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Experimental Investigation of Asymmetry of Vortex Flow Over Single Delta Wings

G. Atashbaz[1]

It is generally believed that, on slender delta wings, there is a critical state at which strong asymmetric vortices are found along the leading edge on the lee-side of the delta wing. These asymmetric vortices can lead to high lateral forces even when slender delta wing is at the zero angle of yaw. Some experimental studies reported recently, cast considerable doubt as to the validity of the above explanations. A wind tunnel investigation was, therefore, performed to study afresh this phenomenon. The flow over four sharp edged delta wings with aspect to a ratio ranging of 0.56 to 1.46 was investigated using flow visualization with laser light sheet and some surface pressure as well as hot wire measurement. The tests were conducted for angles of attack ranging from 0 to 30 deg and at a free-stream velocity of 30m/s corresponding to a Reynolds number of 4.8×10^5 *based on the center line chord of the wing. The results obtained suggest the absence of asymmetry in the vortex core position in the flow.*

NOMENCLATURE

AR	aspect ratio $= b^2/S$
b	Wingspan, m
Cp	pressure coefficient $=(p - p_\infty)/q_\infty$
C	Wing root chord, m
p	Static pressure, Pa
p_∞	Upstream static pressure, Pa
ρ_∞	Upstream air density, kg/m^3
q_∞	$(\rho_\infty U_\infty^2)/2$
Re	Reynolds number $=U_\infty C/\nu$
S	Wing area, m
s	Local wing span, m
U_∞	Freestream velocity, m/s
x, y, z	Wing-axes system, origin in wing apex, m
Λ	Delta wing sweep angle, deg
α	Angle of attack, deg
β	Angle of sideslip, deg
ν	Kinematic viscosity, kg/ms
U	Velocity,m/s

INTRODUCTION

Thin slender wings with highly swept and relatively sharp edges are of increasing importance for several modern fighter aircraft. At moderate and high angles of attack, the flow over such wings separates at the leading edge, resulting in a steady and stable leading edge vortex flow [Verhaagen and Naarding, 1989]. It is reported in the literature that on slender delta wings in low speed flow, the initially symmetric (with respect to the wing symmetry plane) leading edge vortices on the lee side become strongly asymmetric at some critical angle of attack before vortex breakdown occurs [Polhamous,1971; Wardlaw, 1979 and Stallings,1986]. Some studies [Lowson,1992] suggest that the effect is principally due to nonuniform viscous boundary layer development, perhaps triggered by nonuniformities, but this is difficult to justify. Other studies [Lamount and Hunt, 1973 and Dexter , 1984] have demonstrated that the flow structure and direction of side force are very sensitive to small disturbances near the apex, which can be locally large on an inviscid scale. Other studies [e.g.,Keener and Chapman, 1977] suggest that the vortex flow asymmetry is the result of a hydrodynamic instability in the vortex formation process with strong similarities between slender bodies and slender delta wings.

Numerical studies from standard line vortex

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[1] *Aeronautical Research Center
Malek-e-Ashtar Univ. Tehran, Iran*

model also suggest, asymmetric solutions for the separated vortex flow over a conical slender body even for symmetric boundary conditions [Dyer et al, 1982]. At low angles of attack, the flows are symmetric, but at a critical angle of attack, the solution exhibits a bifurcation to an asymmetricity [Lowson and Ponton,1992]. Further attempts [Fiddes and Smith, 1982: 1987: and Fiddes, 1987] using a fuller vortex sheet model, produced similar results.

It was , however, suggested that flatter bodies, for such as elliptic cones would be more resistant to the appearance of asymmetries. In particular, at sufficiently low thickness-chord ratio, no asymmetry would occur. Recent experimental works, [Stahl,1992; Erricson, 1992, and Lowson, 1992] found no asymmetry in vortex position in the flow over an ideal slender wing. This conclusion is of special interest as it is in direct contradiction to the suggestion of Keener and Chapman [1977] of asymmetric conditions occurring on slender wings or bodies. Woolard, [1982] attempted to derive a mathematical relation between the wing and cone flows, but this analysis contained an error, and the flows could not be mapped in the manner described. Several workers have reported asymmetries and/or unsteadiness in the flow on slender delta wings at high angles of attack, which might be presumed to result from mechanism related to those on slender circular bodies. However, just recently Hung and Chow [1996] showed numerically that the vortex pair is stable to disturbances of small amplitude.

This it is clear that although the question of asymmetry over delta wing flow has attracted a lot of attention, the problem, nevertheless, remains unresolved. A look into this very important phenomenon, therefore, forms the basis of this paper. Initial attempts to quantify the asymmetric features of the flow using static surface pressure measurement and hot wire anemometry showed some signs of asymmetry even at zero sideslip. A flow visualization technique using laser light sheet was installed to observe qualitative behaviour of the flow for additional support. The flow visualization results, however, did not find any strong asymmetry in vortex core position on the delta wings tested. The different factors associated with experimental setup and measurements were, therefore, investigated thoroughly.

EXPERIMENTAL SETUP

The large subsonic open circuit wind tunnel with a square test cross section measuring $460mm \times 460mm \times 1220mm$ located in the Aerodynamics Laboratory of the University of New South Wales (Australia) was used for these experiments.

Four different low aspect ratio sharp-edged delta wing models were designed and constructed for use in the present investigations. The root chord of all these delta wings was 254 mm and the sweep angles were 70°, 76°, 80° and 82°. The maximum thickness (located at the trailing edges) was 5.12% of the chord. Table 1 shows the geometric details of the models.

Provision was also made to change the pitch angle of the delta wing by a mechanism mounted in the support of the wing, which could be set from -10deg to +35 deg. The whole support of the delta wing was rotated by another mechanism to change the sideslip angles ranging from -15 to +15 deg. The uncertainties in the pitch and sideslip angle settings was between + 0.1 deg. The delta wing under investigation was positioned in the middle of the wind tunnel test section.

For flow visualization experiments, the cross section of the vortices was illuminated by a thin sheet of intense light produced by a 30m Watt Helium-neon laser in conjunction with an optical system. Available smoke generator was used to produce smoke. The laser source was mounted on a traversing platform enabling translation in all three directions. To clearly visualize the vortex flow by laser light sheet flow visualization method, experiments had to be performed in the dark in the night time to avoid having any other light except laser to have a black background. Just a small concentrated ray of light with adjustable brightness had to be directed through the top section glass to illuminate the model surface. For this purpose a fiber optic light source with flexible arm was employed. This device was also located the roof of the wind tunnel.

Surface pressure measurements were made on the leeward side of the models. Pressure tap points between 11 to 17 were incorporated in each delta wing according to its geometry at $x/c = 0.75$. Static pressure of the ports was connected to a multitube manometer with PVC tubes.

For velocity measurements, the hot-wire anemometry system used was of the constant temperature type. Miniature, single element platinum based tungsten probes (DISA, Model 55P15 and 55P11) of 5μm diameter and 1.25mm sensing length were used and a traversing gear was employed to move the hot wire probe to the required measurement positions. There was also a provision to rotate the hot wire about its own axis. The hot-wire signal was linearized through a linearizer and, after accurate calibration, fed into a 486DX computer through an analog to digital converter [ADC of HS-DAS-12] board. A commercially available software called SNAPSHOT was used to take the burst of hot-wire reading in equally spaced intervals of time during each experiment. The sampling rate was set at 2000 samples per second of hot-wire readings. The data were collected over a 5 second period.

Schematic views of the setup used for the laser light sheet technique and surface pressure and hot-

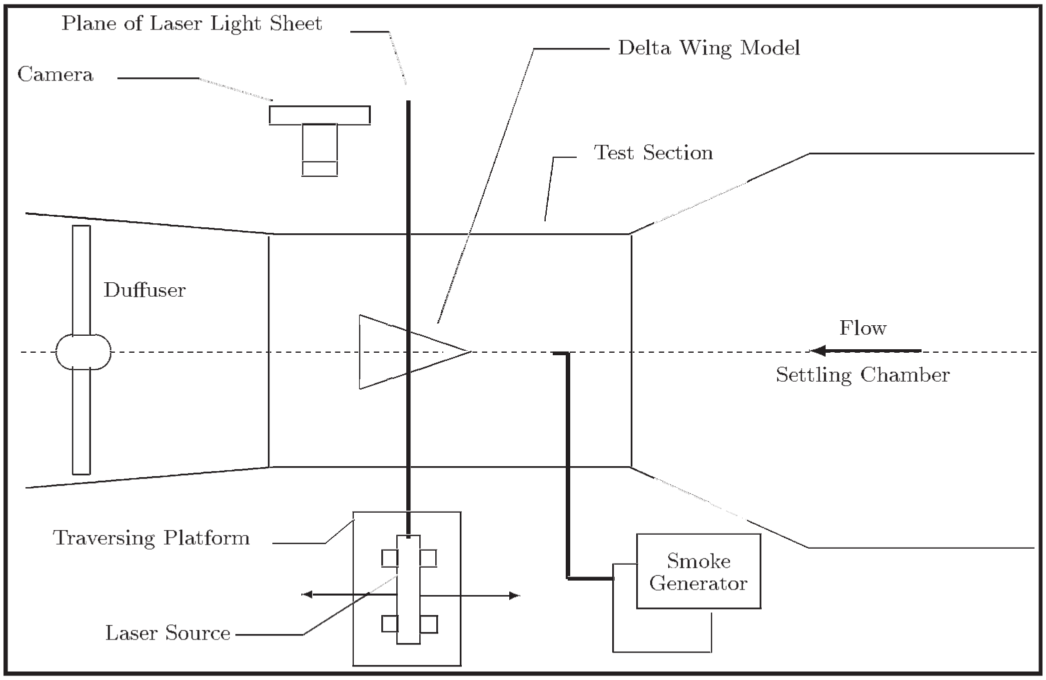


Figure 1. Schematic of laser light sheet setup.

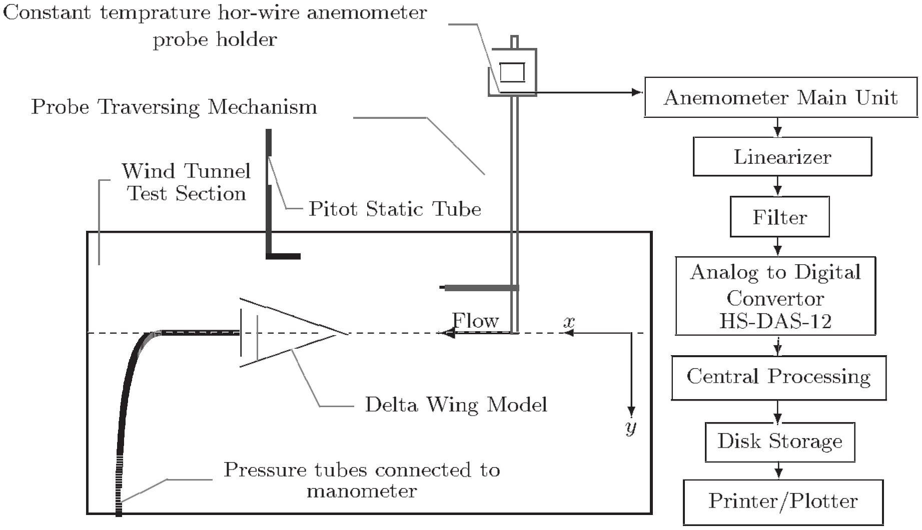


Figure 2. Experimental setup for surface pressure and hot-wire measurements.

wire measurements are shown in Figure 1 and Figure 2 respectively.

Strategy of Experiments

To investigate vortex asymmetry,a series of qualitative and quantitative experimental methods was conducted at a constant upstream velocity. As a result, laser light sheet flow visualization,surface pressure measurement, and Hot-wire velocimetry were adopted. A freestream velocity of 30m/s corresponding to the Reynolds number of 4.8×10^5 based on root chord was used for these experiments.

To conduct laser light flow visualizations, the streamwise development of the vortex flow from $x/c = 0$ (the tip of the wing) to $x/c = 1.1$ (after trailing edge) was visualized for each of the slender single delta wing with sweep angles of 70°, 76°, 80° and 82°, corresponding to aspect ratios of 1.46, 1.0, 0.7 and 0.56 respectively. The flow patterns were photographed at different angles of attack ranging from 0 to 30 deg and also at different sideslip angles ranging from -15 to +15

Table 1. Geometric details of models.

Delta Wing No.	Delta Wing Sweep Angle λ deg.	Aspect Ratio AR	Wing Centerline Chord C mm	Length of Wing Span at $x/c = 0,75$ mm	No of Pressure Taps used
1	70	1.46	254	141	17
2	76	1.0	254	95	17
3	80	0.7	254	67	15
4	82	0.56	254	54	11

deg. The flow visualization information was recorded on both photographic film and videotape.

As for the pressure measurements, each delta wing was positioned at different angles of attack (0, 5, 10, 15, 20 and 30 deg) and surface pressure was measured by multi-tube manometer. Surface pressure data reduction essentially consisted of measuring the spanwise static pressure of the wing at $x/c = 0.75$, and plotting pressure coefficient as a function of y/s for different angles of attack for various delta wings using the following equation:

$$\mathrm{Cp} = \frac{(p_s - p_\infty)}{\frac{1}{2}\rho\ u^2}$$

With respect to the hot wire velocimetry,it the hot-wire was initially traversed at different heights of several spanwise and longitudinal positions upstream of $x/c = 0.75$. It was observed that there were little or no variations in pressure readings at $x/c = 0.75$, thus, providing confidence that vortex bursting or breakdown was not initiated by placing the hot-wire probe upstream of this location. Hot-wire measurements were conducted over the leeside of all the four delta wings. The hot-wire probe was positioned at $x/c = 0.523$ and measurements were conducted at subsequent vertical and spanwise locations for a constant angle of attack of 30°.

RESULTS

Flow Visualization

Visualization of the leading edge vortices on different streamwise positions at a constant angle of attack (30 deg) showed no asymmetry for different delta wings unless vortex breakdown occurred. Since the generation of vortices starts from the tip of the wing, more focus was attempted in that area but no sign of vortex asymmetry was found. It is necessary to mention that very small misalignments or dissimilarities on the tip or each side of the wing can generate dissimilar vortices. Figure 3 shows these vortices for the wing with $\Lambda = 82°$ at $x/c = 1.0$ (trailing edge) for $U_\infty = 30$m/s. This location is the most probable place where either vortex breakdown or vortex asymmetry is likely to occure for this delta wing. Although the span gets smaller for low aspect ratio wings at a specific x/c than higher aspect ratio ones, as the aspect ratio was reduced, the tip vortices on either side drew closer. It was found that the leading edge vortex remained stable along the wing surface for different angles of attack up to $\alpha = 30°$ and the height of the core above the wing increased with the increase in the angle of attack; nevertheless, the spanwise position decreased. This shows that although the span has been decreased and the vortices have got closer, they did not impinge on each other. Instead the height of the vortex core departs from the wing surface. Figure 4 demonstrates the vortex asymmetry occurring at a sideslip angle of -10 deg for aspect ratio of 0.56 delta wing at $\alpha = 30°$ and $U_\infty = 30$m/s. Sideslip caused the vortex to become irregular and dramatically changed the flow pattern.

Surface Pressure Measurement

The influence of six different angles of attack ranging from 0° to 30° on surface pressure distribution for each delta wing is presented in figures 5(a)-(d). The tests were carried out at a constant Reynolds number of 4.8×10^5 based on the chord length. An increase in the strength of vortex can be related to an increase in the pressure difference [Verhaagen,1989]. The pressure differences were found to increase with an increase in the angle of attack due to the formation of strong vortices are formed. These patterns were found to be similar on the extreme end of the wing in the spanwise direction suggesting symmetry of vortical flow over these low aspect ratio delta wings.

In order to investigate the effect of sweep angle on delta wing models, surface pressure distributions over these wings have been compared. This was done by keeping the angle of attack constant at $\alpha = 20°$ for the four low aspect ratio delta wings in zero sideslip. The results are shown in Figure 6. It can be seen that

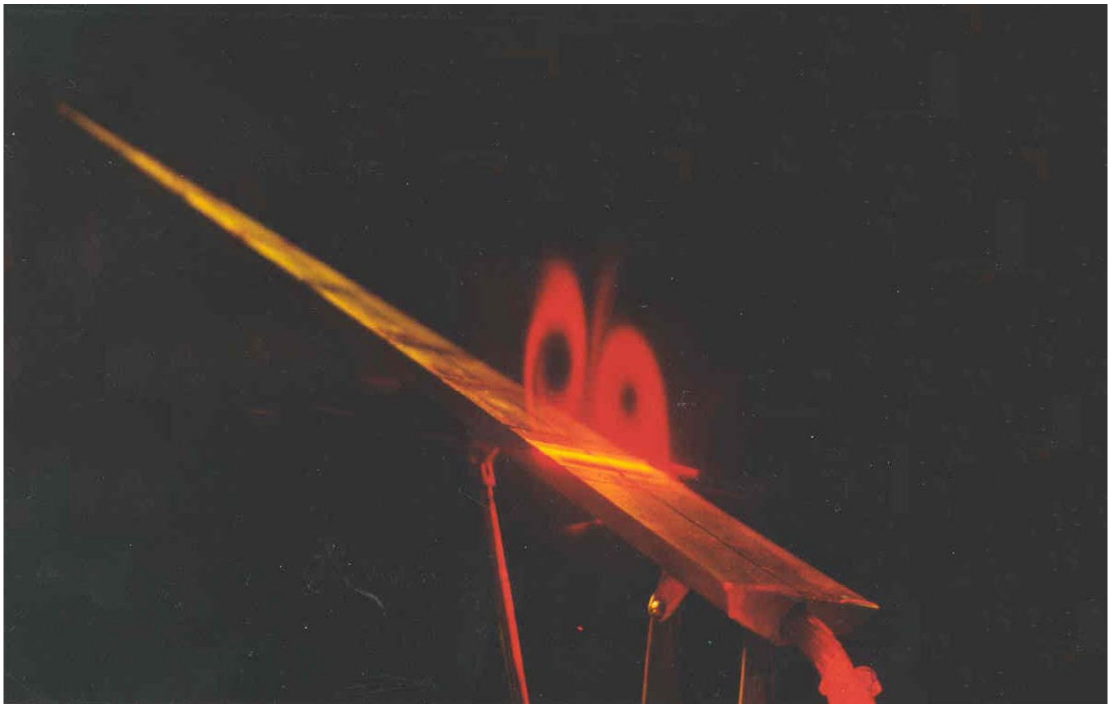


Figure 3. Visualization of the leading edge vortices for delta wing, $\Lambda = 82^\circ$, $\alpha = 30^\circ$, $x/c = 1.0, U = 30\text{m/s}$.

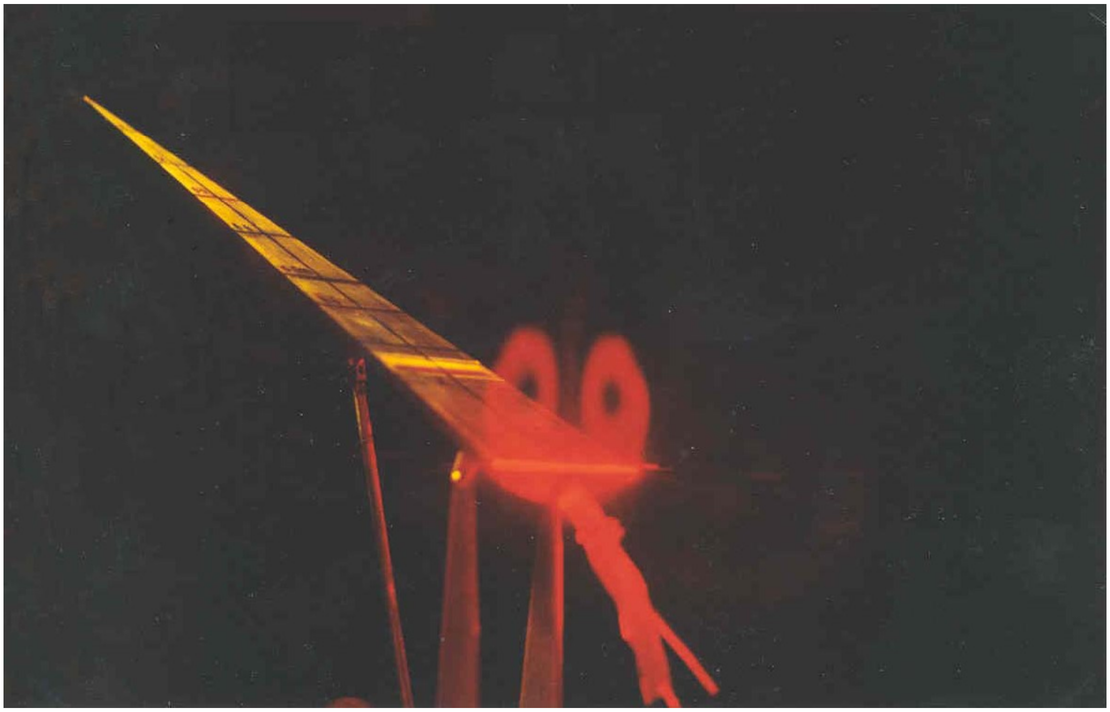
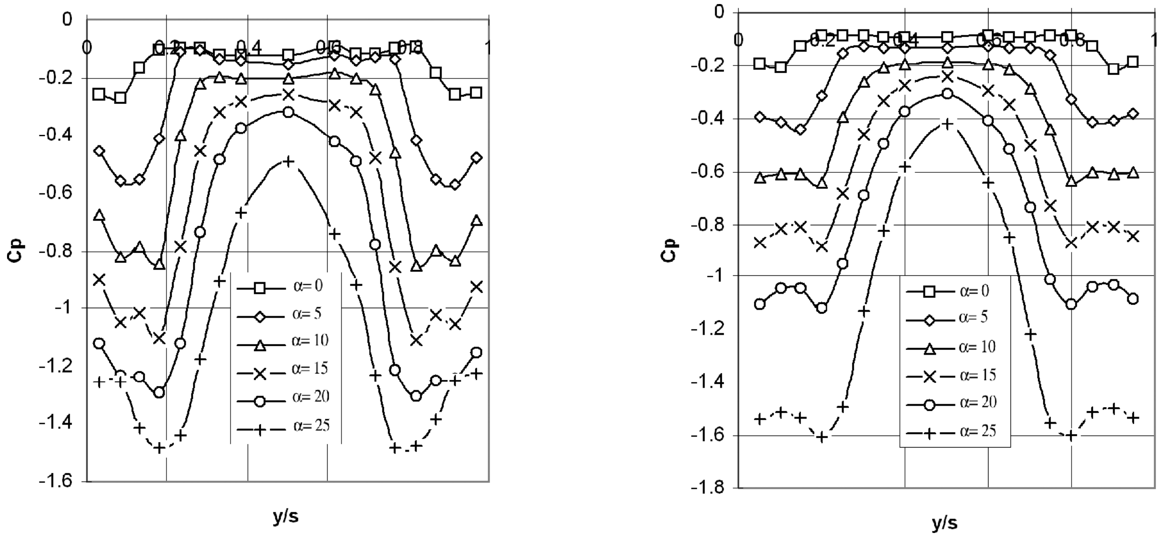


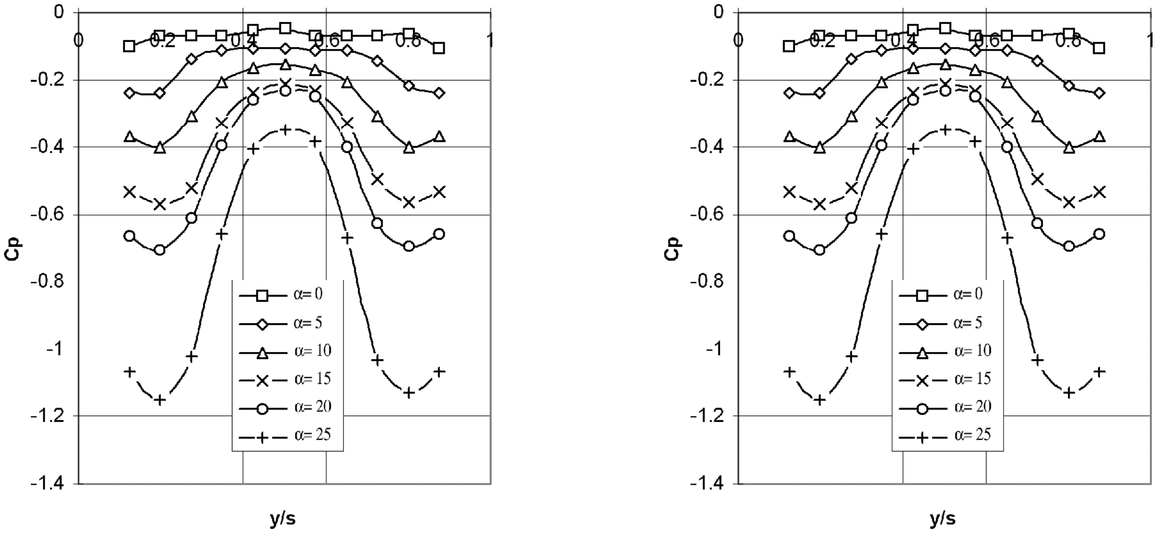
Figure 4. Vortex asymmetry due to sideslip over delta wing, $\Lambda = 82^\circ$, $\alpha = 30^\circ$, $\beta = -10^\circ, x/c = 0.75, U = 30\text{m/s}$.

surface pressure are symmetrically positioned about the wing centerline. For a constant chord length, as the sweep angle increases, the wing span will decrease. The higher the sweep angle, the less the strength of the vortices. It is also reported in the literature (Hemsch and Luckring 1990) that higher aspect ratio wings (lower sweep angles) create more lift. As the pressure difference between the windward and leeward surfaces of the wing are considerable, they create stronger suction on the leeward side of the wing.

It was reported in literature that sideslip is one of the important parameters in making the vortices



(a) $\Lambda = 70°$ (a) $\Lambda = 76°$



(a) $\Lambda = 80°$ (a) $\Lambda = 82°$

Figure 5. Surface pressure distribution over four sharp edge delta wings, $\alpha = 30°$, $\beta = 0°$, $U = 30\text{m/s}$.

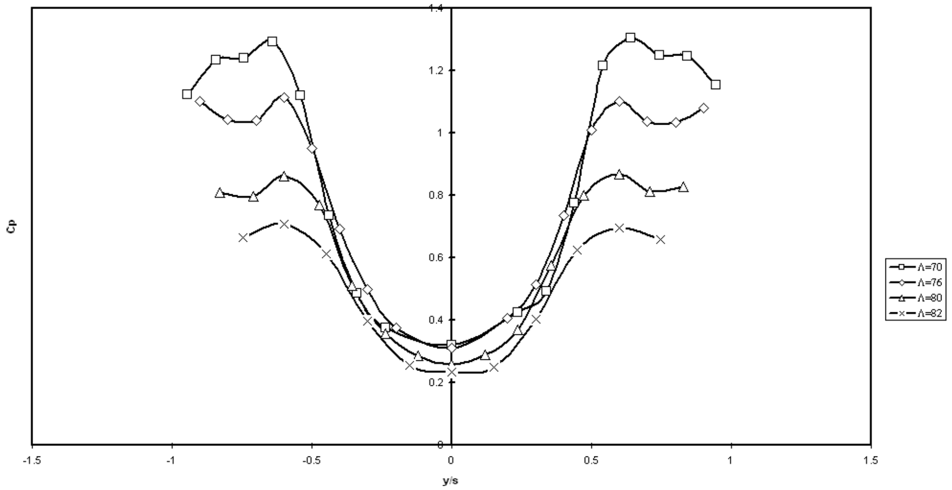


Figure 6. Surface pressure distribution at a constant angle of attack, $\alpha = 20°$, for different low aspect ratio single delta wings in zero sideslip, $x/c = 0.75$, $\text{Re} = 4.8 \times 10^5$.

asymmetric (Atashbaz and Ahmed, 1996). When a single delta wing is positioned at a sideslip angle, on the upper surface, the windward and lee-ward side of the wing will experience different effective sweep angles. The effective sweep angle of windward side will be less than the original sweep angle of the wing, and lee-ward side will experience an effective sweep angle more than the original sweep angle of the wing. This is shown in figure 7.

When a single delta wing is positioned at a sideslip angle, the vortex on the windward side of the upper surface of the wing gets closer to the wing surface and the vortex on the lee-ward side of the wing moves away from the wing surface. This behaviour has been shown in Figure 4. As a result the windward side of the wing senses more suction on the surface while the lee-ward side senses less. The maximum negative Cpvalues also move toward the lee-ward side and the windward vortex move towards the wing centerline. Figure 8 shows surface pressure variations for the delta wing with sweep angle of $\Lambda = 80°$ at $\alpha = 20°$ with and without sideslip at $x/c = 0.75$, at Re $= 4.8 \times 10^5$. It can be seen that the vortex on windward side is stronger than the other side. Figure 9 shows the same results for delta wing with $\Lambda = 82°$ as well. These results clearly demonstrate that the vortices significantly become asymmetric in sideslip. It was also shown that an increase in the sideslip on all of these four models caused more suction for the vortices on the windward side and less suction for those on the lee-ward side.

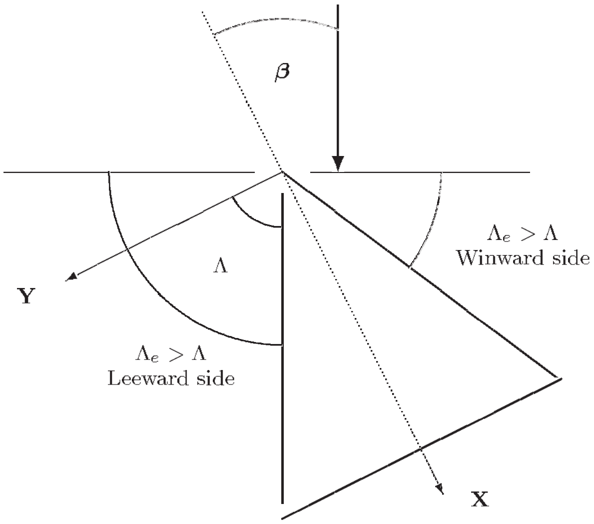


Figure 7. Surface delta wing at a sideslip angle.

Hot-Wire Measurement

Hot-wire measurements were conducted over the leeside of the four slender delta wings with sweep angles of 70°, 76°, 80° and 82°. The tip of the hot-wire probe was positioned at a constant chordwise position ($x/c = 0.523$) and measurements were conducted at subsequent vertical and spanwise locations for a constant angle of attack of 30°. A freestream velocity of 30m/s was used which corresponded to the Reynolds number of 4.8×10^5 based on root chord.

The streamwise mean velocity distribution for a constant height of 10 mm above the surface of various low aspect ratio delta wings is shown in Figure 10. As can be seen the symmetric profile of velocity distribution is presented. The maximum velocity occurs at the core of the vortex and also exceeds the freestream velocity. Such a higher velocity is expected due to acceleration around the leading edge.

CONCLUSION

The flowfield over four low aspect ratio delta wings with sharp leading edges at different angles of attack was investigated experimentally in a low speed wind tunnel. Surface pressure, velocity measurements and flow visualization were performed. Sideslip was found to be an important parameter in vortex asymmetry generation. These investigations suggest that there is no sign of asymmetry in vortex flow on the lee side of single delta wings before vortex breakdown occurred.

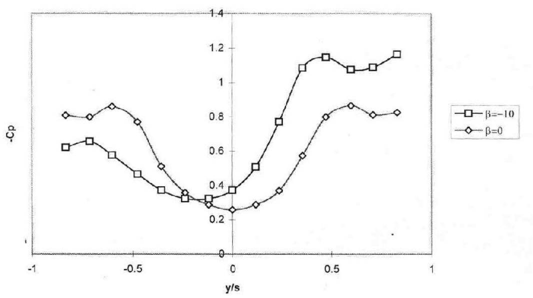


Figure 8. Spanwise surface pressure distribution over single delta wing with sweep angle of $\Lambda = 80°$ at $\alpha = 20°$ with and without sideslip at $x/c = 0.75$, Re $= 4.8 \times 10^5$.

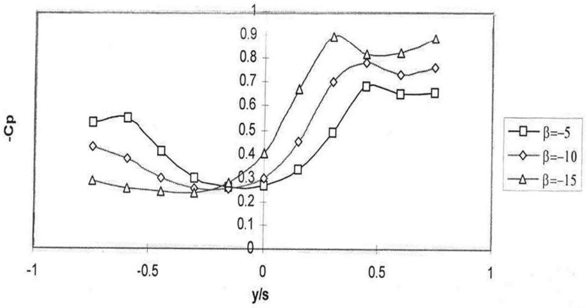


Figure 9. Spanwise surface pressure distribution over delta wing with sweep angle of $\Lambda = 82°$ at $\alpha = 15°$ for different sideslip angles at $x/c = 0.75$, Re $= 4.8 \times 10^5$.

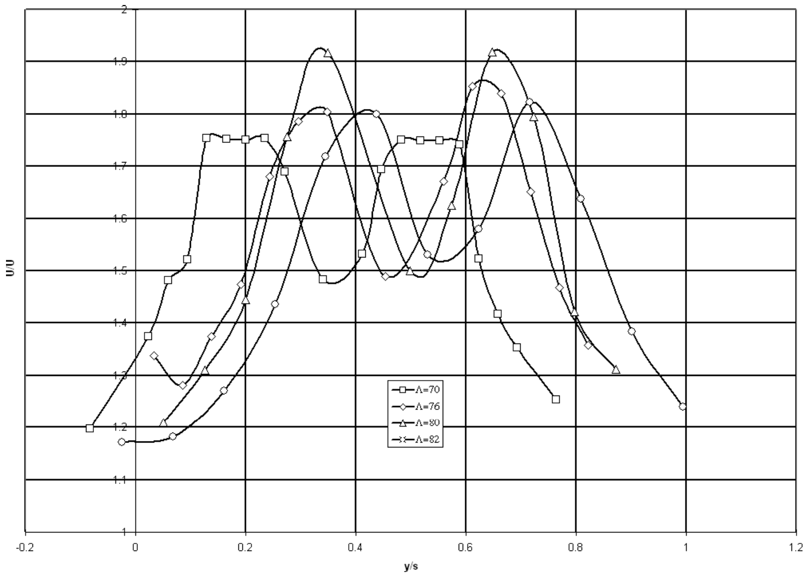


Figure 10. Streamwise mean velocity distribution at a height of 10mm above different low aspect ratio delta wings, $\alpha = 30$, $\beta = 0$, $U = 30\text{m/s}$.

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