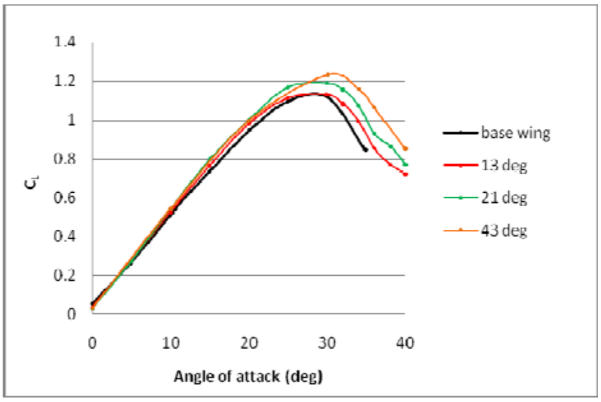

Fig. 5 Lift coefficient versus angle of attack with flap deflection variation for the inverted 60 degree swept flap

It can be seen that at low angles of attack, the lift curve was relatively unchanged from that of the sole base wing.

At an angle of attack of between 5 and 10 degrees, the flap configuration results deviated from the base wing, producing an increase in maximum lift with increasing flap deflection. The corresponding drag was also observed to increase, resulting in a constant lift-to-drag ratio.

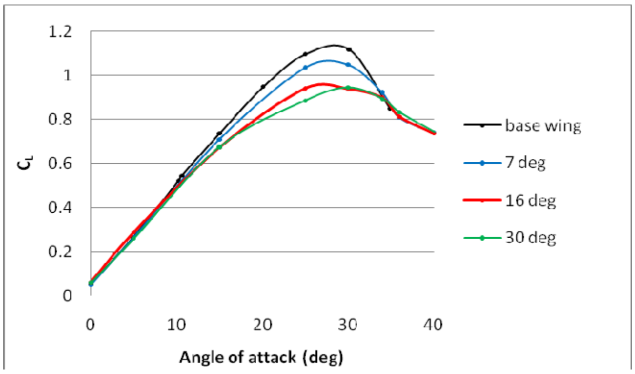

Fig. 6 Lift coefficient versus angle of attack with flap deflection variation for a 75 degree swept flap

Furthermore, it can be observed that with increasing flap deflection, lift and drag values increased above that of the base wing until a certain angle of attack. Then they fall below that of the control case. This angle of maximum lift also increased with increasing deflection.

The next set of results was obtained on a 75-degree flap and the results are presented in Fig. 6. The 75 degree swept flap did not display any change in lift curve slope for angles of attack below 10 degrees.

However, for larger angles of attack, the curve deviated from the base wing. The lift curve slope became lower compared to the base wing suggesting lower lift production. This departure became more noticeable with higher flap deflection angles. This flap appeared to provide little benefit concerning lift generation and was, therefore, not subjected to further experimentation.

IV.b Effect of flap thickness

For load cell experiments on the thicker flap model of 5 mm thickness, observing the results of Fig. 3, three flap deflection angles of 13, 21 and 45 degrees were chosen. The results are given in Fig.7

From Fig.7, it can be seen that the lift curve slope for the base wing was similar at lower angles of attack, but became more pronounced with higher angle of attack.

The stall angle of the base wing, however, was higher than those with flaps having different angles. The base wing also had a much steeper drop at stall conditions than the other cases.

Although an increase in thickness affected the results, the effect of variation in flap deflection angles was less pronounced both for lift and drag coefficient curves. From this figure, the 45-degree flap deflection appeared to produce the highest lift at lower angles of attack.

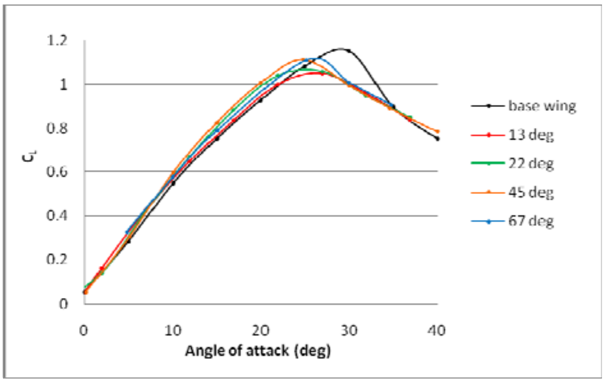

Fig. 7 Lift coefficient versus angle of attack with flap deflection variation; 5 mm thick model with 60 degree swept flap

To investigate further, the effect of thickness, flap defection of 45 degrees was chosen for testing an additional flap having a thickness of 1.2 mm. A similar trend with relation to the base wing was also observed for the 1.2 mm case.

For greater clarity, the thickness effect at 45-degree flap deflection angle for 1.2 mm and 5 mm thicknesses respectively was re-drawn and presented in Fig. 8.

Observing the lift coefficient variation with angle of incidence of flaps of 1.2 mm and 5 mm thickness, there was hardly any change in the lift curve slope up below 20 degree of incidence.

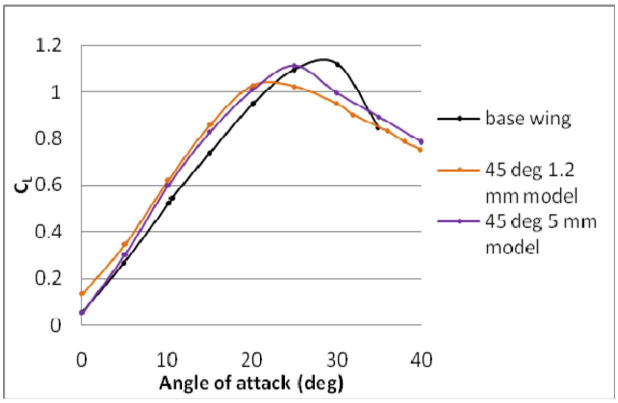

Fig. 8 Comparison of lift produced by the 45-degree flap deflection for different model thicknesses

The stall angle, however, was higher for the 5 mm case. The thickness also did not appear to affect the nature of lift drop and were more gradual than the base wing case as can be seen in Fig.8.

V. Conclusion

The effect of Hurley's forward facing leading edge flap was studied on a 60 degree swept delta wing at low speeds with varying flap defection and angles of attack.

It was found that with an increase in flap deflection angle there was an increase in lift at low angles of attack with the largest lift increment happening at around 45-degree flap deflection angle.

It was also found that the effect of thickness was minimal at low angles of attack but becoming less favourable in terms of lift increase at high angles of attack.

Overall, the study shows promise of the delta wing-flap configuration as a useful method to increase the lift of delta wings at subsonic speeds.

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