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BACKGROUND AND THEORETICAL CONSIDERATIONS FOR
UTILIZING WATER TUNNEL FLOW VISUALIZATION

A Thesis

Presented for the

Master of Science

Degree

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David Martin McDaniels

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ABSTRACT

The water tunnel is a valuable tool for education, basic research and aerodynamic design. This work addresses the topic of water tunnel flow visualization as a design tool.

The foremost advantage of the water tunnel is the ease with which the flow field can be made visible. Testing is quick and inexpensive. The water tunnel also has some inherent difficulties, which can be grouped into the categories of Intrusion, Streakline Interpretation and Dynamic Similarity. These three topics were investigated with the intention of educating potential water tunnel users about its associated problems so that future investigations can proceed in an intelligent and realistic manner.

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LIST OF SYMBOLS

a	angle of attack
b	sweep angle
c	wave speed
d	diameter
h	height
p	pressure
r	radius
t	time
u	longitudinal velocity
x, y, z	cartesian coordinates
L	cross-sectional size of vortex structure
M	Mach number
Q	volume flow
R	Reynolds number for tube flow
V	velocity
a_1, a_2	wave amplitudes
P_∞	free stream pressure
q_∞	free stream dynamic pressure
r_t	radius of swirl tube
C_{ps}	pressure coefficient at separation point
G_s	circulation parameter
M_∞	free stream Mach number
R_o	reference radius
Re	Reynolds number

R_L	Reynolds number based on length
V_O	free stream velocity
V_A	vortex axial velocity
V_H	horizontal velocity
V_V	vertical velocity
α^*	angle of attack in equivalence plane
u'	perturbation velocity
α	wave number
γ	vortex core angle
ϵ	wing apex angle
ν	kinematic viscosity
Λ_{LE}	sweep angle
Ω	circulation parameter

I. INTRODUCTION

Background

The classic experiments of O. Reynolds (1883) served not only to foster an understanding of transition but also to establish the water tunnel as a valuable source of fluid dynamic information. The ability to visualize a phenomenon has proven to be a large step toward understanding it and developing or validating its theoretical explanation. Since 1883, many important investigations have been done using the water tunnel: Prandtl used it to conceptualize the boundary layer and explain the starting vortex, Knapp and Roache observed that transition occurs in stages, and Emmons discovered turbulent spots [Collins, 1982]. The list of water tunnel investigations continues to the present, with numerous accomplishments.

As well as being a boon to basic research, water tunnel flow visualization is a useful aerodynamic design tool. Its real usefulness, in this respect, is the ease with which the flow can be made visible. Using the water tunnel as a design tool, an engineer can make an inexpensive model and visually observe how it interacts with the flow field. Upon identification of a problem, the model can be easily and quickly modified and reevaluated in the water tunnel.

The process of flow visualization involves the injection into the flow of some sort of tracer material - usually dye. This dye, if chosen to be neutrally buoyant and injected with the same velocity of the surrounding water, will make visible a streakline of the modelled flow field. Ideally, the observation of key streaklines can give the investigator some understanding of the flow field in question.

The type of flow which is of interest to the designer typically consists of an aerodynamic configuration immersed in a steady free-stream flow. These flows often include instabilities, separations and imbedded vortices - all of which become visible to the observer with the aid of flow visualization. Although the freestream flow is steady, instabilities can cause unsteadiness in the resulting flows. In order to study these flows analytically the full unsteady equations of motion must be used. If one were to study a basically unsteady flow, such as an oscillating cylinder, added mass effects would have to be taken into consideration.

Problem Statement

In addition to the benefits mentioned in the previous section, modelling an air flow in the wind tunnel involves some difficulties that must be understood and allowed for in order to obtain the most useful results. These problems generally fall into one of three categories:

- 1) Intrusion (dye, probe or support)
- 2) Streakline Interpretation
- 3) Dynamic Similarity

Intrusion. These are the most obvious of the problems that must be addressed. They all stem from the fact that something must be physically placed in the flow field that is not present in the full scale situation. Dye probes cause disturbances upstream of the model. Model supports cause aberrations in the pressure field. Even the

presence of the dye, if its density differs appreciably from that of water, can alter the appearance of the flow field.

Streakline interpretation. The interpretation and evaluation of streaklines deserves considerable attention by the water tunnel user. Fluid dynamics, as taught in most engineering schools, makes use of Euler's streamlines to theoretically describe a flow field. Unfortunately, except in purely steady flows, the dye streak does not make visible a streamline, even though the mean flow is steady. The line that is made visible by the dye streak is self defined - that is, it is the locus of points connecting all particles that have passed through a given fixed point in space over a given period of time - hence its name, the streakline. If the streakline is interpreted as if it is a streamline, in an unsteady situation, it can lead to erroneous or illusory conclusions, as will be addressed in a later section.

Dynamic similarity. The rules of dynamic similarity ensure that the forces acting on the model and on the full scale aircraft will be of the same ratio and direction. The dominant parameters for aerodynamic model testing are Reynolds number and Mach number. Unfortunately, it is impossible to match these parameters from the water tunnel model to the actual full scale conditions for problems of engineering interest because of the low test speeds and the relatively high viscosity of water (as compared to air). Fortunately, there are many fluid dynamic phenomenon which are known to be relatively insensitive to variation in Reynolds number. It is these that are ideal

for water tunnel investigations. Regrettably, the distinction between this type of flow structure and the type that is sensitive to Reynolds number is not a sharp one. Some may have a weak dependence on Reynolds number. Researchers, to deal with this problem, often will examine the flow anyway with the understanding that the results are strictly qualitative. In most cases, this is a good approximation that will yield useful qualitatively correct information. As will be pointed out in later sections, care must be taken when following this approach, though all too often it is the only one open to the researcher.

Objective

The purpose of this paper is to provide the reader with enough information and understanding of the difficulties to intelligently utilize water tunnel flow visualization for the restricted class of flows previously described.

II. FLOW VISUALIZATION THEORY

Intrusion

As to the physical intrusiveness of flow visualization, the biggest problem comes from the probe used to inject the dye. The probes or tubes used to inject dye are typically cylindrical in shape and generate vortex street disturbances in the flow (as discussed in later sections). These problems are minimized by placing the probe far enough upstream that its effect is not felt near the model or by injecting the dye from ports in the model itself. If the latter is used, the injection pressure must be carefully controlled so as not to add any velocity to the flow perpendicular to the body.

However the dye is injected, it is recommended that the Reynolds number characterizing the dye stream to be kept below a value of 10 where,

$$R = Vd/\nu = 4Q/\pi\nu d,$$

with V the mean velocity through the nozzle, relative to surrounding fluid

d the diameter of the nozzle,

ν the kinematic viscosity of the dye

Q the volume flow through the nozzle.

If this criterion is not met then the dye jet could develop its own instability that could be falsely attributed to the flow [Reynolds, 1962].

One typical dye is made of food coloring mixed with milk.

Chemically, milk is described as a colloidal suspension. This means

that it is a system of particles and fluid (water) that is not a solution and not a precipitate, but something in between the two.

Colloidal particles, while too small to be seen under a typical microscope, are nevertheless large enough to reflect light [Sorum, 1955]. Therefore, a dye/milk combination is less likely to be diffused away and more likely to be seen than plain dye.

It is important that the density of the dye mixture be the same as water so as to eliminate the effects of buoyancy or gravity on the visible streaklines. Practically, the density is easily adjusted by adding a small amount of alcohol (to lessen it) or milk (to increase it). Though less obvious, it is also desirable to choose a dye with viscosity close to that of water in order to correctly model such viscosity linked phenomena as flow separation and vortex generation [Bocheng, et al., 1983].

Obviously, there are many other types of tracer materials available for use including other dyes, particles and bubble techniques. This report will focus on dye injection. Some other liquids that have been used to mark streaklines include diluted rhodorsil, ink, plain dye, carbon tetrachloride-benzine (care must be taken with this as it is now classified carcinogenic) and potassium permagnate [Werle, 1973].

Streakline Interpretation

As mentioned in the Introduction, when an investigator decides to use dye injection as a means of seeing the flow field it must be kept in mind that it is a streakline which is made visible and not a

streamline. For sake of clarity, the definitions of each as stated in Advanced Mechanics of Fluids [Rouse, 1959] are:

Streamline - "a line that is tangent at a given instant to the velocity vector at every point upon it"

Streakline - "a line connecting all particles that have passed successively a given point in space."

In a steady flow it can be seen that these two lines will coincide, but many of the flows of interest to a water tunnel investigator such as three-dimensional flow separation and vortex generation are of an unsteady nature, even though the free stream is steady. Hence, when analyzing a streakline, special care must be taken to remember that it does not show the paths of particles, rather, it shows the locus of all particles passing through a particular point.

The simple case of a single cross-stream vortex being convected downstream offers many illusions to the casual observer, as is pointed out by Dr. Kurosaka in a recent paper [Kurosaka and Sundaram, 1986]. The streaklines that are shown in solid lines in Figure 1 were generated computationally using a potential vortex convected in a uniform flow. The system of differential equations that govern the vortex motion were allowed to vary incrementally in time to determine the location of each particle making up the streakline.

Examining Figure 1, not only does the vortex appear to increase its size but the fluid seems to spiral two-dimensionally ever inward. These impressions could not be farther from the truth. In fact, the vortex strength remains constant and the paths of the individual fluid particles trace out one of three simple trochoidal patterns as shown by the broken lines in Figure 1.

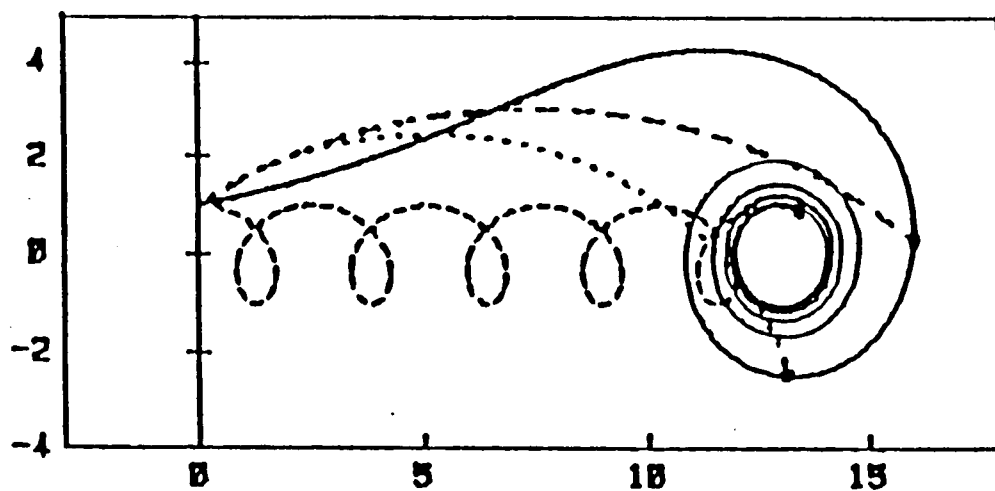


Figure 1. Computed streakline for convected potential vortex. Dashed lines represent three possible pathline forms [Kurosaka and Sundaram, 1986].

Kurosaka also addresses the illusions presented by the streaklines of the classic Karman vortex street of constant strength. The streakline patterns presented in Figures 2 (the top figure only) and 3 were generated similarly using the system of differential equations which governs the generation of the unsteady Karman vortex street. This method, which does not include the effects of viscosity, generates a potential vortex of the correct strength and places it at the proper position in the flow according to the solution of the system of equations. Figure 2 shows a streakline pattern computed by this method [Sundaram, 1986] over a photograph of a water tunnel produced visualization of the vortex street downstream of a circular cylinder [Cornish, 1982] for comparison.

As can be seen in Figure 3(a), the widening of the streakline pattern in the downstream direction suggests an illusory growing of the vortex street. The vortices seem to be extending their influence into the flow and each vortex looks larger than its successor. The truth of the matter is that each potential vortex has an equal extent and an equal influence in the flow. They only appear to grow because as each vortex spends more time in the flow field it has more time to accumulate tracer particles in its influence - the oldest vortex appearing the largest.

In a real fluid flow, with viscous diffusion effects, both the vorticity pattern and the particles that form the streaklines will diffuse outward. This is not so much growth as spreading. The effects of vorticity diffusion will be discussed later in this section with relation to Figure 4. If the effects of diffusion were added

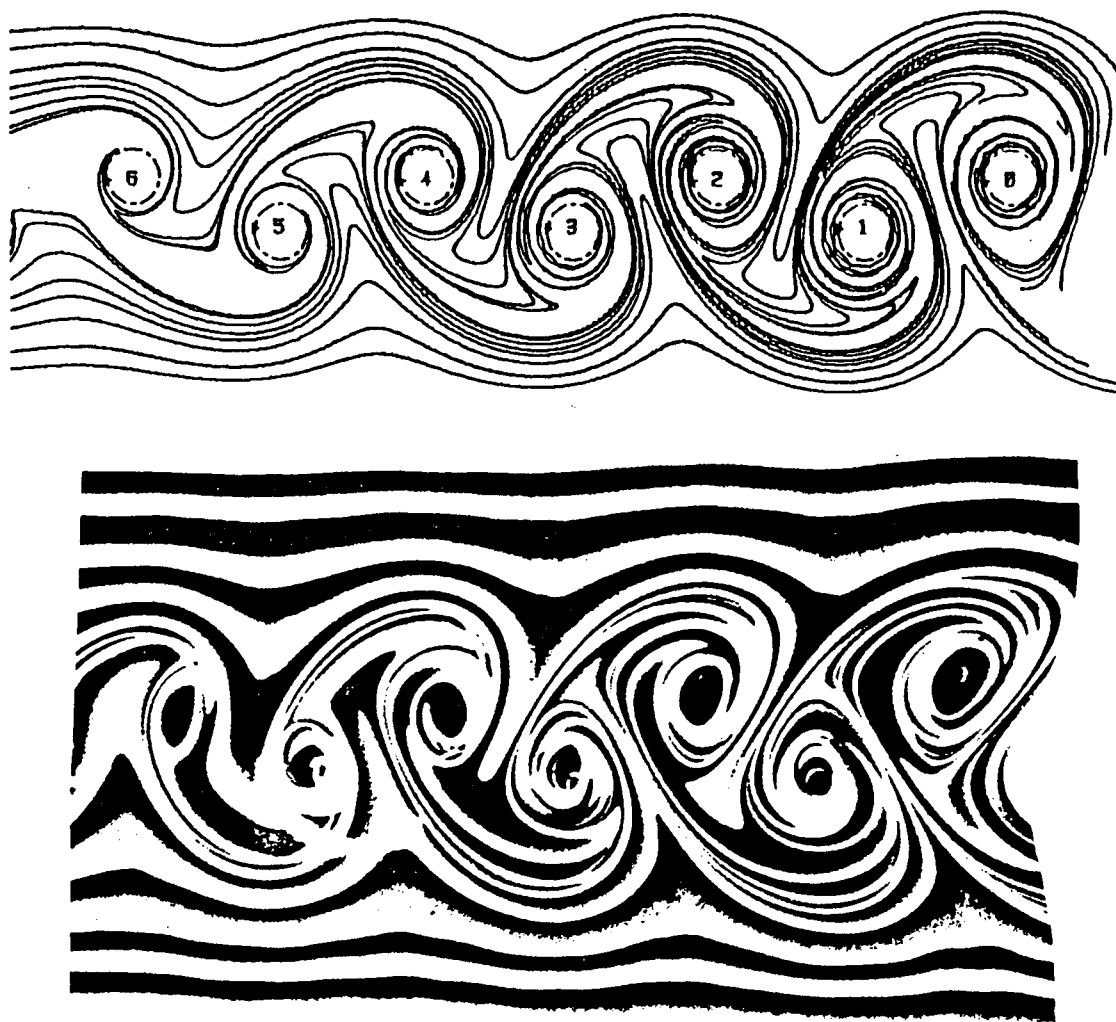


Figure 2. Comparison of computed vortex street pattern to observed pattern. Computed streakline pattern of Karman vortex street at top [Sundaram, 1986] without viscous diffusion effect is very similar to water tunnel visualization [Cornish, 1982].

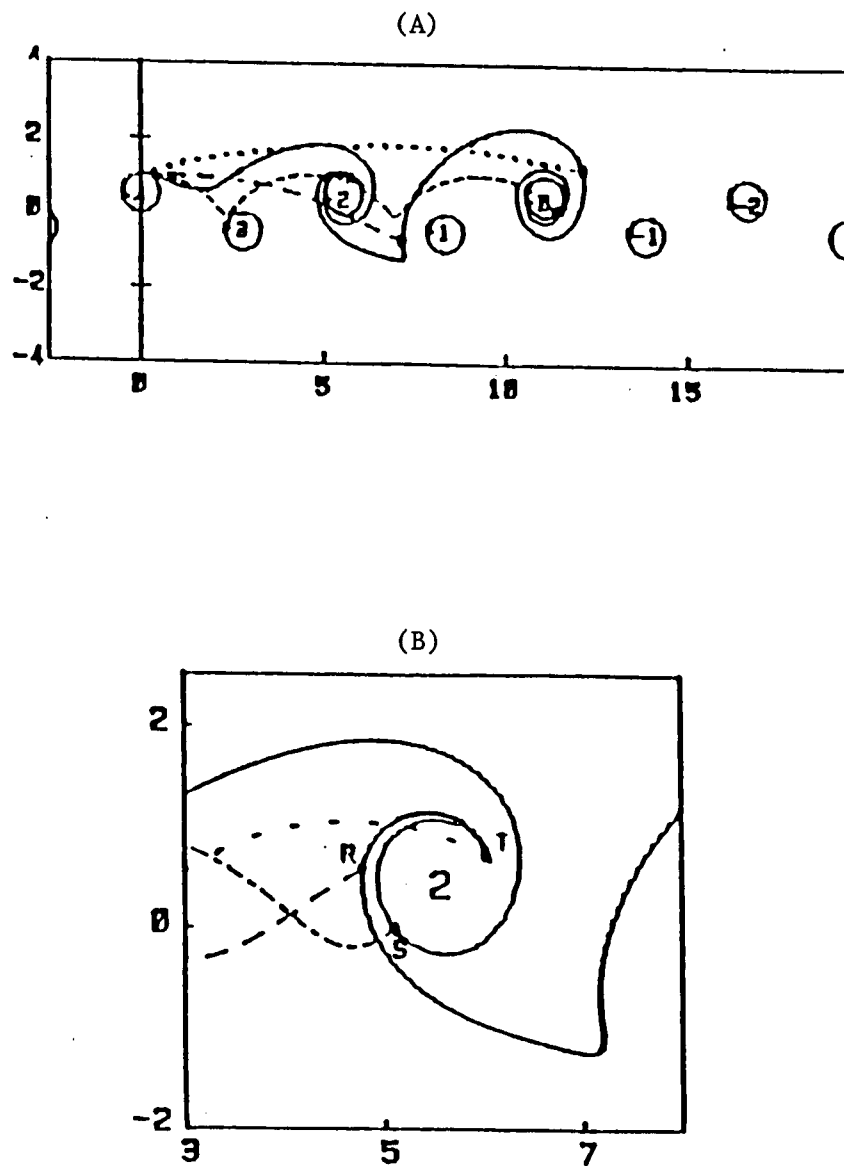


Figure 3. Computed streakline of vortex street showing illusions of growth and turning point. (A) Dashed lines show possible pathline types. (B) Enlargement of turning point region in (A). [Kurosaka and Sundaram, 1986].

into the code that produced Figure 3 the pattern would show some actual spreading, but compared to the illusory growth explained above it would be very slight - especially in the first ten or twenty diameters.

The final illusion discussed in this paper is that of the so-called "turning points". Figure 3(b) shows a close-up of the same instant depicted in Figure 3(a) with the pathlines of three particles shown in broken lines. This streakline structure, if improperly interpreted, might suggest an abrupt reversal of flow direction. To further strengthen that illusion, try sketching that same figure by hand. As you trace the figure starting at the left your pencil point moves backward into the time history of this streakline. Upon reaching point T you will find your stroke must halt and reverse its direction in order to spiral out and away from vortex "2". This motion is misrepresentational of the actual fluid motion that gives rise to this pattern.

Once again, it must be remembered that a streakline in unsteady flow does not show flow direction. The point T in Figure 3(b) in fact shows the location of the particle that was released when the distance between the injection point and the vortex center was a minimum. To further clarify the figure, particle R was released slightly before T and S slightly after.

The vortex street has one final illusion to offer the casual observer, as shown in Figure 4 [Panton, 1984]. This is a series of five photographs of the same smoke wire visualized vortex street. The only difference between the photographs is that the smoke is injected

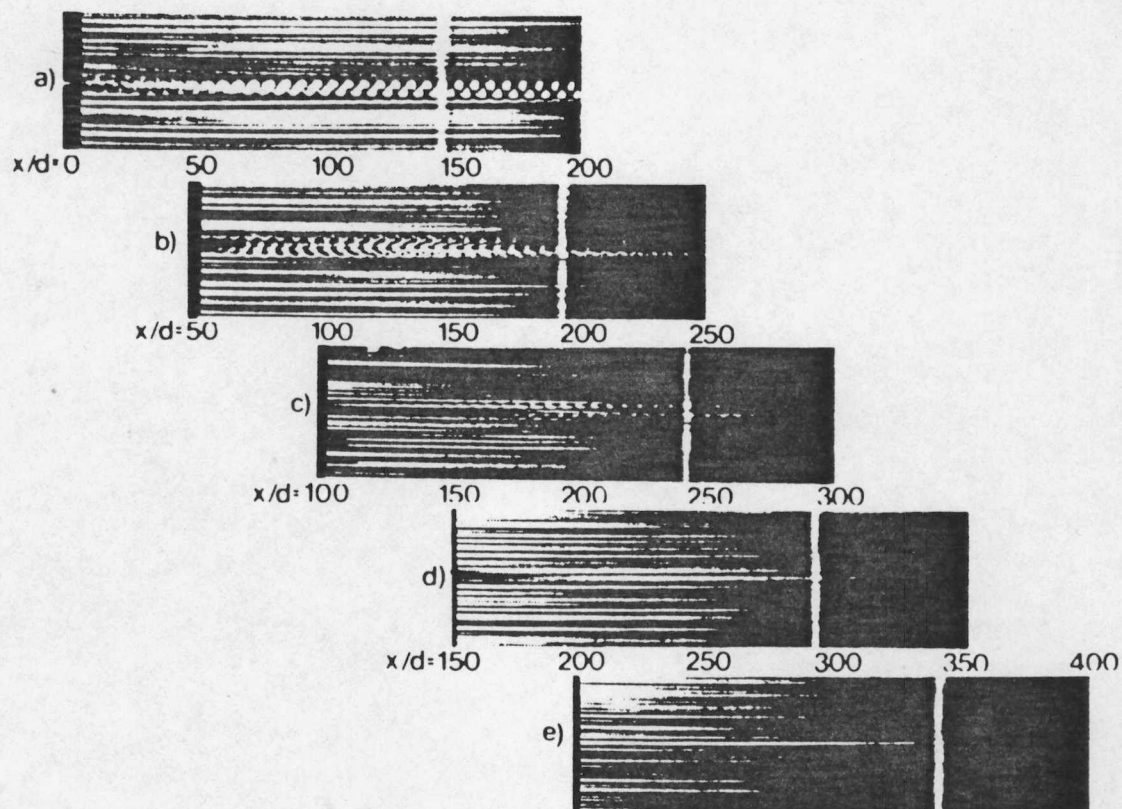


Figure 4. Series of smoke pictures showing illusory nature of vortex street pattern. Each frame shows the wake of a circular cylinder at $Re = 93$ with the smoke wire at different locations [Panton, 1984].

at successively greater downstream distances. Looking at 4(a) the street seems to extend its influence far downstream. This is illusory. When the smoke is introduced 150 or 200 diameters downstream the effect of the street is not seen at all. Once the smoke has been entrained into the street pattern in 4(a) it remains in that pattern well after the vorticity distribution that created it has diffused into nothingness and is simply convected downstream - giving the impression of an extended complex wake where none exists.

It has been said that "one picture is worth a thousand words." This common phrase serves as promotional advertisement for the flow visualization business, but as has been pointed out by the pictures in this section, if the picture is not fully understood it is worth a thousand wrong words.

Up to this point, the illusions created by streaklines which have been discussed have all involved vortex flows. A much more disturbing example is cited in the work of F. R. Hama [Hama, 1962]. The flow field in question consists of a simple shear layer perturbed by a travelling sine wave of constant amplitude. This study, like the previous reference, uses a computational representation of the idealized flow field that does not include the effects of viscosity and has no added vortices. When a series of streaklines are made visible in this flow it appears that the wave is amplified in the critical layer, that is, the layer where the stream and perturbation vortices are equal, to the point where it rolls up into a line of discrete vortices. Appears, in this sentence, is the operative word. It has been shown by Hama, and more recently by Williams and Hama [Williams and Hama,

1980] using more powerful computing methods, that there is in fact no wave amplification and no discrete vortices in this flow field.

The rolling up of the streakline that is traditionally associated with the presence of a vortex (Figure 5) is in this case attributed to the effects of the cat's-eye streamlines (first described by Lord Kelvin). The cat's-eye streamlines are only discernable in the coordinate system that is moving with the mean velocity of the flow. In this system the local mean particle velocity in the critical layer is the same as the wave speed thus causing the cat's-eye streamlines to be stationary with respect to the critical layer. As a result of this phenomena, any particle released in one of these critical layer cat's-eyes will remain trapped there, rolling around the center of the eye and impersonating a vortex.

In conclusion of his 1962 work, Hama offers this broad and fearsome warning to "those, who utilize flow-visualization techniques in one way or another":

"...practically no truth can be obtained from streakline or pathline observations as to the nature of time-dependent phenomena and that images, which one might receive from such observations, can be entirely misleading."

It should be noted that this study as well as the following one, are simple idealized models of complex viscous flows. Since viscosity could not be easily included, its two major effects were included as given - the velocity gradient and the instability wave. The purpose was to "examine the general behavior of streaklines in a perturbed shear flow."

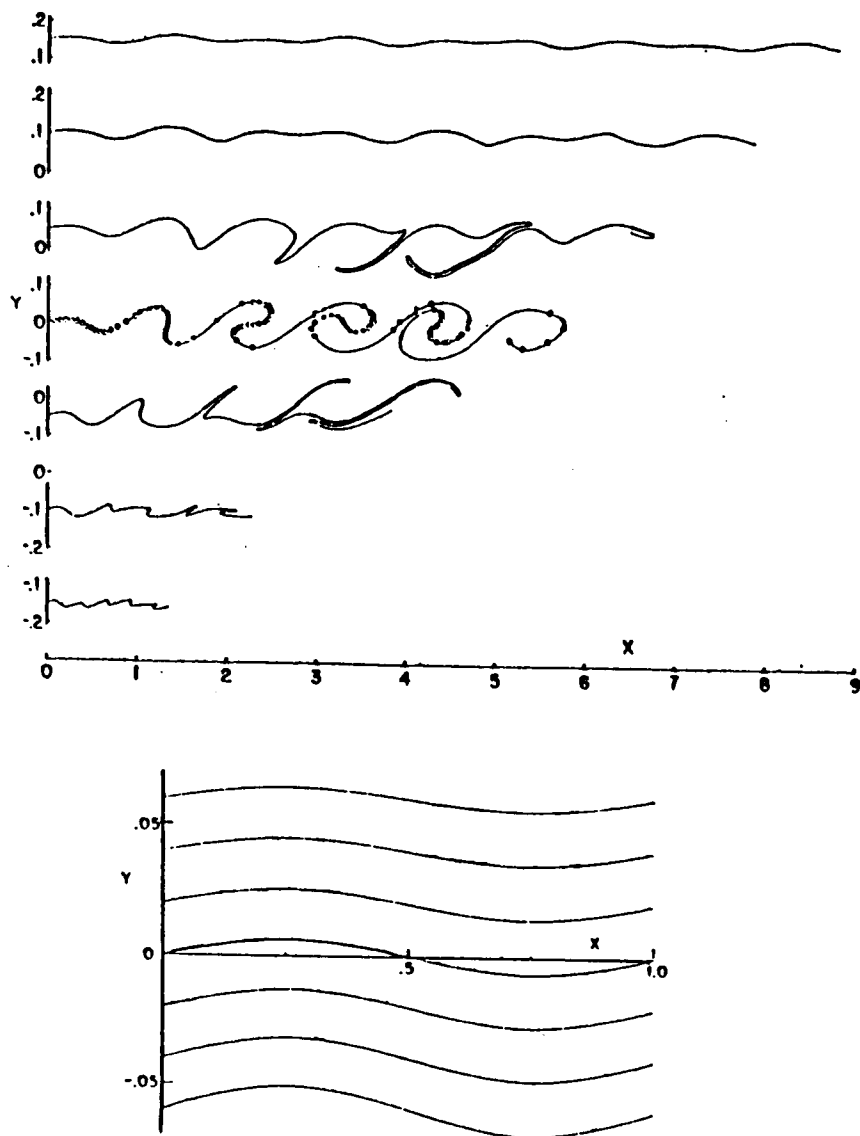


Figure 5. Computed streaklines, streamlines and pathlines of a perturbed shear layer showing the illusory appearance of discrete vortices. Above are the streaklines and streamlines in a fixed coordinate frame [Hama, 1962].

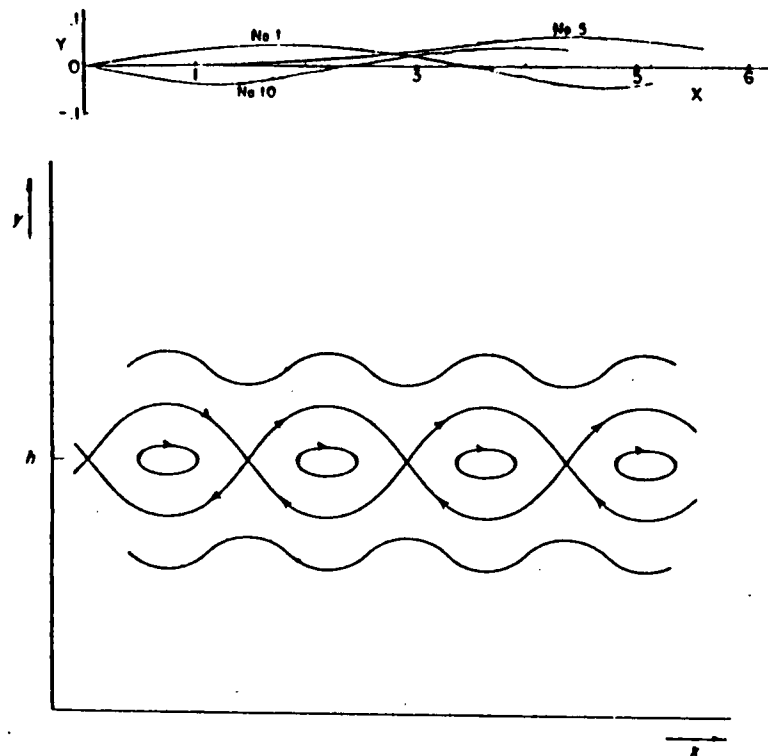


Figure 5. (Continued).

At top is shown three representative pathlines of the perturbed shear layer [Hama, 1962].

Below is the streamline pattern of an oscillating shear flow in a coordinate system moving with the wave velocity forming the so-called cat's eyes [Betchov and Criminale, 1967].

The previously mentioned work of Williams and Hama [Williams and Hama, 1980] not only updates Hama's earlier work but also points out that the phenomena known as vortex merging, in the case of a laminar shear layer perturbed by multiple waves, may be what can be best described as an illusion within an illusion.

In this work, instead of exciting the idealized shear layer with a simple sinusoidal disturbance they used a fundamental oscillation with its related subharmonic superimposed. The shear layer and disturbance were modelled as follows:

$$u = 1 + \tanh(y)$$

$$u' = 2a_1 \operatorname{sech}(y) \tanh(y) \sin \alpha(x-ct) + 2a_2 \operatorname{sech}(y) \tanh(y) \\ * \sin \alpha/2(x-ct),$$

where a_1 and a_2 are constants, α is the wave number and c is the wave speed. By continually integrating the equation of motion with the spatial initial condition required to represent a streakline they generated a simulated visualization that not only further substantiates Hama's earlier work but also shows a phenomenon that is amazingly representative of the vortex merging observed in simple viscous shear flow, an example of which is described by Winant and Browand [Winant and Browand, 1974]. At first glance, if one believed Hama's first paper this later find seems to be a moot point - how can there be vortex merging when there are no distinct vortices in the flow?

The answer is there cannot, but that is not the point. The point is that, at least in laminar flows, the process that has been studied

and labeled "vortex merging" is actually a combination of illusions created by the cat's-eye streamline patterns and the mean instantaneous vorticity distributions.

This type of study should rightfully give a certain sense of skepticism to the experimentalist, but its primary purpose is not to discourage water tunnel use but to educate the dye watchers in the complexities of what it is we are actually seeing. With this in mind, it should also be noted that the studies cited so far have been limited to cross-stream vortices. As will be seen later, the more complex (because of its structural three-dimensionality) streamwise vortex is of more immediate interest to the modern aerodynamicist.

Dynamic Similarity

Once an engineer has a firm understanding of the concepts of streaklines, streamlines and pathlines and their differences in unsteady situations, flow visualization can be approached in an intelligent manner. One can observe dye streaks in a water tunnel and deduce the major elements of the modelled flow field. One can photograph them for later study with the understanding that a still photograph is but an instant in a constantly changing unsteady flow, whether the unsteady flow is caused by instabilities of flow phenomena within a mean steady flow or the basic flow is unsteady. Now that an understanding of the model flow field has been established, one must wonder how closely this flow field matches the situation in the 'real world' that the water tunnel is being used to study.

Compressibility effects. The first problem that comes to mind stems from the fact that we are using water to model air (in most cases). The noticeable difference in density brings with it a more important difference in compressibility. In subsonic air flows the effects of compressibility are analytically accounted for using standard similarity rules until the critical velocity is reached where shock waves begin forming. Since we obviously cannot model shock waves in the water tunnel these situations are excluded. As will come to light later, three-dimensional separation and vortex generation are among the prominent flow features to be examined in the water tunnel. Of the great number of works on these topics none that the author has read deal conclusively with the effects of compressibility on these phenomenon but most mention the topic.

The most favorable, if not somewhat circumspect pronouncement, comes from K. C. Wang in the introduction to a symposium on viscous flows [Wang, 1976] where he states that "the separation patterns appear to be rather independant of the Mach number from all the evidence that has been examined."

A more reasonable and verifiable position is that of D. Peake [Peake, 1976] and [Peake and Tobak, 1980] whose rule of thumb is: "Compressibility alters the quantitative, but not the qualitative features of three-dimensional separated flows." This is deduced from the fact that experimentally increasing the Mach number reduces the scale of the rolled-up shear layers with respect to the oncoming boundary layer thickness or the wing semi-span of slender wings. This assumes, of course, that the flow contains no critical flow regions.

A question that needs to be answered is how much does compressibility alter the quantitative features. To illustrate the vast differences in water tunnel Mach number and full scale Mach number look to the test conditions reported in Water Tunnel Visualization of the Vortex Flows of the F-15 [Lorinez and Friend, 1979], which compares water tunnel results with full scale flight results. Here we find a model Mach number value of approximately $M = 6.4 \times 10^{-5}$ and a flight Mach number value of $M = 0.3$. The difference in the subsonic compressibility factor for these two conditions is of the order of 10%. Is there not some extreme value of this difference that would force the qualitative features into distortion? This is a question that is rendered more difficult due to the coupling of Mach number to the Reynolds number. One point to keep in mind is that even in situations of relatively low Mach number there could be some small regions of critical flow on the aircraft, especially at high angles of attack. If this hypothetical region of compressed flow were to occur in the vicinity of some pressure sensitive phenomenon, for example a leading edge vortex core, it could alter the qualitative features of the flow field.

A positive example of the water tunnel being used in a closed loop study of a compressible flow situation is the as yet unpublished work of D. Beale [Beale, 1986]. The problem involved some large scale vortices that formed in two separated regions in a scale wind tunnel model of a large transonic test facility operating at a Mach number value of 0.6. Despite the Mach number mismatch, a model of the facility was constructed in the UTSI water tunnel and the vortices

were located and found to be comparative in extent and sense. A fix was found in the water tunnel which eliminated the vortices and was applied to the wind tunnel model - where it successfully eliminated the large vortices, thus closing the design loop.

Reynolds number sensitivity. The best way to begin a discussion of Reynolds number sensitivity is to take a 'back to basics' look at the Reynolds number itself. This dimensionless parameter is simply a ratio expressing the balance of inertial to viscous forces - a high value indicating that inertial forces dominate the flow.

The problem is a matter of degree of accuracy. By modelling a high Reynolds number situation in a low Reynolds number water tunnel we are bound to introduce some inaccuracies in the gathered information. In the worst case, situations that are pressure field controlled in actual conditions may become boundary layer controlled in the water tunnel. In many cases, however, the qualitative details of the flow are left intact. These are the situations that are ideal for water tunnel studies. For examples of both ideal and worst case situations we will again look to three-dimensional separation. The best case is the entirely pressure controlled separation on a slender, sharp-edged wing at high angle of attack. Here the boundary layer on the lower surface of the wing cannot sustain the large adverse pressure gradient at the edge so it separates at a fixed line for any Reynolds number (see Figure 6) [Erickson, 1980]. This illustrates the general rule that the location of any well defined fixed separation can be modelled accurately in the water tunnel. It should be noted

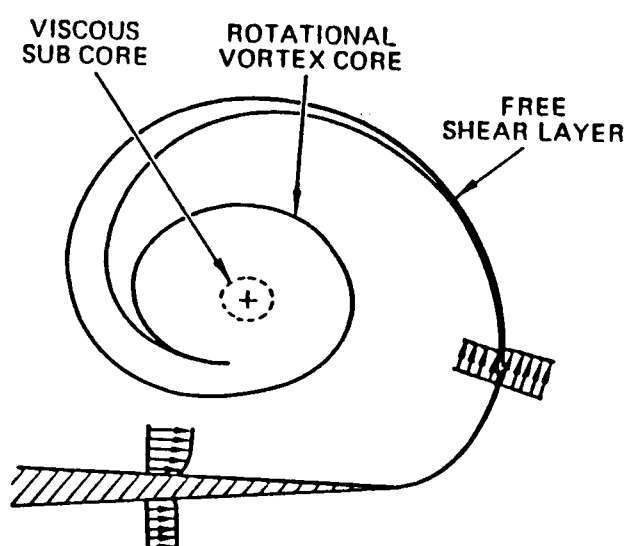


Figure 6. Vortex sheet roll-up on a thin slender wing.
View is from trailing edge looking forward
[Erickson, 1981].

that the boundary layers shown in the figure that feed the vortex are still sensitive to the Reynolds number. This will show up in the size and location of the vortex sheet and core, as will be shown in a later section.

The worst case is demonstrated by the geometric antithesis of the sharp edged wing, the circular cylinder (thought of here as a no-edged wing). The separation of the flow on the surface of the cylinder and the subsequent wake is controlled by a complex interaction of pressure fields and boundary layers. In a classic review paper on this topic M. Morkovin catalogs and describes no less than seven independent regimes of flow as the Reynolds number is varied from less than one to as high as he could envision (see Figure 7) [Morkovin, 1964].

The Reynolds number sensitivity of cylinder flows is a problem for any simulation that involves this type of geometry. Dye probes are typically cylinders and can cause large disturbances in the flow. Struts, supports and even long forebodies at high angle of attack will show this sensitivity.

An example of a class of flows that logically seems pressure driven but is deceptively linked to the boundary layer is the forward and backward facing step (see Figure 8). While the separation (in the case of the former) or reattachment (in the case of the latter) is caused by the pressure gradient, the location of these events is determined by the state of the boundary layer - whether laminar, transitional or turbulent. This state is functionally linked to the Reynolds number [Chapman, 1957]. In the laminar case, the separation point is insensitive to Reynolds number change. In the transitional

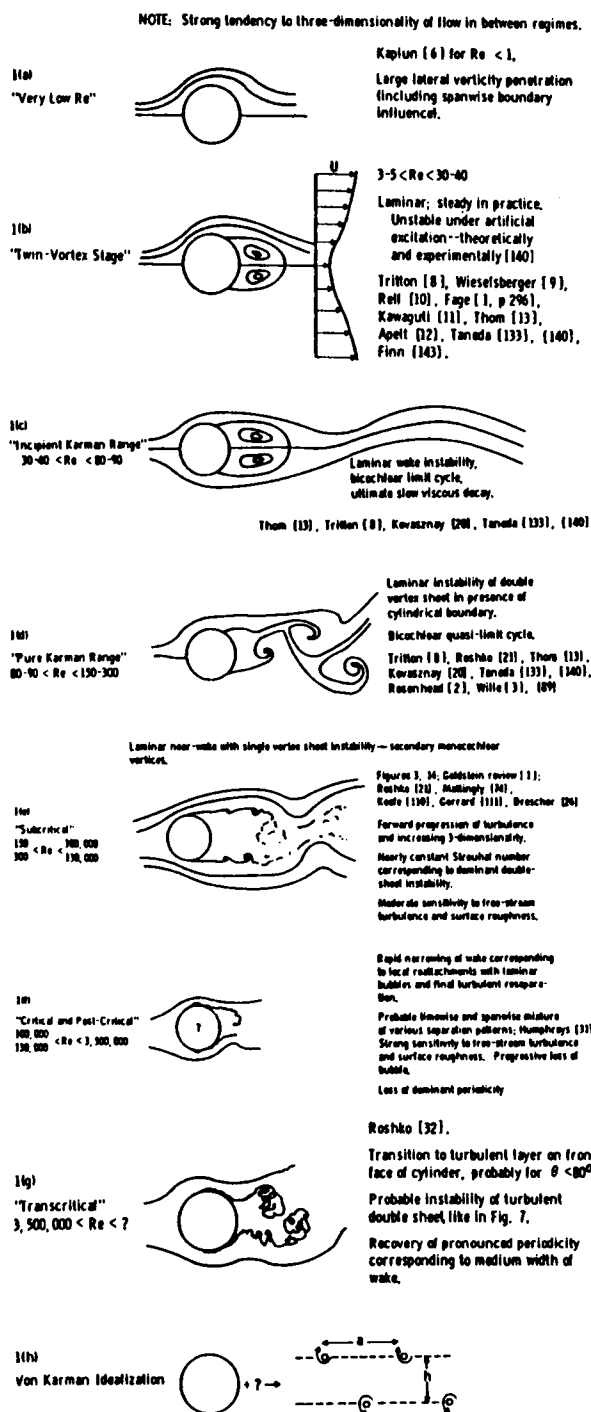
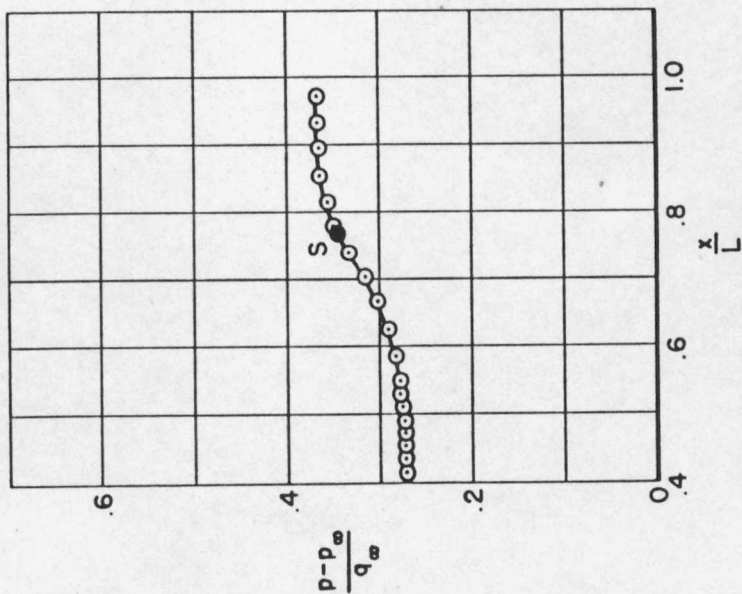


Figure 7. Summary of characteristics of major Reynolds number regimes of circular cylinder flow. [Morkovin, 1964].



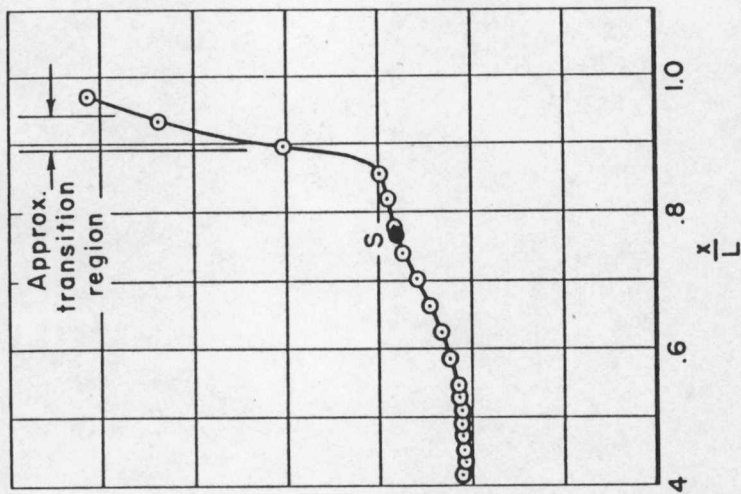
Pure laminar



(a) S-3; $M_\infty=0.61$; $\alpha=-4.5^\circ$;
 $R_L=0.106 \times 10^6$



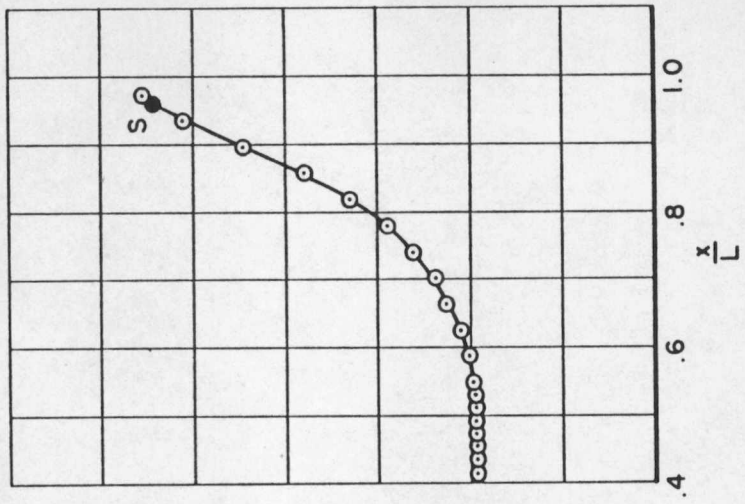
Transitional



(b) S-3; $M_\infty=0.61$; $\alpha=-4.5^\circ$;
 $R_L=0.358 \times 10^6$



Turbulent



(c) S-3 (trip 1); $M_\infty=0.61$; $\alpha=-4.5^\circ$;
 $R_L=0.407 \times 10^6$

Figure 8. Three regimes for a step in subsonic flow. The type of separation depends on Reynolds number indirectly through the state of the boundary layer [Chapman et al., 1957].

case, the separation is unstable and is a function of Reynolds number. The turbulent case has a delayed separation and occurs at higher Reynolds number than the first two, but once established is insensitive to variations.

Having discussed the best and worst cases, we must at least mention the in-between, where most realistic wings are to be found. The separation pattern of a traditional wing with rounded leading edge is a very complex function of not only Reynolds number and Mach number, but also wing shape and body interactions. At low Reynolds number the laminar boundary layer is more likely to separate at a region of adverse pressure gradient than the turbulent boundary layer that would exist at higher Reynolds number. It must be remembered that the correct simulation of the separation line is guaranteed only for a sharp edge.

III. FLOW VISUALIZATION IN PRACTICE

The Delta Wing Vortex Flow Field

The engineer in industry often uses the water tunnel as a tool for the design and modification of modern jet aircraft. This is fortunate because the highly swept, sharp edged slender wings of these aircraft provide a complex vortex dominated flow field that lends itself well to the use of flow visualization for assisting understanding.

The question of how accurately this particular class of flows can be represented in the water tunnel is addressed in two reports commissioned by the Air Force Flight Dynamics Laboratory, both of which were published in the Fall of 1980. Vortex Flow Correlation [Erickson, 1980], by Gary E. Erickson of the Northrop Corporation, gives a mostly favorable prognosis while Correlation of Vortex Flows in Test Facilities with full Scale Flow Phenomena [Wortman, 1980] by A. Wortman offers mostly skepticism and cautionary notes. Both will be referenced liberally in this section giving a more balanced view with comparisons from other sources on individual topics.

The flow field of the sharp edged delta wing is dominated by a fixed separation line which results in the shear layer rolling up into a large scale vortex over the leeward surface of the wing. According to Erickson, in order to correctly model this flow field in the water tunnel, one must simulate the following three phenomena:

- (1) Vortex Generation
- (2) Vortex Sheet and Core Location

(3) Vortex Breakdown

Consider each phenomenon separately.

Vortex generation. Vorticity is directly related to angular fluid velocity which in turn is related to velocity gradient. Any solid surface, such as a wing or body, because of the no-slip condition, creates a large velocity gradient near its surface. Following this line of reasoning a wing may be thought of as a source of vorticity.

In the case of fully attached flow over a wing this vorticity is shed at the trailing edge and wing tips resulting in the familiar trailing vortices that plague airport runways and form contrails in the sky. In the case of separated flow, as found on high speed wings flown at low speeds, this vorticity is shed at the leading edge and rolls into a large stable vortex over the wing. As has been mentioned previously, a sharp edge produces a strong enough adverse pressure gradient that separation will occur there at all but the lowest Reynolds numbers - hence the first simulation criteria is met. It should be noted, however, that the inclusion of leading edge flaps will add a certain amount of Reynolds number dependence into the separation phenomenon [Hall, 1986].

Vortex core and sheet location Vortex sheet and core location as a criterion also brings with it connotations of relative size and strength. To examine the effect of Reynolds number on these phenomena, Wortman developed that he calls an "equivalence plane" model

based on the idea presented by Batchelor [Batchelor, 1967] that delta wing flows resemble time dependent two-dimensional flows.

The Equivalence Plane is a plane whose normals are everywhere parallel to the leading edge (see Figure 9a). By expressing the defining flow parameters in this plane (for example, the oncoming velocity is expressed as:

$$V_0 = V/(\sin^2 a \cos^2 b)^{1/2}$$

he shows mathematically that "the extent of the vortices on the lee side of the wing will be proportional to the length required to decelerate the normal component of the oncoming flow." The parameter that describes the extent of these vortices is the circulation parameter:

$$G_s = \cos(a) \sin^2(a^*) \sqrt{1 - C_{ps}}$$

where C_{ps} is defined as the pressure coefficient at separation and is a strong function of both the Reynolds number and the amount of turbulence in the flow. Because of this dependence we see the increase in size of the vortex with decreasing Reynolds number as seen in Figure 9(b).

Erickson's treatment of vortex sheet and core location comes in the form of comparisons between water tunnel models and various analytic models, the most notable of which are: the leading-edge suction analogy, the quasi-vortex-lattice method, the free-vortex-sheet method and Northrop's own nonlinear lifting surface theory. These methods are all inviscid approximations that satisfy the trailing edge Kutta condition. They do not take into account surface boundary layer or vortex sheet and core viscous effects. Erickson's main point here is that "computational methods ignoring viscous effects are capable of

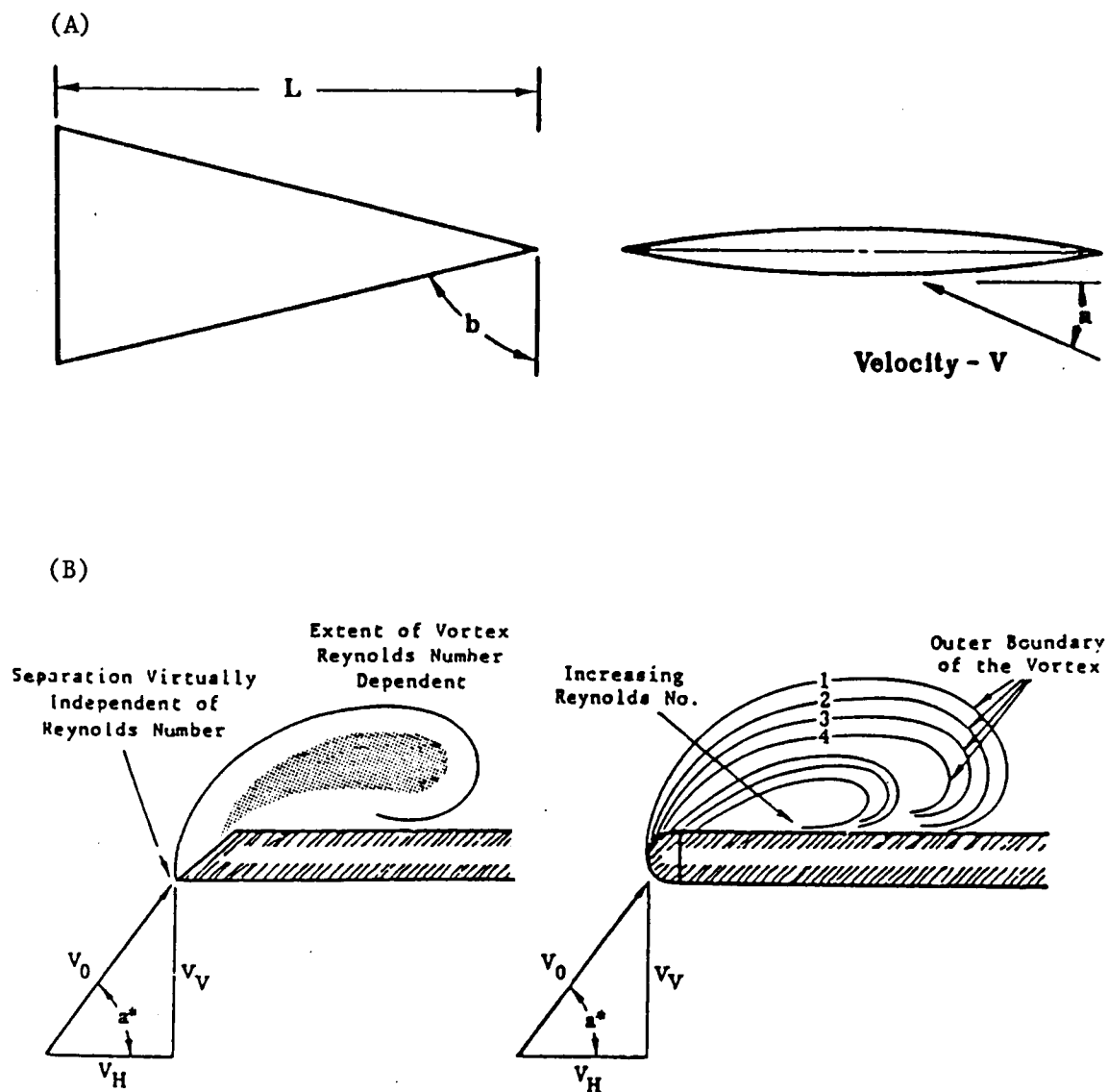


Figure 9. Description of parameters for equivalence plane model. (A) Geometry of thin sharp wing. (B) Origin of vortices at sharp and blunt leading edges [Wortman, 1980].

predicting the aerodynamics of vortical flows with reasonable accuracy [which] is one indication of the Reynolds number insensitivity of such flows."

As an example of how reasonable Mr. Erickson's standards of comparison are, the reader should examine Figure 10. This shows results from two different water tunnel studies and two theories which are described as being in "good agreement".

The first major concession that Erickson makes to the skeptics is in reference to the secondary vortex (see Figure 11). The boundary layer under the primary leading edge vortex flows outward toward the leading edge. On its way it encounters the very strong pressure gradient, somewhere between the minimum pressure line and the edge, where it is forced to separate and consequently rolls up into a small secondary vortex of opposite sense to the primary. Because this vortex is formed from the boundary layer it is very Reynolds number sensitive and hence is not modelled correctly in the water tunnel - or, as Erickson would say, "it can at most be observed in a qualitative sense."

One aspect of the secondary vortex that Erickson does not stress enough is the fact that its presence alters the rest of the pressure field over the wing. He does mention this effect with respect to the difference between laminar and turbulent flows as shown in Figure 12. Here we see the primary vortex formed from a laminar boundary layer to be higher and closer to the centerline as compared to the turbulent case. This is mostly a result of the displacement effect of the secondary vortex. As the secondary vortex grows it pushes the rest of

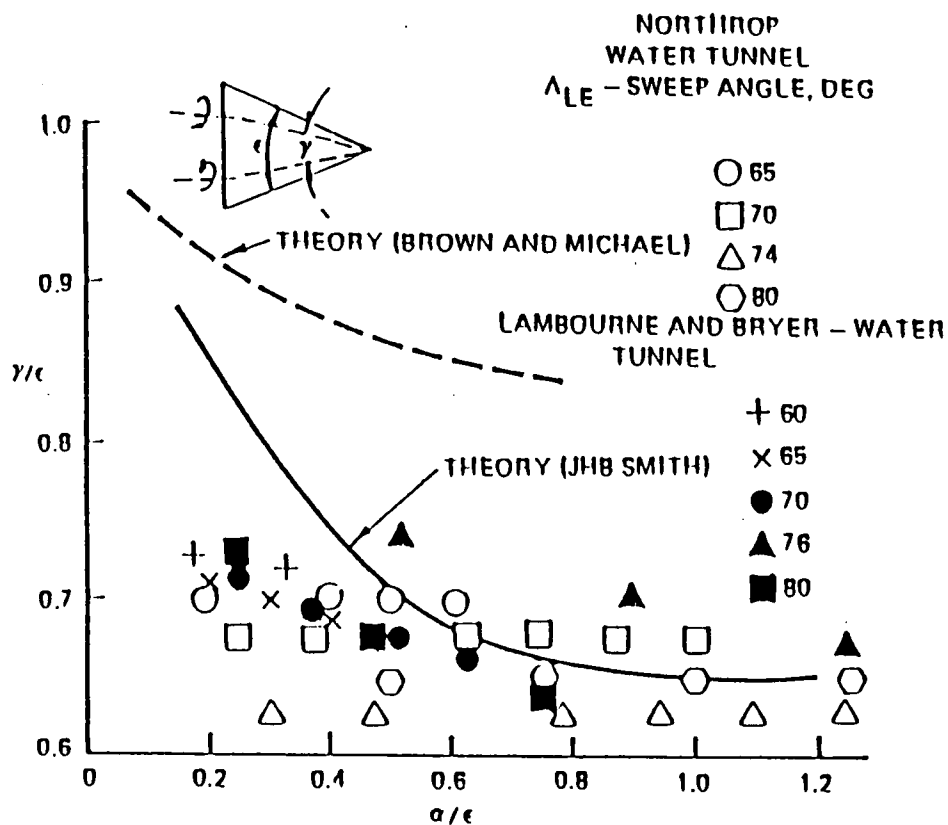


Figure 10. Comparison of vortex core trajectories measured in different facilities with theory. [Erickson, 1981].

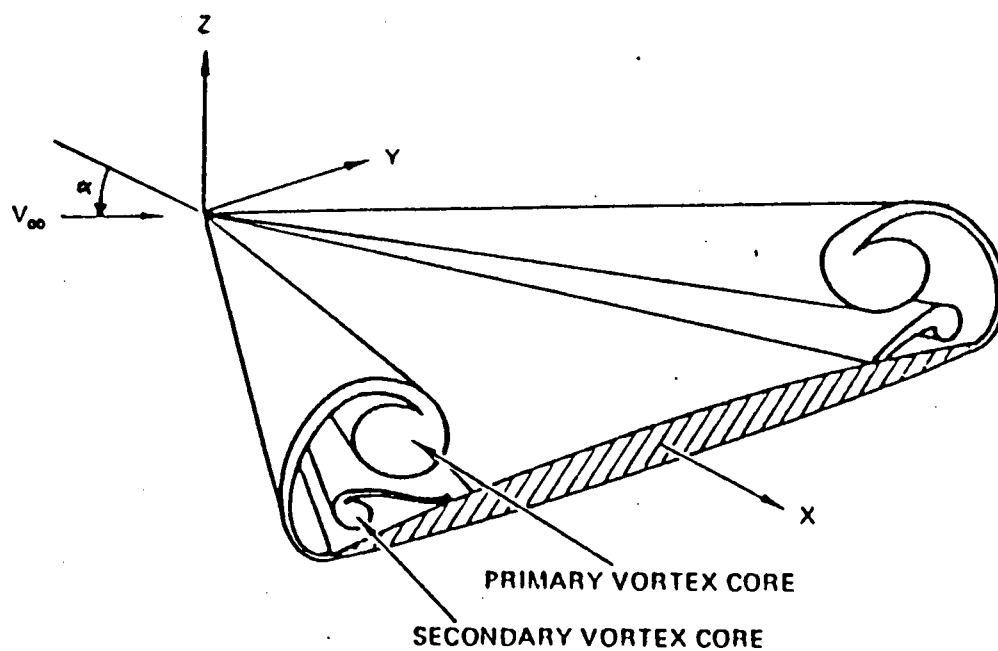


Figure 11. Primary and secondary vortex cores. [Erickson, 1981].

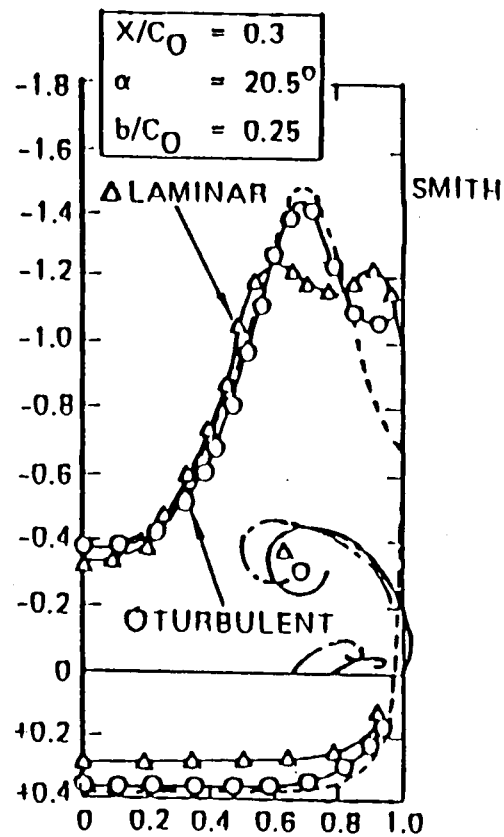


Figure 12. Pressure distributions over a thin delta wing at low speeds with laminar and turbulent flows. Note sketch of primary and secondary vortex positions showing displacement effect [Erickson, 1981].

the flow field upward and away from the edge. As can be seen in the figure, the laminar secondary vortex is larger than its turbulent counterpart, causing more displacement.

Before moving on to vortex breakdown, mention should be made of Erickson's detailed discussion of vortex structure. The structure of a vortex is determined by the transport of vorticity, both through diffusion and convection. During the time t an element of vorticity will be convected a distance Ut , where U is the average velocity of the element during the interval. During the same time t it diffuses outwards a distance of order $(\nu t)^{1/2}$. The ratio of scales of diffusion and convection being of the order of $1/Re^{1/2}$ [Maskell, 1962].

The rate of expansion of a vortex with distance x along its axis is of the order of L/x , where L is the cross-sectional size of the large-scale structure of the vortex. In the upper range of Reynolds numbers that the water tunnel operates in, L/x is much larger than $1/Re^{1/2}$, but as the local Reynolds number decreases, the vortex core, which is diffusion dominated, expands to encompass the large-scale structure and L/x becomes of the same order as $1/Re^{1/2}$ - i.e., the entire vortex becomes diffusion dominated. Another way to think of this is to say simply that the vortex becomes submerged in the boundary layer.

What this leads to is the identification of two regimes of vortex flow - viscous and inviscid - as depicted visually in Figure 13 [Maskell, 1962]. This graph does not represent data - it is only illustrative of the vortex regimes as described by Maskell - the data still does not exist to make this curve quantitative. If the vortex

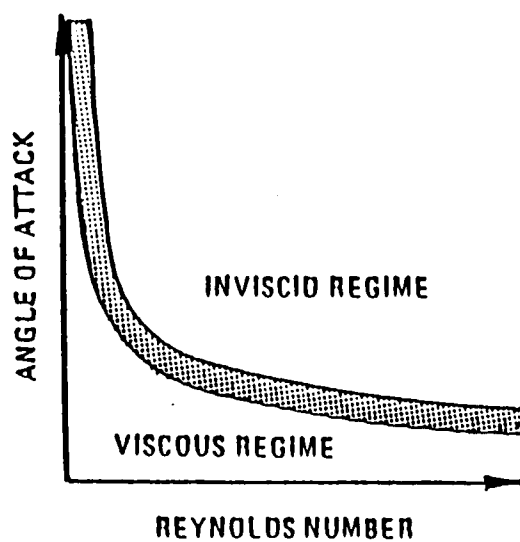


Figure 13. An illustrative representation of the inviscid and viscous regimes of vortex flow. Data is not yet available to quantify this plot [Maskell, 1964].

is of the inviscid type it can be 'reasonably' well modelled in the water tunnel. Following the analogy of the vortex becoming submerged in the boundary layer and examining the figure one can easily see that the problem becomes more than just one of low Reynolds number but also one of low angle-of-attack. Looking at Figure 13 it is not hard to imagine a situation where a model tested at a given angle of attack in a water tunnel will have vortices of different regime than the prototype.

A rule of thumb based on Erickson's water tunnel experience is to require the vortex sub-core height above the surface to be of the order of ten boundary layer thicknesses so as to be safely in the inviscid regime. To use this rule an estimate must be made of the boundary layer thickness on the water tunnel model for the test conditions under which it will be examined.

Vortex breakdown. Vortex breakdown is a complex but interesting topic for the fluid dynamicist. It can be observed and studied, cataloged by type or analyzed with instability theory. To the aerodynamicist, on the other hand, a vortex burst is more of a problem. Modern sharp-edged highly swept wings depend on vortex suction for a good part of their lift and maneuvering forces. If that vortex bursts over the wing or a control surface the result is a radical change in the forces on that surface and the forces needed to control the aircraft. Consequently, it is important to be able to predict where a given vortex will burst.

To examine the accuracy of such predictions using a water tunnel we must examine vortex burst from the viewpoint of a fluid dynamicist.

Vortex burst, as described by T. Sarpkaya, is characterized by "a rapid deceleration, deformation, and/or expansion of the core, flow reversal, and changes in the velocity and pressure distribution in the surrounding swirling flow" [Sarpkaya, 1971].

Sarpkaya goes on to classify breakdown into three types: double-helix, spiral and axisymmetric - as observed in a controlled experiment with a constant pressure gradient intended to study the fundamental mechanisms of breakdown. The type and location of the observed bursting turns out to be a function of Reynolds and circulation numbers as shown in Figure 14. The ordinate of this plot shows the flow Reynolds number and the abscissa shows the nondimensionalized distance at which the vortex broke down. Each of the symbols in the figure represent a different type of breakdown which can be seen to fall neatly on lines of constant circulation. There even appears to be hysteresis effects on each constant circulation line (between the dashed lines).

Analytically, Sarpkaya attributes breakdown to one of two mechanisms - hydrodynamic instability or finite transition to a sequent state. He theorizes that each of these mechanisms may dominate in different regions of the Reynolds number-circulation number domain and that "predominance of the effects of one mechanism in one region does not exclude the existence of another mechanism in another region." This means that not only could the water tunnel show the wrong location for the vortex burst, but it could show the wrong type of breakdown as well.

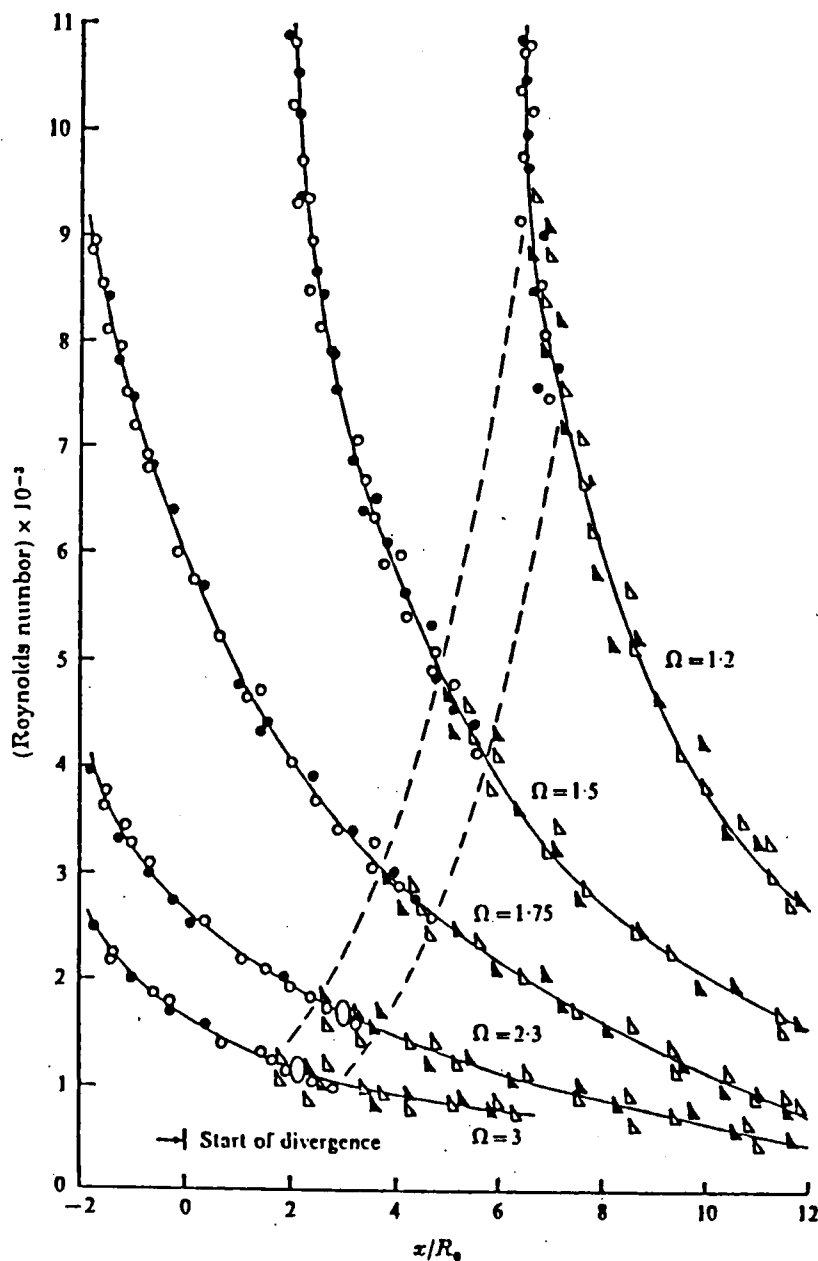


Figure 14. Vortex breakdown as a function of Reynolds and circulation numbers. The abscissa is nondimensionalized distance of breakdown. The circles are axisymmetric, the triangles are spiral and the ovals are helix types of breakdown. The dashed line marks the region of hysteresis [Sarpkaya, 1971].

A similar but more in-depth study was done at Cornell by J. H. Faler and S. Leibovich [Faler and Leibovich, 1977]. Using apparatus modelled after Sarpkaya's, with the addition of laser Doppler anemometry, they have identified six different types of breakdown where the type and location is a function of Reynolds and circulation numbers as shown in Figure 15. Each type of breakdown is discussed in great detail in the reference and is referred to descriptively as follows:

- 0 - axisymmetric
- 1 - low circulation, high Re axisymmetric
- 2 - spiral
- 3 - spiral/flattened bubble combination
- 4 - flattened bubble
- 5 - double helix
- 6 - large amplitude, low Re disturbance.

Analytically, they derive expressions for the swirl (V) and axial (W) velocity profiles:

$$W(r) = W_1 + W_2 \exp(-Ar^2),$$

$$V(r) = K r^{-1} [1 - \exp(-Ar^2)],$$

where r is a dimensionless radius, A is an increasing function of Reynolds number which determines the extent of the vortex core and W_1 , W_2 and K are all constants. This result shows the structural dependence of the vortex on the Reynolds number.

Erickson begins his treatment of vortex breakdown simulation with the following statement - "The highly viscous nature of the vortex

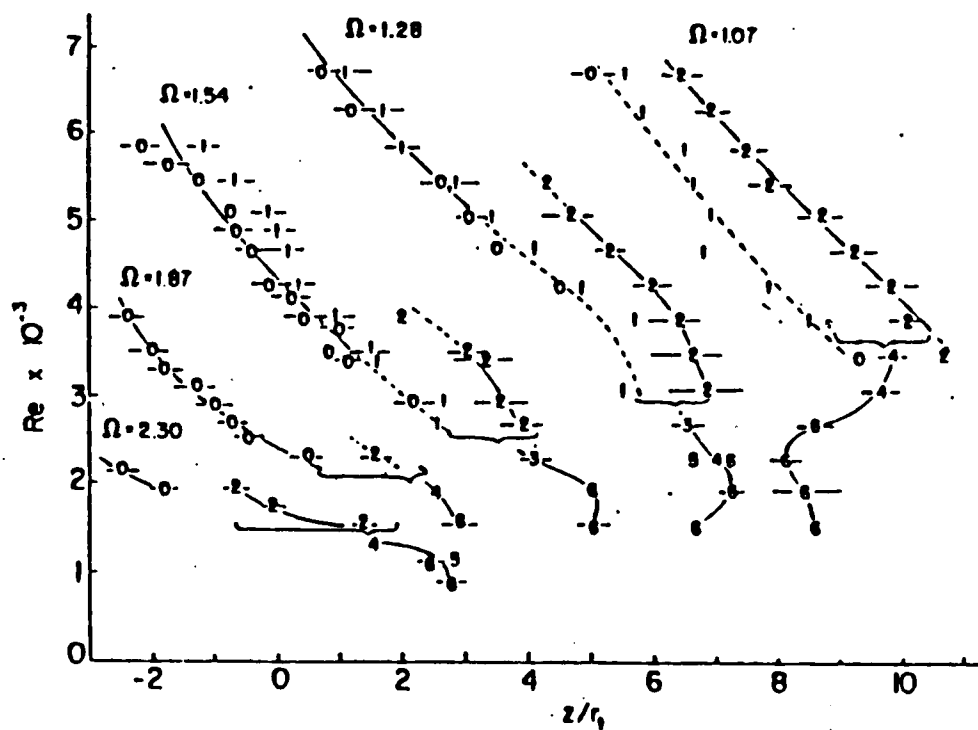


Figure 15. Another study of vortex breakdown as a function of Reynolds and circulation numbers. The type of disturbance (0-6) and its mean axial location versus Re for five values of circulation [Faler and Leibovich, 1977].

inner core suggests that the low Reynolds number laminar core behavior in the water tunnel will be quite unlike the turbulent core behavior at high Reynolds number. The correlations that have been obtained to date, however, suggest that under certain conditions the relative significance of the key parameters is simulated in the water tunnel." Once again, an example of what he calls "a truly impressive correlation of water tunnel data with flight data" can be seen in Figure 16. The photo is of a demonstration flight at an air show printed in Aviation Week and Space Technology [Aviation Week, 1979] with no data on angle of attack or airspeed, a nice photo but a questionable comparison.

Despite the dubious nature of the above mentioned correlation, Erickson does address more directly the specific case of breakdown of water tunnel model vortices. Probably the most important point that he brings up is that the vortex core behavior is strongly influenced by the external pressure field. More specifically, breakdown can be promoted by a deceleration in the flow, a sudden expansion or the pressure rise at the rear of a wing. As leading edge sweep is decreased, that final point becomes more important. A smaller sweep angle produces a more negative pressure difference over the wing and hence a sharp rise in pressure at the rear as the pressure 'recovers' to the free stream value.

A common feature of this type of vortex is the strong axial current down its axis of symmetry. The radial pressure gradient serves to balance the centrifugal forces. Changes in the rotational motion with downstream distance produces a favorable axial pressure

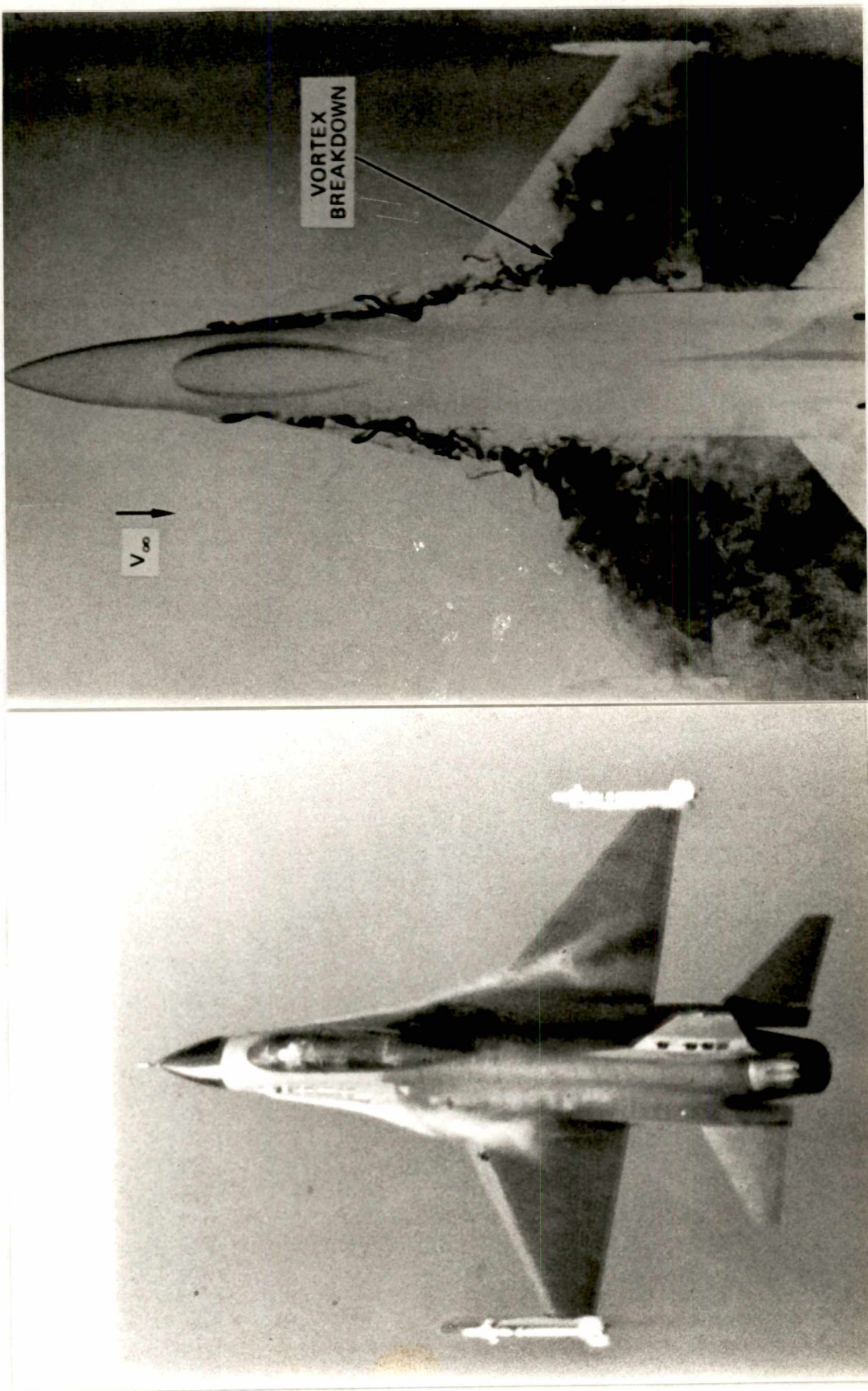


Figure 16. Correlation of vortex breakdown on a current fighter aircraft in a water tunnel and in flight at approximately 26 degrees angle of attack [Erickson, 1981].

gradient and hence axial acceleration. As the rotational motion is slowed by viscosity the axial pressure gradient gradually becomes positive causing a loss of axial momentum that eventually results in vortex breakdown [Batchelor, 1964]. As shown in Figure 17, this axial velocity does vary with Reynolds number. The data in this figure comes from pitot-static measurements in a wind tunnel and pulsed dye measurements in a water tunnel [Lambourne and Bryer, 1960].

A final point that Erickson makes is related to the earlier mentioned importance of the external pressure field to vortex breakdown. He has documented a large difference in delta wing burst point aft of the trailing edge depending on the kind of strut arrangement that is used. As a result, extra care should be used in mounting water tunnel models.

Literature Survey

Unlike a traditional literature survey found at the beginning of many papers, this section will serve as a catch-all for useful or interesting pieces of information found in the literature that did not seem to fit elsewhere in the structure of this thesis.

Slender body flows. The first topic of mention will be slender body flows. The nose and afterbody of most modern aircraft can be regarded as a slender body. The flow over such a body can be quite complex, depending on its cross-sectional shape, and is very sensitive to variations in Reynolds number. Like on the cylinder, the separation point location is critical in determining the rest of the flow field and is a function of Reynolds number. In the water tunnel the

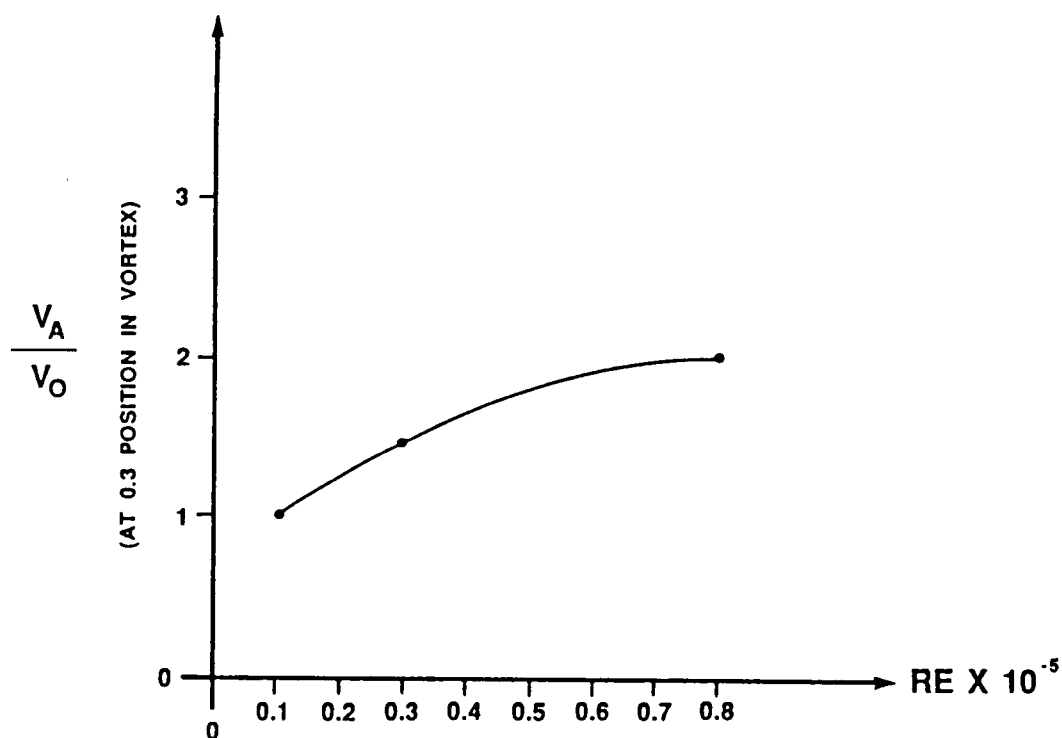
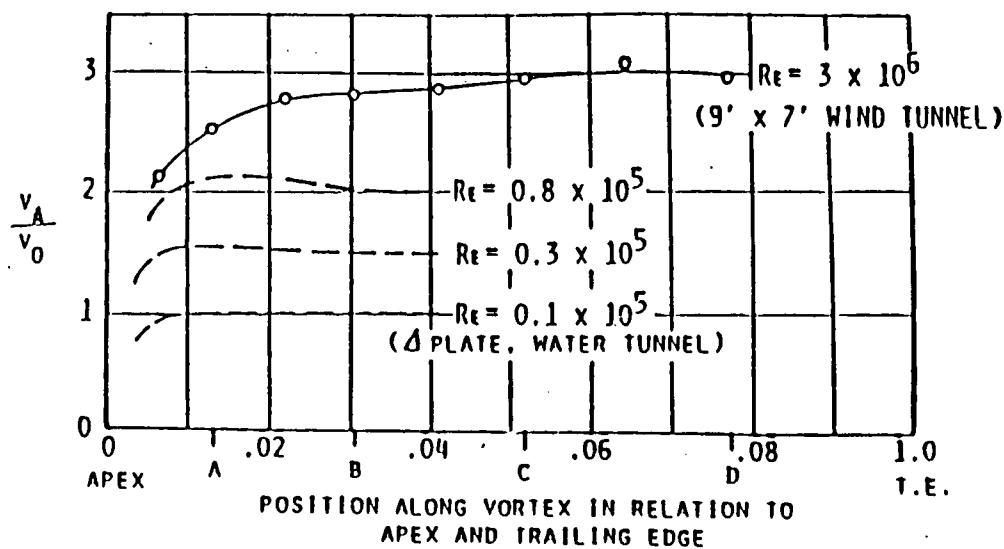


Figure 17. Variations of vortex axial velocity with Reynolds number. [Lambourne and Bryer, 1959].

separation and consequent vortex generation on the nose and body will occur at lower angles of attack than in the real situation [Erickson, 1980]. It should be noted that these nose vortices will interact with what could be an otherwise correctly modelled wing flow to produce an overall picture that is qualitatively out of proportion.

Another problem with nose vortex shedding involves the onset of vortex asymmetry. A slender nose will shed its vortices asymmetrically at high angle of attack as shown in Figure 18. This will cause a side force on the aircraft with a large moment arm from the center of gravity that produces a strong yawing moment at zero sideslip. This gives the aircraft poor spin entry characteristics [Spangler, 1976]. The difficulties with modelling this situation in the water tunnel are twofold. First, because of the reduced Reynolds number the onset of vortex asymmetry is delayed. Second, the asymmetry is very sensitive to small variations in the nose shape making it difficult to guarantee that the model used will be accurate enough. Perhaps a slightly encouraging note on this topic is Erickson's claim that, "Water tunnel observations of the F-5F/Production Nose configuration have clearly shown an asymmetric forebody vortex pattern at high angles of attack and zero sideslip which is in qualitative agreement with the asymmetric yawing moments experienced in wind tunnels and flight test" [Erickson, 1979].

Three-dimensional separation. Another topic that deserves some further attention is that of three-dimensional separation. The most obvious difference between water tunnel boundary layer flows and

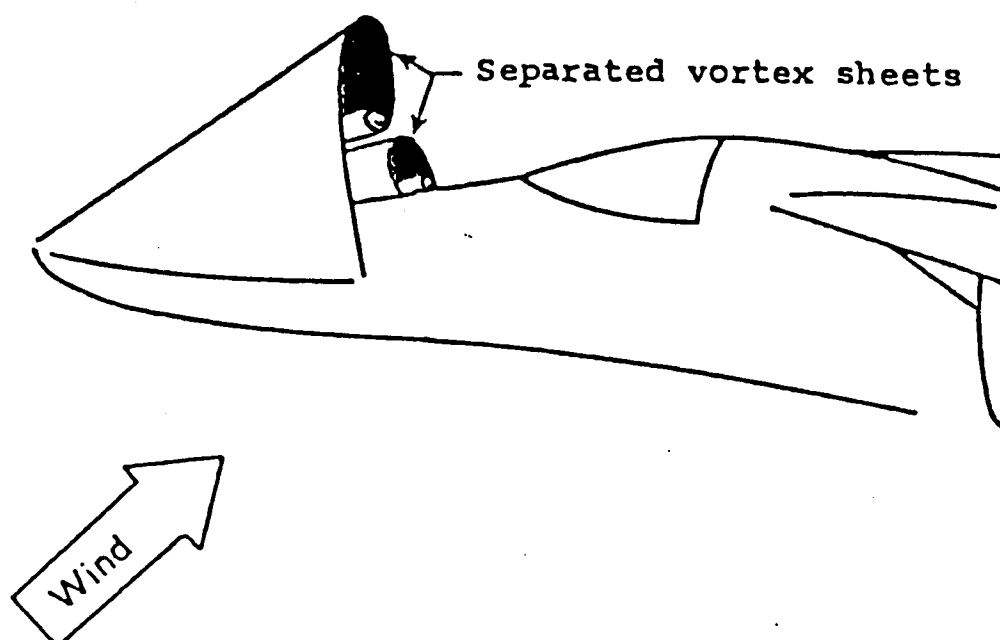


Figure 18. Asymmetric vortex separation on an aircraft nose.
[Spangler, 1976].

flight conditions is that the first is generally laminar while the later is usually turbulent. As far as separation is concerned, a laminar separation depends on the Reynolds number and covers more body area, while a turbulent separation is insensitive to Reynolds number and is less in extent. "The difference," as K. C. Wang so eloquently states it, "is a matter of degree, rather than character" [Wang, 1976].

In a more recent glossary of three-dimensional separated flows, [Peake and Tobak, 1980], Peake and Tobak contradict this statement by saying, "Under high Reynolds number conditions with turbulent boundary layers existing, it is likely that the external flow may have a topology different from that in laminar flow and that it may be steady." They also have some interesting information to offer concerning proturbance flows.

They did water tunnel flow visualization of oval and circular section proturbances and then tested the same models in a high Reynolds number wind tunnel. As predicted by their general statement, the separation of the turbulent boundary layer was closer to the model than in the water tunnel. These results are depicted in Figure 19 for a 2:1 oval and a 4:1 oval showing the primary and secondary separation lines for both the turbulent and laminar cases.

Typical justifications. The final area to be discussed is not so much a topic as a series of examples illustrating the ways that other investigators have justified their use of the water tunnel, both

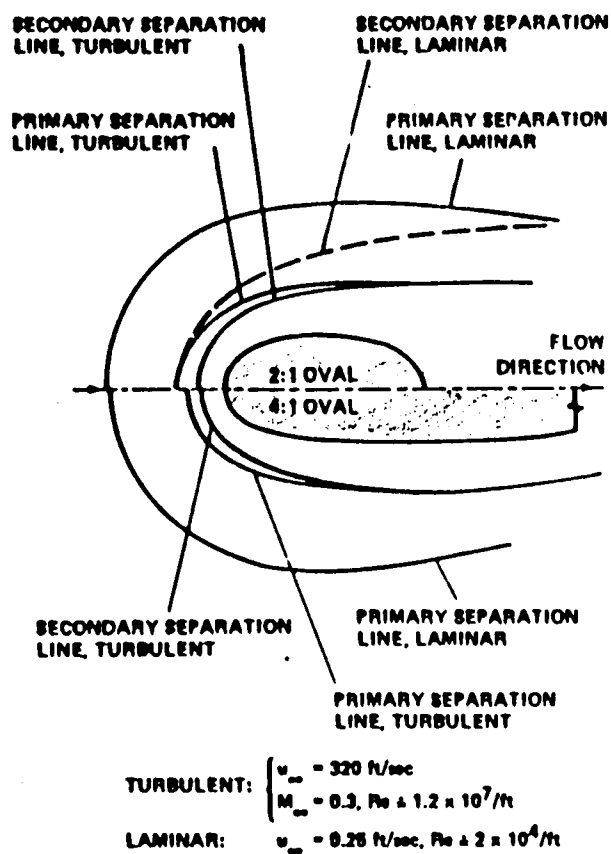


Figure 19. Comparison between experimental separation line positions in laminar and turbulent flows about oval cylinders. Body is shaded [Peak and Tobak, 1980].

before and after the fact. Perhaps the most famous of water tunnel users are Philippe Poisson-Quinton and Henry Werle at ONERA. Their justification before the fact is the familiar sharp leading edge argument. After the fact, however, they make an interesting comparison to NASA flight films of a modified F5-D (the conditions of which were simulated as closely as possible) and conclude that "vortex bursting above the wing appears at about the same location as in flight, although the Reynolds number was 2000 times smaller" [Poisson-Quinton and Werle, 1967].

Another pair that makes use of correlation is Lorinez and Friend [Lorinez and Friend, 1977]. Here a water tunnel and a wind tunnel are both used to study the vortex flows of the F-15. The high angle of attack stability characteristics were measured in the wind tunnel and compared with the vortex visualization results from the water tunnel. The comparisons are mostly favorable, with vortex asymmetry occurring in the water tunnel at around the same conditions as the accompanying variation in moment and force coefficients.

One of the more clearly thought out before the fact justifications comes from Offen and Kline at Stanford [Offen and Kline, 1974], S. J. Kline being the creator of those wonderful educational films on fluid mechanics using his hydrogen bubble technique. This argument centers on the differences between a spatial record and a temporal record. A probe, whatever kind it may be, is an instrument that is fixed in space. It produces a 'temporal record' of the measured quantity of successive bits of fluid that pass it. It can show the time history of organized fluid motion, "only if the motion consists of

elements which move in a related manner as each in turn passes over the probe." In other words, it has to be in the right place at the right time. Flow visualization, however, is not limited by preselected sampling positions - it covers a good sized flow field and can reveal events at one location that are related to events at several other locations. This is aided by the fact that the human eye has a tendency to search out and follow recognizable patterns, making flow visualization not only a spatial record but also a slightly temporal one. For the specific case of vortical flows they suggest that since "bursts and vortices can be characterized by their spatial uniqueness, they may not be characterizable by a temporal record at one or two points" [Offen and Kline, 1973].

IV. RECOMMENDATIONS

This section contains three different levels of recommendation. The first includes a few items of a practical nature to keep in mind while using a water tunnel. The second puts forth some ideal to keep in mind while building or choosing a water tunnel facility. The last contains a brief description of a very well thought out experiment proposed by Wortman in an Appendix of his report that would "demonstrate conclusively and quantitatively the effects of Reynolds numbers on vortex flows over slender wings," for the time being, anyway.

Practical Considerations

The first thing to remember when setting up an experiment is that the working fluid is water instead of air and has some differences that need to be compensated for. One obvious consideration, that is nevertheless often ignored, is the difference in hydrostatic pressure across the model. This difference may seem slight but it is much greater than it would be in air and it can seriously alter the pressure field being modelled.

When working in a horizontal test section on, say, an aircraft model at high angle of attack - an easy way to minimize the hydrostatic pressure difference across the areas of interest is to mount the model on its side and measure the angle of attack laterally (see Figure 20).

Another fact about the working fluid that is often ignored is that the boundary layer in water is approximately three times larger

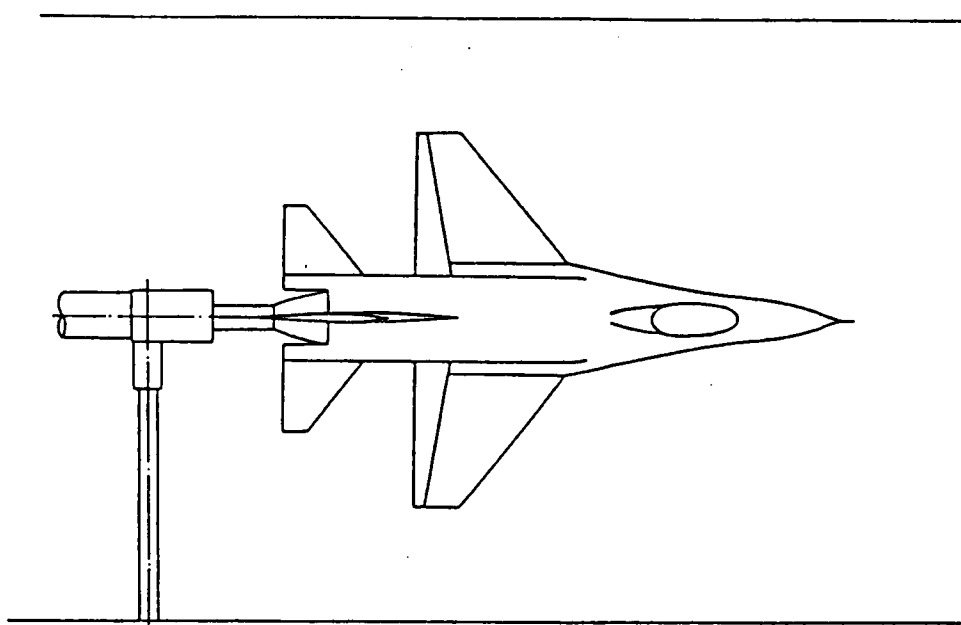


Figure 20. Side view of model mounted in test section.
[Collins, 1982].

than it is in air. Hence, if one has a model with any large gaps, the flow through these gaps will not be simulated correctly unless some modification to the model geometry is made to account for the thick boundary layer [Stieb and Gross, 1981].

A point that should be remembered is that most of the flows of interest are vortex flows directly related to separation which are, by their nature, unsteady. To record such flows, high speed film is the medium of choice because still photographs, no matter how quickly and close together they are taken, still leave out a large number of instants that could be important in a developing time-dependent flow.

Another recommendation of a practical nature concerns improved methods of dye injection to avoid the intrusion of the probe. One interesting possibility involves the use of thymol blue [Baker, 1966]. This method uses as its working fluid a 0.01% by weight solution of thymol blue titrated to its end point. Two electrodes are placed in the flow - the positive being a fine wire in the region of interest. As a small current is passed through the wire a proton transfer reaction causes the solution near the wire to change color as it flows by, creating a streak. If the voltage is pulsed, the velocity can be calculated from the spacing, hence giving some quantitative capabilities to the method.

Facility Design

For those that are building or simply trying to choose a water tunnel to work in, there are a couple of points that might not be obvious. The first concerns flow anomalies produced by the structure

of the tunnel itself. An example is the Northrop tunnel, which is in the form of a vertical loop. The water is pumped upward into a settling tank where the turbulence is supposedly damped out and then is turned ninety degrees downward to flow vertically through the test section as shown in Figure 21 [Erickson, 1980]. This turn could conceivably induce a strong enough adverse pressure gradient near the wall to form a region of separated flow which would, in turn, add some background vorticity to the flow that would be undesirable to the downstream test section. This sort of turn also introduces secondary flows which could prove problematic in the test section.

One of the recommendations that stands out in the Wortman paper that would eliminate most of his problems with current water tunnel studies is the use of higher test section velocities, thus guaranteeing turbulent flow instead of laminar. This would probably entail the use of particles for visualization because of turbulent diffusion of dye streaks. As shown by F. N. M. Brown in his beautiful book, See the Wind Blow [Brown, 1971], the use of larger contraction ratios ahead of the test section can reduce the coarse free stream turbulence to produce a smoother turbulent flow with smaller scale turbulent structures.

Wortman's Proposed Definitive Experiments

The final recommendation of this section is entirely credited to A. Wortman. The experiment he proposes will demonstrate the effects of Reynolds number on slender wing vortex flows and will include the effects of leading edge bluntness, wing thickness as well as angle of attack.

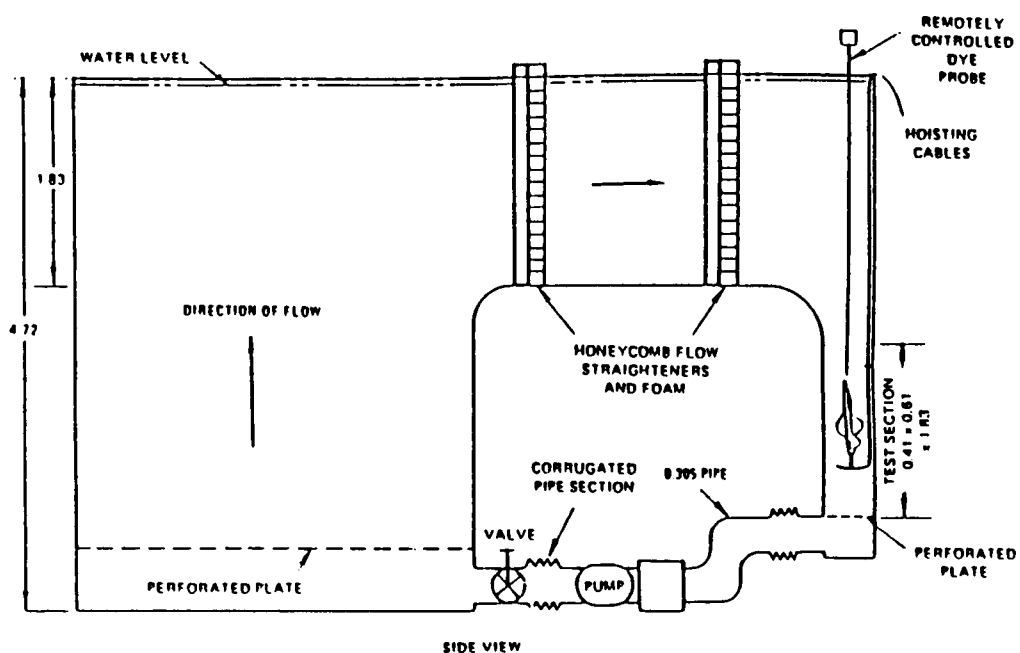


Figure 21. Schematic of the Northrop Diagnostic Water Tunnel Facility (all dimensions in meters). [Erickson, 1981].

The model to be used (shown in Figures 22 and 23) consists of three elements: a blunt edged delta wing split in the horizontal plane and an addition that fits on top giving additional thickness and camber to the wing. These elements are to be assembled into the following five combinations:

- "1. Blunt leading edge flat delta (both plates)
2. Sharp leading edge flat delta (top plates)
3. Half blunt leading edge flat delta (bottom plate)
4. Sharp leading edge thick delta (top plate and addition)
5. Blunt leading edge thick delta (all elements)."

Each of these configurations are to be tested over a Reynolds number range of 0.5 to $2 * 10^6$ with measurements taken of lift, drag and moments as well as a comprehensive flow visualization study.

Among the results that Wortman expects to produce are: force and moment coefficients as a function of Reynolds number for fixed angle of attack and as a function of angle of attack for fixed Reynolds numbers, effects of leading edge shape on force and moment coefficients at selected Reynolds numbers and angles of attack, effects of thickness on force and moment coefficients and - the effects on the flow pattern of transition, leading edge radius and wing thickness. "The ultimate statement," in his own words, "will be a definitive statement regarding the correlation of laminar flow results with full scale turbulent results." This is, to say the least, a confident expectation of a result that would be of great value to the world of experimental aerodynamics and is eagerly awaited.

Some logical additions to Wortman's test plan might include leading and trailing edge flap deflections and some sort of generalized nose/body and strake attachments to further clarify the Reynolds

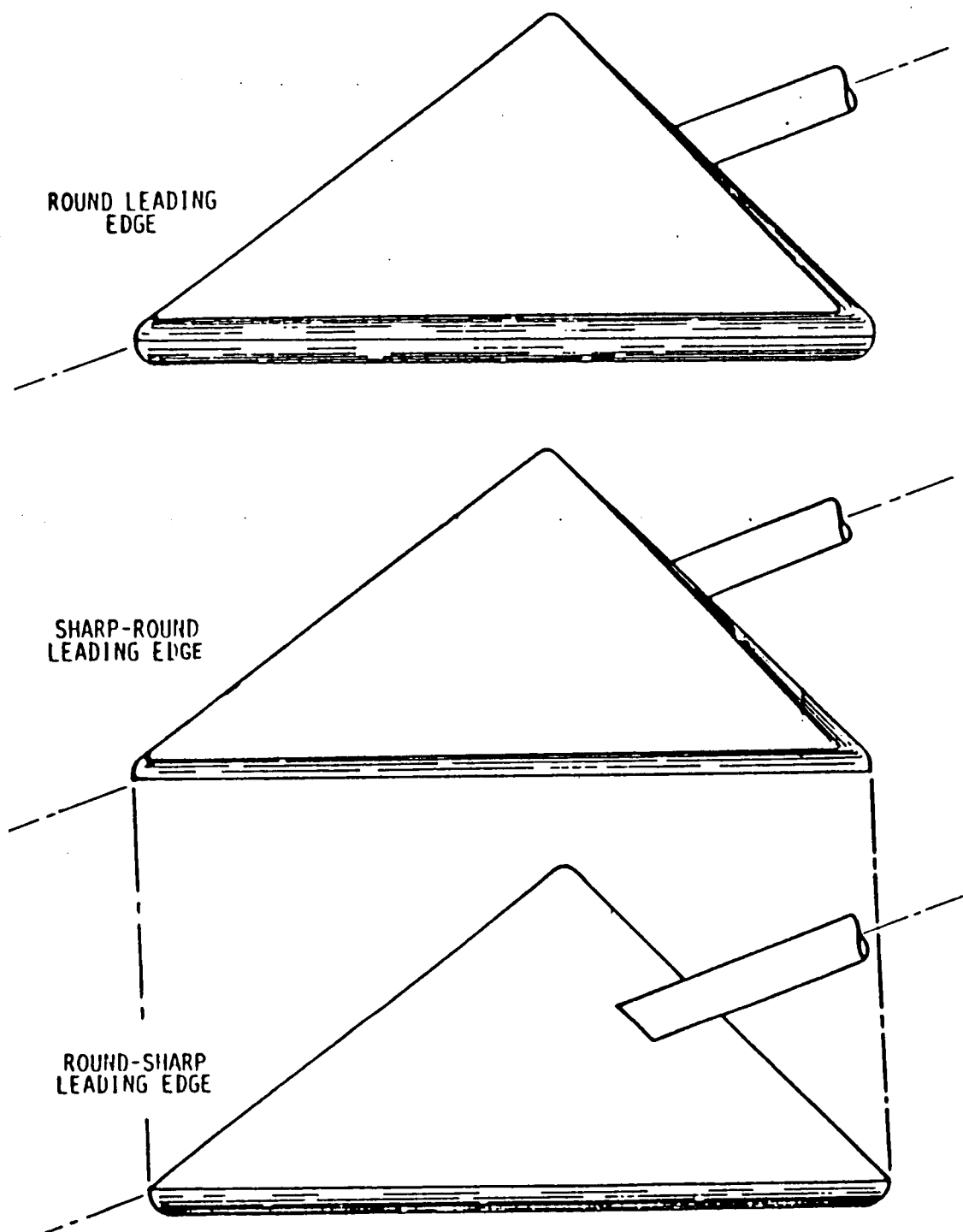


Figure 22. Three configurations of Wortman's model.
[Wortman, 1980].

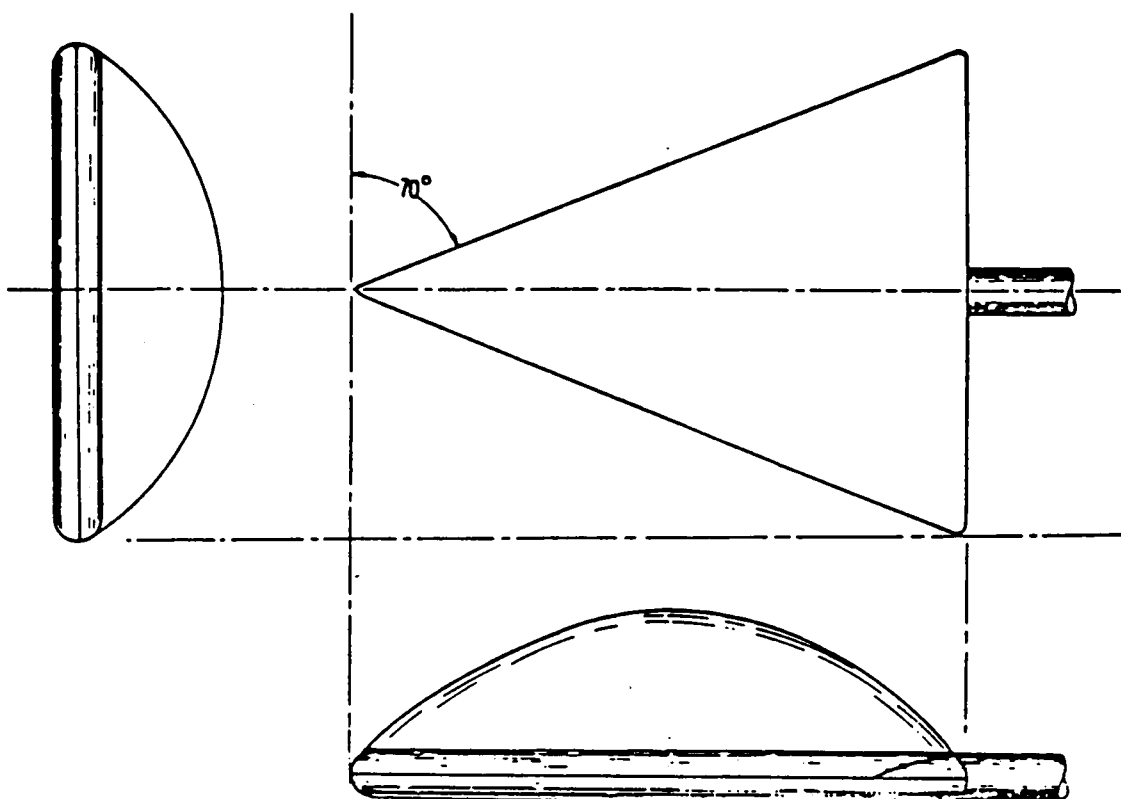


Figure 23. Wortman's assembled critical test model.
[Wortman, 1980].

number effects on these aircraft structures. Another suggestion would involve developing a similar experiment to clarify the effects of Mach number scaling on the flows of interest.

V. CONCLUSION

The water tunnel, like most pieces of equipment, is often over-rated by its proponents and under-rated by the skeptical. Nonetheless, it is a valuable tool to the engineer in all his aspects: educator, researcher and designer.

As an educational tool the water tunnel is invaluable. It can demonstrate, by visual example, the major concepts of fluid mechanics and dynamics. In this aspect it can give the student an intuitive background which has the effect of rooting in reality the elegant mathematical descriptions as put forth by Reynolds, Kelvin, Stokes and the rest.

As a research tool, history has proven the great value of the water tunnel. It was in a water tunnel that Reynolds first observed the phenomena of transition. Here also was discovered the turbulent spot by Emmons and the boundary layer by Prandtl [Collins, 1982]. The list goes on. In the present, flow visualization is still being used to advance all those previously mentioned concepts as well as pioneering work in vortex breakdown and coherent structures, to mention but a few.

Only recently has the water tunnel been used as a design tool, and its value in that regard has been the basis for this paper. The problems with using the water tunnel for design are nicely summed up by Schraub who says "that they only provide qualitative results; more important, they are extremely difficult to interpret properly in unsteady flows" [Schraub, Kline, et al., 1965]. These are limitations

that, when understood, can be accounted for by an engineer who can use the advantages of the water tunnel while minimizing its disadvantages. This paper is intended to promote a clearer understanding of those limitations.

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