

The Relationship between Crossflow Velocity and Off-the-Surface Streamtrace Topology for a Moderately Swept Wing at Transonic Mach Numbers

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(Abstract)

The purpose of this thesis is to investigate the crossflow and off-the-surface velocity traces on a moderately swept wing at transonic Mach numbers. Computational Fluid Dynamics (CFD) was used to generate the data used to visualize the flow field. This was done for angles of attack of 6, 7, 8 and 10 degrees at a Mach number of 0.8.

An overview of flow topology and singular point theory is given as a means to describe the flow field and describe the differences between it at various angles of attack. After performing an investigation of the crossflow velocity traces it was verified that the use of a line of separation in the flow topology as an indication for flow separation is a necessary condition. It was also found that the crossflow topology is more sensitive to shock location than to angle of attack.

It has been verified that a line of separation, as defined by Tobak and Peake [ref 1], in the crossflow is an indication that separation may be present on the surface of the wing. Furthermore, shocks complicate the crossflow. In all of the cases the crossflow just aft of a shock becomes much more complex than it was before the shock. New singular points appear and interactions between singular points arise. As angle of attack is increased the flow topology changes critically only in the change from 6 to 7 degrees. This is the range in angle of attack in which a sudden shift in the location of the shock occurs, so it may be postulated that for this wing the flow topology is more sensitive to shock location as opposed to angle of attack. Comparing the topology between the 7, 8 and 10 degree cases, supports this hypothesis as the topology is similar before and after the shock for each case. The flow topology for each case before the shock is much different than the topology just aft of the shock.

The investigation of off-the surface traces has shown that as angle of attack is increased the area of separated flow not only grows but also becomes more complex. For

the 6 degree angle of attack case, the region of separated flow was concentrated near the surface and as one moved off the surface the flow quickly returned to the attached flow direction with no singular points. This was the case for the 7 degree angle of attack case only the flow did not reattach until after one moved approximately 0.25 feet off the surface. As the angle of attack was increased the distance off the surface in which the flow returned to moving in the downstream direction increased. Furthermore, as angle of attacked was increased the number of singular points and their intensity grew.

It was also verified that in all of the cases investigated the presence of a line of separation was an indication of separated flow. Moreover, in all but two cases there were two lines of separation. One located along the furthest outboard and inboard area of the separated region. No lines of separation were observed in or around attached flow, thus the lines of separation may not only indicate that separation is present but in fact give a location for the separated region.

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Chapter 1 Introduction

1.1 *Background*

In the past twenty years, great advances in technology have led to significant advances in fluid mechanics. Computational procedures allowing aerodynamicists to investigate flows using complex three-dimensional computational fluid dynamics (CFD) to extract the flow topology are now widely available. Delery [ref 2] states that Legendre [ref 3] pioneered flow topology research by proposing that wall streamlines be considered as trajectories having properties consistent with those of a continuous vector field, the principal being that through any nonsingular point there must pass one and only one trajectory. This postulate implies that the singular points of the vector field can be categorized mathematically. Therefore, the number, type and relation between singular points can be said to characterize the pattern. Tobak and Peake [ref 1] took Legendre's work a step further using singular point mathematics along with bifurcation theory to define specific singular points in fluid flow topology along with their implications to the fluid flow. Since then, much research has been done on fluid flow topology, ranging from Chapman [ref 4] and Wang [ref 5] who classified flow topology for separation on three-dimensional bodies to Cipolla and Rockwell [ref 6] who investigated the instantaneous crossflow topology using particle image velocimetry.

The classification of three-dimensional singular points for flow topology has enabled aerodynamicists to successfully investigate, predict, and fix the separation phenomena alleviating adverse aerodynamic characteristics associated with separation. These classifications have been limited to surface and crossflow velocity traces of configurations with simple geometries. Classifications of off-the-surface and crossflow singular points for a swept wing have yet to be made and are the purpose of this thesis.

1.2 Approach

There has been significant recent interest in the complicated flow behavior that arises on modern fighter/attack aircraft wings after significant flow separation begins to occur. Thus an investigation of CFD solutions has been done. Solution files for a moderately swept wing at a Mach number of 0.8 for the angles of attack of 6, 7, 8 and 10 degrees were provided by the Navy and investigated. The grid, which consists of approximately 6 million points and 46 zones, was solved using the WIND [ref 7] code that uses Reynolds Averaged Navier-Stokes equations with the Shear Stress Transport (SST) [ref 8] turbulence model. The Reynolds number corresponds to an altitude of 15,000 feet. The solution files were used to calculate the pressure coefficient, and velocity vectors using the standard Plot-3D equations. The velocity vectors were then plotted to obtain plots of the off-the-surface and crossflow velocity traces using Amtec Tecplot version 8 [ref 9]. Figure 1 displays the wing which was investigated and shows exactly what was modeled.

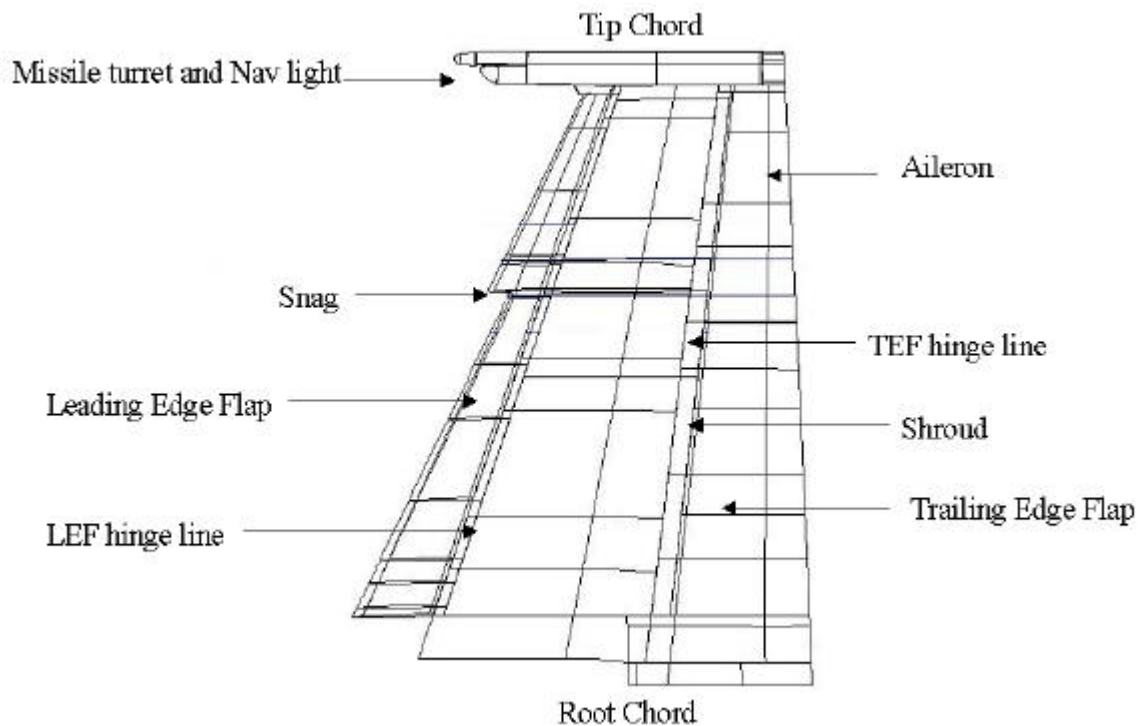


Figure 1. Wing Geometry and Definition

Off-the-surface velocity traces were constructed by extracting slices of the CFD files, which lie perpendicular to the crossflow and parallel to the horizontal surface at various distances off the wing surface. The velocity traces were then plotted on the extracted slice. Slices range from approximately one quarter of an inch off the surface to about 4.5% of the span. Singular points were identified and catalogued. Surface streamtraces were not investigated because the boundaries of each zone do not lie flush and Tecplot's streamtrace function will not plot the vectors between zones of this type.

The crossflow velocity traces were generated by extracting slices in the crossflow plane from the CFD files at various chord positions. Velocity traces were plotted on the extracted slice and the singular points were identified as well as catalogued. The catalogued singular points for each of the crossflow and off-the-surface traces were compared with all the cases studied.

Chapter 2 outlines the definitions necessary to describe fluid flow topology. The latter chapters contain the research and results performed in the attempt to correlate crossflow and off-the-surface flow topology.

Chapter 2 Fluid Flow Topology

2.1 *Topology and Terminology*

There has been much work done in the field of flow topology in the past twenty years. All of which confirms that the starting point is to consider a steady viscous flow over a smooth three-dimensional body where the skin-friction lines or streamlines on the surface of the body form a continuous vector field. One translates this vector field into a mathematical model in terms of the surface velocity, shear stress and vorticity vector components as documented in Tobak and Peake [ref 1].

With the completion of the mathematical model, one must investigate where the magnitudes of the derived vector fields are identically zero. Such points in the vector field are called singular points. Singular points may be classified as two types: nodes and saddle points. The classification of nodes can be further divided into nodal points and foci, of either separation or attachment.

A nodal point is a point common to an infinite number of streamlines. If the streamlines converge to the nodal point, as seen in Figure 1a, it is said to be a nodal point of separation. Conversely, if the streamlines diverge from the nodal point it is said to be a nodal point of attachment, seen in Figure 2b.

Foci differ from nodal points in that an infinite number of streamlines spiral around the node. If the streamlines spiral away from the node, as seen in Figure 2c, the node is defined as a foci of attachment. Streamlines, which spiral into the node, seen in Figure 2d, are defined as foci of separation.

A saddle point may be defined as a singular point in which only two particular lines intersect at the singular point, each of which is in the direction towards or away from the singular point. All other streamlines miss the singular point and follow the directions of the adjacent lines that pass through the singular point as seen in Figure 2e.

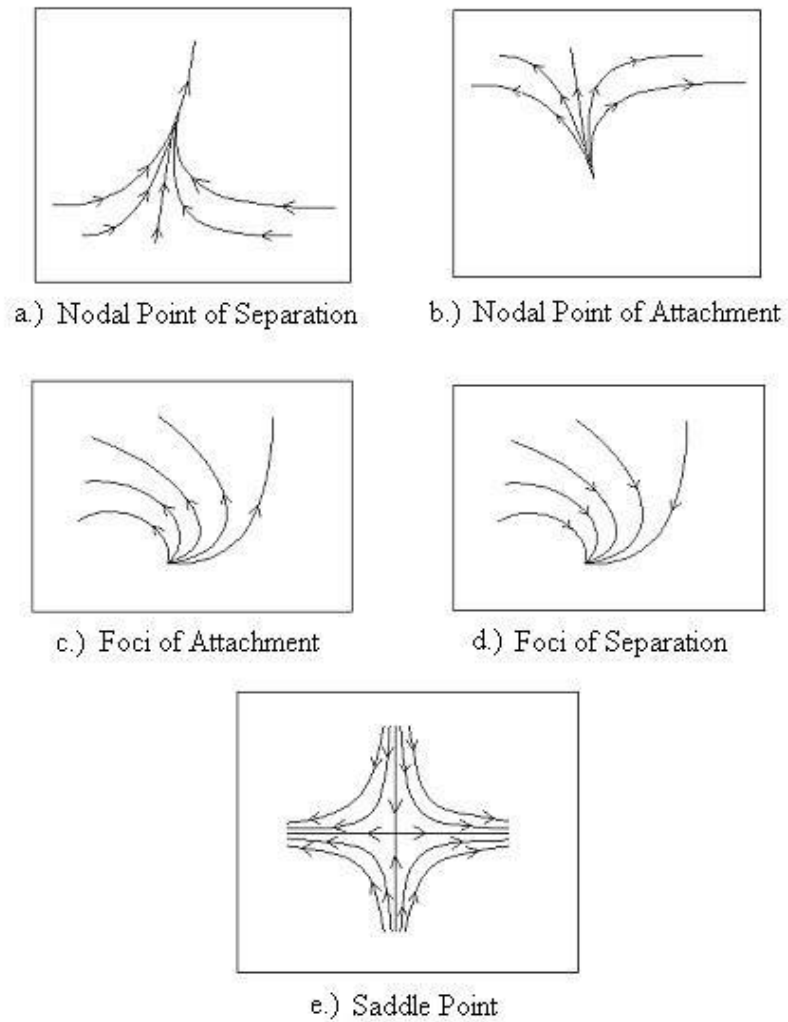


Figure 2. Singular Points - 2a. Nodal Point of Separation, 2b. Nodal Point of Attachment, 2c. Foci of Attachment, 2d. Foci of Separation and 2e. Saddle Point

Different combinations of nodal/saddle points and how they work together have received much attention by Tobak and Peake [ref 1] and Chapman [ref 4]. For the purpose of this paper, we shall only be concerned with the specific singular point interaction in which a line of separation emerges. A line of separation is present when the streamlines emerging from the nodal points of attachment are prevented from crossing by the presence of a particular streamline emerging from the saddle point as defined by Lighthill [ref 10] and seen in Figure 3. Most researchers agree that the convergence of streamlines on either side of a particular line is a necessary condition for separation however; it should not be used solely to define it as this may occur in other situations as well.

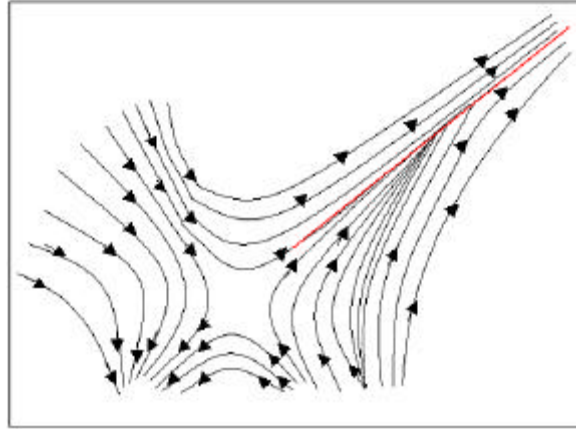


Figure 3. Line of separation

According to Tobak and Peake [ref 1], lines of separation may be further subdivided into global and local lines of separation. A global line of separation is a streamline, which emerges from a saddle point and leads to global flow separation. On the other hand, if a streamline not originating from a saddle point has other lines converging on it, that streamline is defined as a local line of separation and leads to local flow separation. This terminology is not necessarily common amongst all researchers but will suffice for this paper.

2.2 Implications of Flow Topology

Singular Points acting in isolation or in combination fulfill certain characteristic functions that largely determine the distribution of streamlines on the surface (Tobak and Peake) [ref 1]. A nodal point of attachment typically represents a stagnation point on a forward-facing surface, such as a leading edge of a wing, where as, a nodal point of separation acts as a sink where the streamlines that have moved over the body have vanished. Saddle points typically act to separate the streamlines from adjacent nodes.

When studying the topology of fluid flow, especially of separated flows, it is often useful to consider the change of topology as different parameters are changed. One might want to examine how the topology changes with angle of attack, Mach number, Reynolds number or possibly geometric changes. The bifurcations are those, which change the structure of the singular points in the vector fields. One applies bifurcation theory to study the changes in singular points with respect to parameters and investigate if new singular points appear, singular points change from attachment to separation or vice versa, or if singular points change from a nodal point to a saddle point.

Because the patterns of skin-friction lines and external streamlines reflect the properties of continuous vector fields, we are able to characterize the patterns on the surface and on particular projections of the flow. Hunt et al [ref 11] have shown that the notions of singular points and the rules that they obey can be extended to apply to the flow above the surface on planes of symmetry and on crossflow planes. Most recently Delery [ref 2], discussed the collaboration of Legendre, a theoretician, and Werle', an experimentalist, in their pursuit to construct a theoretical tool allowing the elucidation of the structure of largely separated three-dimensional flows. In this paper, Delery discusses the implications of flow topology off the surface as well as reviews the work done in the flow topology field to date.

Chapter 3 Investigation of Off-the-Surface Streamtraces

3.1 *Off-the-Surface Streamtraces*

If one were to look down onto a wing and plot the axial and spanwise velocity components, u and w , at various heights above the wing these would be considered off-the-surface streamtraces. This was done for each of the 6, 7, 8 and 10 degree angle of attack cases at heights ranging from approximately on the surface to about one foot off the surface. The streamtraces were laid on top of a reversed axial flow contour for the corresponding height. The blue region indicates positive axial flow where the red region is used to display areas a negative or zero value of axial flow. Zero or negative values of axial flow are a good indication of separated flow because separation is normally accompanied by flow reversal.

3.2 *Off-the-Surface Grid and Data Generation*

Amtec Tecplot was used to generate the off-the-surface grids and data. The imbedded Tecplot Slice function was used to extract 2-D planes out of the 3-D grid. The Slice function interpolates the data points in the grid to create a 2-D plane at a specified position on, in this case, the y-axis. Because the slice is created at a specified position, the height of the off-the-surface plane increases from the wing root to the wing tip. For the purpose of this paper the height of the surface at the wing root will designate the label. The planes generated are showed in Figure 4. Data for this grid, the u and w components of the velocity vector was calculated by dividing out the density from the momentum vector in the CFD solution files. Tecplot also has a streamtrace function that allows the user to plot 2-D vectors. This was taken advantage of to plot the off-the-surface streamtraces using the u and w components of velocity as the vector variables.

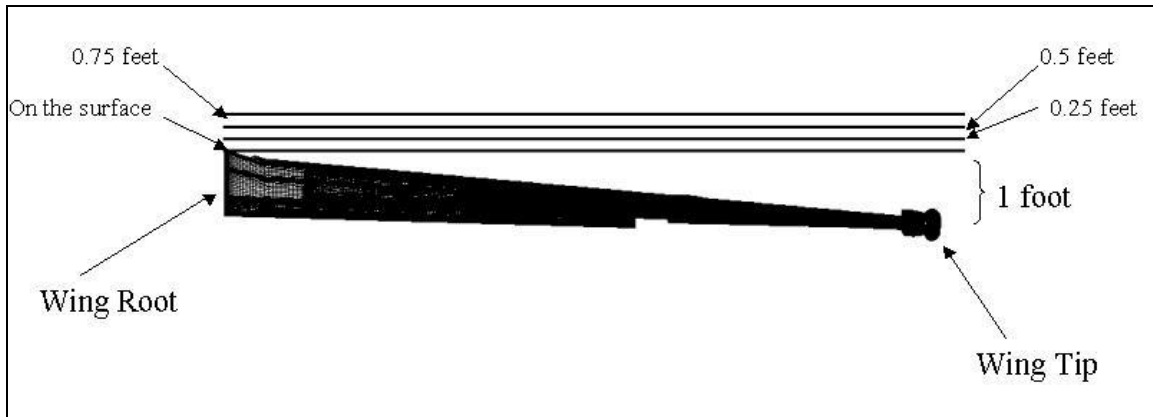


Figure 4. Off-the-Surface Planes

3.3 Investigation of Off-the-Surface Streamtraces

Figure 5 displays the off-the-surface streamtraces approximately on the surface for an angle of attack of 6 degrees and at Mach number of 0.8. Because there is no reversed flow there is only one singular point, a nodal point of separation. It is located midchord near the wing root is a product of the LEX vortex. Figure 6 shows the off-the-surface streamtraces for an angle of attack of 7 degrees and a Mach number of 0.8 approximately on the surface. Starting inboard and moving outboard the singular points will be identified. First, there appears to be a nodal point of separation at about midchord of the wing which is a consequence of the LEX vortex interacting with the freestream flow. The rest of the singular points appear aft of the snag and from midwing to the trailing edge. Two foci of separation are located within the region of separation. These both feed into saddle points. From the saddle points emerge a line which feeds to a nodal point of separation, not letting the lines from the node cross. Thus there are two lines of separation, one at the beginning of the separated region furthest outboard and the other at the end of the separated region furthest inboard. It appears that the separation lines not only indicate that separation is present but may also be an indication of the location of the separated region. This will be investigated further as more cases are observed.

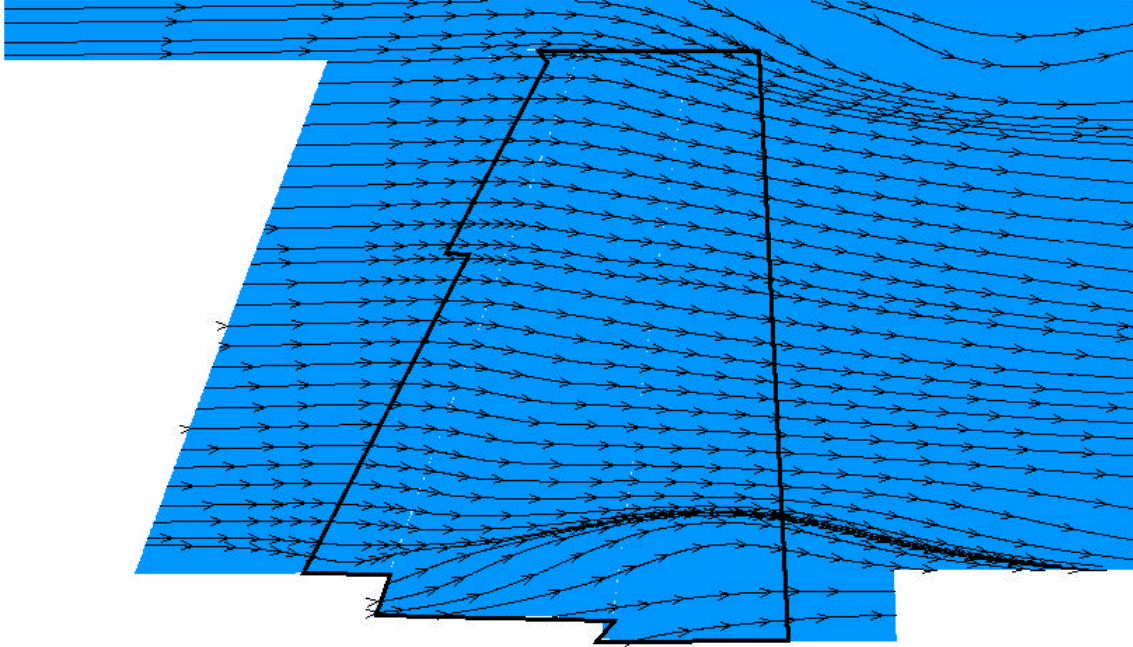


Figure 5. Off-the-Surface Streamtrace for AOA of 6deg & $M = 0.8$
(approx on the surface)

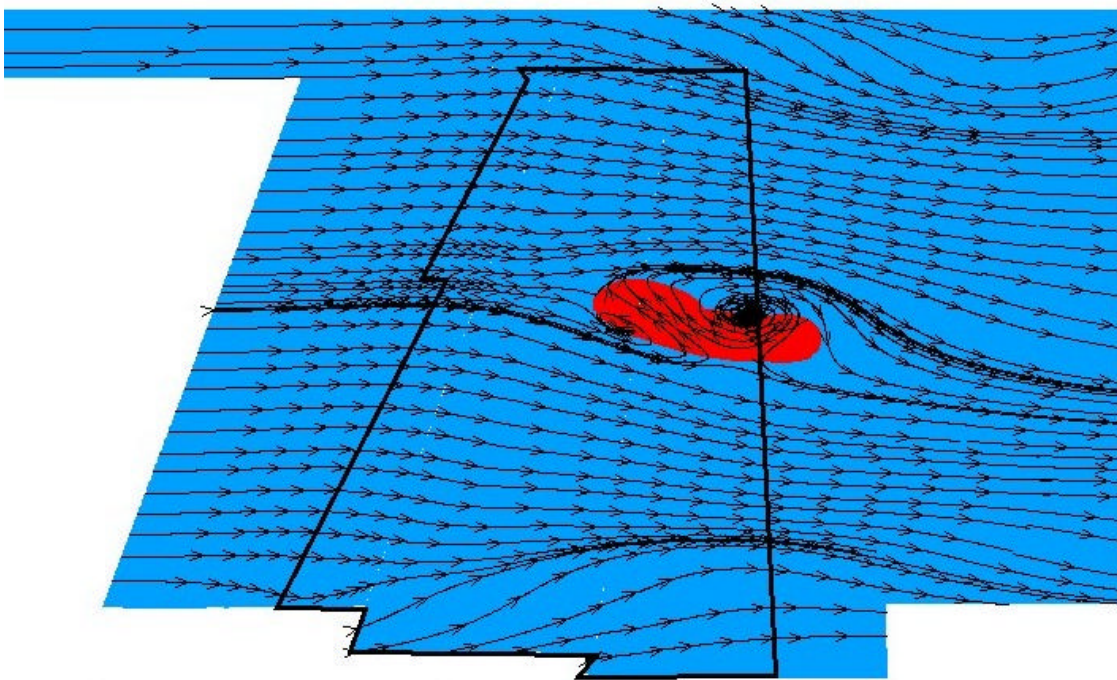


Figure 6. Off-the-Surface Streamtrace for AOA of 7 deg & $M=0.8$
(approx on the surface)

The off-the-surface streamtraces for the 8 degree angle of attack case are shown in Figure 7. As expected, the LEX vortex is still present, represented by the flow turning outboard at the most inboard section of the wing. Just aft of the snag, there are a number of singular points. First we see a focus of separation and a saddle point which feed to a line of separation. These are located aft of the snag in the separated region closest inboard. Moving outboard, there is a focus of attachment and a nodal point of separation. The nodal point is located in the center of the red region and the focus is present just in front of the trailing edge of the wing. Finally, aft of the snag at midchord there is a saddle point and a focus of separation. These two singular points interact and form a line of separation. Again we see two lines of separation, one along the most outboard section of the separation region and the other along the most inboard section of the separated region.

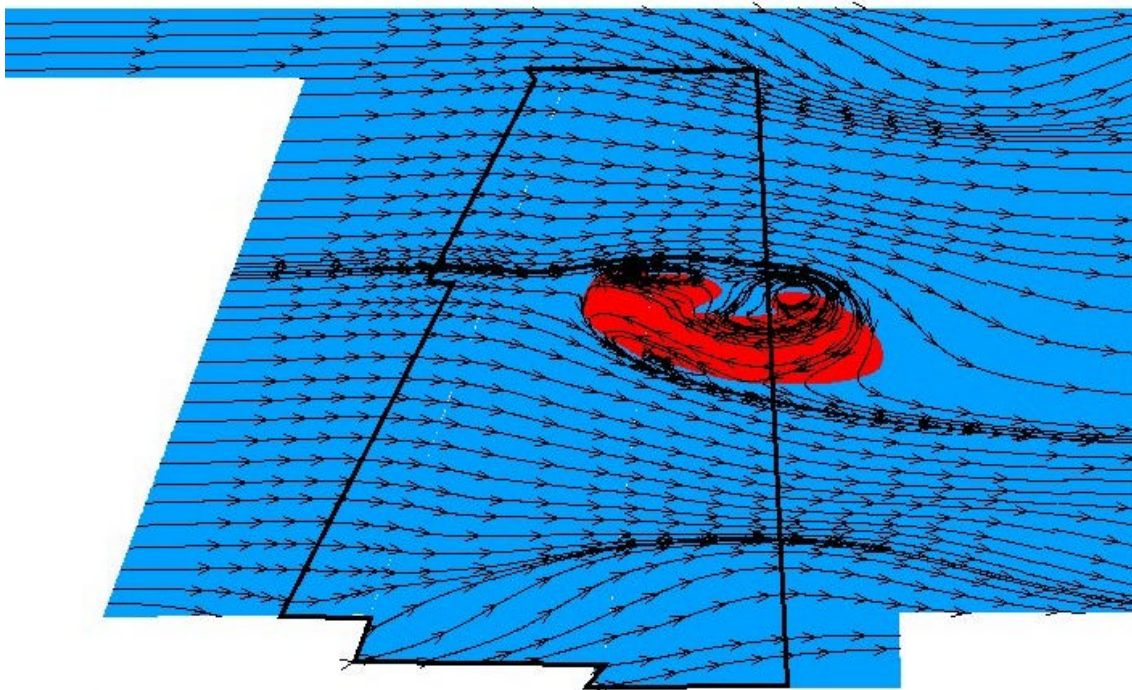


Figure 7. Off-the-Surface Streamtrace for AOA of 8 deg & M=0.8
(approx. on surface)

As we move off the surface approximately 0.25 feet for the 8 degree case, we see in Figure 8 that flow field has simplified drastically however there are still singular points present. At the trailing edge of the wing on the most inboard section of the separated region a saddle point is present. Just aft of the saddle point is a nodal point of separation. These two singular points form

a line of separation. A focus of attachment is located right at the trailing edge of the wing along the boundary of the separated region. Directly in front of the focus is a nodal point of separation but no saddle point or line of separation. This case has shown one line of separation along the most inboard region of separated section but none on the outboard region.

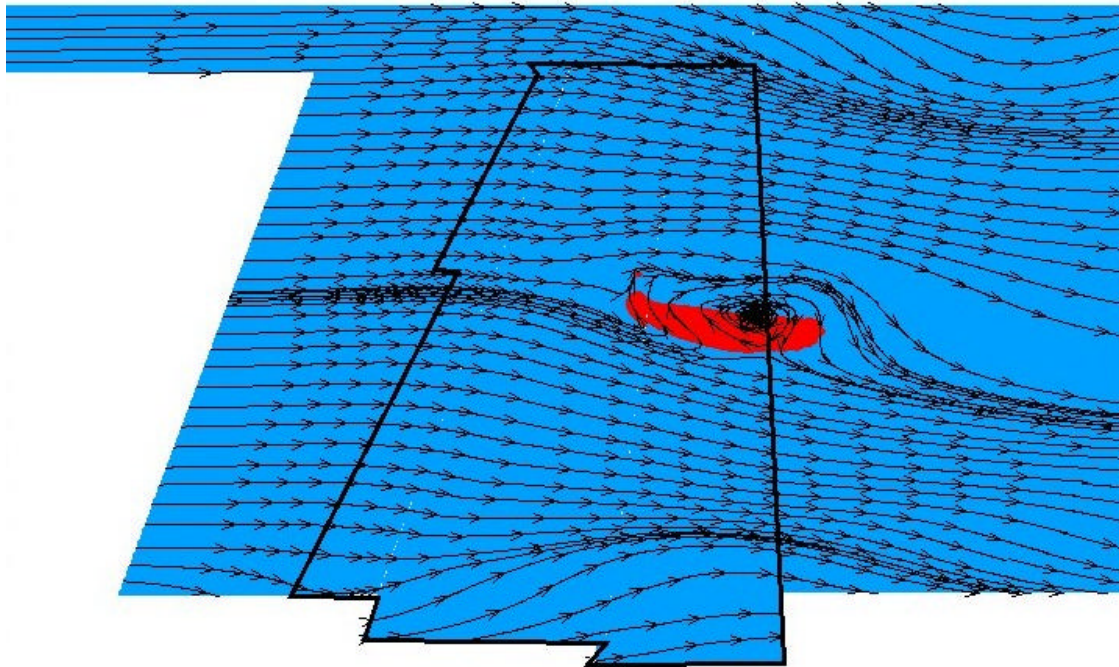


Figure 8. Off-the-Surface Streamtrace for AOA of 8 deg & $M=0.8$
(approx. 0.25 ft off the surface)

For the 10 degree case there are many singular points when looking at the off-the-surface streamtraces. While investigating the streamtraces approximately on the surface as seen in Figure 9, it is apparent the separation region has grown tremendously from the lower angles of attack. The LEX vortex and its corresponding nodal point of separation is present on the inboard section of the wing. Two foci of attachment separated by a saddle point are present along the most inboard section of the separated region. These singular points along with a nodal point of separation located just ahead of the first focus form a line of separation along the inboard border of the separated region. Just aft of the snag at about midchord there lies a nodal point of separation. Further aft on the trailing edge a large focus of attachment is located. Looking in the wake just aft of the focus is a saddle point. The lines emerging from the focus and nodal point are prevented from crossing because of the presence of a line emerging from a saddle point located in the wake. Thus there is a line of separation on the outboard separated region. The lines of separation in this case indicate the size and location of the separated region.

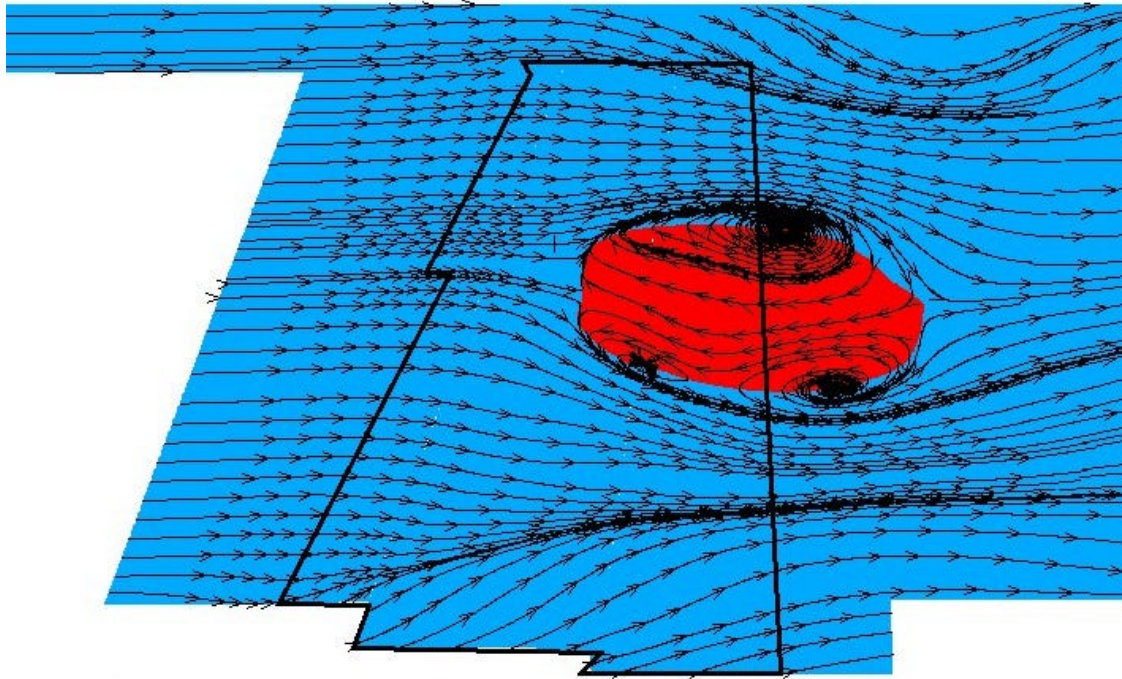


Figure 9. Off-the-Surface Streamtrace for AOA of 10 deg & $M=0.8$
(approx. on the surface)

The streamtraces at a height of approximately 0.25 feet off the surface for the 10 degree angle of attack case are seen in Figure 10. These streamtraces look very similar to those in Figure 7. The topology is virtually identical, only the foci are not as large. The same two foci of attachment separated by a saddle point which feed a line of separation are present. Looking further outboard on the wing, there is a nodal point of separation just aft of the snag at about midchord. This nodal point feeds into a focus of separation. Aft of the focus of separation is another nodal point however it is of the attachment type. A saddle point in the wake at the furthest aft area of the separation prevents the lines from the nodal point and focus from crossing so we have another line of separation. Again, we see a line of separation on the furthest outboard and inboard area of the separated region.

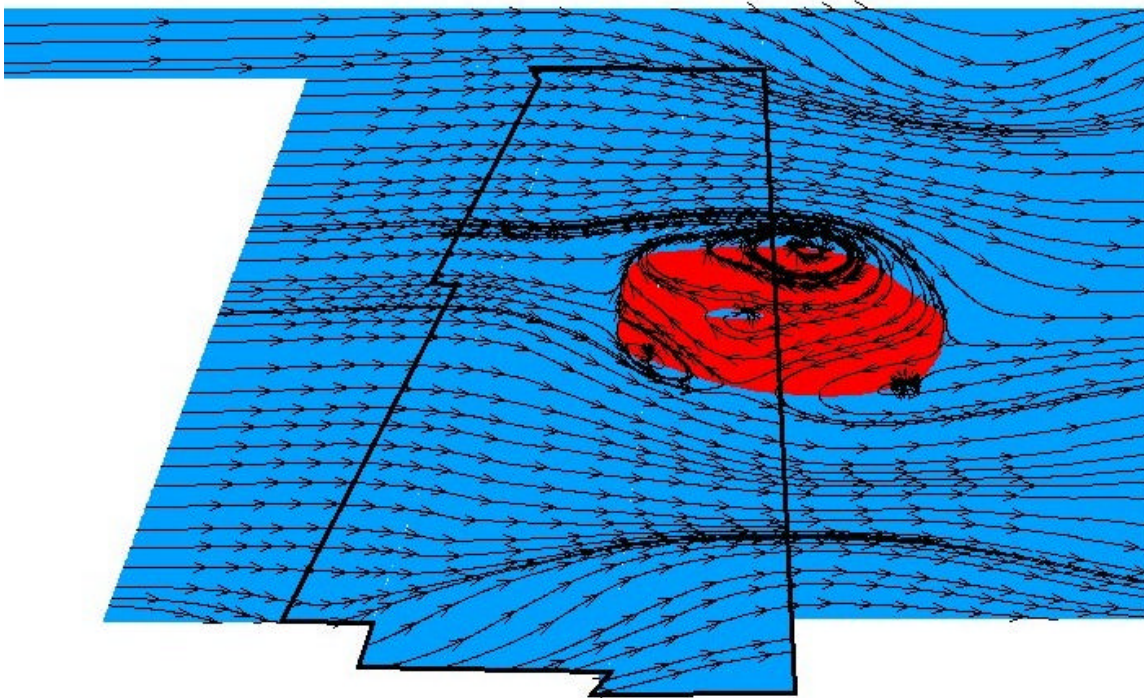


Figure 10. Off-the-Surface Streamtrace for AOA of 10 deg & $M=0.8$
(approx. 0.25 ft off the surface)

Figure 11 shows the off-the-surface streamtraces for the 10 degree angle of attack case approximately 0.5 feet off the surface. There are three singular points present, a saddle point at the most inboard section of the separated region and two foci of separation, one located on the trailing edge aft of the snag and one just outboard of the latter in the wake. Freestream lines just outboard from the focus in the wake are sucked inboard and are reversed. The other focus further pulls these lines inboard until the inboard freestream lines pull the flow back and try to straighten it out. These lines are prevented from crossing by the saddle point mentioned earlier and a line of separation emerges on the inboard region of the separated flow.

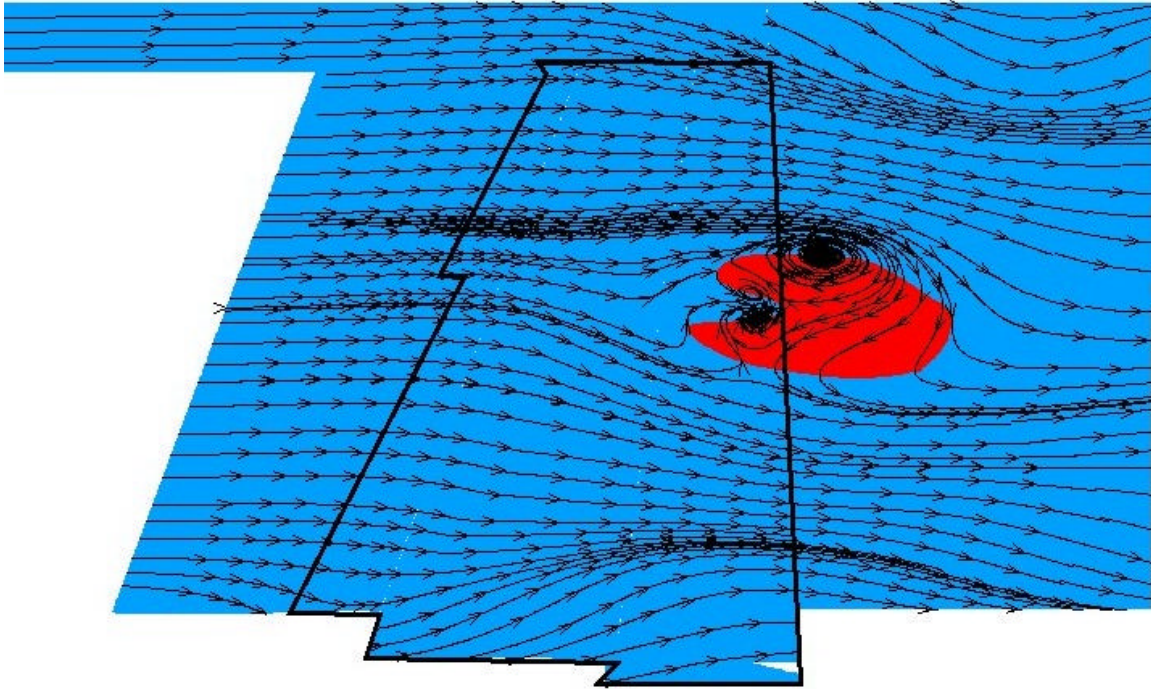


Figure 11. Off-the-Surface Streamtrace for AOA of 10 deg & $M=0.8$
(approx. 0.5 ft off the surface)

Once moving to 0.75 feet off the surface for the 10 degree angle of attack case as seen in Figure 12, the flow simplifies drastically. Here all of the singular points are located in the wake of the wing. There is a nodal point of separation located inboard of the snag just off the trailing edge. Moving inboard, there is a saddle point directly aft of the snag on the trailing edge. The saddle point separates the nodal point and a focus of separation which is located just outboard of the snag in the wake. Lines from the nodal point and focus are prevented from crossing because the saddle point thus a line of separation is also present along the most inboard area of the separated region.

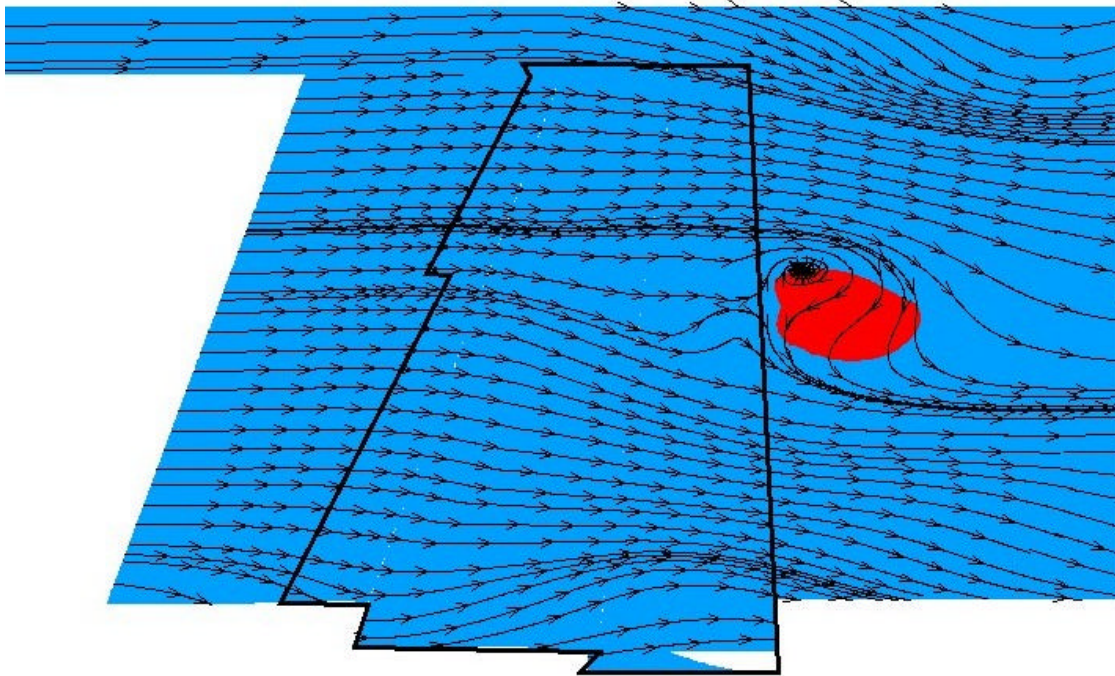


Figure 12. Off-the-Surface Streamtrace for AOA of 10 deg & $M=0.8$
(approx. 0.75 ft off the surface)

3.4 *Conclusions from Off-the-Surface Streamtraces*

Investigating the off-the-surface streamtraces have shown that as angle of attack is increased the area of separated flow not only grows but also becomes more complex. For the 6 degree angle of attack case, the region of separated flow was concentrated to the surface and as one moved off the surface the flow returned entirely to the axial direction. This was also the case for the 7 degree angle of attack case only the flow did not return uniform until after one moved approximately 0.25 feet off the surface. As the angle of attack was increased, the distance off the surface in which separation of the flow did not occur increased. Furthermore, as angle of attacked was increased the number of singular points and their intensity grew.

It was also verified that in all of the cases investigated the presence of a line of separation was an indication of separation. Moreover, in all but two cases there were two lines of separation. One located along the furthest outboard and inboard area of the separated region. No lines of separation were observed in or around attached flow, thus the lines of separation may not only indicate that separation is present but in fact give a location for the separated region.

Chapter 4 Investigation of Crossflow Velocity Traces

4.1 *Crossflow Defined*

Flow which moves inboard, outboard and up off the surface of the wing. The velocity components in the vertical and spanwise directions, v and w , define the crossflow velocity. Tracing the crossflow and investigating it sheds light on the mechanics of the flow field which may not be seen or understood in the streamwise or surface planes. Such flow field mechanics may be vortices generated by a Leading Edge Extension (LEX vortex), tip vortices, snag vortex, inboard and outboard flow interaction, or vortex interactions.

Experimentally, little work has been done regarding the investigation of crossflow and separation in the crossflow. This is due to the complexity of probing the flow field off-the-surface without disturbing it. Simpson et al [ref 12] measured three-dimensional crossflow separation using laser Doppler velocimetry. This provided the most detail about the separation flow field but at great expense and with the limitation of requiring the knowledge of the separation line direction. Therefore, CFD is a common tool in the study of crossflows. Delery [ref 2] suggests that flow topology off the surface and in the crossflow may be insightful when investigating three-dimensional flows and separation.

4.2 Crossflow Grids and Data Generation

Amtec Tecplot was used to generate the crossflow grids and data. An imbedded Tecplot Slice function was used to extract 2-D planes out of the 3-D grid. The Slice function interpolates the data points in the grid to create a 2-D plane at a specified position on, in this case, the x-axis. Data for this grid, the v and w components of the velocity vector was calculated by dividing out the density from the momentum vector in the CFD solution files. Tecplot also has a streamtrace function that allows the user to plot 2-D vectors. This was taken advantage of to plot the crossflow using the v and w components of velocity as the vector variables.

4.3 Definition of Streamwise Stations

With crossflow and its implications on the flow field addressed, it is necessary to investigate the crossflow velocity traces and their implications on the flow field in the vicinity of a moderately swept wing at a Mach number of 0.8. One must decide where on the wing singular points might appear and choose chordwise stations which will prove fruitful for investigation. This was done by comparing pressure coefficient contours, separation contours and investigating different flow field characteristics such as shock location, movement of the shock location and shock interaction.

Figure 13 shows the pressure coefficient contours for the wing at angles of attack of 6, 7, 8 & 10 degrees. The green and yellow areas indicate regions of low-pressure, which are close to zero. It can be observed that the low-pressure region grows rapidly with angle of attack. This is a possible indication of separated flow. These contours also show a jump in shock location. This is indicated by the light blue area in the 6 and 7 degree AOA cases jumping forward or 'pinching' towards the leading edge. Thus the area just before and aft of the light blue area would be good chordwise positions to investigate the crossflow because changes in the flow field due to shock location may have a major effect on the flow topology.

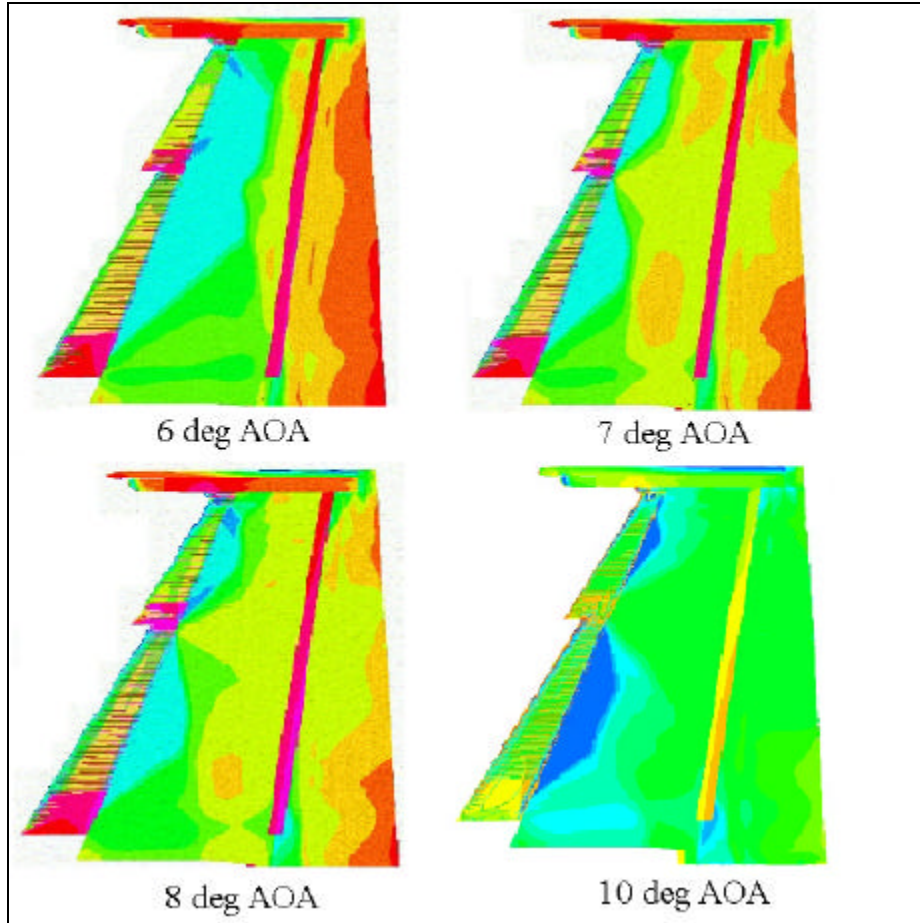


Figure 13. Pressure Coefficient Contours for 6, 7, 8 & 10 deg AOA

A reversed or zero axial flow velocity can indicate surface separation of the flow field. This can be used as a good preliminary tool for investigating if a flow field is separated or not. Figure 14 displays reversed axial flow contours for the wing at each angle of attack. The blue region indicates positive axial velocity on the first grid off-the-surface where the red region is used to visualize the negative or zero axial velocity. As one might observe the area of separation drastically increases with angle of attack in the center portion of the wing. This area of separation is just aft of the pressure contour 'pinch', which indicates that there is a shock followed by separated flow. Since separation of three-dimensional flows and its topology are of great interest to aerodynamicists, this region will be investigated as well.

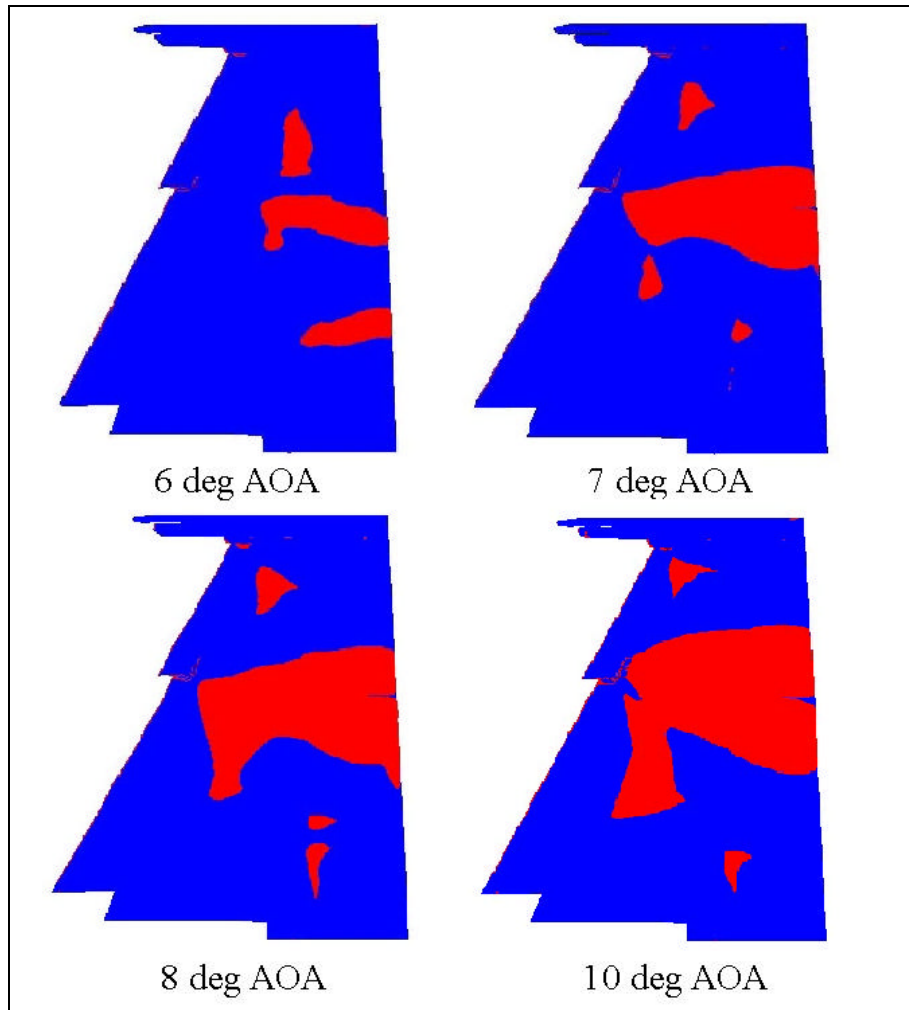


Figure 14. Reversed Axial Flow Contours for 6, 7, 8 & 10 deg AOA

Shocks and their interaction with other shocks are also areas in flowfields which lack understanding. Figure 15 displays a pressure isobar for the wing at an AOA of 6 degrees. This isobar indicates that there are two oblique shocks and one normal shock present. These shocks are highlighted in red and the the interactions or merging of the them are circled blue. The interaction is where we will focus our attention.

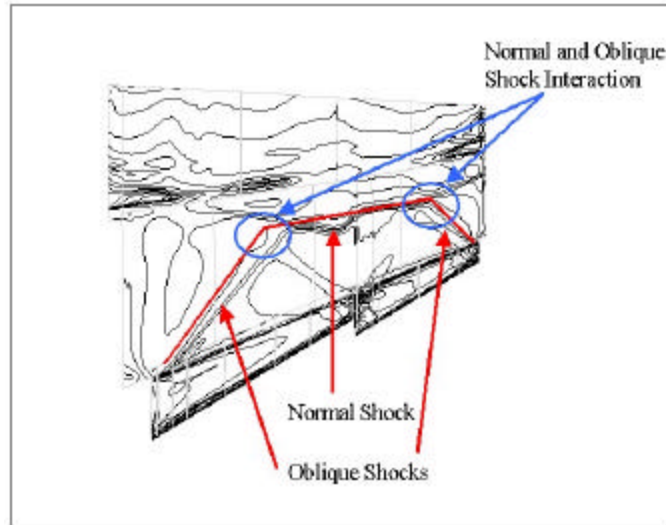


Figure 15. Oblique and Normal Shock Interaction

Taking into consideration all of the flow field features listed previously, eight chordwise stations were chosen to try and capture the crossflow topology for each of the flow field features at 6, 7, 8 & 10 degrees angle of attack. The stations were chosen such that the crossflow topology fore and aft of the oblique and normal shock interaction for each angle of attack could be observed. Stations were also chosen within the regions of separation such that the separation growth with angle of attack could also be observed. It was determined that the eight chordwise stations defined in Figure 16 were sufficient to make these observations.

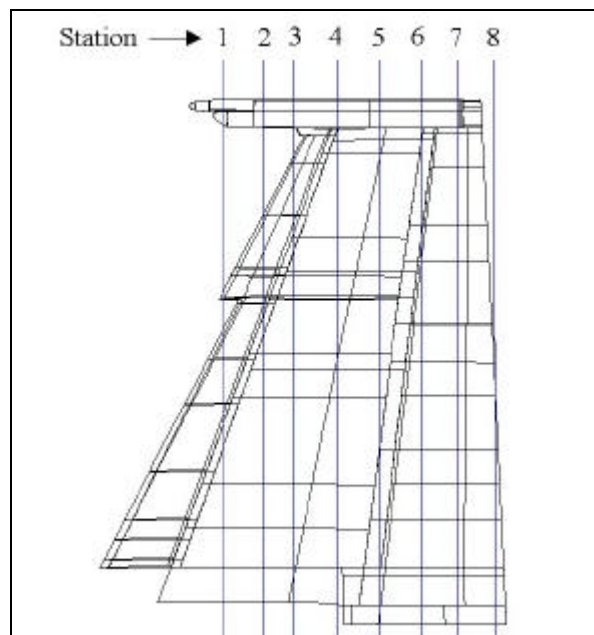


Figure 16. Definition of Chordwise Stations

4.4 Crossflow Traces in Detail

The reversed axial flow contours shown in Figure 14 suggest that for the 6 degree case there is no separation present within Stations 1-4 however there is some separation within Stations 5-8.

Plotting the crossflow velocity vectors, we can see in Figures 17 and 18 that the crossflow topology correlates with the separation contour. In Stations 1-4 the crossflow topology appears to be uneventful as the only singular points present are foci and nodes of attachment. These respectively translate to the Leading Edge Extension, LEX, vortex and the flow over the snag. Separation lines and complex singular point interaction presence are not seen. This suggests that the flow field is behaving in an orderly fashion and that the flow is remaining attached.

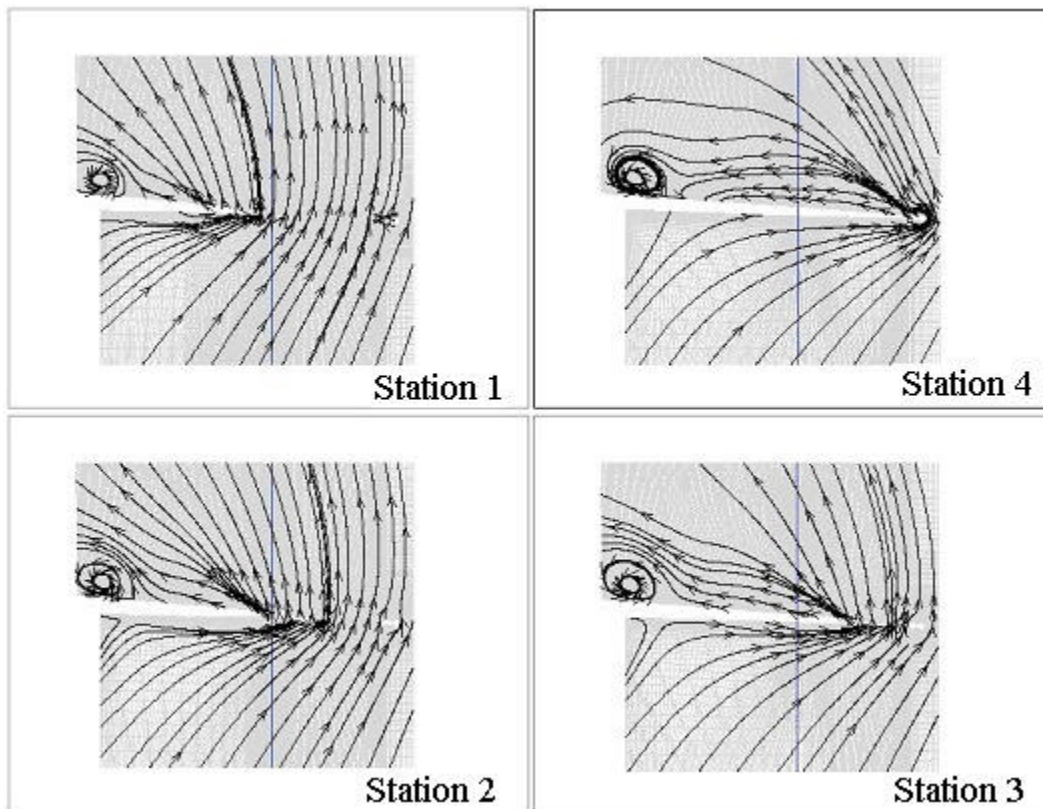


Figure 17. Crossflow Velocity Traces for AOA of 6 deg & $M = 0.8$ (Stations 1-4)

Observing the crossflow topology at Station 5 in Figure 18 shows just the opposite result. Singular points are located all over the crossflow. Station 5 shows a focus of attachment interacting with a node of separation. Between these two singular points is a saddle point in which a velocity line emerges which does not allow the streamlines from the nodal and focal point to cross. We have defined topological feature such as this in Chapter 2 and have named it a

line of separation, which is a necessary, but not a sufficient condition for separation. In this case, we see that this line of separation does in fact imply separation on the wing as the separation contour indicates it.

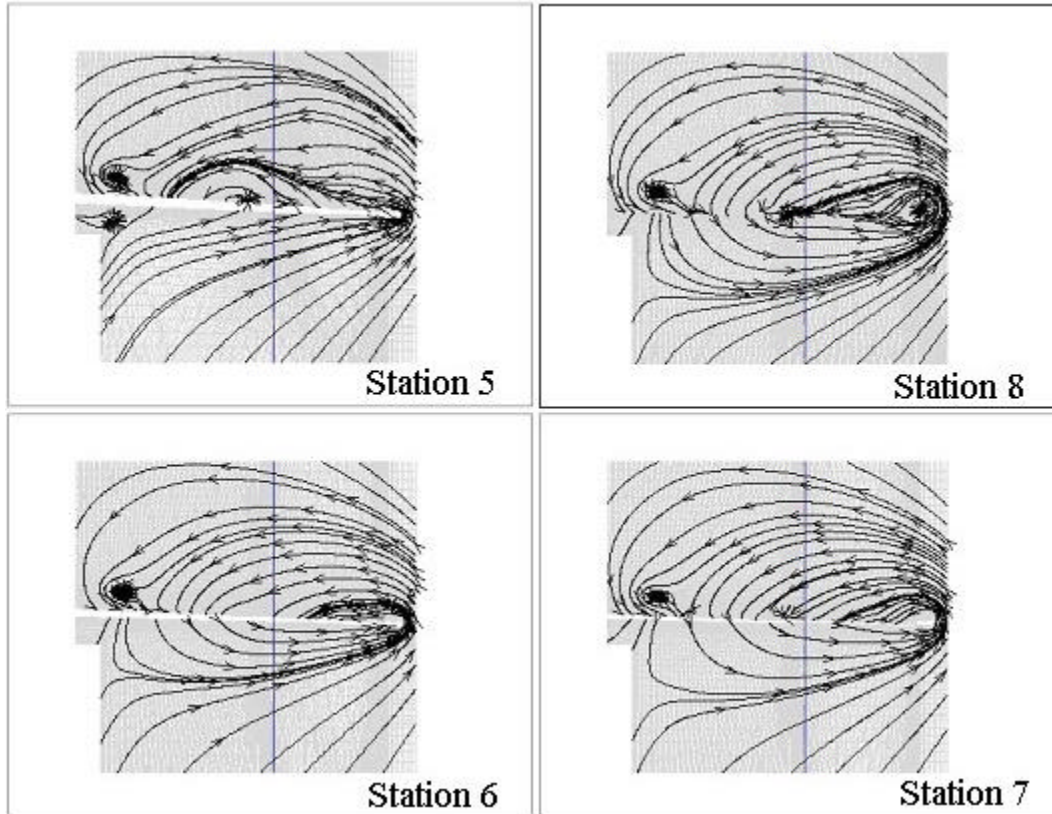


Figure 18. Crossflow Velocity Traces for AOA of 6 deg & $M = 0.8$ (Stations 5-8)

Stations 6-8 do not suggest anything in particular as there are not any complex singular point interactions as well as no lines of separation. However, they do suggest some questions. At all three stations, the crossflow appears to spill from the high pressure region under the wing to the low pressure area above the wing. This flow then curls and seems to end on the surface which is an impossibility because the flow has to go somewhere, although we must keep in mind that we are looking at a two-dimensional section of a three-dimensional flow thus the flow could be moving aft as well as curling into the wing. Thus, we can make no generalizations at this point about the crossflow in Stations 6-8 and its implications of separation.

For angles of attack of 7, 8 and 10 degrees, the region of reversed axial flow for the off-the-surface streamtraces will be zoomed in on and investigated with the crossflow. Only the crossflow planes in the region of separated flow will be discussed as the crossflow before the

separated region is similar to the 6 degree case. This was not done for the 6 degree angle of attack case because there was no reversed axial flow off-the-surface.

Figure 19 shows the region reversed axial flow for the 7 degree angle of attack case approximately on the surface zoomed in. The crossflow velocity traces for the planes located in the region of reversed axial flow are presented around this contour. Their location on the wing is represented by the yellow lines. The location of the snag has also been marked on the off-the-surface and crossflow planes by an orange and blue line, respectively. According to the reversed axial flow contour, separation is likely in Stations 5-8. A saddle point can be seen in Station 5 just outboard of the snag. A focus of attachment is located just inboard of the snag. Lines emerging from the focus converge on a line from the saddle point, thus a line of separation is present just outboard of the snag. This line of separation in the crossflow is in the same vicinity as the line of separation in the off-the-surface plane. This line of separation is present in the crossflow and off-the-surface planes in Stations 6 and 7 as well. Other singular points located in Stations 5-8, include a focus of separation (LEX vortex) close to the wing root along with another saddle point just outboard of the focus separating the two foci. No line of separation is present in the crossflow inboard of the wing for this angle of attack.

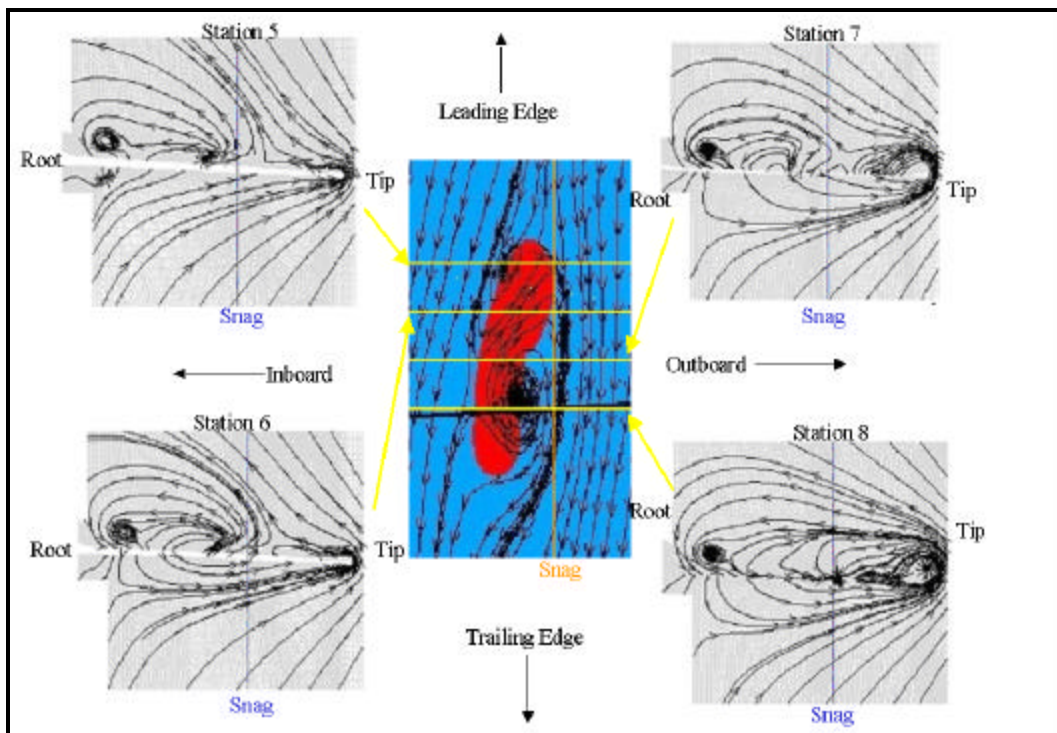


Figure 19. Crossflow Velocity Traces for 7 degree AOA (reversed axial flow is approx. on the surface)

Figure 20 displays the crossflow topology along with the reversed flow region approximately on the surface for an angle of attack of 8 degrees. According to the reversed flow contour, separation is likely present at Stations 4-8. At Stations 4-7 the same saddle point/focus interaction, as seen in Figure 19, is present just outboard of the snag forming a line of separation. This is also in the same vicinity as the line of separation for the off-the-surface plane. Other visible singular points in these Stations are a focus of separation, corresponding to the LEX vortex, located near the wing root along with a saddle point which separates the two foci. At Stations 5-8 there is another focus of separation located between the snag and the wing tip.

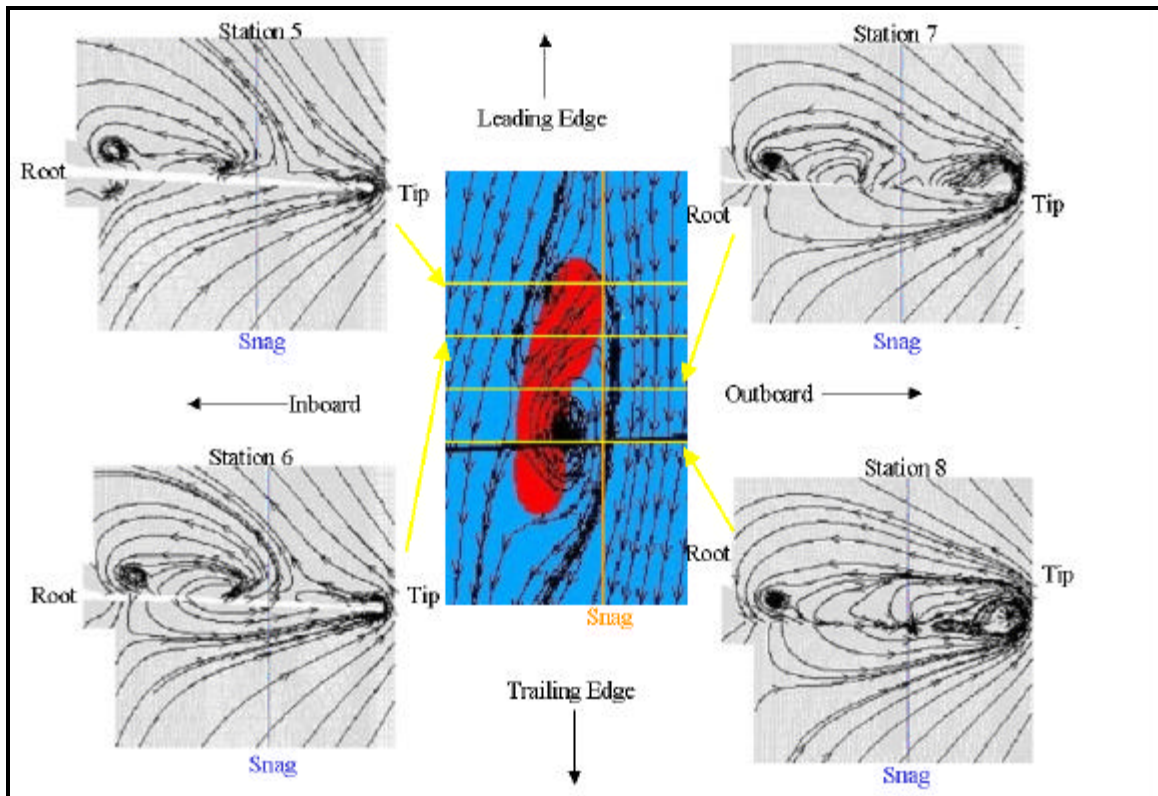


Figure 20. Crossflow Velocity Traces for 8 degree AOA
(reversed axial flow is approx. on the surface)

The crossflow and off-the-surface velocity traces for the plane located approximately 0.25 feet off-the-surface at an angle of attack of 8 degrees can be seen in Figure 21. Here there is no line of separation off-the-surface just outboard of the snag, however there is one inboard of the snag. No line of separation is located inboard of the snag in the crossflow planes. Thus there is no

correlation between the lines of separation in the crossflow and off-the-surface planes for this case.

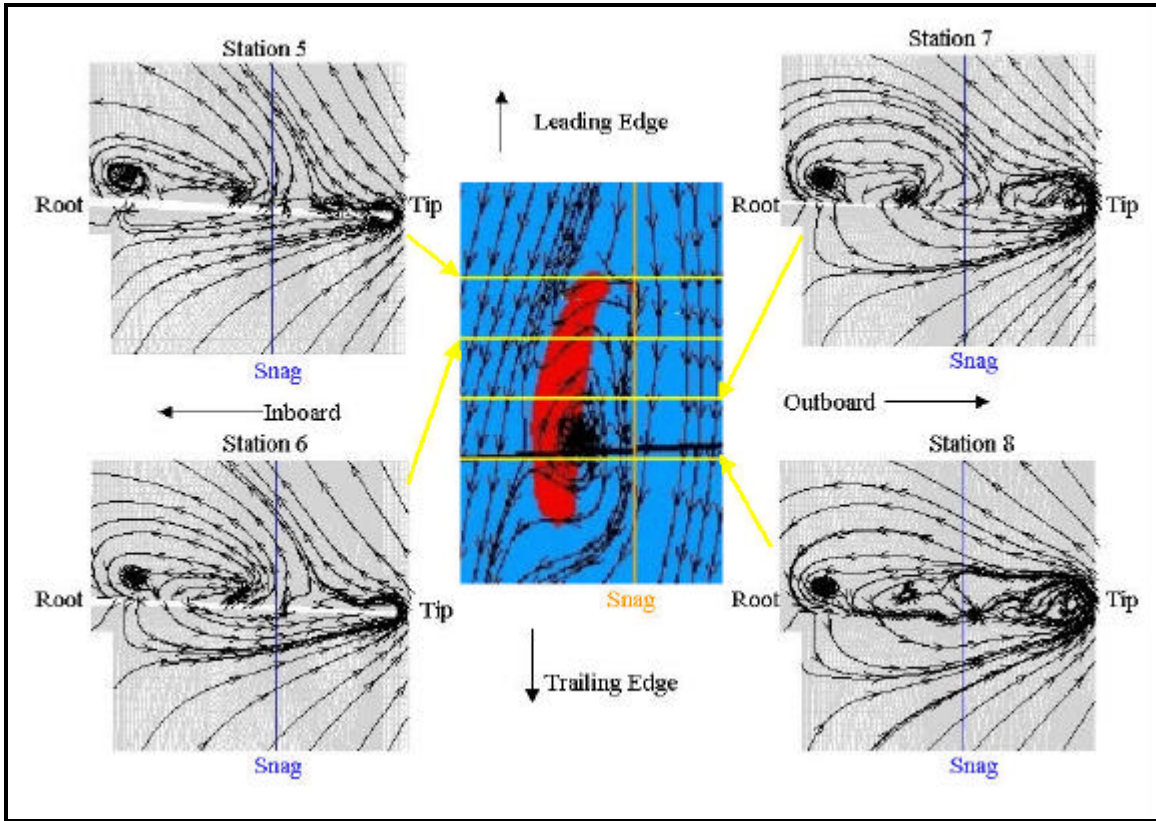


Figure 21. Crossflow Velocity Traces for 8 degree AOA (reversed axial flow is approx. 0.25 feet off the surface)

As one might expect, the crossflow topology for the 10 degree angle of attack looks very similar to that of the 7 and 8 degree cases. Figure 22 shows the crossflow topology for Stations 4-8 together with the region of separated flow approximately on the surface for 10 degrees angle of attack. At Stations 4-7, a saddle point is located outboard of the snag. This saddle point prevents the lines from a focus of attachment located around the snag from cross the flow from the high pressure lower surface over the tip of the wing from crossing. This is a line of separation and it is located just outboard of the snag. The topology from the off-the-surface plane also has a line of separation just outboard of the snag. Another focus, this of the separation type, is located on the outboard section of this wing near the wing tip. The LEX vortex is also visible by the wing root and is represented by the focus of separation. Just outboard of the snag is a saddle point separating the two foci. At Station 8, which shows the crossflow at the trailing edge, there does not appear to be a line of separation.

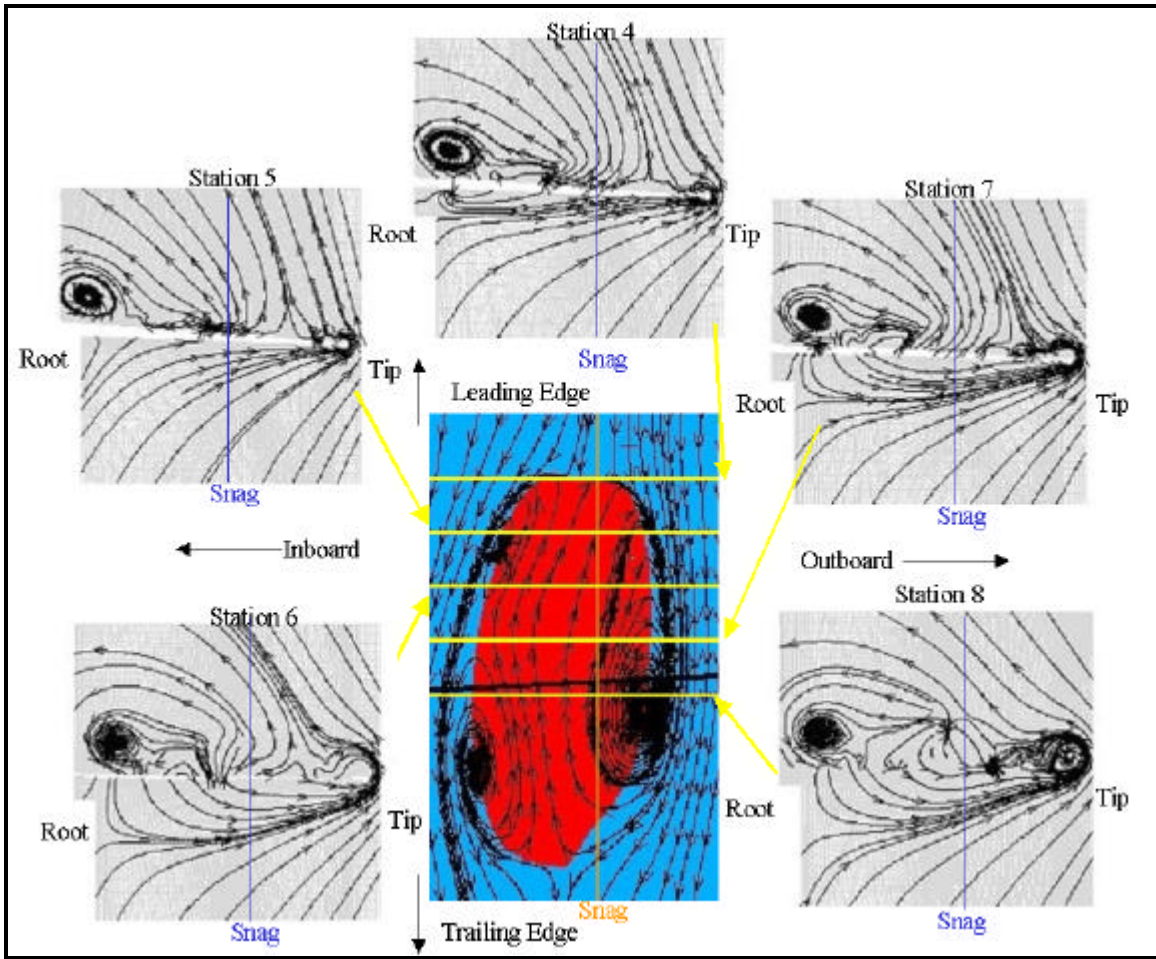


Figure 22. Crossflow Velocity Traces for 10 degree AOA
(reversed axial flow is approx. on the surface)

Figure 23 displays the crossflow velocity traces along with the reversed axial flow contour and off-the-surface streamtraces approximately 0.25 feet off-the-surface for 10 degrees angle of attack. At this distance off-the-surface, the lines of separation inboard and outboard of the snag are still present. The line of separation outboard of the snag is in the same vicinity as the line of separation present in the crossflow at Stations 5-7. There is no line of separation present inboard of the snag in the crossflow.

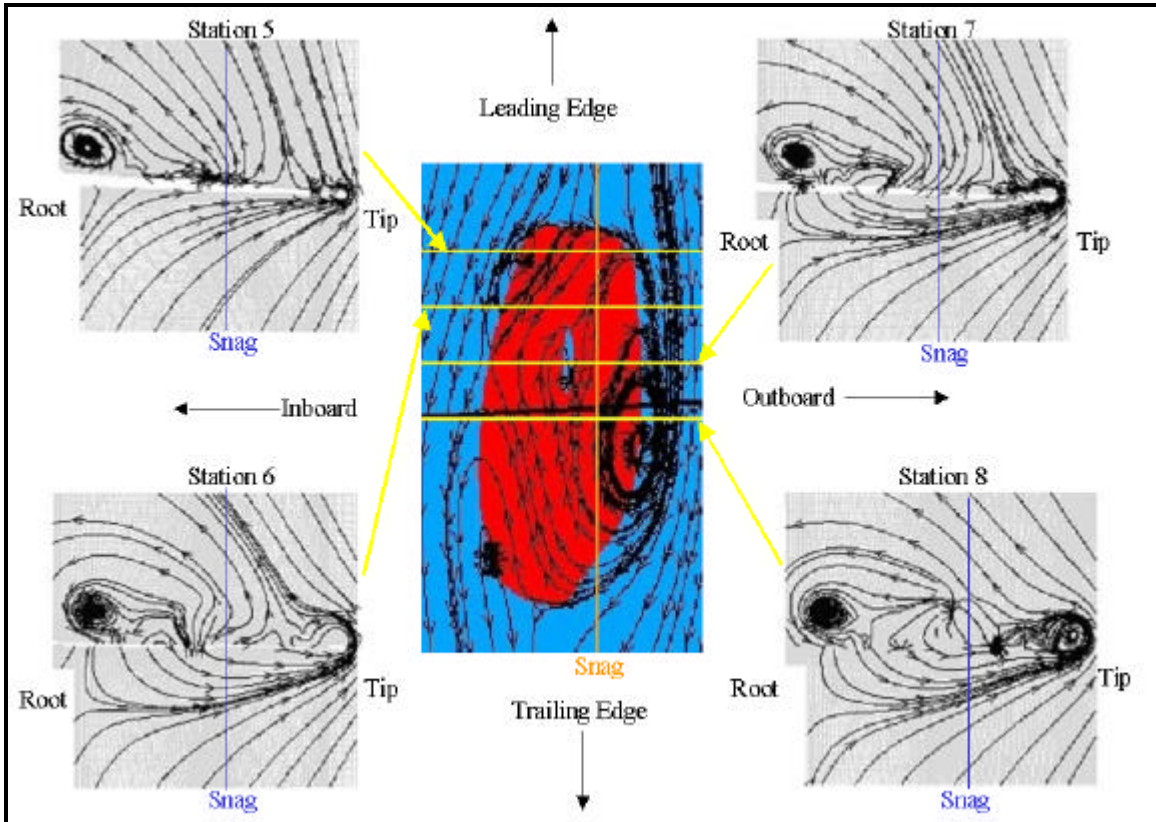


Figure 23. Crossflow Velocity Traces for 10 degree AOA
(reversed axial flow is approx. 0.25 feet off the surface)

The crossflow velocity traces presented with the off-the-surface streamtraces approximately 0.5 feet off the wing for an angle of attack of 10 degrees is displayed in Figure 24. Observing the streamtraces at this distance off-the-surface of the wing reveals that only one line of separation is present in both the crossflow and off-the-surface planes. This line of separation is inboard of the snag and not close to the line of separation in the crossflow for any of the Stations.

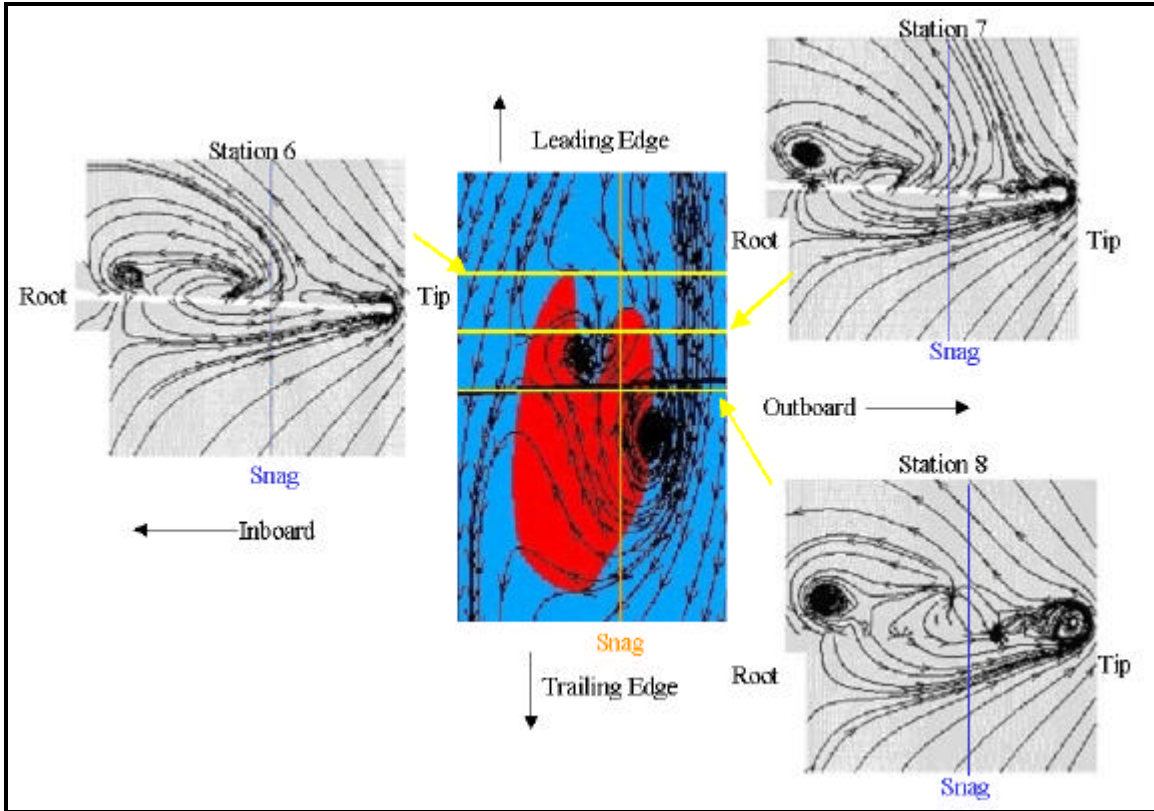


Figure 24. Crossflow Velocity Traces for 10 degree AOA
(reversed axial flow is approx. 0.5 feet off the surface)

4.5 Conclusions from Crossflow Velocity Traces

Investigating the crossflow velocity traces for four different angles of attack at eight chordwise stations has proven fruitful. It has been verified that a line of separation in the crossflow is an indication that separation may be present on the surface of the wing. Furthermore, shocks complicate the crossflow as it was seen in all of the cases that the crossflow just aft of a shock becomes much more complex. New singular points appear and interactions between singular points are seen. As the angle of attack is increased the flow topology changes critically only in the change from 6 to 7 degrees. This is the range in angle of attack in which the shock jumps rapidly forward so it may be postulated that for this wing the flow topology is more sensitive to shock location as opposed to angle of attack. Comparing the topology between the 7, 8 and 10 degree cases, supports this hypothesis as the topology is similar before and after the shock for each case. The flow topology for each case before of the shock is much different then the topology just aft of the shock.

Chapter 5 Conclusions

Flow topology off-the-surface and in the crossflow has been investigated and discussed for angles of attack of 6, 7, 8 and 10 degrees for a moderately swept wing at a Mach number of 0.8. An investigation of crossflow velocity traces at eight chordwise stations has proven fruitful. It has been verified that a line of separation in the crossflow is an indication that separation may be present on the surface of the wing. Furthermore, shocks complicate the crossflow as it was seen in all of the cases that the crossflow just aft of a shock becomes much more complex. New singular points appear and interactions between singular points are seen. It may be postulated that for this wing the flow topology is more sensitive to shock location as opposed to angle of attack.

Investigating the off-the-surface streamtraces has shown that as angle of attack is increased the area of separated flow not only grows but also becomes more complex. For lower angles of attack, the region of separated flow was concentrated near the surface and as one moved off the surface the flow returned entirely to the axial direction. As the angle of attack was increased, the distance off the surface in which separation of the flow did not occur grew larger. Furthermore, as angle of attack was increased the number of singular points and their intensity grew. It was also verified that in all of the cases investigated the presence of a line of separation was an indication of separation. Moreover, the lines of separation may not only indicate that separation is present but in fact give a location for the separated region.

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Appendix A

Annotated Bibliography and Extended Reference List

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Chapman, Gary T., "Topological Classification of Flow Separation on Three Dimensional Bodies," AIAA Paper 86-0486, 1986.

Cipolla, K.M. and Rockwell, D., "Instantaneous Crossflow Topology on a Delta Wing in Presence of Vortex Breakdown," *Journal of Aircraft*, Vol.35, March 1998, pp. 218-222.

Cipolla and Rockwell present their investigation of crossflow structure of the leading-edge vortices on a delta wing with the use of particle image velocimetry. They compare instantaneous images to characterize the transformation of the streamline topology as the vortex breakdown position moves upstream or downstream of its nominal value.

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Wetzel reports his investigation of detecting the location of three-dimensional crossflow separations using different parameters and techniques. He provides several definitions of separations and the physics for the separation process along with descriptions of the separated flowfield. Techniques used for measurements range from oil flow visualization, laser Doppler velocimetry, surface pressure, and surface hot-film skin-friction measurements.

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The design and design process used to develop the F/A-18E/F aircraft is described in this paper concentrating on providing a background for researchers developing Multidisciplinary Design Optimization.

Vita

Kevin Waclawicz was born on February 22, 1977, in Long Branch, New Jersey. He grew up in Middletown, New Jersey, with his parents, Ralph and Pat and his older sister Stacie. After 12 years of Catholic schooling, Kevin began college in 1995 at Virginia Polytechnic and State University and obtained a dual degree in Aerospace and Ocean Engineering in 1999. Once receiving his Bachelor of Science degree he opted to stay another two years at Virginia Tech to obtain a Master of Science degree in Aerospace Engineering with a concentration in aerodynamics. In August of 2001, Kevin finished his requirements for his Master of Science degree and began working for TRW Systems & Information Technology in San Bernardino, California.