FLOW FIELD STUDY OVER THE WING OF A FIGHTER-TYPE AIRCRAFT MODEL

M. R. Soltani, T. Khadivi, A. Abbasi Hoseini

Department of Aerospace Engineering, Sharif University of Technology
Tehran, Iran

(Received: October 11, 2002 – Accepted in Revised Form: October 14, 2004)

Abstract An extensive experimental investigation to study the flow structure over the wing of a fighter type configuration model has been conducted. The model used for this study was similar to the High Alpha Research Vehicle (HARV) that has been used in various European research centers for studying its force and moment characteristics. Tests were conducted at two subsonic speeds and at low to moderate angle of attack. The wing surface pressure distribution and velocity profiles at various angles of attack were measured. This investigation also included suction effects on the wing surface pressure signature. Smoke and tufts were used to visualize the flow over the wing. The results indicate formation of a relatively weak vortex over the wing surface at low angle of attack. As alpha increases, this vortex widens, covering a large portion of the wing, disappearing at moderate angle of attack. Suction affects surface pressure distribution at low to moderate angle of attack, while its effect is reduced at high alpha. It also modifies the velocity profile shape near the surface of the wing.

Key Words Vortex, Suction, Surface Pressure, Velocity Profile, Flow Structure, Post Stall

چکیده تحقیق گسترده ای در زمینه ساختار جریان روی بال مدل یک جنگنده در دانشگاه صنعتی شریف انجام گرفته است. مدل استفاده شده در این تحقیق مشابه مدل (HARV) می باشد که در مراکز مختلف تحقیقاتی اروپا مورد استفاده قرارمی گیرد. آزمایشات در دو سرعت مختلف مادون صوت و در زوایای حمله پایین تا متوسط انجام گرفته است و توزیع فشار سطح بال و پروفیل سرعت در زوایای حمله مختلف اندازه گیری شده است. این تحقیق همچنین شامل اثرات مکش سطح بال روی توزیع فشار سطح آن می باشد. برای آشکارسازی جریان از دود و تافت استفاده شده است. نتایج, شکل نسبتاً ضعیف گردابه را در زوایای حمله پایین نشان می دهند. با افزایش زاویه حمله, این گردابه گسترش یافته و سطح وسیعی از بال را دربرمی گیرد. مکش سطح بال در زوایای حمله پایین تا متوسط, روی توزیع فشار سطح بال موثر می باشد. در صورتیکه در زوایای حمله بالا این اثرات کاهش می یابد. همچنین تغییرات شکل پروفیل سرعت در نزدیکی سطح بال بر اثر این مکش دیده می شود.

1. INTRODUCTION

Aerodynamics Technology is historically rooted in the principle of avoiding or reducing the dissipative and unpredictable flow phenomenon associated with separation, turbulence and etc., by shape design as well as angle of attack restrictions to ensure efficient and safe operation of flight vehicles. Of relatively recent origin is the idea of promoting and manipulating dominant vortical flow structures, to enhance aerodynamic control of vehicles at the limits of lift and into post stall regime. This approach has been spurred by the need for supermaneuverability and agility across a virtually unlimited angle of attack range, of the new generation of combat aircraft within the configurational constraints as dictated by low observable.

For an effective combat aircraft, high aerodynamic efficiency needs to be maintained up to high angles of attack, on configurations for which the wing shape is largely determined by transonic and supersonic performance requirements [1-8].

Highly sweep back wings have been used for these aircrafts mainly to prevent flow separation when operating at high angles of attack. However, at a very high angle of attack, appropriate to instantaneous turn performance and combat agility, the flow on combat aircraft wings becomes less ordered due to the boundary layer separation phenomenon, deteriorating the aircraft stability and

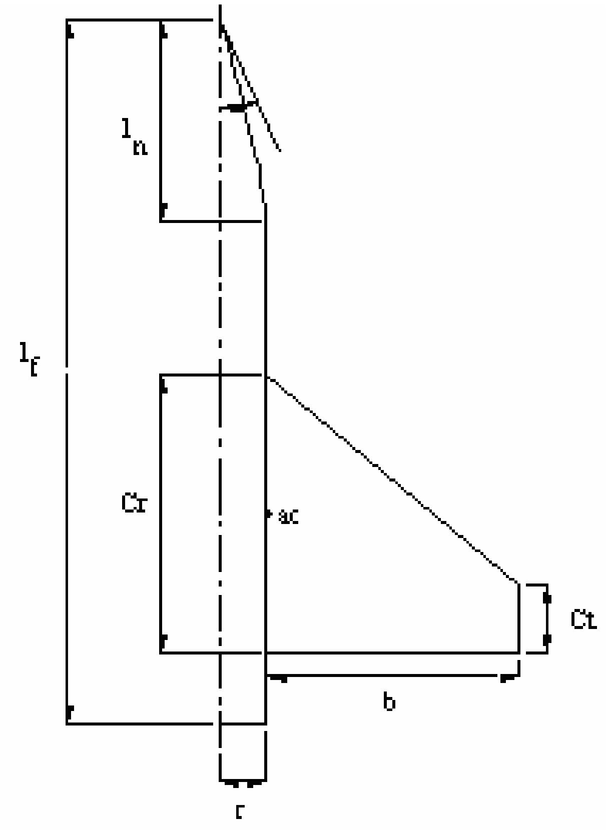


Figure 1. Schematic of the model.

control criterion and causing a large increase in drag [9-12]. Historically, boundary layer control has generally been in the form of laminar flow control where distributed suction has been used to delay transition or relaminarize the boundary layer. In recent years, however, turbulent boundary layer control, both passive and active, in the form of suction, injection, riblets, etc., have received considerable attention. There are mainly three methods for stabilizing a boundary layer and delaying separation [1-3]: 1)shaping the surface to provide long runs of favorable pressure gradient, 2)providing more stable boundary layer through suction, and 3)providing more stable boundary layer through surface cooling. Boundary layer control as an aerodynamic art has been practiced through the 20th century. The last 25 years have witnessed a fairly continuous effort at developing the technology for laminar flow aircrafts using surface suction. The difficulties of maintaining the aerodynamic surfaces with their numerous suction slots have triggered many thoughts and developments [3-5].

A series of experimental studies on flow behavior over the wing of HARV model such as surface pressure and velocity profile measurements at various angles of attack, effects of suction and canard shape and its position on the wing surface pressure signature, etc. have begun at Sharif University of Technology department of aerospace engineering [13-16]. This paper, as a part of this ongoing research, presents the wing surface pressure and velocity profile results at various angles of attack. The effects of suction on the flow field over this configuration will be presented too.

Both spanwise surface pressure distribution and velocity profile at various angles of attack for suction on and off cases have been measured. Some flow visualization tests including smoke visualization and tufts were carried out to investigate the flow patterns at various angles of attack. The results confirm presence of a relatively weak vortex on the wing at angles of attacks of about 6deg.

2. EXPERIMENTAL SETUP AND TEST PROCEDURE

2.1 Model Figure 1 shows the used model for these investigations. This is half model and has a conical nose with 15deg angle of apex, $(l_n/l_f)=0.3$, and a flat plate cropped delta wing with a leading edge sweep angle of 40°. The selected wing has a chamfered edge and rounded leading edge, b=214mm, Ct=60mm and Cr=240mm. This wing is equipped with small holes for suction tabs and surface pressure measurements. Tests were performed for clean model and model with two types of surface roughness using sand papers located at the wing leading edge.

2.2 Wind Tunnel The experiments were carried out in the subsonic wind tunnel of Sharif University of Technology. This open-circuit wind tunnel has a closed test section of $46 \times 46\ cm^2$ and with a variable speed of 0 to 45m/sec. Figure 2 shows variations of the test section turbulence intensity with speed section

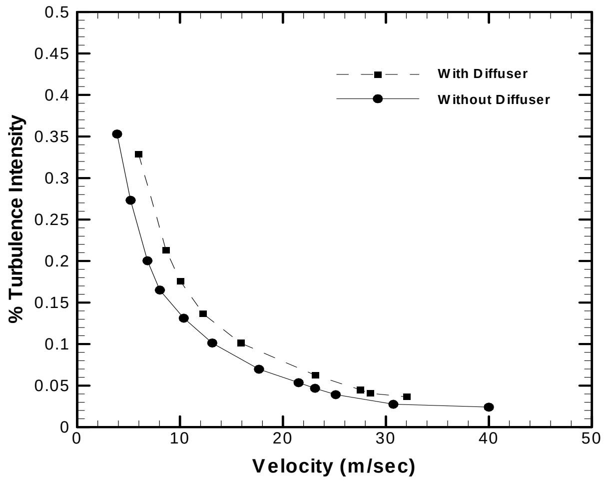


Figure 2. Variation of test section turbulence intensity with speed.

by a hot wire anemometer. Note that the turbulent intensity is decreased as the wind tunnel speed is increased.

2.3 Instruments Static pressures as well as total pressures have been measured using highly sensitive pressure transducers. Data for each transducer was collected via a multiplexer and transferred to the computer through a 16 bit analog to digital (A/D) board. The 16-bit A/D board was selected to increase the system accuracy. Various sampling rates were performed and finally the best one was selected. Figure 3 shows flowchart of this data acquisition system that used for these investigations.

Flow field measurements were obtained using a pitot rake tube. Velocity profile was measured by a hot wire anemometer system.

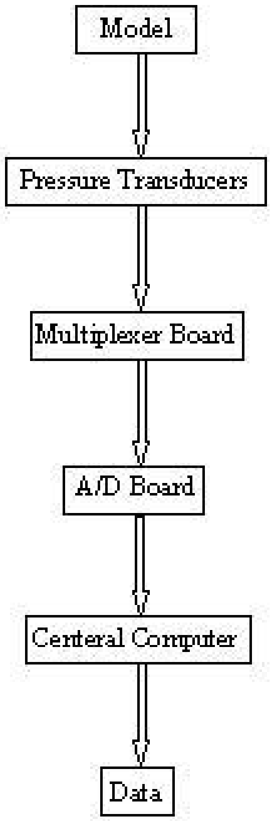
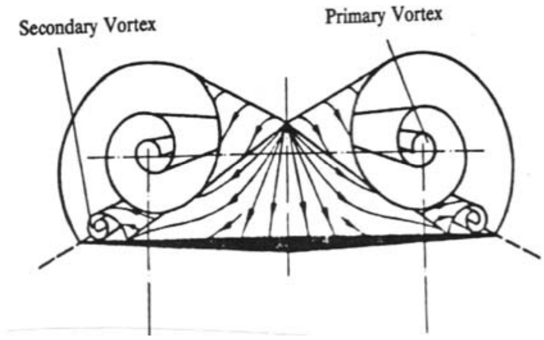


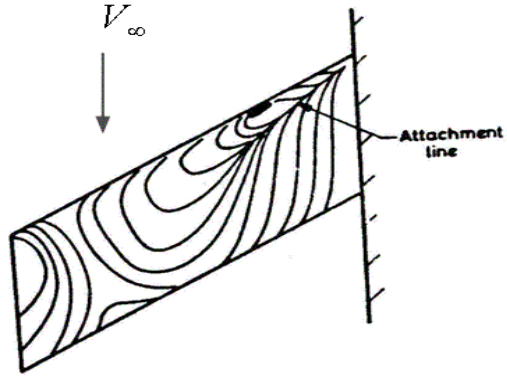
Figure 3. Data Acquisition Flowchart.

3. RESULTS

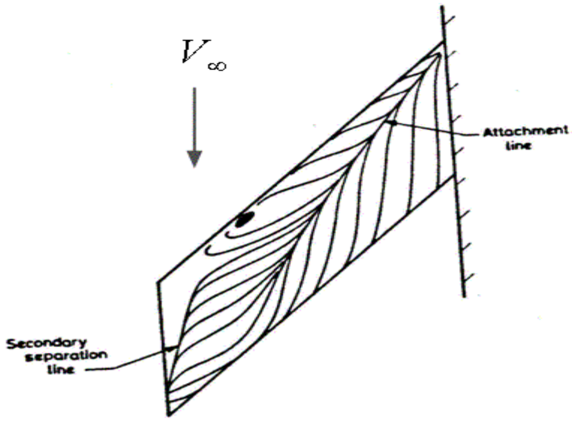
Figures 4.a-g shows the flow field over a delta wing with leading edge sweep of 70°, two swept wings with sweeps of Λ=30° and Λ=45°, a cropped delta wing with Λ_{LE}=30° and the tuft visualization results of the present investigations. As can be seen, a pair of counter-rotating vortices primarily dominates the flow over a delta wing at moderate to high angle of attack. These vortices contain a large amount of energy and remain stable for a wide range of angles of attack. The surface oil-flow patterns shown over two swept wings, figures 4.b and c indicate the existence of a vortex sheet, an attachment line, and vortex burst phenomenon, figure 4.b. As the wing sweep angle increases, figure 4.c, Λ=45°, the vortex is seemed to align itself with the free stream, similar to that of delta wing, figure 4.a. The vortices formed over these wings, figures 4.b and c, are somehow similar to delta wing vortex but do not contain as much energy as the delta wing vortices do. This vortex is shed from the wing apex and moves towards the wing tip. From there it becomes parallel to the free stream flow. The movement of these shed vortices towards the wing tip is probably due to the cross flow velocity component over the wing surface. Also shown in figure 4 is the low speed flow pattern over a cropped delta wing with leading edge sweep of Λ_{LE} = 30°, visualized by oil strakes at two angles of attack, α = 6° and 12°, figures 4.d



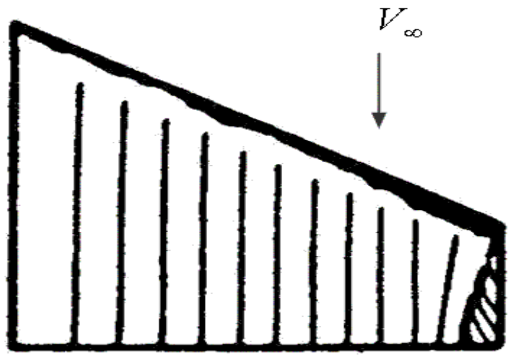
a) Delta wing, Λ=70° [10]



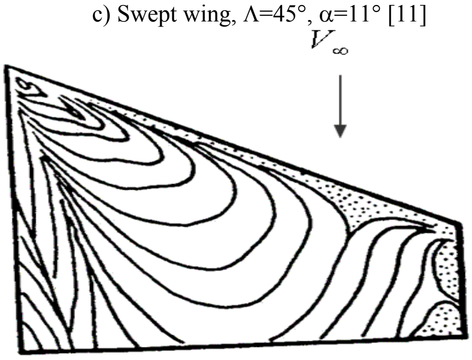
b) Swept wing, Λ=30°, α=10° [11]



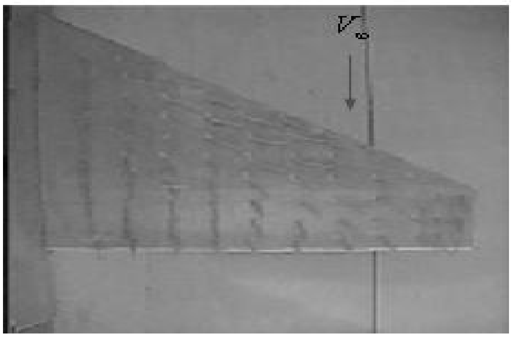
c) Swept wing, Λ=45°, α=11° [11]



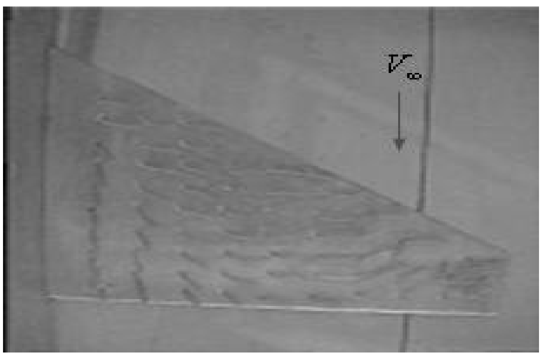
d) Cropped delta wing, Λ_{LE}=30°, α=6° [12]



e) Cropped delta wing, Λ_{LE}=30°, α=12° [12]

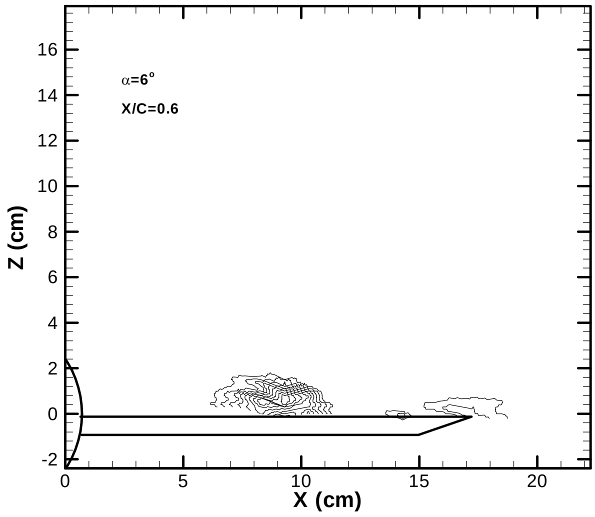


f) The tuft visualization result, Λ_{LE}=40°, α=6°

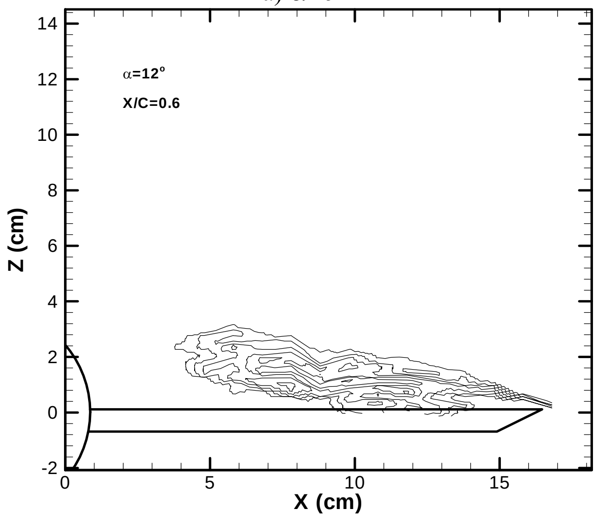


g) The tuft visualization result, Λ_{LE}=40°, α=12°

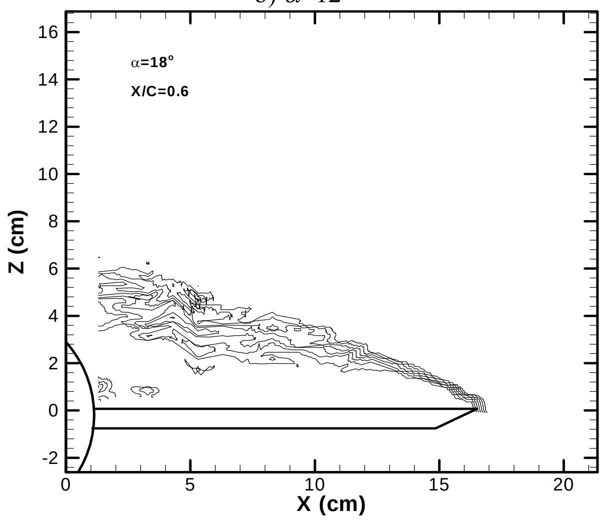
Figure 4. Flowfield over several wing plan forms.



a) α=6°

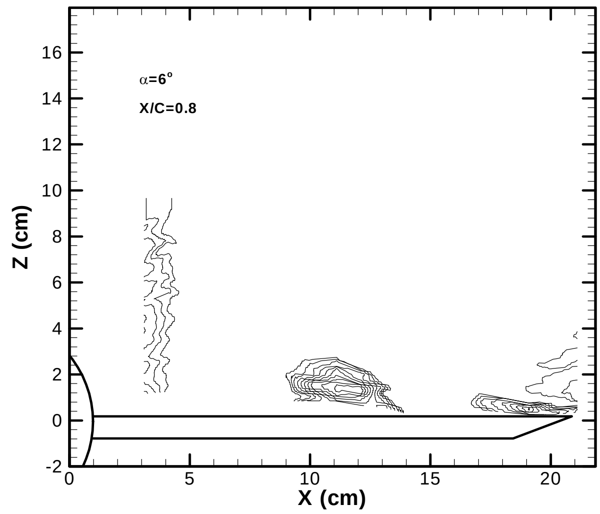


b) α=12°

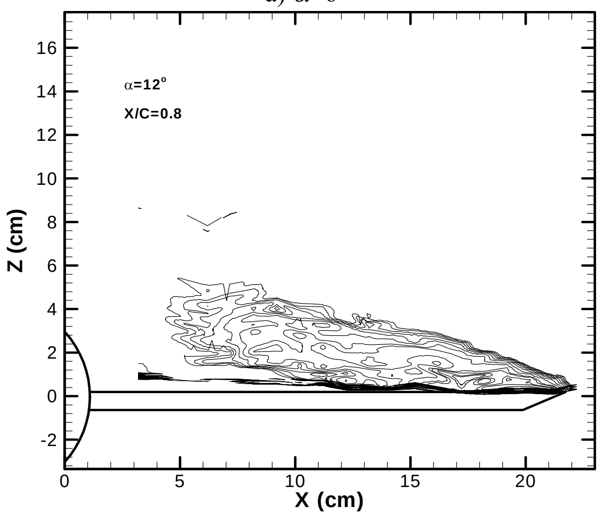


c) α=18°

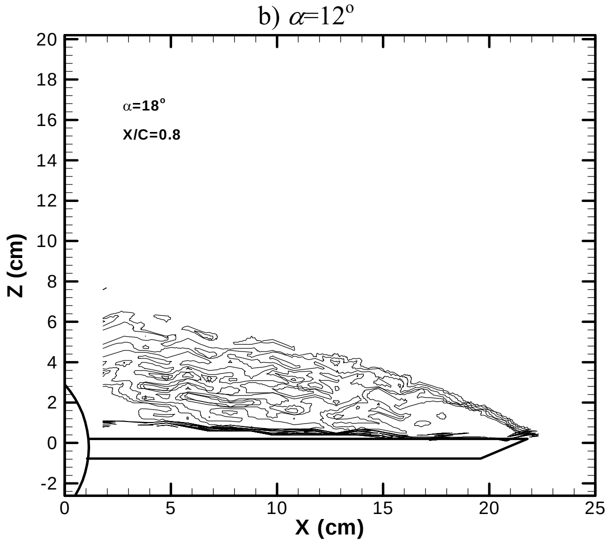
Figure 5. Velocity Contour at X/C=0.6.



a) α=6°

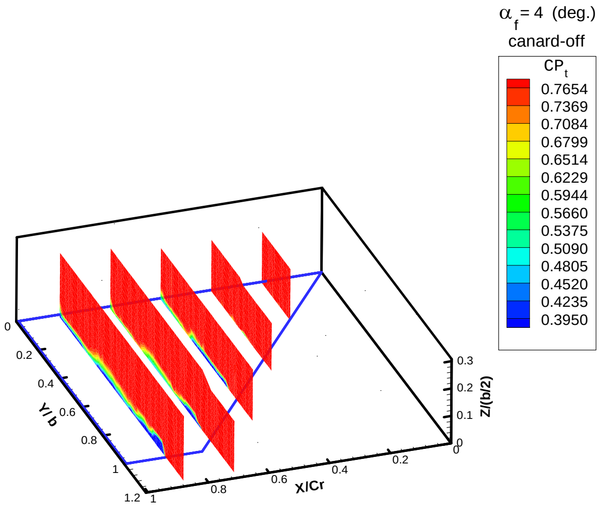


b) α=12°

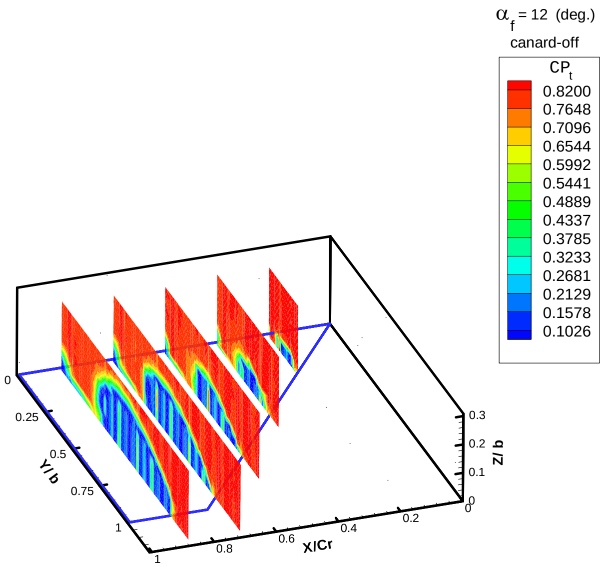


c) α=18°

Figure 6. Velocity Contour at X/C=0.8.



(a) $\alpha = 4\,\text{deg}$



(b) $\alpha = 12\,\text{deg}$

Figure 7. Total pressure contour over the wing.

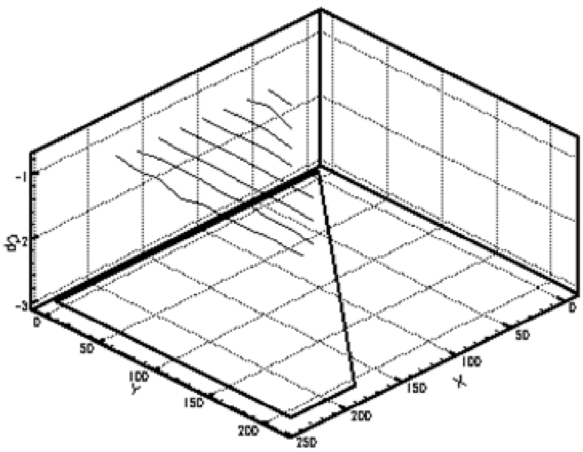


Figure 8. Wing surface pressure Distribution at $\alpha = 4\,\text{deg}$.

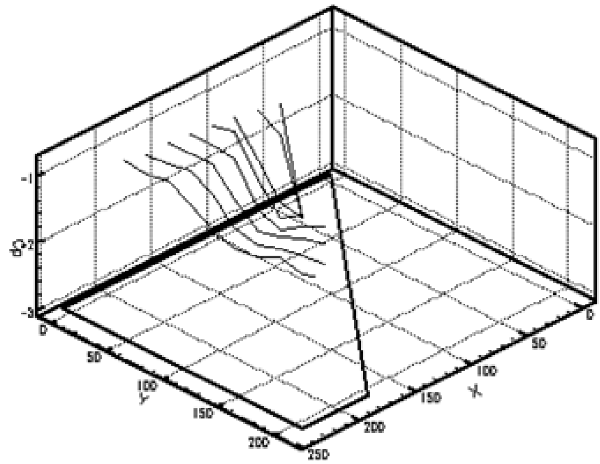


Figure 9. Wing surface pressure Distribution at $\alpha = 12\,\text{deg}$.

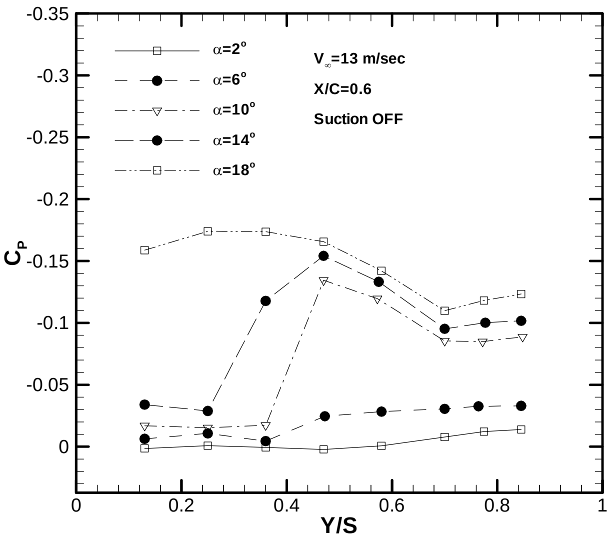


Figure 10. Spanwise pressure distribution, X/C=0.6.

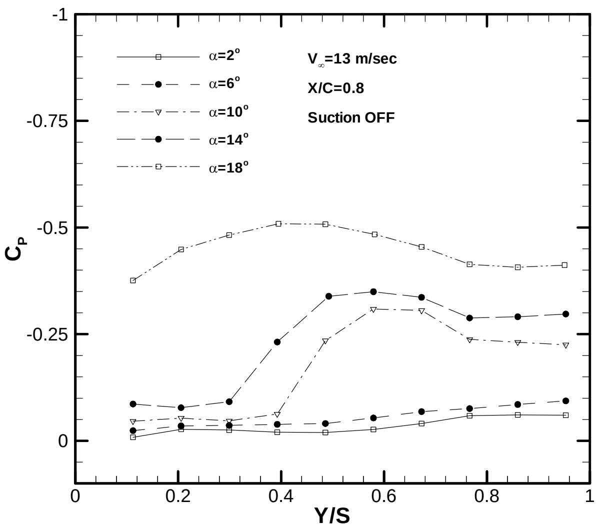


Figure 11. Spanwise pressure distribution, X/C=0.8.

and e. At low angle of attack, α = 6°, the flow is characterized by completely attached flow with a weak tip vortex and a weak leading edge bubble, figure 4.d. The oil accumulation along the entire leading edge is an indication of the leading edge bubble, which is formed by the flow separation from the leading edge of the outer panel and reattaching on the surface again. However, for this angle of attack, α=6°, no separation is observed as shown by the straight attached lines. At 12° angle of attack, figure 4.e, the flow pattern is completely different. The wing tip vortex is still visible, but the attached flow region is less than that shown in figure 4.d. Instead there exists a large region of reversed flow and a large leading edge and wing tip separation regions shown by dots. This phenomenon causes a large decrease of lift along with a change in the pitching moment variation, deteriorating the aircraft stability and control criterion, hence its maneuverability. Shown in figure 4 is also the tuft flow visualization result of the present experiments. As can be seen, at low angle of attack, the tufts are moved toward the wing tip indicating the type of flow shown in figures 4.c and e. However, as the angle of attack increases, flow field study shows that the vortex covers a large portion of the wing and its shape is similar to that of delta wing vortices when they burst. The reason for the differences in the flow field seen between figures 4.a and e with those of figures 4.f-g is probably due to the differences in the shape of the wings, sweep angles, and the airfoil shape. However, the characters of the flow over all 3 wings are similar. As seen from these figures, figures 4.a-g, the flow structure over these types of wing, i.e. the wing of present experiment, is neither exactly the same as those of delta wing, vortex dominated flow, nor swept wing. The flow over cropped delta wings with sweep angles greater than 35deg prior to separation is of vortical type flow, not exactly vortex dominated flow. This means that the vortices formed over these wings have less energy, cover a large portion of the wing surface, and disappear at much lower angle of attack than those formed over delta wings with sweep angles greater than 65deg, figure 4a.

Figures 5 and 6 show velocity contours over the wing surface at two different stations, X/C = 0.6 and X/C = 0.8, and at angles of attack of 6, 12 and 18 degrees. From these figures, the formation of leading edge vortices and their expansion over the wing surface with increasing angle of attack is similar to those seen from figures 4.b-g. Comparing figures 5.a and 6.a, it is seen that the leading edge vortex rises from the wing surface as the distance from the wing apex increases, typical of delta wing vortices. At angle of attack of 12 degrees, the vortex covers almost 2/3 of the wing's surface, figures 5.b and 6.b, while at angle of attack of 18deg, the entire wing surface is covered by the vortical type flow, figures 5.c and 6.c.

Figure 7 shows contours of total pressure over the wing surface of two different angles of attack. As shown in Figure 7.a, no vortices are formed over the wing surface at angle of attack 4deg. This indicates that the flow over the wing when set to this small angle of attack is potential. At α=12deg, figure 7.b, the wing vortex is formed from the wing apex and following downstream while widening. This vortex, though similar to the delta wings vortices, is slightly different than them. This is typical of the flow field, vortex like flow, over moderately swept wings, not delta wings, mentioned previously. For detail findings and further figures please refer to reference [15].

At α=4deg, figure 8, the wing surface pressure distribution is uniform and there is no evidence of vortex. When α=12deg, figure 9, the reduction in pressure coefficient over the wing surface is an indication of the vortical type flow. From this figure it is seen that near the wing leading edge the suction peak is narrow while further from it and in the vicinity of the trailing edge the suction peak widens, indicating enlargement of the vortex system. For details please refer to reference [15].

Figures 10 and 11 show span wise static pressure distribution over the wing surface at various angles of attack, α=2°-18°, and at two different stations, X/C=0.6 and 0.8. As seen from these figures, at low angles of attack, α=2° and α=6°, pressure distribution along the span decreases slightly from the wing root to the wing tip, indicating potential flow, similar to the oil data shown in figure 4.d. However, for higher angles of attack, α=10° and α=14°, a large portion of the wing surface is dominated by the low pressure, indicating the presence of the vortex. The surface covered by this vortex increases as the angle of attack increases from 10° to 18°. Also, from both figures, Figures 10 and 11, note that as alpha increases

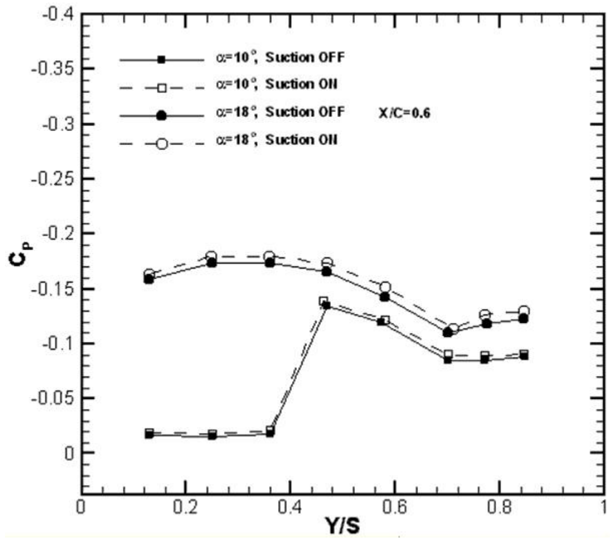


Figure 12. Effect of suction on the spanwise pressure distribution, X/C=0.6.

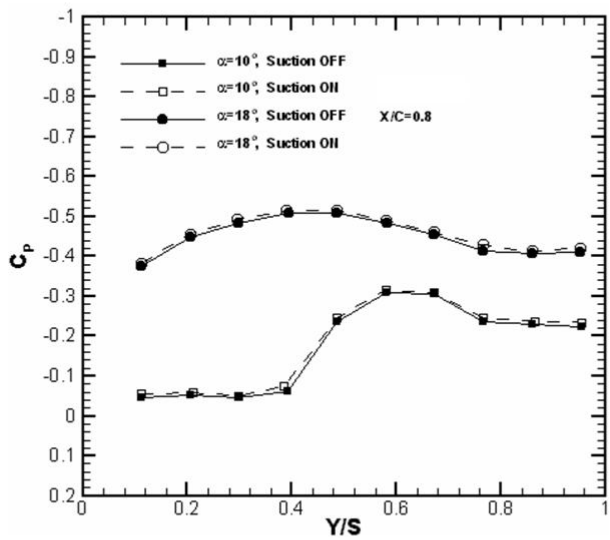


Figure 13. Effect of suction on the spanwise pressure distribution, X/C=0.8.

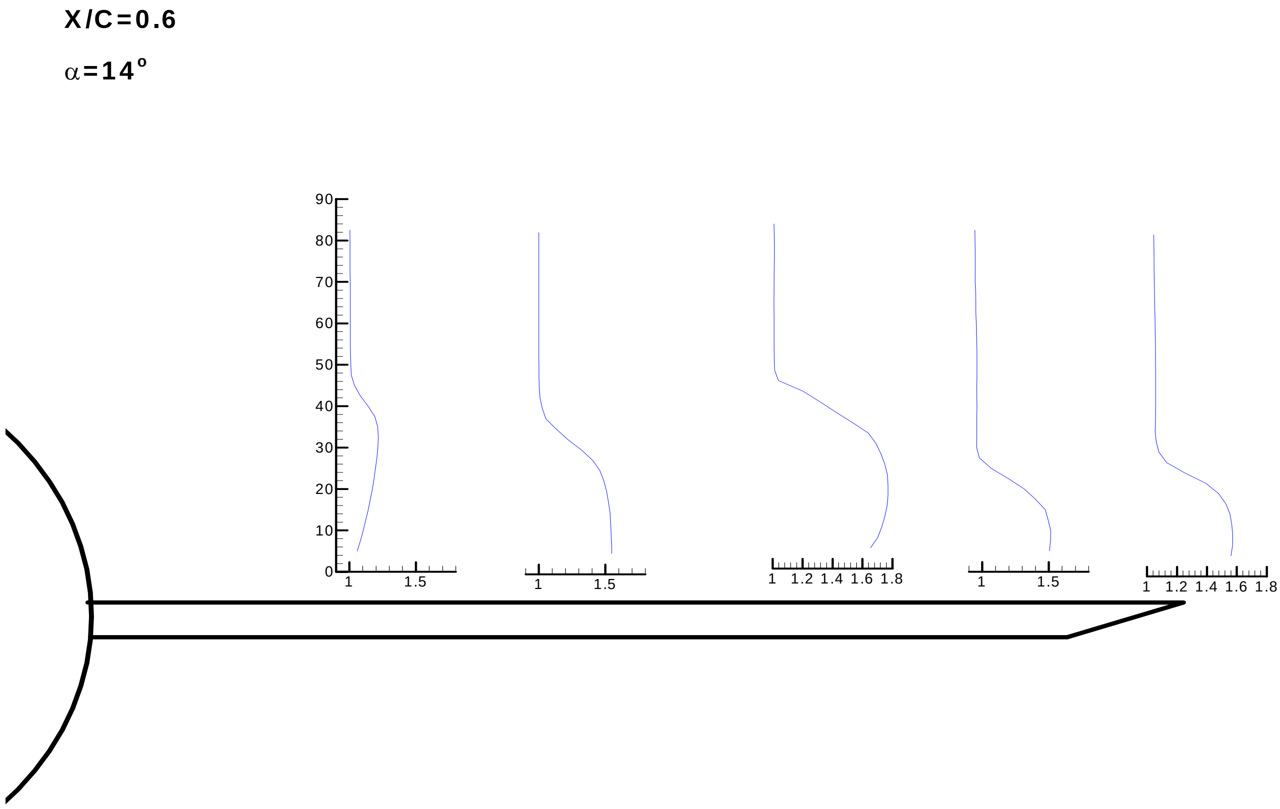


Figure 14. Velocity profile over the wing surface, $\alpha=14^o$, X/C=0.6.

the point of minimum pressure moves close to the wing root. This point of minimum pressure is an indication of the vortex core, shown in figure 4.a known as primary vortex core. Surface pressure distribution for other velocity shows similar trend [16].

Figures 12 and 13 show the effect of suction on

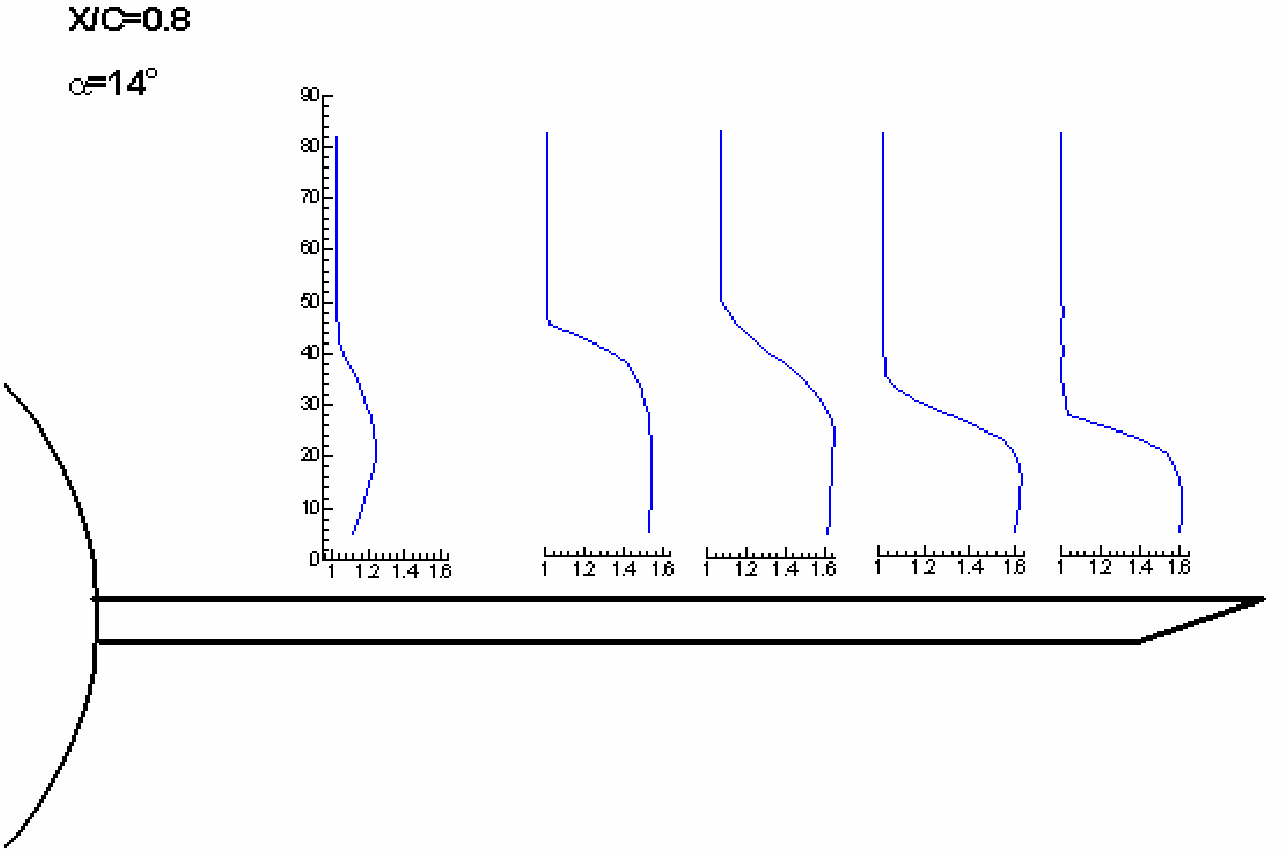
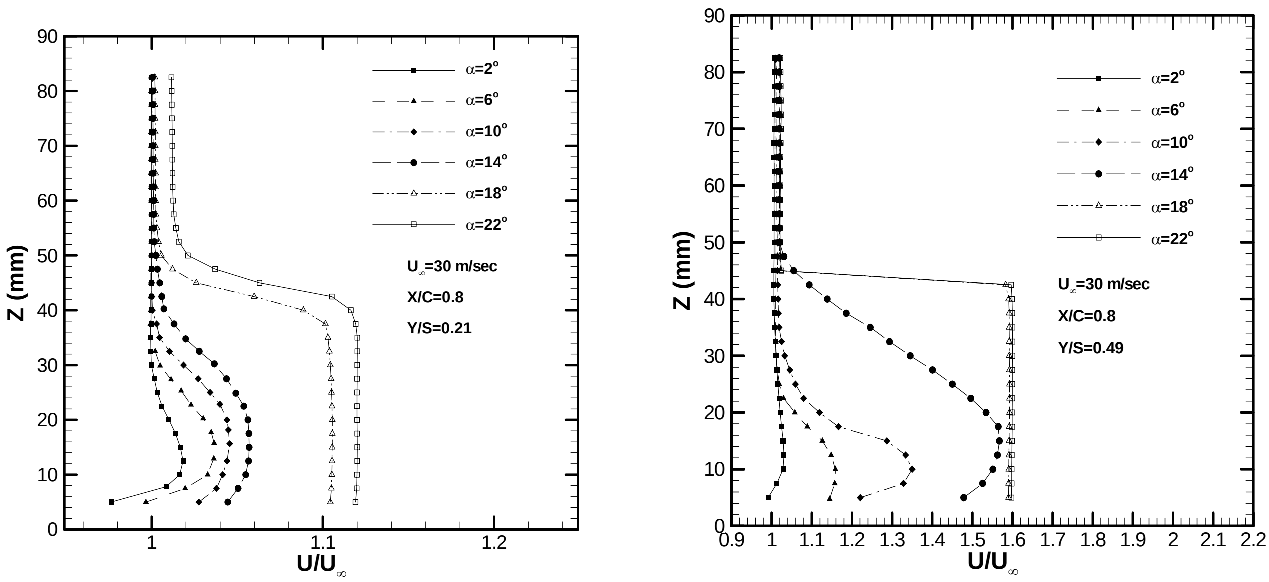


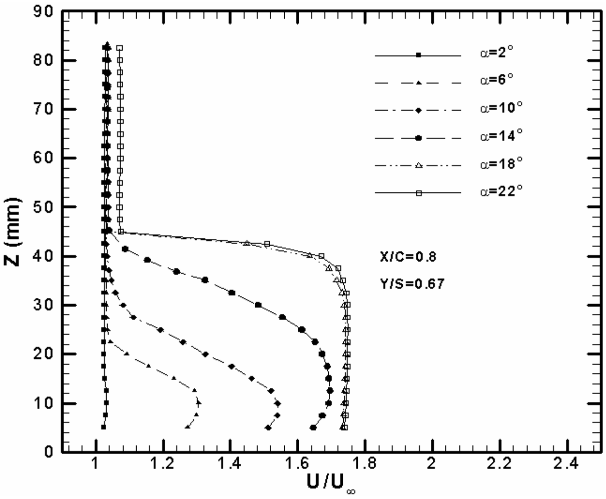
Figure 15. Velocity profile over the wing surface, α=14°, X/C=0.8.



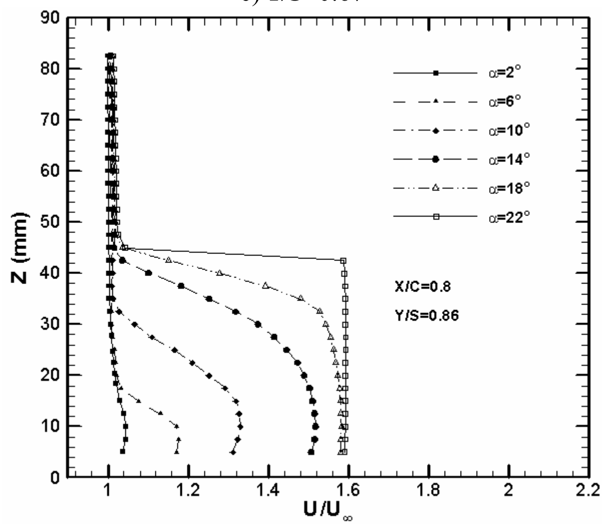
a) *Y/S*=0.21

b) *Y/S*=0.49

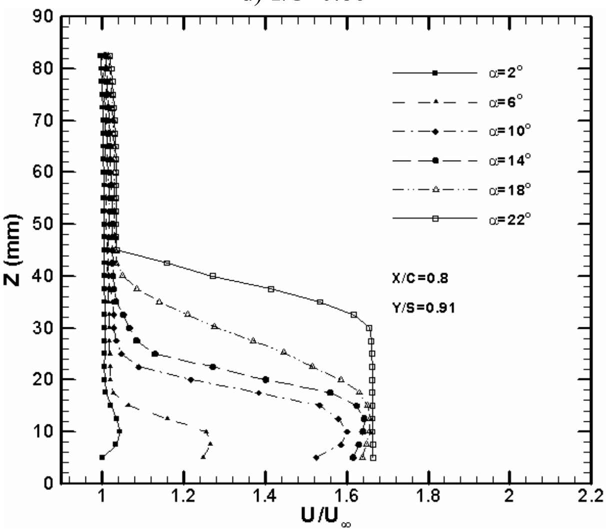
Figure 16. Velocity profiles at X/C=0.8 & U_∞=30 m/s.



c) *Y/S*=0.67

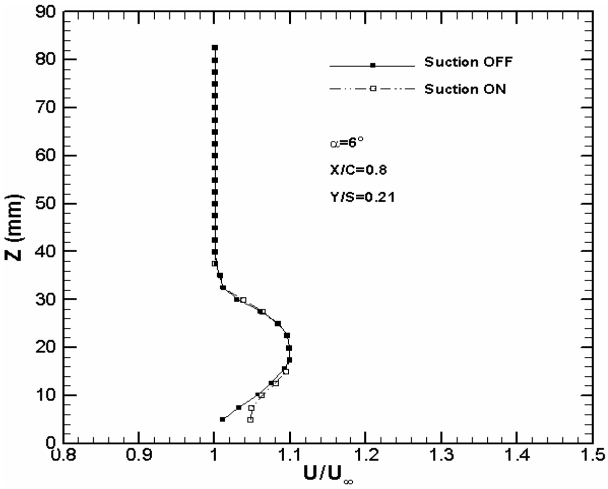


d) *Y/S*=0.86

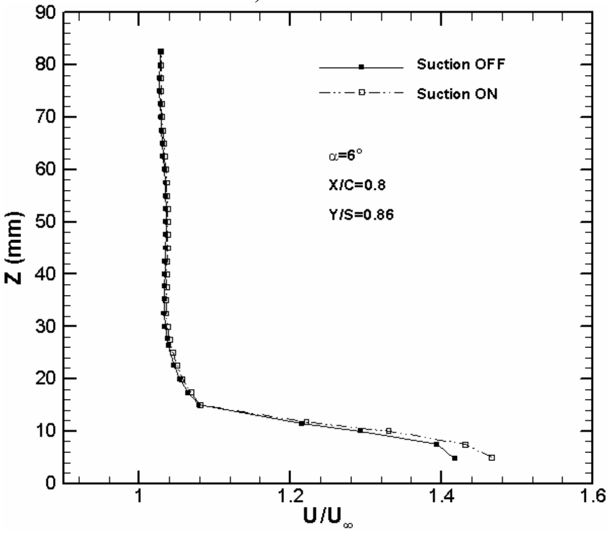


e) *Y/S*=0.91

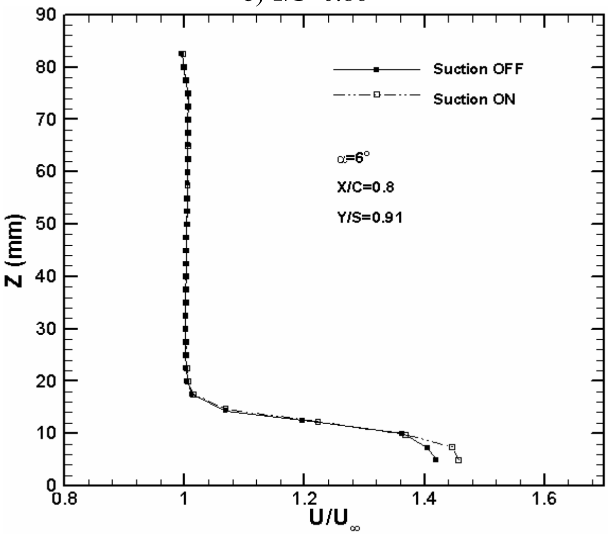
Figure 16. Velocity profiles at *X/C*=0.8 & U_∞=30 *m/s* (Continued).



a) *Y/S*=0.21

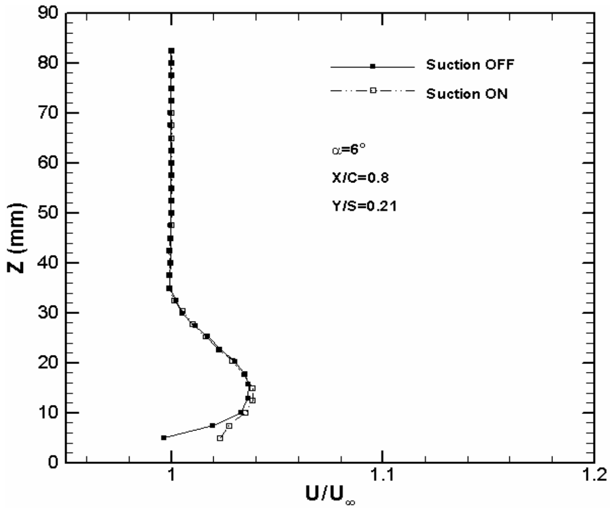


b) *Y/S*=0.86

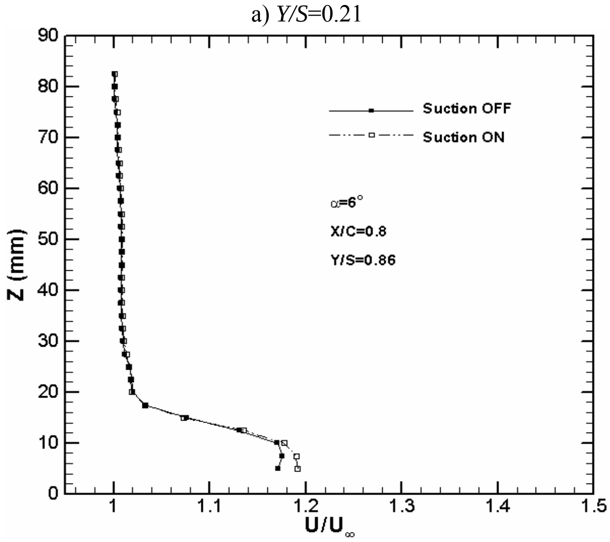


c) *Y/S*=0.91

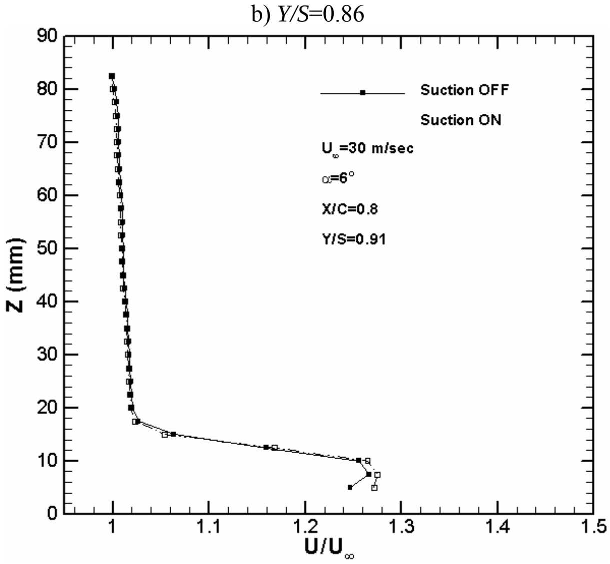
Figure 17. Effect of suction on velocity Profiles, U_∞=13 *m/s.*



a) *Y/S*=0.21



b) *Y/S*=0.86



c) *Y/S*=0.91

Figure 18. Effect of suction on velocity Profiles, U_∞=30 *m/s*.

the spanwise pressure distribution for two angles of attack, α = 10° and α = 18°, and for two different stations, X/C = 0.6 and 0.8. As seen from these figures, suction decreases surface pressure slightly. Its effect is more pronounced in the vicinity of the vortex core, while for the portion of the wing where pressure is constant, potential flow, suction has almost no effect as it should. Also, from both figures it can be noted that the effect of suction at higher angles of attack is more pronounced than at lower alpha. This is probably due to the fact that at low alpha the vortex is attached to the wing surface while by increasing the angle of attack, it lifts up from the surface before it breaks down. Hence, at moderate angle of attack when the suction is applied, it will decrease the distance between the vortex core and the wing surface. However, when the vortices disappear or burst, the effect of suction diminishes too.

Velocity profiles over the wing at five different lateral stations for an angle of attack of 14deg and at two different longitudinal stations, X/C=0.6 and X/C=0.8, are shown in figures 14 and 15. The profiles at each station show the height of the vortices, their core, their strength, and finally their growth with increasing X/C's.

Effects of model angle of attack on the velocity profile over the wing at X/C=0.8 and at various span wise locations are shown in figure 16. Note that due to restriction in the pitot rake tube movement and the diameter of its tubes, the closest distance from the wing surface where data could be acquired was about 2 mm, as shown by the symbols in figure 16. This figure clearly displays the type of flow over the wing surface, formation and expansion of vortices and their separation as well as their variation along the wingspan. It can also be noticed that at low angles of attack, namely α=2°, the flow over the wing is almost potential, with a small classic boundary layer profile and a velocity less than the free stream velocity. At higher angle of attack, α=6°, the vortex begins to form and with increasing alpha, the magnitude of velocity increases too, indicating strength of the vortex. Also as the angle of attack increases, the vortex core moves upward, forming a secondary vortex beneath it (not shown in this figure). The velocity profiles at other stations show a similar trend and are not presented in this paper. Interested readers are referred to reference [16] for further details and findings.

Figures 17 and 18 show the effect of suction on the velocity profiles over the wing surface when set to $\alpha=6°$ and at different span wise stations for two free stream velocities of 13 and 30 m/s. The suction rate for this investigation was constant, about 12 lit/min. For this suction rate, as seen from these figures, the velocity profiles in the vicinity of the surface have been influenced. Further from the wing surface no variation in the velocity profile due to the suction is observed. This is because in the region where the vortex exists, to have some effect on the vortex profile, the suction rate must be increased. But as stated, for these tests the suction rate was constant. Comparing figures 17 and 18, it is clear that the suction has more influence on a velocity profile with lower free stream velocity. The effect of suction on the velocity profile at various angles of attack and different span wise and chord wise stations are given in reference [16].

4. CONCLUSION

As a part of an ongoing research at the Department of Aerospace Engineering of Sharif University of Technology, surface pressure, flow field and velocity profile were measured both with and without suction on the wing of a HARV model. Effect of surface roughness on the wing static pressure distribution was also studied. In this paper, results of flow field measurements for both suction on and off cases, were presented. The following results were obtained:

1. The flow field on the wing surface is similar to that of delta wings with low sweep angle with some differences.
2. At low angles of attack, the flow field over the wing surface is almost potential with a classical boundary layer.
3. The velocity profile over the wing surface at moderate angle of attack differs from that of straight or swept wing, indicating the existence of a vortex.
4. With increasing angle of attack the vortex widens, covering a large portion of the wing surface.
5. Suction influences the velocity profile when the model is set to moderate angles of attack.

Further measurements are underway to better understand the flow field and the parameters that affect it over this type of wing platform that are widely used for combat aircrafts.

5. REFERENCES

1. Hough, G. R. (Ed.), “Viscous Flow Drag Reduction”, ***Progress in Astronautics and Aeronautics***, Vol. 72, (1979), 185.
2. Reshotko, E., “Drag Reduction by Cooling in Hydrogen-Filed Aircraft”, ***Journal of Aircraft***, Vol. 16, (1979), 584-590.
3. Gad-el-Hak, M., “Flow Control: the Future”, ***Journal of Aircraft***, Vol. 38, No. 3, (2002), 402-419.
4. Lachrnann, G. V. (Ed.), “Boundary Layer and Flow Control”, Program Press, London, (1961).
5. Jean Ross, A., Jefferies, E. B. and Edwards, G. F., “Control of ForeBody Vortices by Suction at the Nose of the RAE High Incidence Research Model”, ***AGARD-CP-494***, (1990), 27-1 to 27-1.
6. Lang, J. and Francis, M., “Unsteady Aerodynamics and Dynamics Aircraft Maneuverability”, ***AGARD-CP-38***, (1985), 29-1 to 29-19.
7. Huenecke, K., “Low Speed Characteristics of a Fighter-Type Configuration at High Angles of Attack and Sideslip”, ***ICAS-82-5.8.1***, (1982), 1437-1444.
8. Hummel, D. and Oelker, H., “Low Speed Characteristics for the Wing-Canard Configuration of the International Vortex Flow Experiments”, ***Journal of Aircraft***, Vol. 31, No. 4, (1994), 868-878.
9. Soltani, M. R. and Davari, A., “Experimental Study of the Flow Field Over a Low Aspect Ratio Wing”, ***Journal of Esteghlal***, (Sep. 2001), 181-190.
10. Soltani, M. R., “An Experimental Study of the Relationship Between Forces and Moments and Vortex Breakdown on a Pitching Delta Wing”, Ph.D. Thesis, University of Illinois at Urbana-Champaign, (1992).
11. Poll, D. I. A., “On the Generation and Subsequent Development of Spiral Vortex Flow Over a Swept Back Wing”, ***AGARD-CP-342***, (1983), 6-1 to 6-14.
12. Liu, M. J. et al., “Flow Patterns and Aerodynamic Characteristics of a Wing-Strake Configuration”, ***Journal of Aircraft***, Vol. 17, No. 5, (1980), 332-338.
13. Soltani, M. R. and Abbasi Hoseini, A., “An Experimental Study of the Canard Angle Effects on the Wing Surface Pressure Distribution for a Wing-Canard Configuration”, **Proceedings of the Ninth Asia Congress of Fluid Mechanics**, May 27-31, (2002), A88-95.
14. Soltani, M. R., Khadivi, T. and Davari, A., “Flow Control Over the Wing of a Fighter-Type Configuration Using Boundary Layer Suction”, ***ICAS Congress***, (2002).
15. Abbasi Hoseini, A., “An Experimental Study of the Canard Effects on the Pressure Distribution Over a High Maneuverable Fighter Aircraft”, M.Sc. Thesis, Aerospace Engineering Department, Sharif University of Technology, (2000).
16. Khadivi, T., “Effects of Surface Roughness and Flow Suction on Mean Pressure Distribution Over the Wing of a Highly Maneuverable Aircraft”, M.Sc Thesis, Department of Aerospace Engineering, Sharif University of Technology, (2001).