Laboratory

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Flow Visualization I: Smoke Tunnel
Circulation and High-Lift Aerodynamics

Introduction

This laboratory exercise provides a physical picture of the flowfield patterns around various airfoil sections. The models include the high-lift devices of a trailing-edge flap, a boundary layer suction system, and a blown boundary layer airfoil. Lastly, the effects of circulation can be visualized around a rotating circular cylinder.

Circulation Theory

The Kutta-Joukowsky theorem introduces the theoretical concept of circulation, which is defined by Γ. This theorem has physical implications in the lift-per-unit-span of a wing section and can be implemented as:

$$\frac{L}{b} = \rho_\infty V_\infty \Gamma \tag{8.1}$$

In other words, the lift produced by a 2D airfoil section is directly proportional to the circulation around it. Thus, increasing the circulation will produce an increased lift. Circulation can be produced by rotation of a cylinder or a sphere, or it can be enhanced by changing the shape of the lifting surface (i.e., camber or thickness). This concept can be *physically* seen in the various high-lift devices analyzed in this experiment.

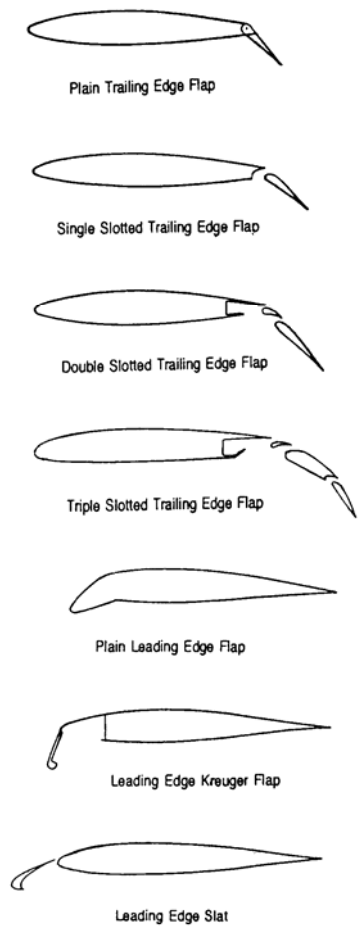
High Lift Devices and Aerodynamic Effects

In general there are three techniques for increasing the lift on an airfoil: camber line changes, area changes and boundary layer control. The various devices which implement these techniques are shown in Figure 8.

Thin airfoil theory shows that both lift and pitching moment increase with increasing airfoil camber. Trailing edge flaps and leading edge flaps use camber line changes to increase airfoil lift. Deflection of a flap increases the effective camber of the airfoil section, thus increasing the lift coefficient at a given angle of attack. Large increases in drag and pitching moment (nose down) about the aerodynamic center along with lower angles of zero lift are observed. The effects of various flap geometries are shown in Figure 9, and these configurations represent a flap that is 25% of the chord deflected at 30°.

Extendable leading edge slats and trailing edge slotted flaps are used to increase the effective airfoil/wing area. However, the airfoil/wing coefficients are still based on the original wing planform area, so large increases in lift coefficient result. Maximum lift coefficients exceeding 3.5 are possible for high lift wing configurations when considering the 2D sectional characteristics.

However, slats and slotted flaps have another, more important effect: delaying the separation of the boundary layer on the upper surface of the airfoil. In so doing, the airfoil section very effectively reaches higher angles of attack and the resultant increases in the maximum lift coefficient. A fixed slat operates the same as a slot but is different geometrically because it is a small airfoil ahead of the leading edge whereas slots are actually cut through an airfoil. In both cases high pressure air from the lower surface is accelerated through a diverging passage and is directed tangential to the upper surface of the airfoil to increase the momentum in the boundary layer. The effect is to delay upper surface separation until a higher angle of attack is reached. This increases α_{stall} and $C_{L_{\max}}$ without changing either α_{L_0} or $C_{M_{AC}}$. If a downward movement of the slat is also used, the effective camber is increased with a small increase in drag and an α_{L_0} shift. A similar effect is used with slotted trailing edge flaps.



• Figure 8. Typical wing high lift devices

Area boundary layer control is also used to either suck the low energy lower regions of the boundary layer off the airfoil surface or to re-energize these layers by actively blowing air tangential to the surface. The result is the same: delayed boundary layer separation and higher airfoil lift. These effects will be very similar to those of the slot or slat. These observations of the effects of boundary layer control are summarized in Figure 10, and may include leading edge slats or boundary layer suction. In general, wing flaps are capable of producing a greater increase in $C_{L_{max}}$ than slats or slots. Used together the effects are additive.

Procedure

Follow these steps to determine the variation of dynamic pressure with velocity:

1) Form up into teams of two or three. Read through the questions at the end so you are prepared to explore the answers.

2) Follow the instructions and precautions of the technician in operating the smoke tunnel and installing the models. Start the blower and turn on the test section lighting.

3) Start the "smoke" (the "smoke" is actually atomized water created by an ultrasonic water mister). The traces of streamlines should become immediately apparent in the tunnel. **NOTE: The ½" tubing connecting the "fog box" to the bottom of the rake in the inlet will occasionally fill up with condensed water. If this happens, simply disconnect it from the rake and drain it.**

4) Install the plain Clark-Y airfoil section. Position it at 0, 10, 20, and 30° AOA and sketch the flow patterns traced out by the smoke. Use the template drawings provided on pages 39-43. Pay

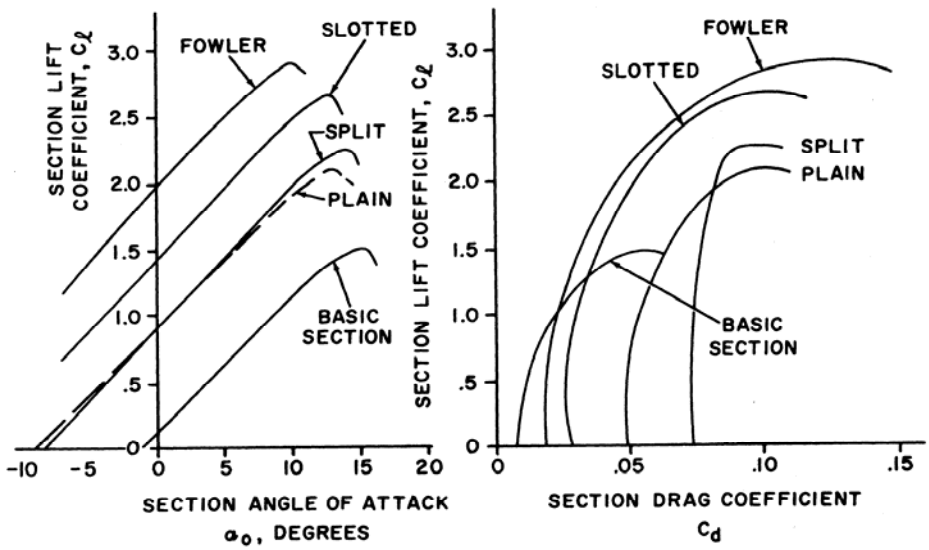
particular attention to the stagnation point and regions of flow separation (i.e., the wake). Label these on your sketches.

5) Install the flapped Clark-Y airfoil section and set a flap angle of approximately 30°. Position it at 0, 10, 20, and 30° AOA and sketch the flow patterns, as in step 4).

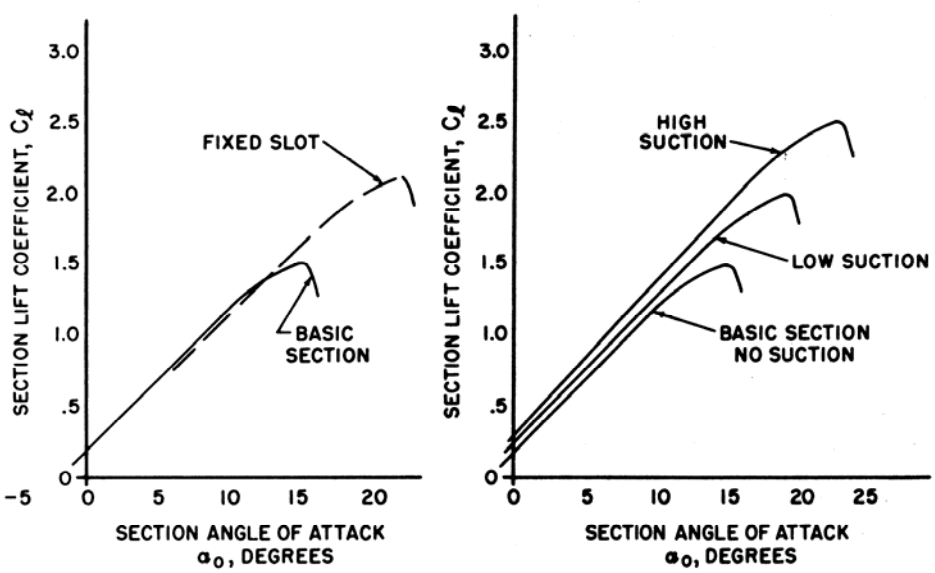
6) Install the boundary layer suction airfoil section and start the vacuum pump. Position it at 0, 10, 20, and 30° AOA and sketch the flow patterns, as in step 4).

7) Install the blown boundary layer airfoil section and start the air pump. Position it at 0, 10, 20, and 30° AOA and sketch the flow patterns, as in step 4).

8) Install the rotating circular cylinder section. Operate it at zero, low, and high rotation rates and sketch the flow patterns, as in step 4).



• Figure 9. Effects of various flap configurations



• Figure 10. Effects of boundary layer control on lift curve

Deliverables

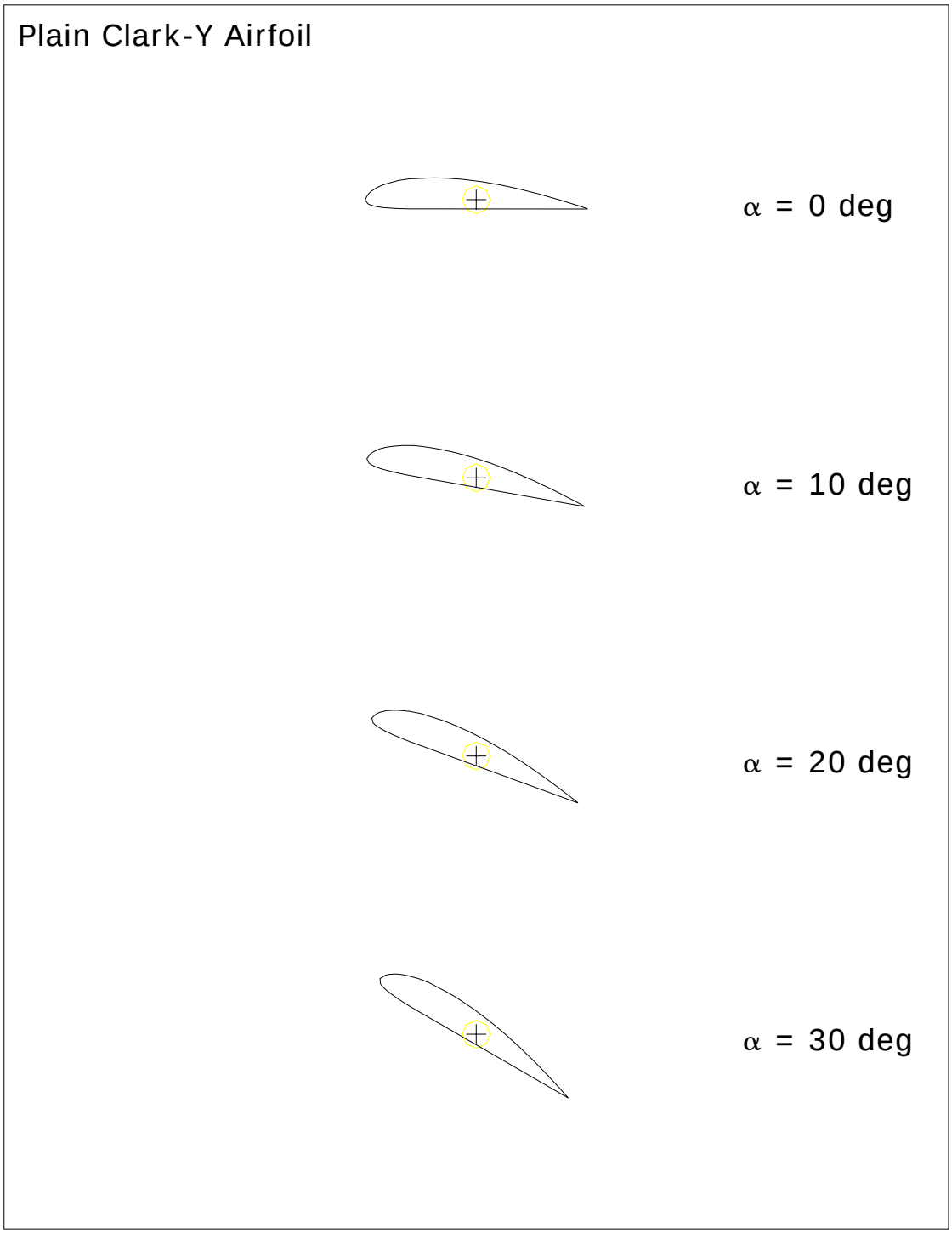
Although no formal write-up section is required for this laboratory exercise, you must hand in your annotated flowfield sketches and the answers to the following questions:

Questions

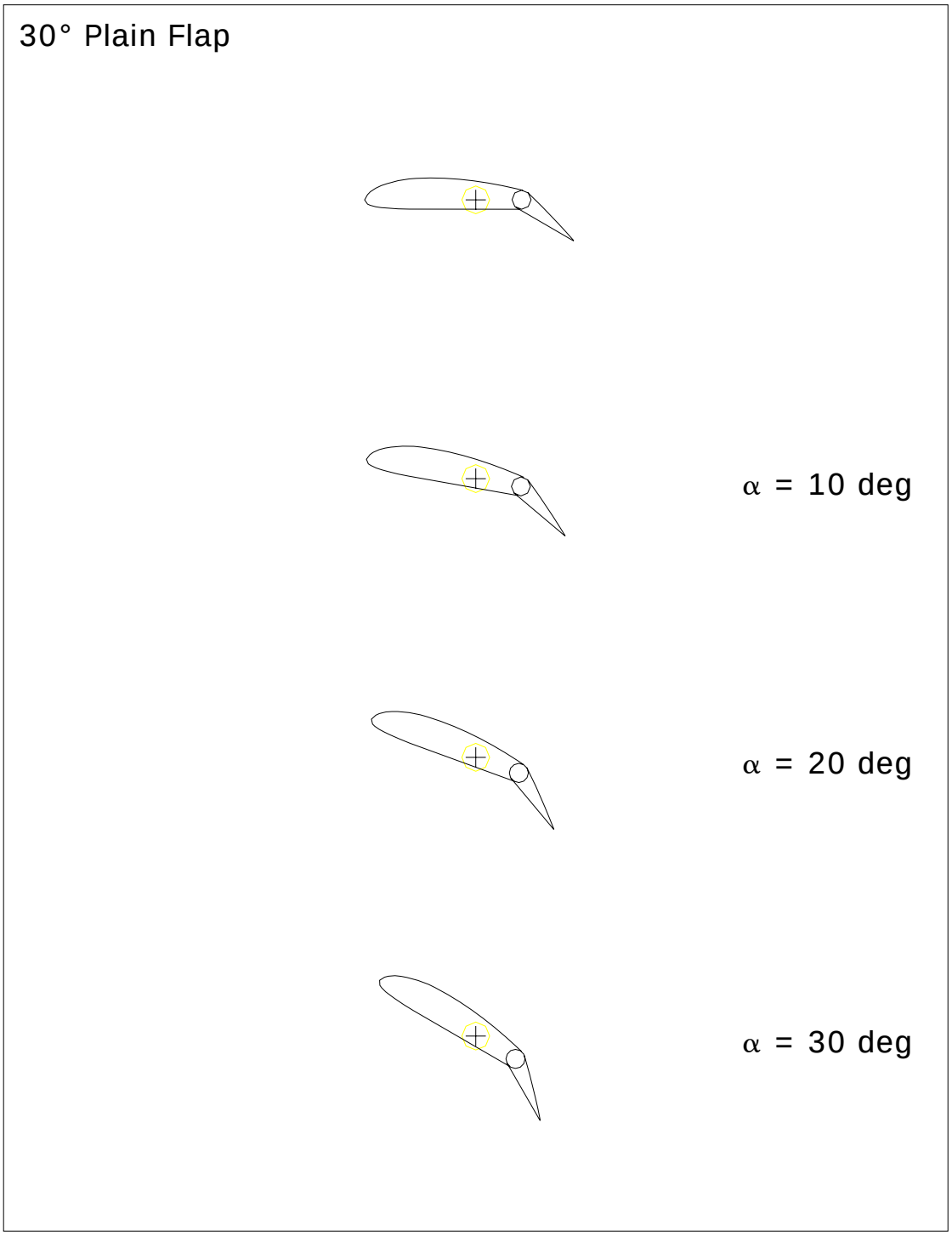
1) Do you observe stall phenomenon on the plain Clark-Y airfoil? What is the estimated stall angle? What about the flapped airfoil?

2) Do you observe stall phenomenon on the airfoil with boundary layer suction? What is the estimated stall angle? How does the wake change? What about the airfoil with boundary layer blowing?

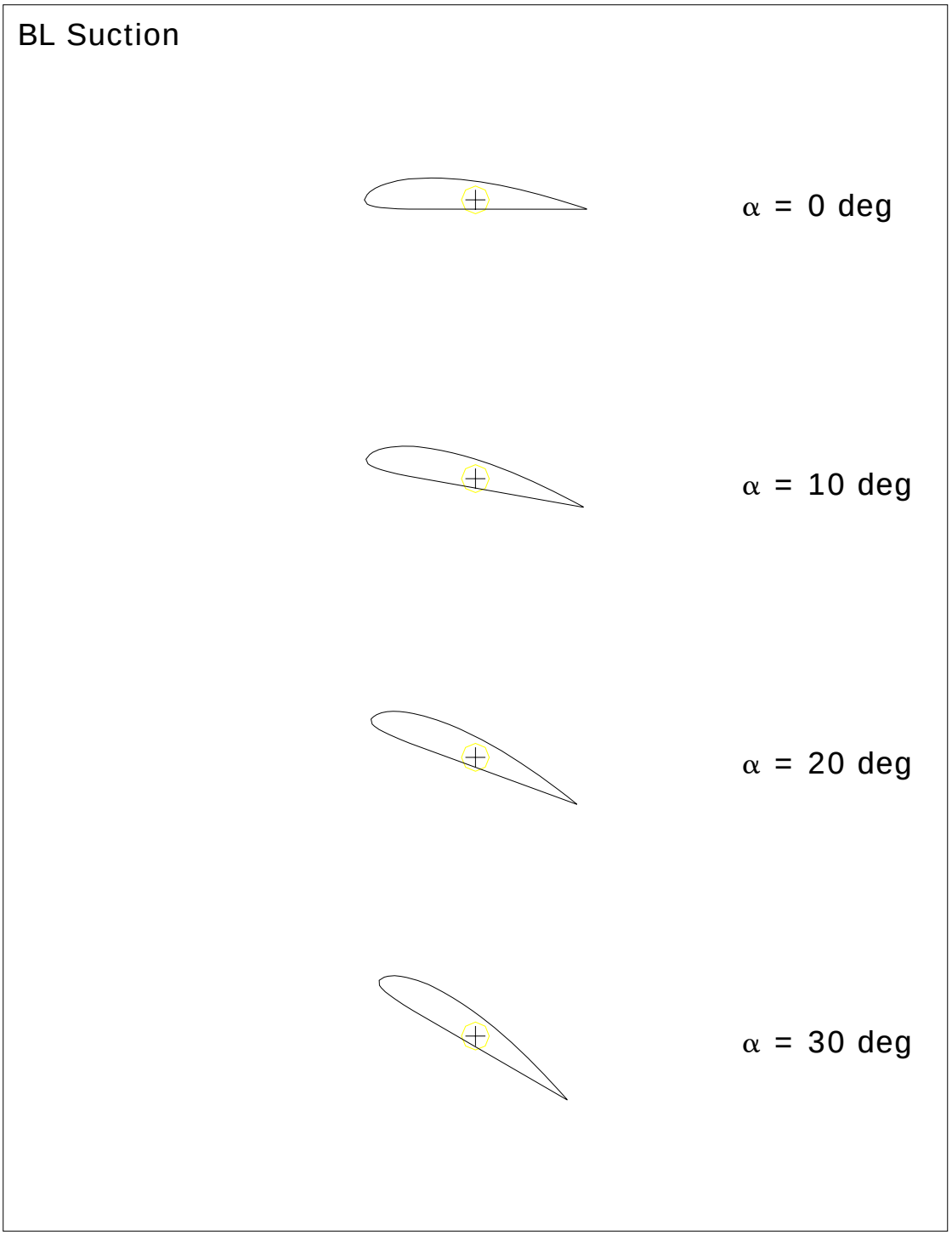
3) What does rotation do to the streamlines around the circular cylinder? What direction is the resultant force? What <u>conceptual</u> aerodynamic quantity is represented by this <u>physical</u> evidence?



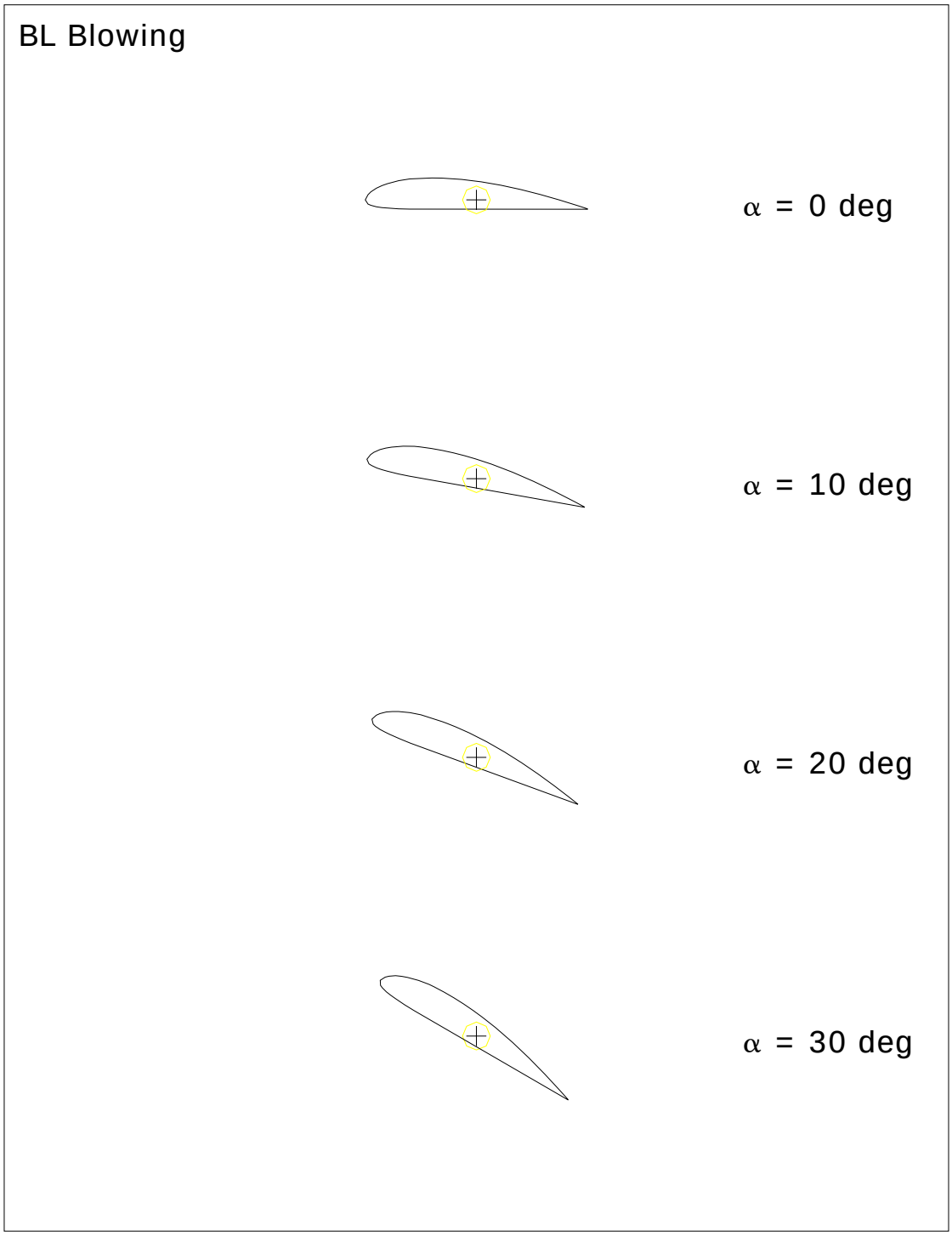
• Figure 11. Streamline patterns for the Clark-Y airfoil



• Figure 12. Streamline patterns for the Clark-Y airfoil with a plain flap



• Figure 13. Streamline patterns for the Clark-Y airfoil with boundary layer suction



• Figure 14. Streamline patterns for the Clark-Y airfoil with boundary layer blowing

• Figure 15. Streamline patterns for a circular cylinder

Laboratory

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Flow Visualization II: Water Tunnel
Delta Wing Aerodynamics

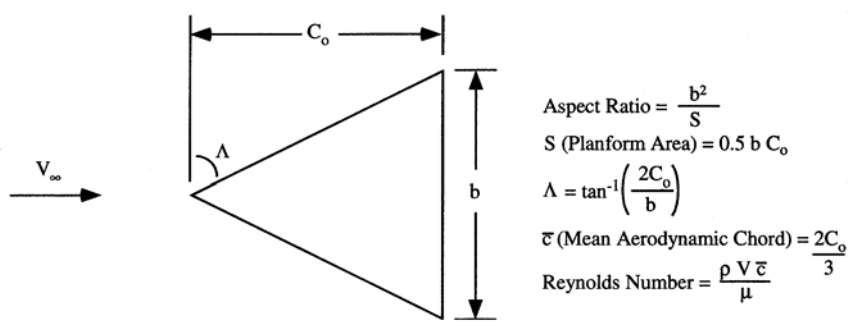
Introduction

This laboratory exercise provides a physical picture of the flowfield patterns around a sharp-edged delta wing with a leading edge sweep angle of 65°. The delta wing models an extreme example of a finite wing (aspect ratio of 1.87) and as such, clearly demonstrates the structure and function of wing tip vortices. These concepts have a direct application to the aerodynamic design of high-performance combat aircraft like the F/A-18.

The aerodynamics of delta wing planforms are significantly different from those associated with relatively straight, moderately swept wings usually designed for subsonic flight. The flowfield of slender, low aspect ratio wings, commonly called delta wings, are dominated by two leading edge vortices which form on the upper surface of the wing. The high axial velocities present at the core of these tight vortex structures produce a significant contribution.

Delta Wing Aerodynamics

The low aspect ratio highly swept triangle planform, commonly know as the "delta wing", originated with the designs of Alexander Lippisch in Germany during the 1940's. The delta wing was developed in an attempt to minimize some of the negative aspects associated with supersonic flight, most notably wave drag and compressibility effects. Some of the relevant delta wing geometric details are shown in Figure 16.



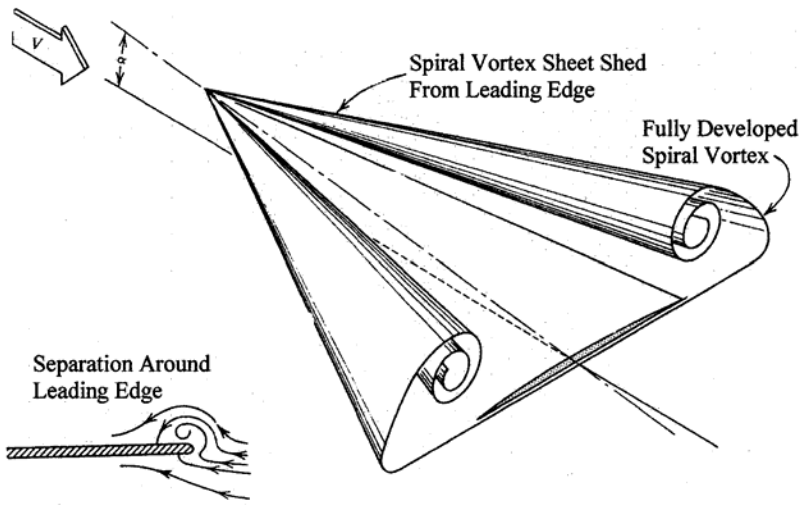
• Figure 16. Delta wing planform geometry description

Leading Edge Separated Flow

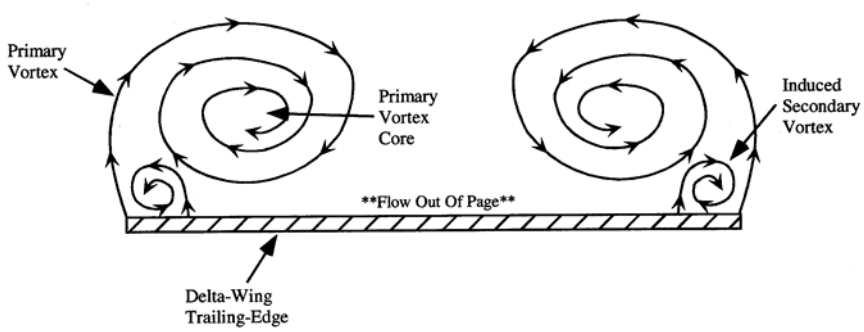
The most interesting aspect of the delta wing flowfield occurs independent of compressibility effects or Mach number. At moderate to high angles of attack (α = 5°-30°), flow separation occurs along the length of each of the leading edges, from the apex to the trailing edge. This separating shear layer (i.e., the viscous boundary layer away from the surface) results in two vortex sheets which roll up to form coherent vortices which stream aft along each leading edge. This flow characteristic is depicted in Figure 17.

For the delta wing at a positive AOA, the leading edge stagnation point lies on the lower surface of the planform. As the flow tries to negotiate the large pressure gradients associated with the sharp leading edge, it is unable to remain attached and separates from the upper surface. The separated free shear layer spirals around and reattaches to the upper surface some distance inboard of the leading edge. This roll-up occurs

along each leading edge of the planform and forms two coherent vortices, beginning at the apex of the delta. Smaller secondary vortices are also induced as a result of the primary vortex, as shown in Figure 18.



• Figure 17. Leading edge separated flow and vortex formation



• Figure 18. Leading edge vortex formation (looking upstream)

Vortex Bursting

Flow underneath the primary vortex encounters an adverse pressure gradient due to the strong rotation of the vortex. The induced adverse pressure gradient causes a secondary separation underneath the primary vortex which forms a secondary vortex whose rotation and vorticity are opposite to that of the primary vortex. The rotational velocities in the core of the primary vortices can be up to 3 times the free stream value. The high core rotational velocities (axial velocities) present in the primary vortex cores generate a low pressure on the upper surface of the planform, resulting in an additional lift force known as vortex lift. At high angles of attack the percentage of the total lift attributed to vortex lift can be upwards of 50%. The amount of vortex-induced lift increases with increasing AOA and is responsible for the nonlinear aerodynamic characteristics of a delta wing. However, it is this additional lift that enables high-AOA flight and maneuvering for high-performance combat aircraft.

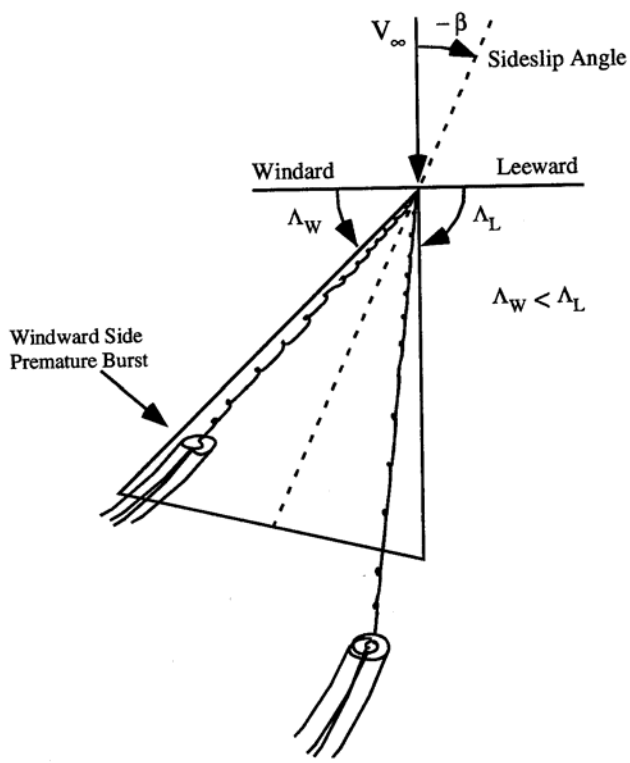
The study of vortex bursting has been an active field of research since the early 1960's. Bursting is a fundamental change in the vortex flowfield and is defined as a sudden enlargement of the vortex with an associated rapid reduction in core axial velocity. The once tightly wound, coherent vortex becomes a diffuse turbulent flow at a sufficient distance downstream of the apex, as depicted in Figure 19. If the bursting occurs over a lifting surface, the loss of the high axial core velocity results in a reduction of the vortex lift.

This reduction in lift due to the vortex bursting is analogous to a conventional wing stall due to flow separation.

There are two types of vortex bursting, a spiral type and a bubble type. At low AOA, the two primary vortices remain tightly wound and coherent from the planform apex to the trailing edge and burst somewhere aft, in the wake. As AOA increases, the burst point moves forward until reaching the trailing edge of the planform. Once the burst point reaches the trailing edge and begins to move up the body towards the apex, the delta wing is said to be undergoing stall. The movement of the vortex burst from trailing edge to apex proceeds rapidly with increasing AOA, and it slows down as the burst point nears the apex.

In addition to angle of attack effects, sideslip or yawing of the delta wing will also affect the vortex structure and burst dynamics. By yawing the planform, the side yawing into the oncoming flow “sees” a lower effective leading edge sweep angle and is termed the windward side. Conversely, the side yawing away from the oncoming flow sees a greater effective leading edge sweep and is termed the leeward side. For a given aspect ratio and AOA, the vortex burst point will move forward with decreasing leading edge sweep angle. As a result, the windward side vortex burst point will move toward the apex and the leeward burst point will move aft.

The vortices are a very useful and controllable source of lift through a large range of AOA, approximately 10° to 30°. Vortex lift provides significant maneuverability at high AOA to high performance fighter aircraft. However, these coherent, high energy, lift-producing vortices eventually undergo a breakdown called "bursting".



• Figure 19. Vortex burst modes on a yawed delta wing

The understanding of vortex burst dynamics and their behavior is of paramount importance to the designer of high performance military aircraft. Unfortunately, the burst process is highly nonlinear and no theoretical or analytical method currently exists for accurately predicting vortex breakdown on wings. Several empirical methods exist based on experimental data but none are generalized enough to accurately predict breakdown over an arbitrary design. The purpose of the delta wing experiment is to study and visualize these leading edge vortices, their behavior, dynamics and bursting through visualization.

Procedure

Follow these steps to determine the variation of dynamic pressure with velocity:

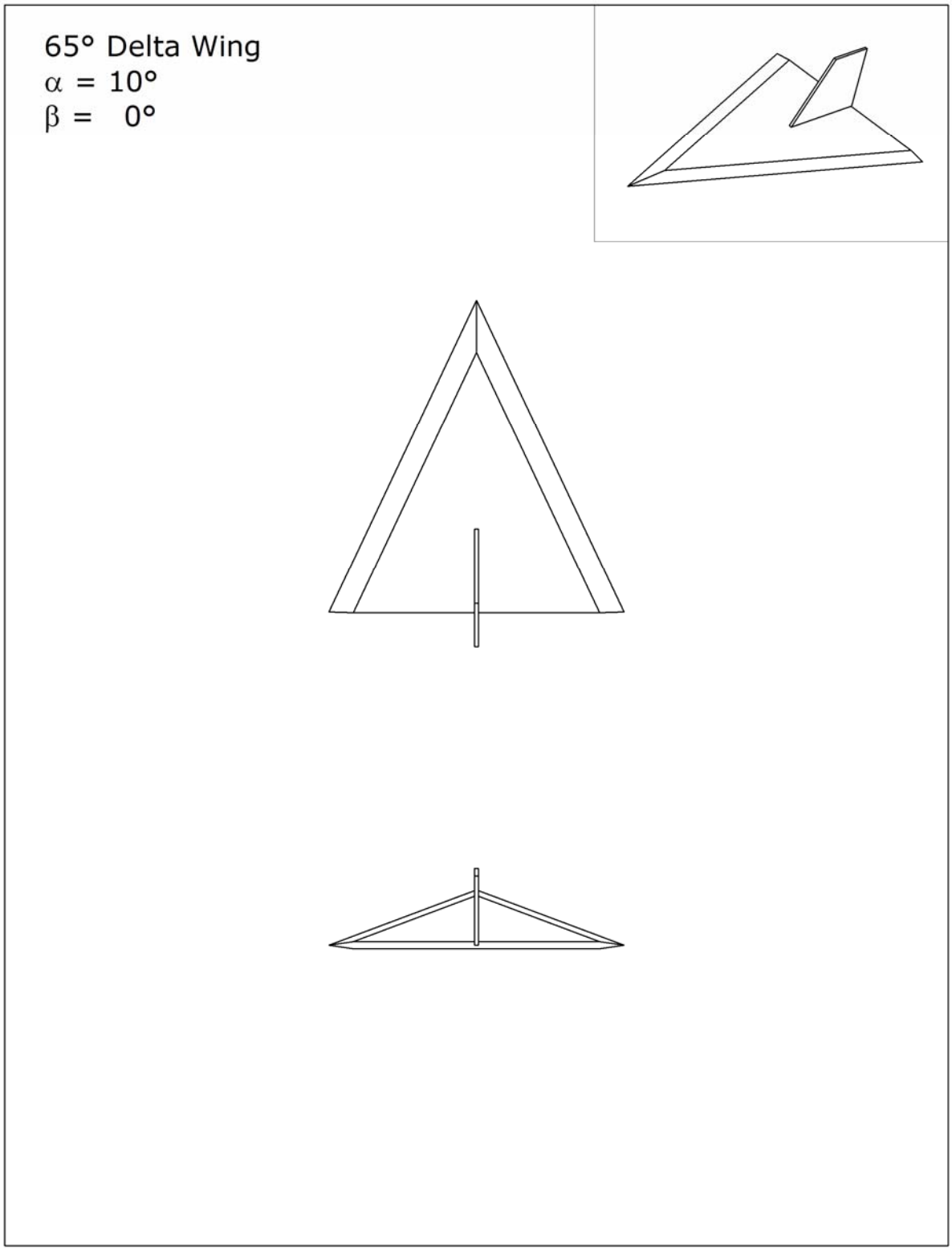
1) Form up into teams of two to four. Read through the questions at the end so you are prepared to explore the answers.
2) Follow the instructions and precautions of the technician in operating the water tunnel and positioning the model. Start the tunnel circulation pump.
3) Position the model at zero sideslip (yaw angle) and 10° AOA.
4) Make sure the air reservoir for the dye injection system is adequately pressurized and gradually open the dye lines until you see thin filaments of dye issuing out of the ports on the model surface. Sketch the flow patterns traced out by the dye streaks. Use the template drawings provided on pages 49-52. Pay particular attention to the symmetry and dimension of the vortices with respect to the model. Indicate the flow direction with arrows on your streamlines. Indicate the location of the vortex burst point.
5) Position the model to 20° AOA and repeat step 4).
6) Position the model to 30° AOA and repeat step 4).
7) Now position the model at a 10° sideslip angle and a 20° AOA and repeat step 4).

Deliverables

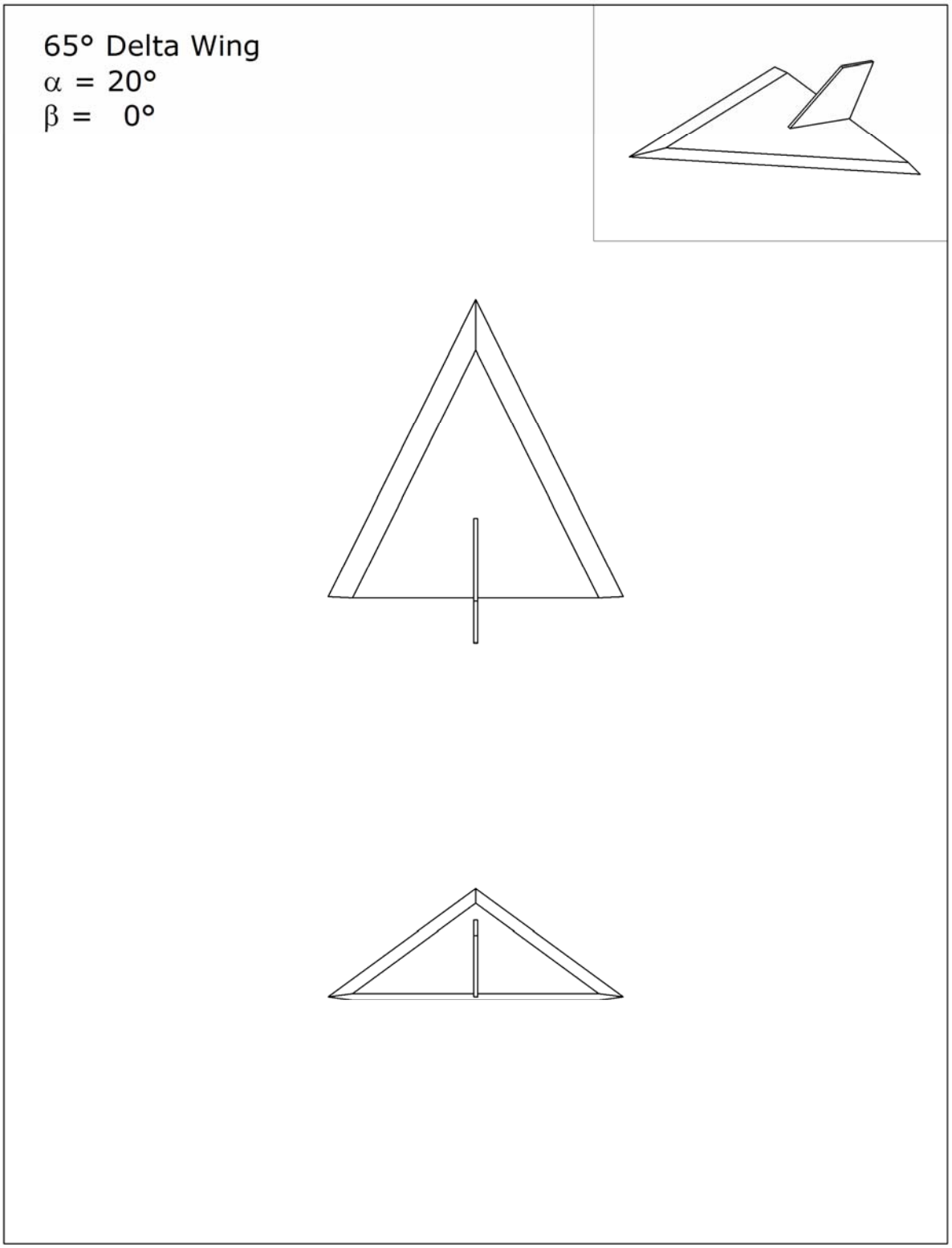
Although no formal write-up section is required for this laboratory exercise, you must hand in your annotated flowfield sketches and the answers to the following questions:

Questions

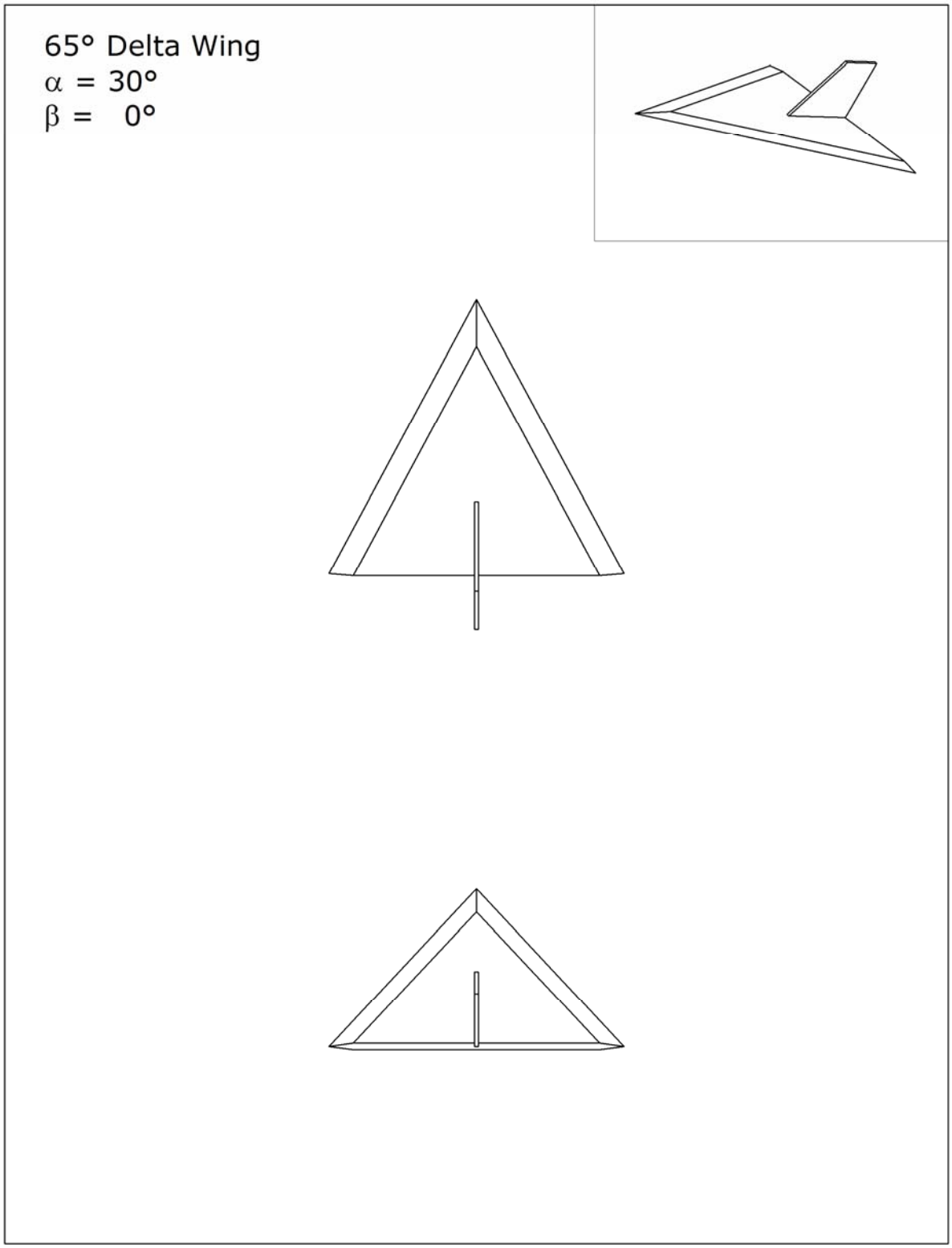
1) Under what conditions can water flow accurately model air flow?
2) What type of motion do the streamlines trace out?
3) If the delta wing is at an angle of attack, what must the wing be producing?
4) The motion of the streamlines, combined with the fact of question 3), is physical evidence of what conceptual aerodynamic phenomenon?
5) Does the wing stall? Explain. How is “stall” manifest in the streamlines?
6) At “stall,” what happens to the aerodynamic phenomenon from question 4)?
7) How does sideslip affect the streamlines?
8) What effect do the vortices have on the wake behind the delta wing at high AOA?



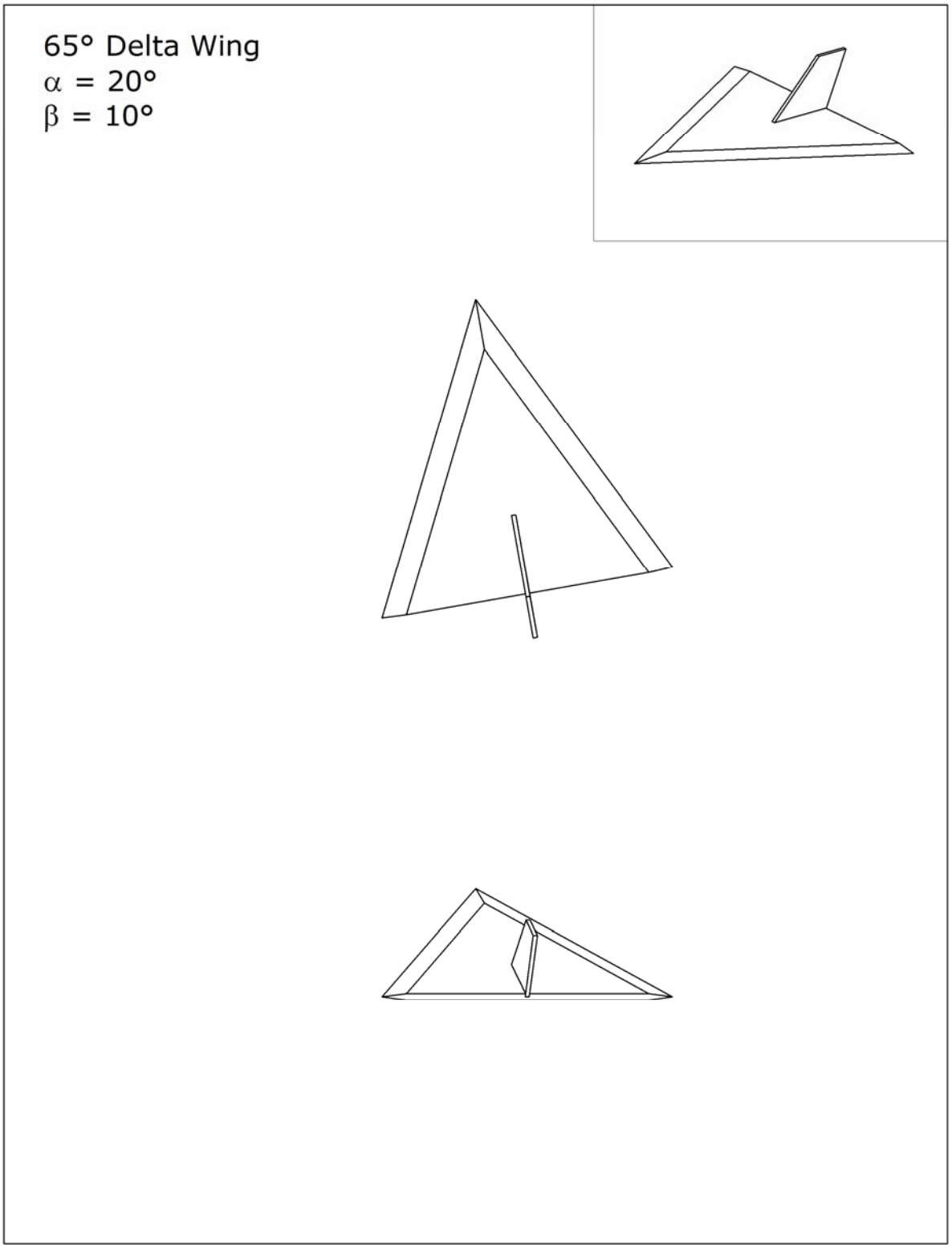
• Figure 20. Streamline patterns for a delta wing at 10° AOA



• Figure 21. Streamline patterns for a delta wing at 20° AOA



• Figure 22. Streamline patterns for a delta wing at 30° AOA



• Figure 23. Streamline patterns for a delta wing at 20° AOA and 10° yaw