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The Determination of the Topological Structure of Skin Friction Lines on a Rectangular Wing-Body Combination

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The Determination of the Topological Structure of Skin Friction Lines on a Rectangular Wing-Body Combination

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Abstract

A short tutorial in the application of topological ideas to the interpretation of oil flow patterns is presented. Topological concepts such as critical points, phase portraits, topological stability, and indexing are discussed. These concepts are used in an ordered procedure to construct phase portraits of skin friction lines from oil flow patterns for a wing-body combination at two angles-of-attack. The relationship between the skin friction phase portrait and planar cuts of the velocity field is also discussed .

Introduction

The determination of the topology of skin friction or limiting flow lines can facilitate the interpretation and discussion of separated flows. The report "Topology of Two-Dimensional and Three-Dimensional Separated Flows" by Tobak and Peake provides an extensive treatment of the practical applications of topology to separated flows (Reference 1). This report augments the Tobak and Peake report and provides a step by step procedure for determining skin friction lines from oil flow photographs. Futhermore, a relationship between the skin friction lines and two-dimensional calculations is discussed.

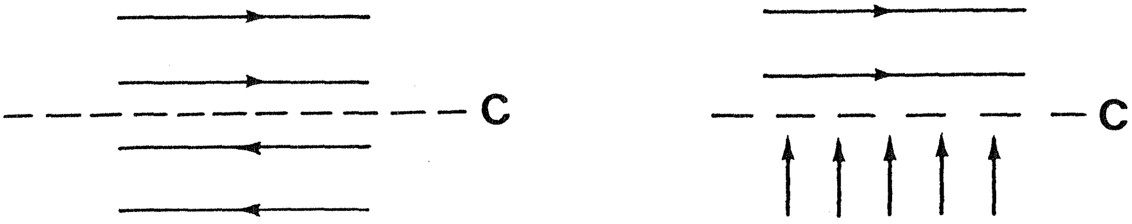
Rules for Construction of the Phase Portrait

The skin friction, (τ_x, τ_y), defines a continuous vector field upon a body's surface. Curves which are everywhere tangent to the skin friction vectors are called skin friction lines and satisfy the equation

$$\frac{dy}{dx} = \frac{\tau_y}{\tau_x}.$$

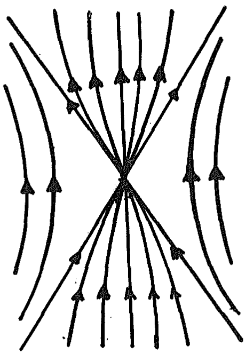
At any point (x,y) on the surface where the magnitude of the skin friction is nonzero, the slope of the skin friction line is uniquely determined, and only one line passes through (x, y). If $\tau_x = \tau_y = 0$ at a point (x_o, y_o), the slope of the skin friction line is undefined at (x_o, y_o), and more than one skin friction line may pass through (x_o, y_o). A point at which $\tau_x = \tau_y = 0$ is called a critical point; a curve upon which $\tau_x = \tau_y = 0$ is a critical line. Lighthill (Reference 2) provides a clear and extensive treatment of continuous vector fields and critical points.

In determining the topological structure of skin friction lines on any three-dimensional body, care must be taken to insure the continuity of the vector field constructed from the skin friction lines and to insure the structural stability of the phase portrait (pattern of skin friction lines). For the vector field to be continuous, structures such as the following

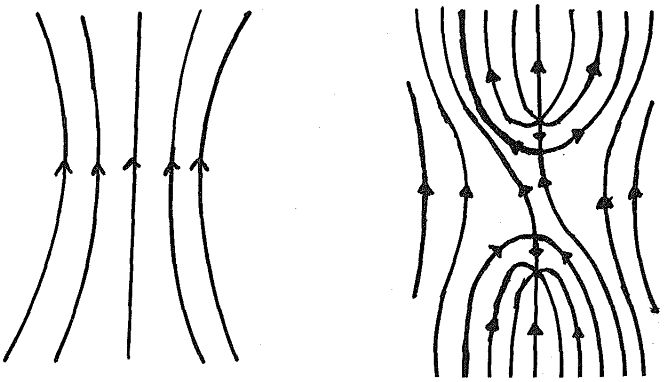


must be ruled out unless *C* is a critical line.

A phase portrait is structurally unstable if small perturbations in the flow parameters produce structural changes in the phase portrait. A structural change occurs when the initial pattern of skin friction lines cannot be continuously mapped onto the pattern of skin friction lines for the perturbed state. In other words, if the initial skin friction lines are represented by rubber bands, these bands cannot be stretched or deformed in any manner to give the pattern of the perturbed state. The perturbed state can only be obtained from the initial state by cutting and re-gluing some of the bands. For example, consider the nonsimple critical point illustrated below. Small perturbations in flow parameters can change this pattern of skin friction lines to a pattern in which no critical points occur or to a pattern which has two nodes and two saddles.

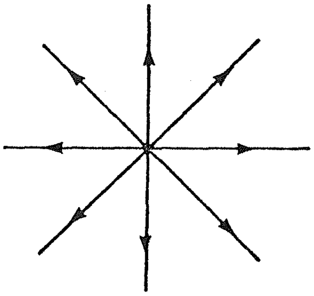


nonsimple critical point

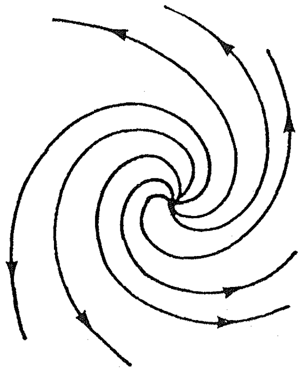


stable patterns

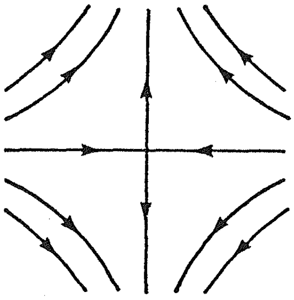
Phase portraits with only simple critical points (nodes, spiral nodes, and saddle points) and no saddle-saddle connections are structurally stable. The types of simple critical points are illustrated below.



node



spiral node
(focus)



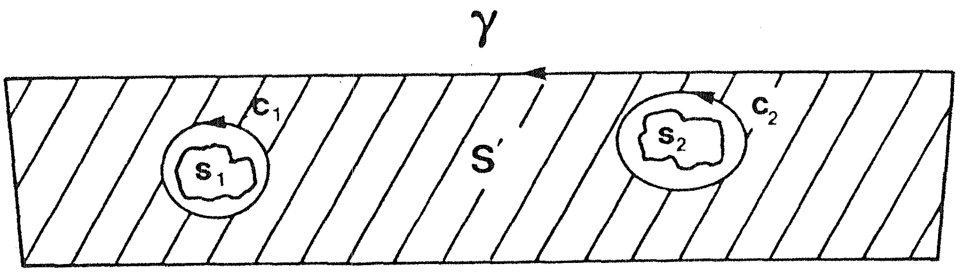
saddle point

Once the continuous vector field has been constructed from the skin friction lines and the critical points have been identified, the topological rules for three-dimensional bodies can be used to verify the results. For a simply connected body, the rule is

$$\Sigma N - \Sigma S = 2,$$

where ΣN is the number of nodes and ΣS is the number of saddles. This rule must be applied to the entire surface of the body. Since only a portion of the vector field is usually available from flow visualization studies, it is often not possible to use this rule.

A second method which can be used for verification of the pattern of skin friction lines is indexing. Let the region



S bounded by the curve γ be the area of interest. As γ is traversed in the counterclockwise direction, the angle which the vector field makes with respect to a fixed vector varies. The index I is given by

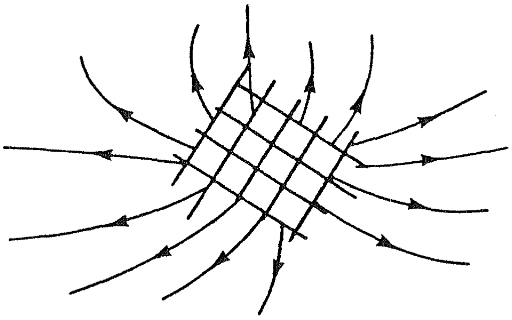
$$I = \Delta/2\pi,$$

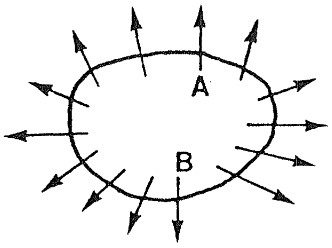
where Δ is the total change in the angle. The topological rule for the region S becomes

$$\Sigma N - \Sigma S = I.$$

If there are regions $S_1, ..., S_n$ contained in S for which the vector field cannot be determined because the flow is weak or time varying, it is possible to remove these regions as follows. A curve C_i is drawn such that S_i is entirely contained within C_i and the vector field is defined at every point on C_i. An index I_i can be determined for the region enclosed by C_i.

As an example of the indexing procedure, consider the following representation of the crosshatched areas in Figure 1f.





At each point on the closed curve drawn about the crosshatched area, the direction of the skin friction lines is known. As the curve is traversed in a counterclockwise direction from A to B, the angle which the skin friction line makes with respect to the vector at A changes continuously from 0 to π. From B to A, this angle changes continuously from π to 2π. The total change is 2π, and the index for this region is 1.

Once the index I and indices I_i have been determined for S and the S_i, the topological rule governing the number of nodes and saddles in the region S' which excludes the S_i is given by

$$\Sigma N - \Sigma S = I - \Sigma I_i.$$

This rule can then be used to check the topological interpretation of the skin friction lines when only a portion of the skin friction field is available.

Step by Step Procedure for the Construction of a Phase Portrait

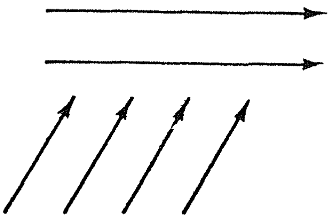
In this section, the procedure for constructing phase portraits of skin friction lines on a rectangular wing-body combination is demonstrated. The oil flow photographs which define the skin friction lines were obtained from a series of experiments conducted by S. Kjelgaard and W. L. Sellers at NASA Langley Research Center. In their tests, Kjelgaard and Sellers used a wing with an aspect ratio of 7.0. The wind tunnel dynamic pressures ranged from 10.5 and 21.5 psf, and the angle of attack ranged from 6° to 22°. In Figure 1, the step-by-step construction of the skin friction phase portrait from the oil flow pattern for the wing-body combination is shown. Figure 1a presents the oil flow pattern for the wing-body configuration at an angle-of-attack of 20°.

Step 1 (Figure 1b). We begin with a region which the direction of the flow is known. For this example, we are confident that the flow at the trailing edge in the region shaded with the fine dot pattern is in the reverse direction. The skin friction lines are shown in this region with their direction defined by the direction of the flow near the wing surface.

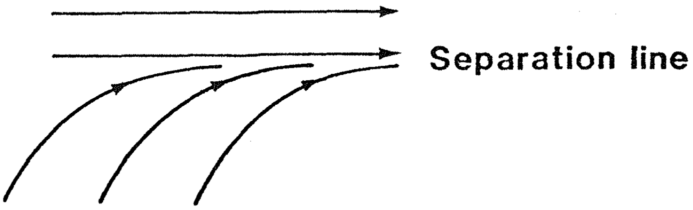
Step 2. The vector fields for the wing tip regions are determined in Figure 1c. Since our aim is to construct a continuous vector field with no structural instabilities and hence, no critical lines, the directions of the skin friction lines in the regions shaded by the medium dot pattern are automatically defined by the adjacent fine dot patterned region. Note that in the wing tip region, there appear to be lines of attachment which feed the wing tip vortices.

Step 3. The vector field for the center of the wing is determined in Figure 1d. Again, the directions of the skin friction lines in the region shaded by the coarse dot pattern are automatically defined by those in the adjacent fine dot pattern regions. Even though two separate fine dot pattern regions are connected through the coarse dot pattern region, no discontinuities or critical lines occurred in this construction. If they had, it would have been necessary to reconsider the assumptions of step 1.

Step 4. The vector fields for the regions near the leading edge are determined in Figure 1e. These regions are shaded with slash pattern. At the junction of the fine dot patterned regions and slash patterned regions on the left wing, the skin friction lines behave as follows:



If the skin friction lines in the fine dot pattern region connect with those in the slash patterned region at a finite angle, there is either a discontinuity in the vector field or a structural instability. Presumably, the skin friction lines in the fine dot patterned regions asymptotically approach a separation line which is parallel to the skin friction lines in the slash patterned region:

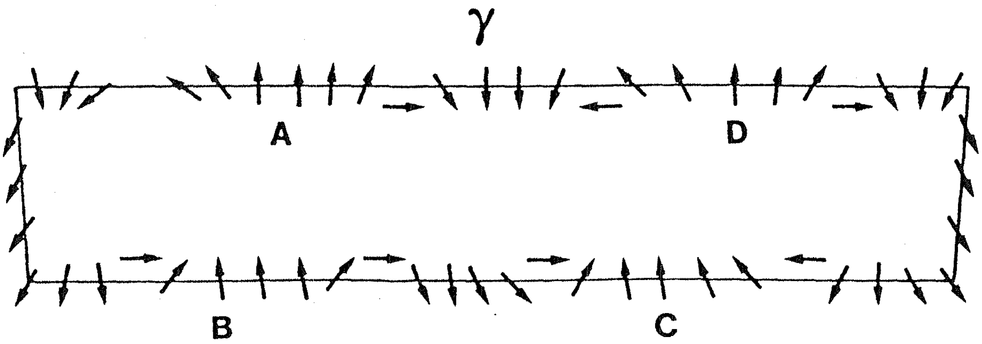


The resolution of the oil is not fine enough to observe this behavior.

In the forward section of the wing, there are areas in which the skin friction lines are not well defined by the oil. These will be indexed out.

Step 5 (Figure 1f). In the final step the nodes, spiral nodes, and saddle points are identified. Nodes and spiral nodes are points where many skin friction lines converge. Saddle points are points which are avoided by the skin friction lines and demonstrate the behavior illustrated previously. Both crosshatched areas have an index of 1. These areas behave as nodes of attachment and have been identified as such.

To check the above results, a curve, γ, is drawn just inside the wing edge. This curve avoids all critical points since the direction of the vector field is not defined at a critical point. The index of the region interior to the curve γ is found as follows.



In the above representation of the curve γ and the skin friction vectors along γ, points A, B, C, and D on γ were chosen so that the skin friction vectors at these points would be aligned. From A to B, the change in the angle which the skin friction makes with respect to the vector at A is 2π. From B to C, the skin friction at first goes through an angle change of $-\pi$ and then change of π. Hence, the total change in angle is 0. From C to D and D to A, the change in the angle is 2π. Therefore, traversing γ in a counterclockwise direction gives a total change of 6π and an index of 3. The topological rule for the region interior to γ is

$$\Sigma N - \Sigma S = 3.$$

In Figure 1f, the number of nodes inside γ is 6, the number of saddle points is 3, and the topological rule is satisfied.

A topological evaluation of the same wing-body combination at $\alpha = 16^\circ$ is included in Figure 2. In this case, either the reversed flow region (shaded with fine dots) on the left hand side or the attached flow region on the right hand side (shaded with a slash pattern) could have been used for the beginning step. The reversed flow region was chosen so that the step by step procedure outlined above could be followed.

Comparison to Two Dimensional Calculations

If the three-dimensional flow field about the rectangular wing-body combination is known, the phase portrait of the velocity components in any plane cutting through the wing can be constructed in a manner similar to that used for skin friction lines. Since this plane contains a wing cross section and only in-plane velocity components, half nodes,N', and half saddles,S', may appear at the wing boundary, and saddle point to saddle point connections are allowed. The topological rule which must be satisified by this portrait is

$$\Sigma N + \frac{1}{2}\Sigma N' - \Sigma S - \frac{1}{2}\Sigma S' = -1.$$

Although the full three-dimensional flow field is not available from oil flow photographs, the direction of the flow near the wing surface can be determined from the skin friction lines. In a plane cutting through the wing at line D in Figure 1, the skin friction lines indicate that near the wing the in-plane velocity components are in the upstream direction at the leading and trailing edges. There is a small region in which the velocity components are in the

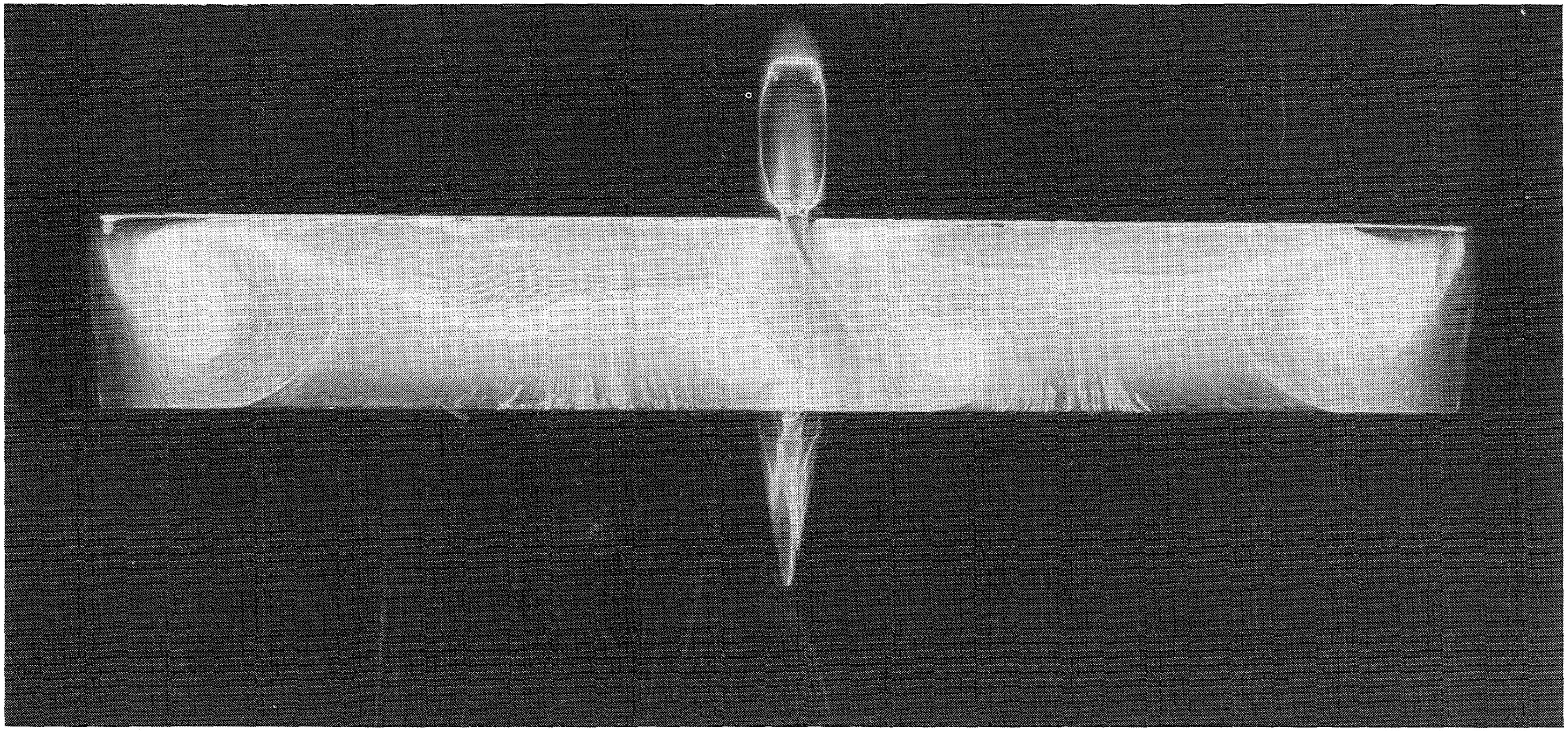


Figure 1a. Oil flow on rectangular wing at $\alpha = 20°$.

$q = 21.5$ psf, $t = 13:00$

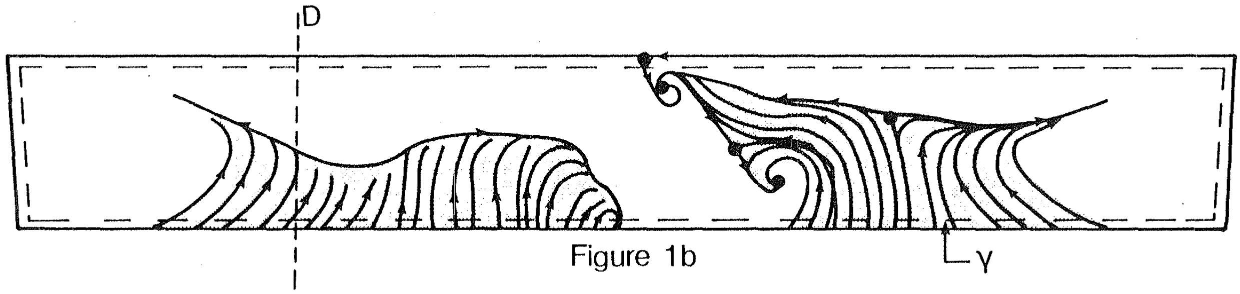


Figure 1b

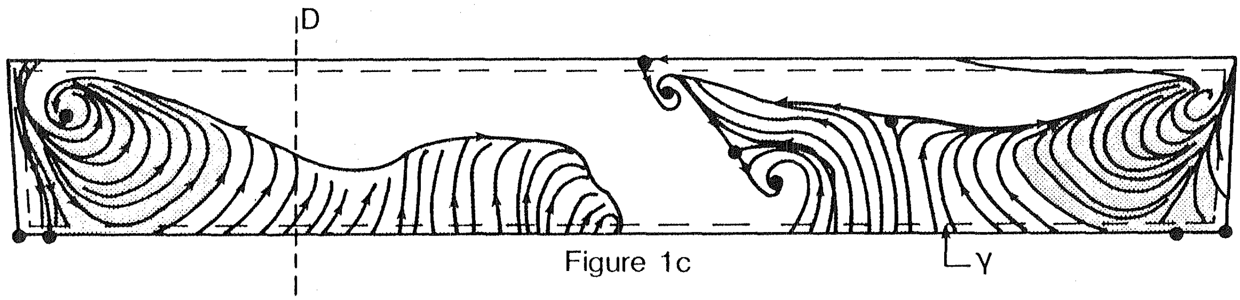


Figure 1c

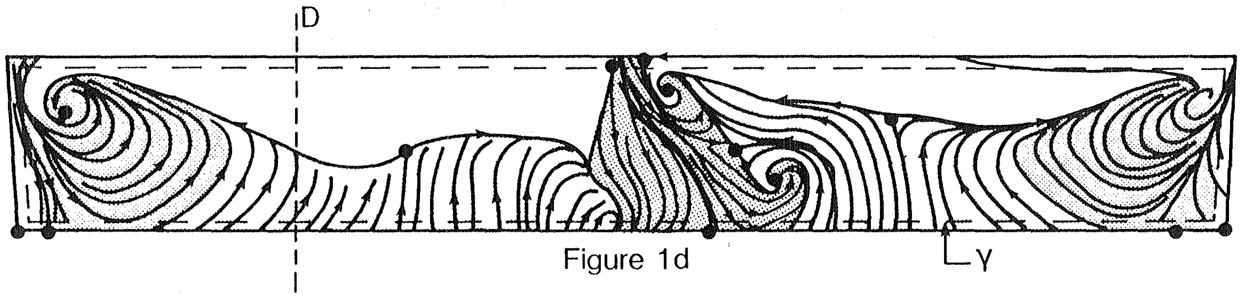


Figure 1d

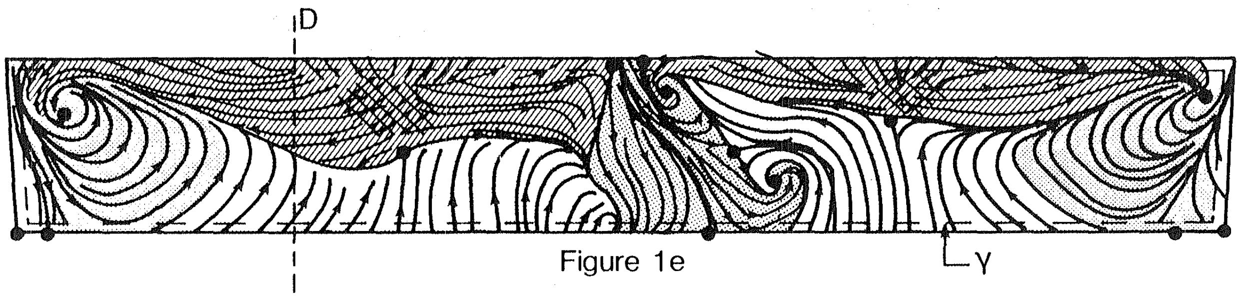


Figure 1e

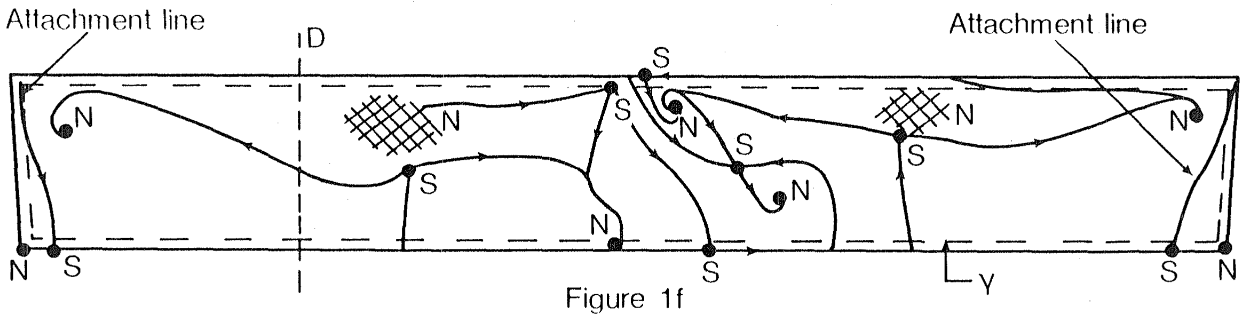


Figure 1f

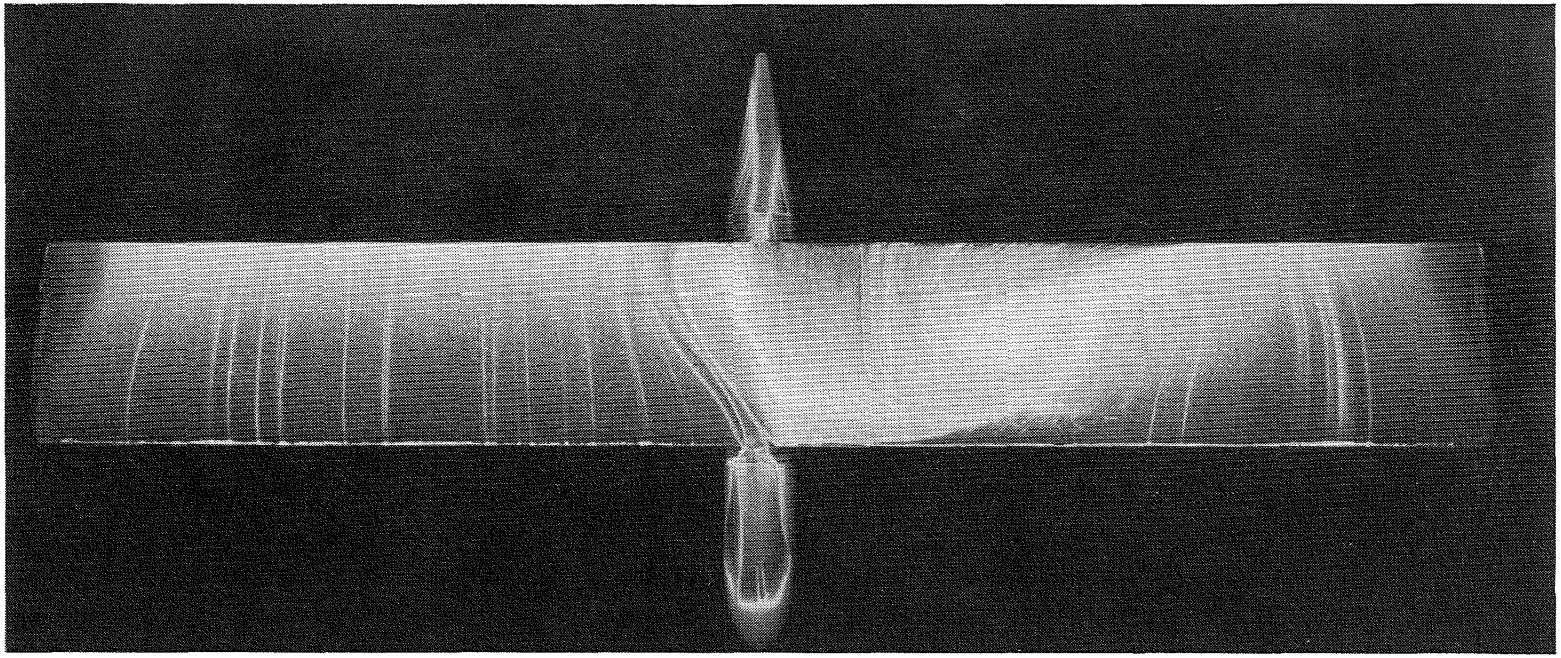


Figure 2a. Oil flow on a rectangular wing at $\alpha = 16°$.

$q = 21.5$ psf, $t = 20:59$

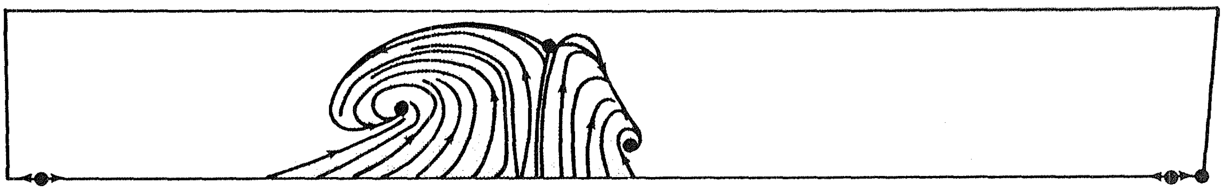


Figure 2b

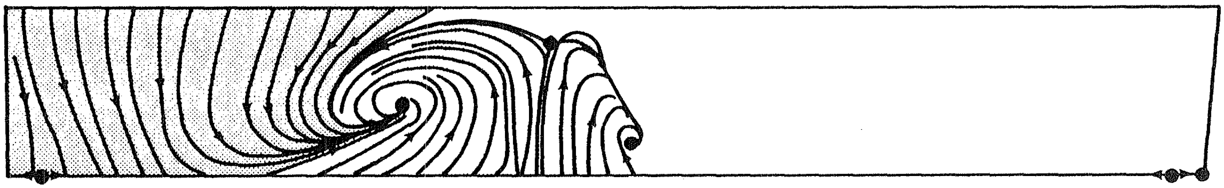
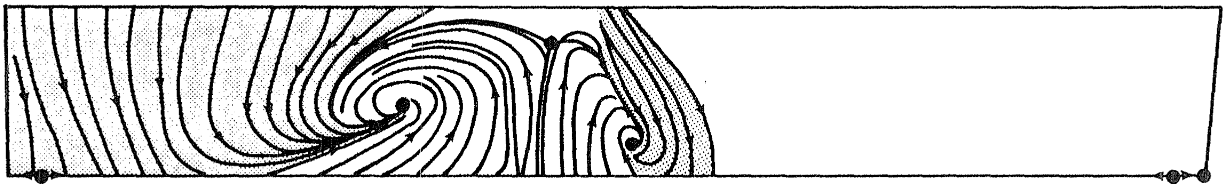


Figure 2c



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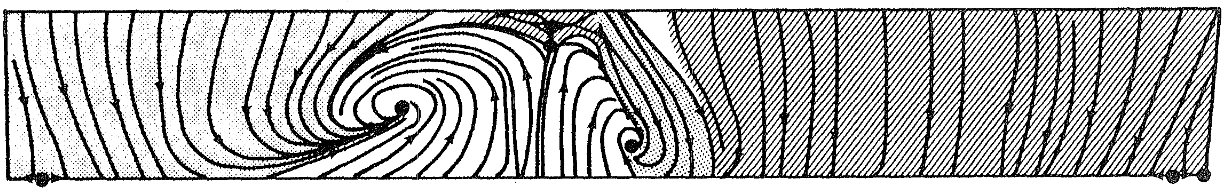


Figure 2e

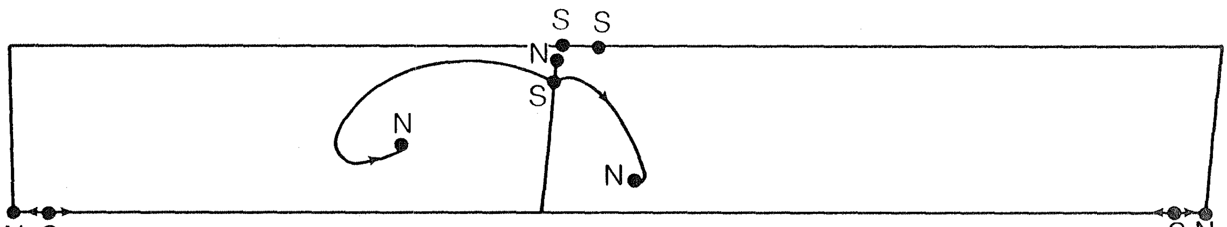


Figure 2f

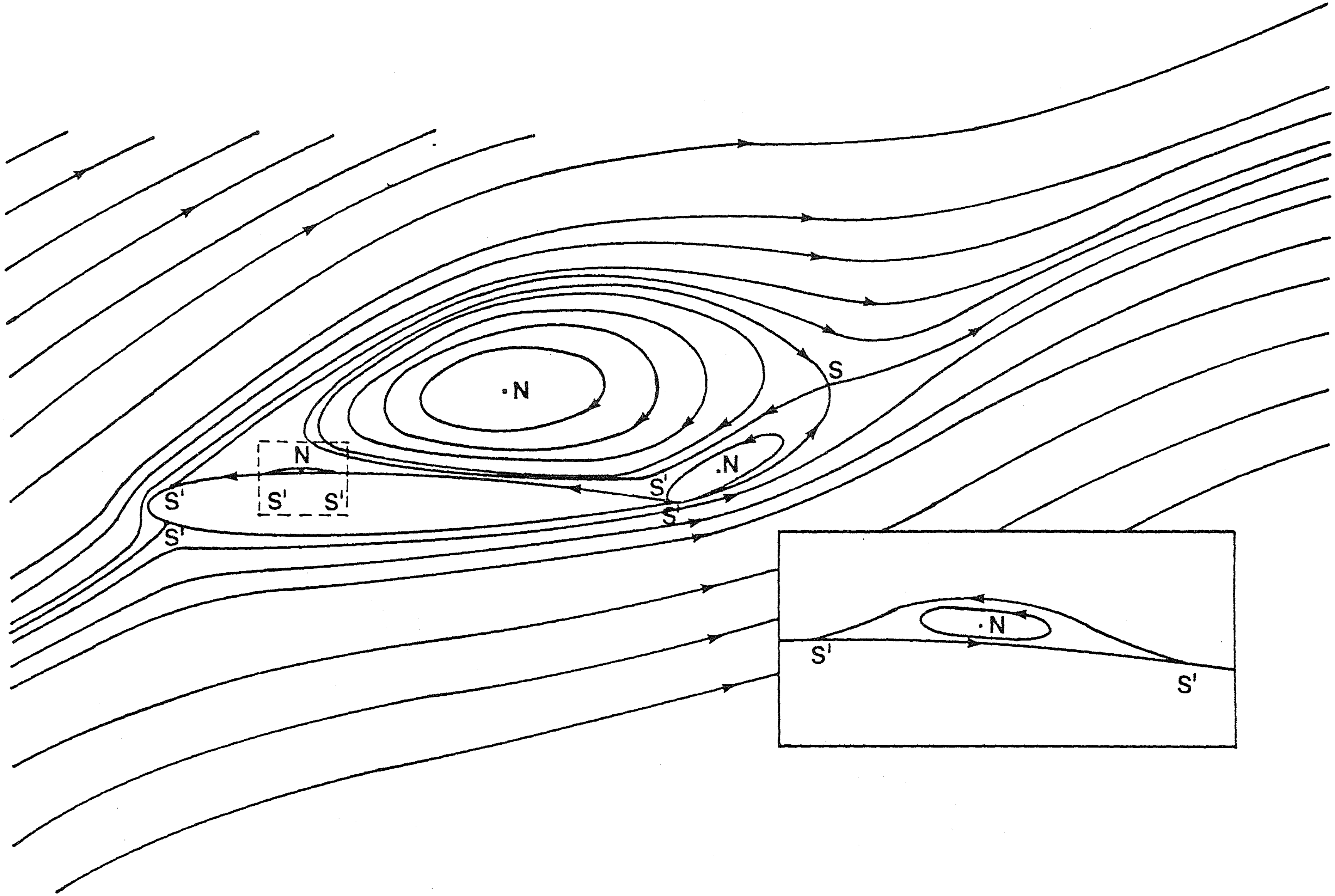
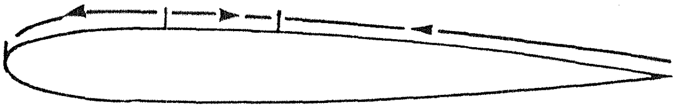


Figure 3. Phase portrait for the velocity field calculated by a two dimensional thin layer Navier-Stokes code.



downstream direction.

In two-dimensional calculations by Anderson, Thomas, and Rumsey (Reference 3) using thin layer Navier-Stokes equations for a NACA 0012 wing at $\alpha = 18°$, the flow has a large recirculation region. Unpublished data from Rumsey of NASA-Langley Research Center indicate a small bubble at $x = 0.3c$ within this recirculation region. Figure 3 shows the phase portrait for the two-dimensional solution which used the maximum number of iterations allowed in Reference 3. This phase portrait satisfies the topological rule stated above for a plane cutting through a three-dimensional body.

Near the airfoil surface, the two-dimensional flow at the leading and trailing edges is in the upstream direction. In the bubble, the flow is in the downstream direction. This agrees qualitatively with the behavior observed along the line D in Figure 1.

It should be noted that the skin friction lines indicate that there may be a large component of the velocity which is parallel to the leading edge. This component and its effects are not included in the two dimensional model. As a result, planes which cut through other sections of the wing need not give flows near the surface similar to that of the two dimensional calculation.

CONCLUSIONS

The use of topological ideas aids in the interpretation of the flow about three-dimensional bodies. For the rectangular wing-body combination studied, this approach readily identified a reverse flow region at the leading edge and the locations of flow separation and attachment. Comparison of the flow direction at the wing's surface determined from the skin friction lines and a two dimensional thin-layer Navier-Stokes code showed favorable agreement for certain regions of the wing.

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3. Anderson, W. K., Thomas, J. L., Rumsey, C. L.: *Application of Thin Layer Navier-Stokes Equations near Maximum Lift,* AIAA Paper 84-0049, 1984.

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