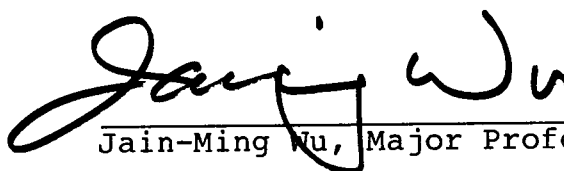


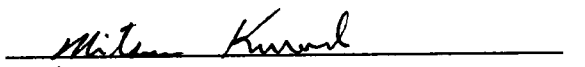
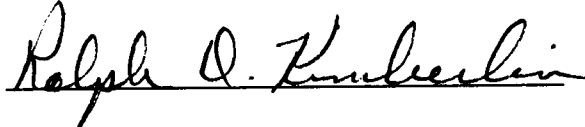
To the Graduate Council:

I am submitting herewith a thesis written by James Dale Hull entitled "The Effects of Multiple Winglets (Sails) on Finite Wing Performance and Vortex Wake." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aerospace Engineering.



Jain-Ming Wu, Major Professor

We have read this thesis
and recommend its acceptance:

Accepted for the Council:


The Graduate School

THE EFFECTS OF MULTIPLE WINGLETS (SAILS) ON
FINITE WING PERFORMANCE AND
VORTEX WAKE

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

James Dale Hull
June 1984

ACKNOWLEDGMENTS

I would like to express my appreciation to several individuals who contributed in so many ways to the completion of this thesis.

Special thanks go to Dr. Jimmy Wu, my major professor, for the opportunity to study this topic and to continue my education; to Dr. Mitsuru Kurosaka, for suggesting the hydrogen bubbles; and to Professor Ralph Kimberlin for his continued encouragement.

Thanks are also extended to Maurice Taylor, UTSI photographer, for technical advice and use of his personal photographic equipment; to Randall Boss, UTSI technician, for assistance at the Water Tunnel Laboratory; to Richard Ray, UTSI technician, for assistance with the timing circuit; to Shan Chi, UTSI graduate research student, for a data reduction program; to Mike Luke, Remote Sensing Division, for use of the department's Bausch & Lomb Zoom Scope®; to Dr. Ahmad Vakili, for assistance in force balance data reduction; and to Jeannie Harper for typing the final manuscript.

ABSTRACT

This thesis attempts to answer the question, "What is the function of tip feathers of soaring birds?"

Multiple sails (feathers) are added to a plain wing and changes in the trailing tip vortex are measured. The same tests are repeated in a wind tunnel to measure changes in the aerodynamic forces. A computer simulation of the shed vortex pattern is also used as a model.

Although incomplete, this study is a good basis for future work, and the results indicate that bird tip feathers increase the effective aspect ratio of the wing, reducing the induced drag.

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NOMENCLATURE

ϕ	Angle between local flow at tip and free-stream flow
α	Free-stream angle of attack
A	Aspect ratio
C_{Di}	Coefficient of induced drag
C_{Do}	Coefficient of parasite drag
$C_{l\alpha}$	Coefficient of lift versus α for an airfoil section
$C_{L\alpha}$	Coefficient of lift versus α for a finite wing
C_T	Tip chord
x	Direction along longitudinal axis of aircraft
y	Direction along span of aircraft
z	Vertical direction, orthogonal to x and y

CHAPTER I

INTRODUCTION

The author's involvement with this subject is covered in the proceeding sections, and the chronological order of the investigation is given because it is important for the reader to understand what knowledge was available when experimental decisions were made.

Identification of Subject

In the spring of 1981, I first became acquainted with Prandtl's lifting line theory and the idea that for given lift there must be a given amount of trailing vorticity. (As presented to me, this was equated with energy-wasted energy.) This struck me as being erroneous. For fifteen years or so I had much noted the flight of the turkey vulture here in Tennessee and how he manipulates the emarginated tip feathers. I felt that the lifting line theory, as understood by me, must indeed be the first order solution, but could there not be some effect produced by the tip feathers which could modify the process and cause it to be more efficient?

About that time, I saw a picture in a trade magazine showing "wing tip sails" designed by the Cranfield Institute of Technology in Cranfield, England. These

"sails" were purported to reduce drag and change the trailing vortex pattern to get better lateral distribution for crop duster aircraft. They claimed about 15% improvement in the overall lift/drag ratio.

I had already begun my introductory studies for the Master of Science in Aerospace Engineering. Soon thereafter, I was fortunate enough to become introduced to Professor J. M. Wu and be given the opportunity to study multiple sails in the Low Speed Wind Tunnel (LSWT) and water tunnel of The University of Tennessee Space Institute (UTSI).

Dr. Wu had already noted the tip feather configuration as it was cited in some texts along with pictures of birds in motion. However, scientific investigation of how and why this configuration worked was lacking, to our knowledge. It is to be noted that Raspet of Mississippi State University had trained a vulture to fly in a wind tunnel, but the bird died just as it was about to be useful. It is felt by this author that the untimely death of Dr. Raspet was not only a loss to humanity but to scientific knowledge as well. Some random pictures of birds showing various wing tip feather configurations during flight are given in Figure 1.

Professor Ralph Kimberlin provided me with a paper written by Professor J. J. Spillman of the Cranfield

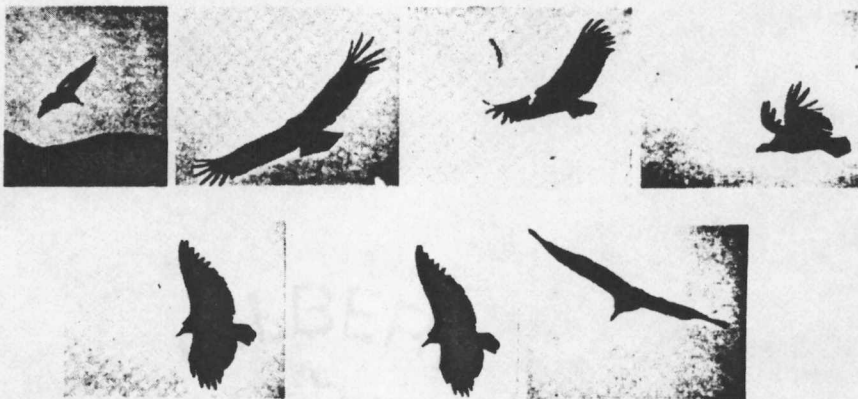


Figure 1. Bird Pictures Showing Tip Feather Action.

Institute. As a result, we had copies of some of their first published results [1].¹ They first measured how the flow at the tip varied as the distance from the tip increases (spanwise). This is shown in Figure 2. Note that at distances from the tip surface greater than 0.1 times the wing tip chord, the local incidence amplification, ϕ/α is a function of wing incidence but is not extremely dependent upon the distance aft of the leading edge. This means sails (designed for a given α) could be identical from 10% of tip chord (i.e., $0.1 C_T$) outward. Inboard of this point a standardized sail would not be optimized for locations other than the one for which it was designed. "Sails" were designed to extract thrust from this flow. The camber lines were circular arcs. The airfoil coordinates off these circular arcs were NACA 63012 coordinates. Sail span was 0.41 of wing tip chord. The root chord was 0.16 of wing tip chord for the aircraft they tested. The angles between the tangents to the camber line at the leading edge and trailing edge are as shown in Figure 3. This allowed local flow to be parallel to tangents at the leading edge when wing incidence is 6° and the sail is 60% of tip chord behind the leading edge. The sails tested at UTSI are modeled after these sails.

¹Numbers in brackets refer to similarly numbered references in the Bibliography.

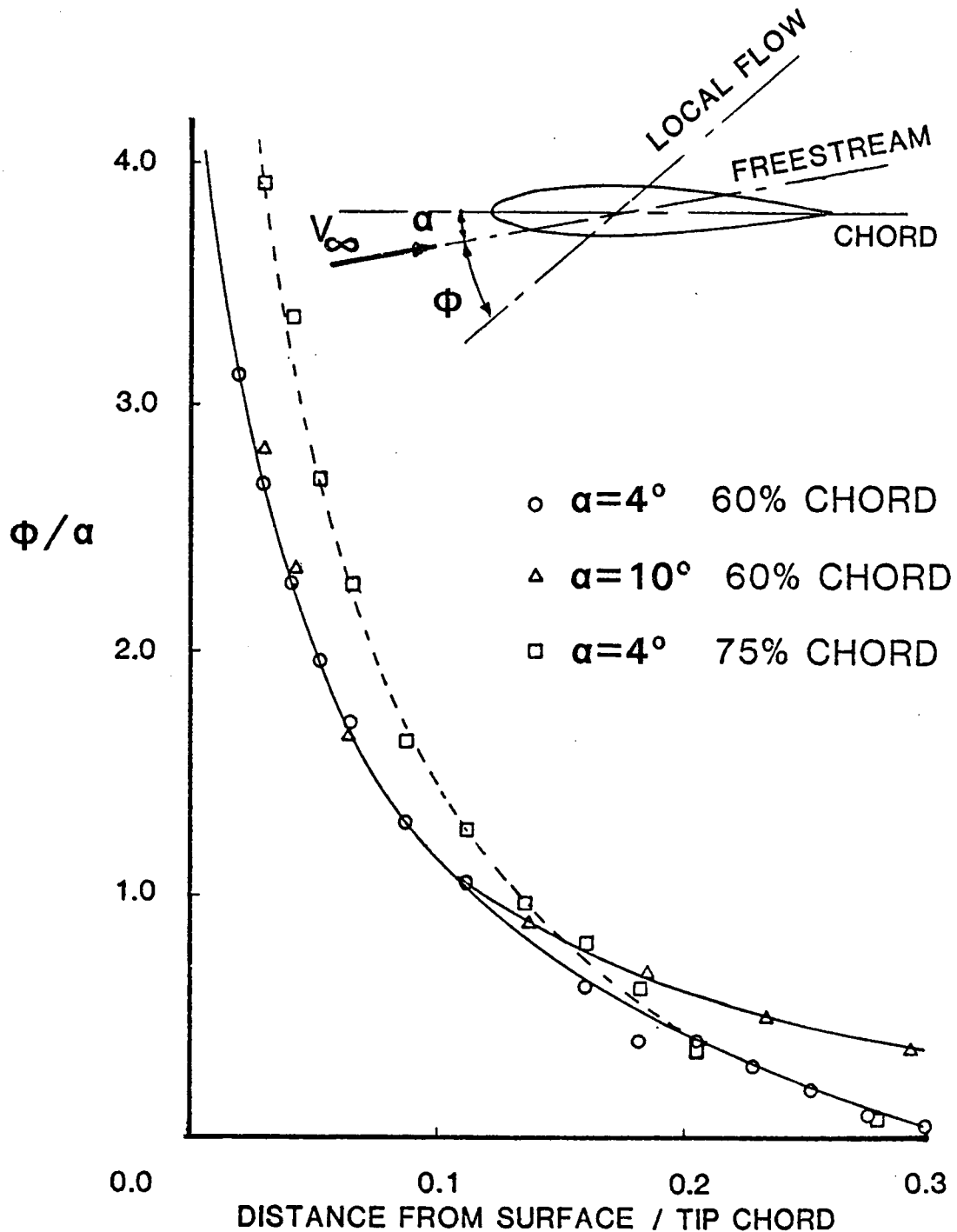


Figure 2. Cranfield's Wing Tip Flow Angle Measurements [1].

Ψ (ANGLE BETWEEN TANGENTS TO CAMBER LINE
AT LEADING EDGE AND TRAILING EDGE)

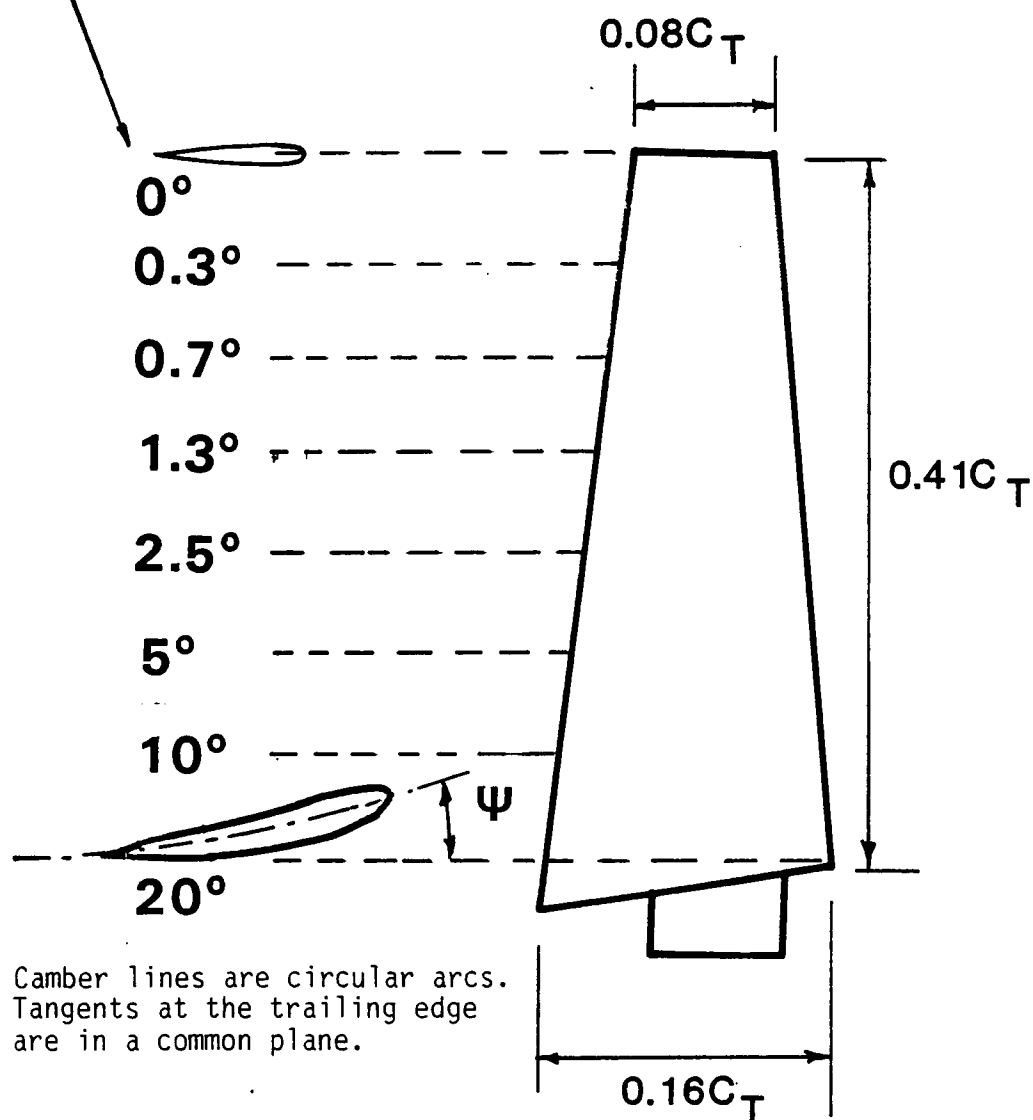


Figure 3. Cranfield's Sail Configuration [1].

Cranfield placed three sails on a wing tip. The rear sail was at 75% of the chord and at 0° dihedral. The front sail was at 50% chord and at 90° dihedral. A sail between these two was at 45° dihedral. Using this, they obtained an increase in L/D of 21% at a C_L of 0.35. Their results are shown in Figures 4, 5, and 6.

They concluded, by other tests, that little is gained by exceeding four per wing tip or spanning more than $0.3 C_T$. When structural problems were considered, these numbers became three sails per wing tip and a span of no more than $0.25 C_T$.

Their data also indicate that ϕ/α increases toward the trailing edge, as in Figure 7. This is a key point to remember when analyzing their results. This study will utilize this fact in hypothesizing bird tip feather configuration.

With consideration of these previous studies behind us, we began our own study.

Work Chronology

The work on this investigation developed in the following manner. With a knowledge of the first Cranfield work (three sails at 90° , 45° , and 0°), we built, from intuition, a five-sail model using Cranfield airfoils, at dihedral angles equally spaced from 16° in front to -8° at

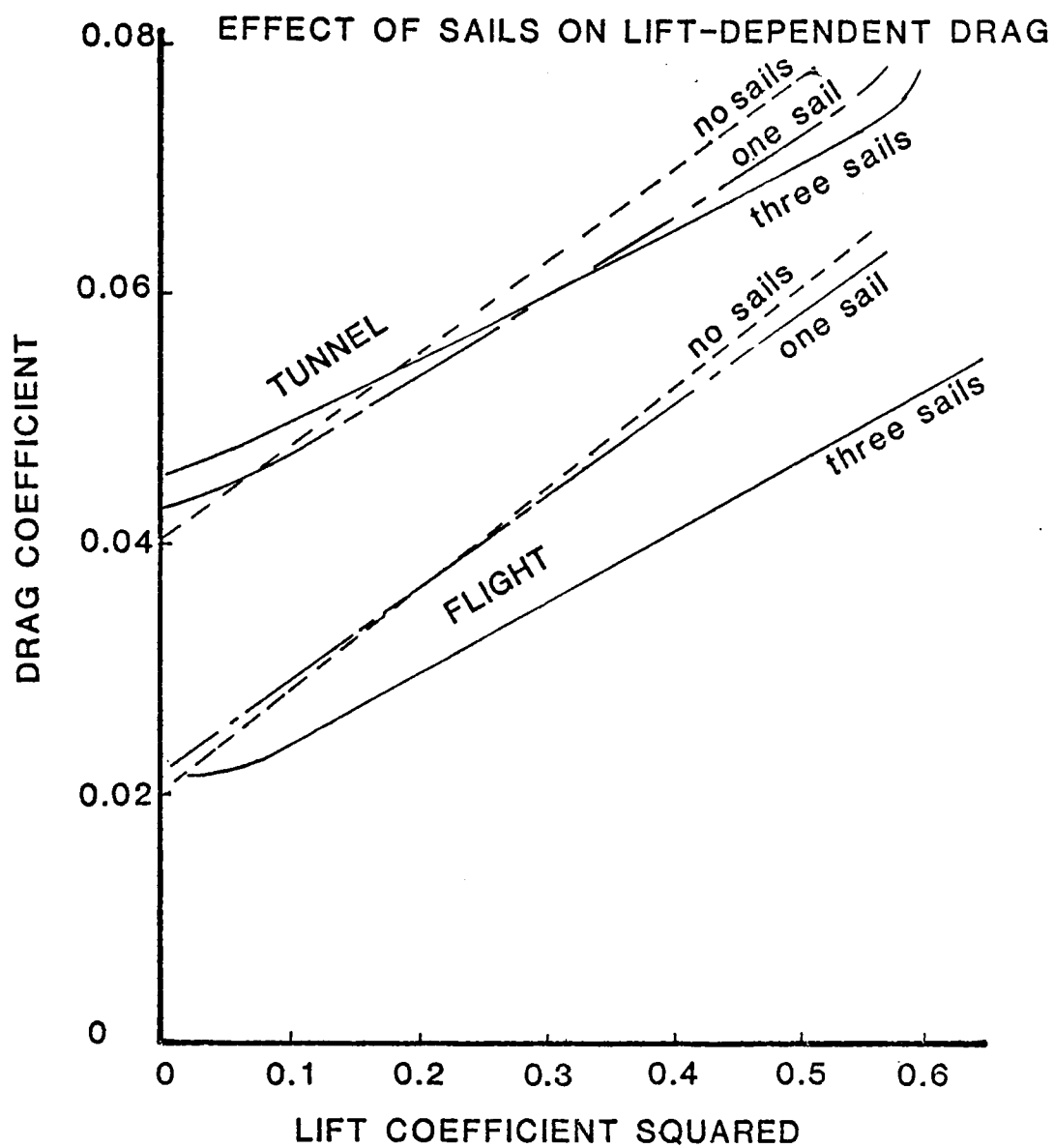


Figure 4. Cranfield's Initial Induced Drag Results [1].

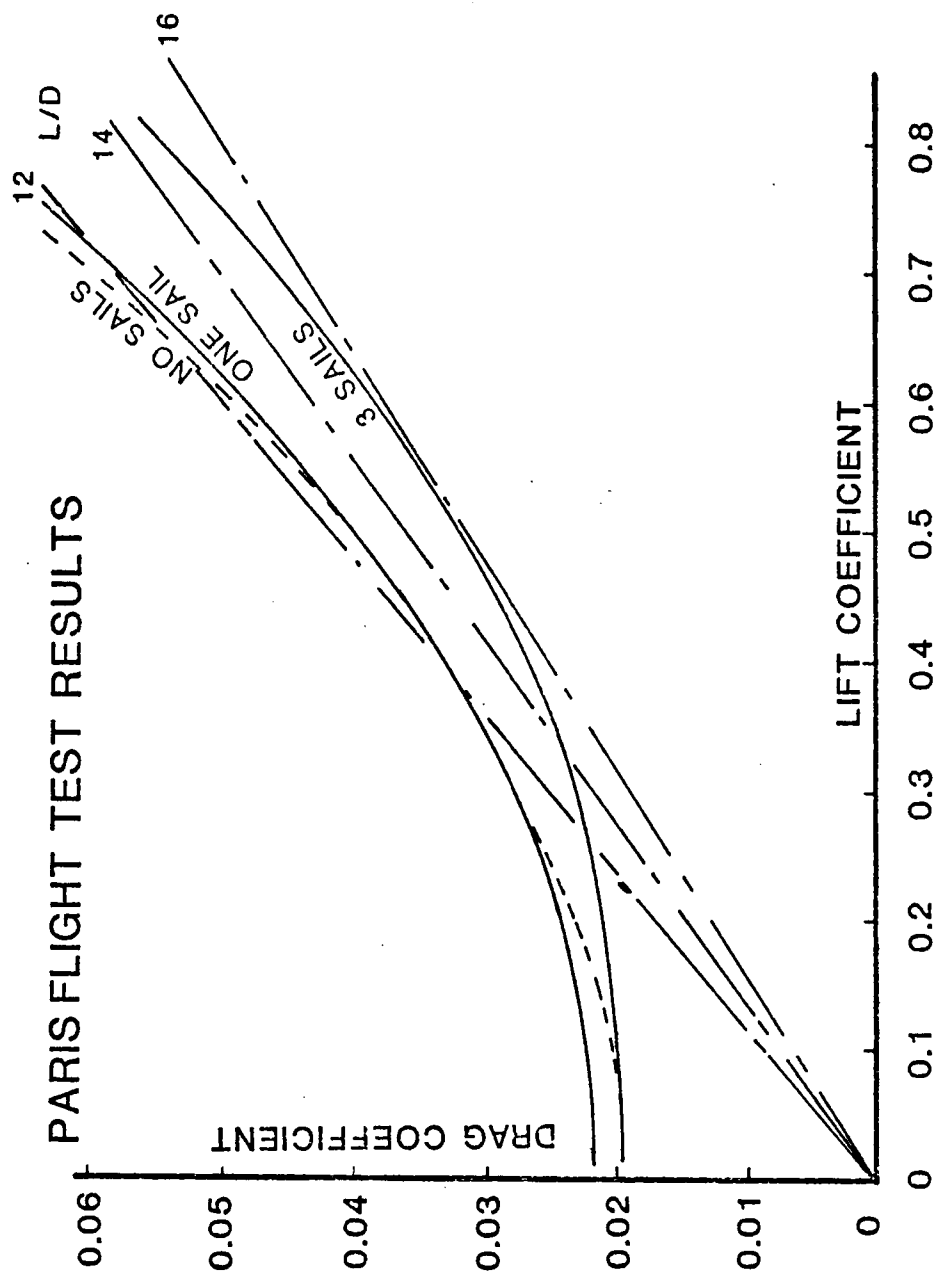


Figure 5. Drag Coefficient versus Lift Coefficient for Cranfield's Initial Tests.

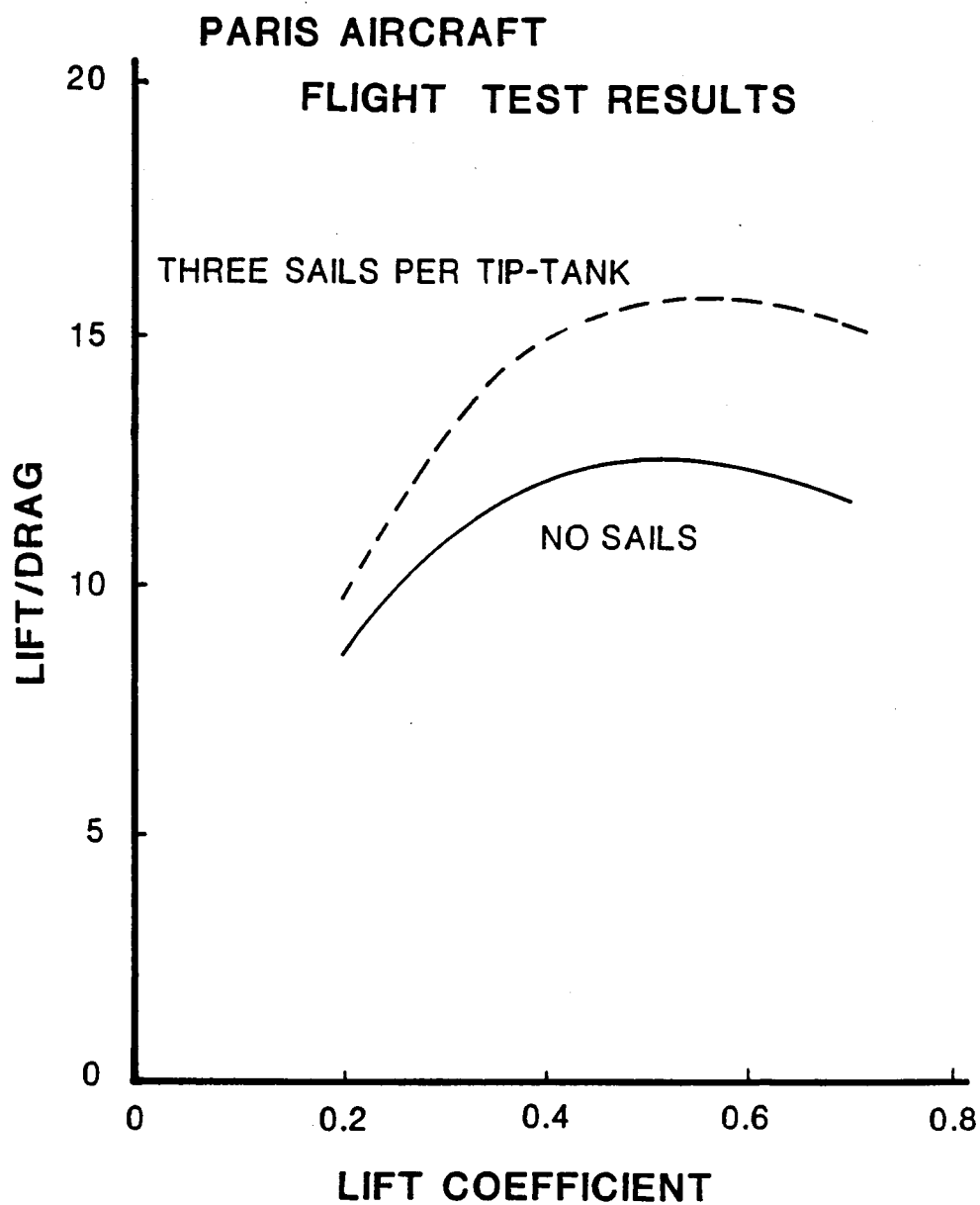


Figure 6. Lift to Drag Ratio for Cranfield's Initial Tests.

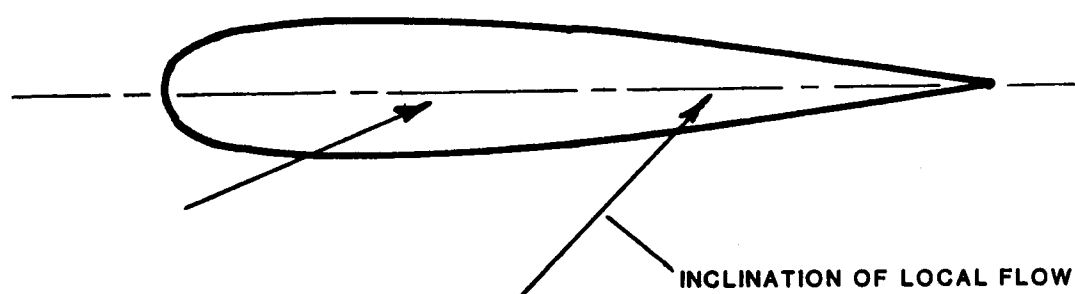


Figure 7. Variation of Local Flow Angle Along the Chord at the Wing Tip Taken from Cranfield's Initial Tests.

the rear. Much time was spent trying to find a way of measuring the wake vorticity in the UTSI water tunnel. Finally, the photographing of hydrogen bubbles proved acceptable. During this time, a report by Virginia Polytechnic Institute (VPI) [2] was discovered. They used plain tips of varying configuration and "Whitcomb"-type winglets and variations thereof.

By accident we discovered an old article on man-powered flight [3] which opened up several sources to the study of both birds and airfoils. At this time we were also involved in putting our model into the UTSI Low Speed Wind Tunnel and, as a result, did not have time to study in detail the bibliographical information which was accumulating. Study of the same led to areas suggested for future work.

If the discovery of References [2-6] had been made prior to the experimental work, the sails would have changed shape (spanwise camber) and had varying incidences among them for a given configuration. The work of Cone [4,5,6] shows the benefits of the spanwise camber, and the paper by Mitrovitch [3] combined with the Cranfield data, give indications of incidence angle settings for experimentation.

CHAPTER II

BACKGROUND INVESTIGATION

Vortex Studies

If we assume that some kind of wing tip (in this case, say, a multiple tip) can increase aerodynamic performance, we would expect to see a decrease in energy in the Y-Z plane of the trailing vortex wake.

Many times in literature when single wing tips are being discussed, "Crow Instability" is referred to as a mechanism for vortex decay. This is applicable to the case of a single, concentrated vortex from each tip, separated by the span of a finite wing.

In the derivation, Crow points out that it does not apply when the vortex diameter is comparable to the separation distance [7]. This is what we have when multiple vortices are shed from a single wing tip. If we can measure a decrease in rotational energy fairly close behind a wing tip, that decrease should be due to some other mechanism. This decrease would decrease the induced drag.

Von Karman derived, in 1934, that the energy in the wake equals the induced drag multiplied by the longitudinal velocity imparted to the wake [8]:

$$E = D_i V_x .$$

The induced drag is a function of the integral of the velocities in the Y-Z plane (velocities added due to the passage of the wing).

Let us note, at this point, the following. If we have a vortex with a given circulation function denoted by:

$$\Gamma = 2\pi r V_t ,$$

where V_t is the tangential velocity in the Y-Z plane, there is a finite viscous rotational core associated with it, as shown in Figure 8.

If the core size is increased, the integral of the velocity profile in the core will be decreased, but the velocities outside the core remain the same (i.e., for the same circulation, the energy contained in the Y-Z plane of the wake may be reduced) [2, p. 9]. Note that if this core velocity is reduced, the downwash will be less at the tip and cause a better wing lift distribution at the tip.

We are going to look at two mechanisms which may be responsible for reducing the core velocities:

(a) vortex interaction and (b) out-of-plane effects.

Vortex Interaction

Fohl and Turner, based on observation, published a paper which states that when two vortices, in real fluids, encounter each other the entrainment and merging of the two vortex cores become significant [9]. They asserted

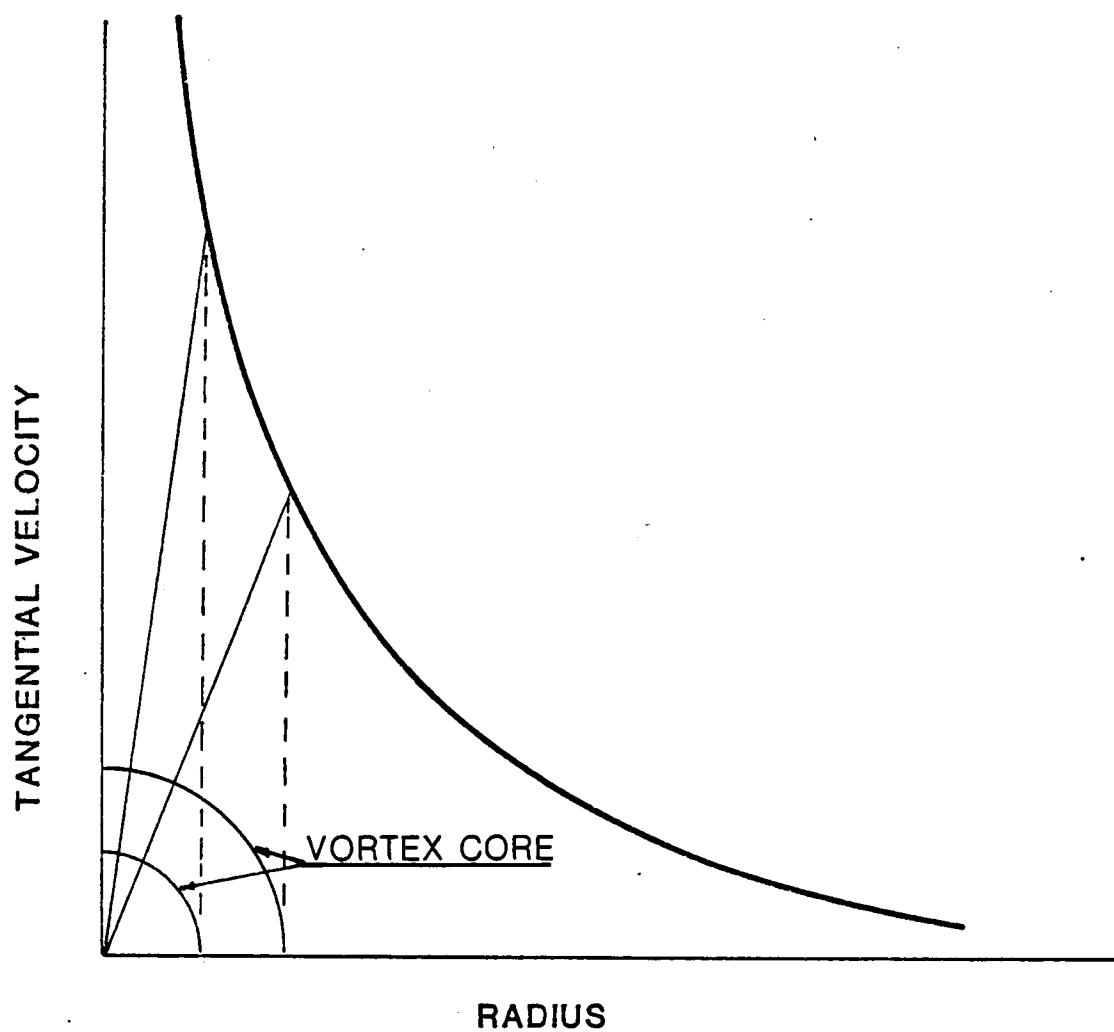


Figure 8. Velocity Profile for an Elementary Vortex (Planar) [4].

that when the cores merged, viscous diffusion will tend to annihilate the vorticity in the region of contact.

Figure 9 is reproduced from their paper (points A and B are closer to the observer than are C and D).

Rossow has done a great deal of work with vortex generation and modification along wingspans [10]. Rossow shows, by experiment, that vortex generators spaced along the span of a Boeing 747 can alter C_{D_i} . For one case, "The results indicate that properly designed fins can reduce the associated penalties and, in fact, can increase the lift and reduce the drag of the conventional B747 landing configuration." Rossow attributes this to reduction in flow separation. But it may be the mechanism we have already cited--vortex interaction--creating a better lift distribution. The tapered wing of the B747 is not a good test bed since wing tip devices are most suitable for constant chord planforms, where a strong tip vortex can be utilized and reduced. (See the discussion by Spillman [1].) Rossow's optimum location for a top wing surface vortex generator was at 0.5 span. (See also Rossow's discussion [11, p. 162].)

Rossow does note the same conclusion concerning kinetic energy and circulation we have previously noted. Under the topic of "Rectangular Fins on Span Loading," he states:

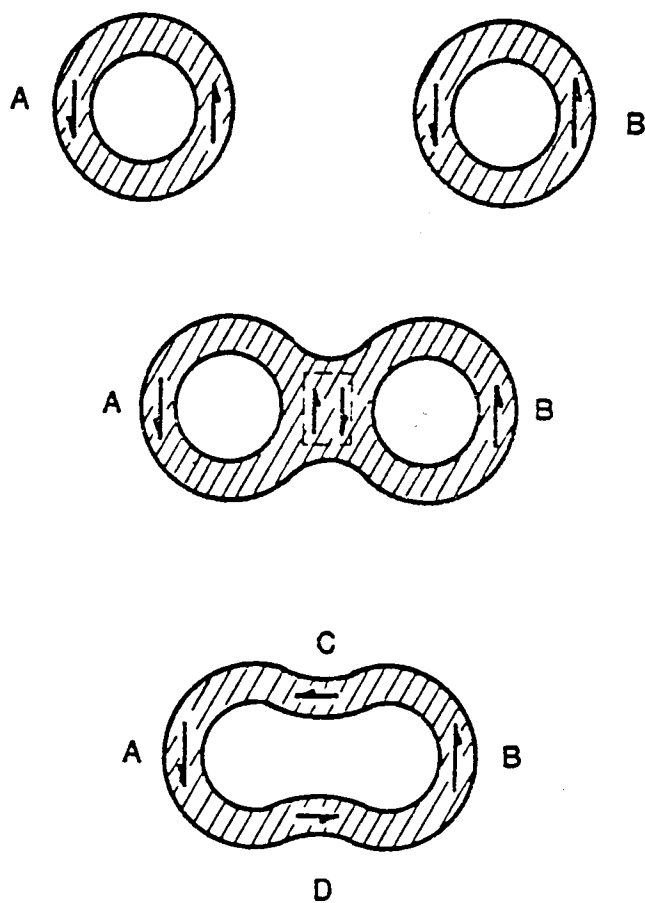


Figure 9. Illustration of Vortex Merging [9].

The fin appears to redistribute the wake vorticity so that the interior of the vortex has reduced velocities but the outer parts are hardly changed Such a large difference in rolling moments (analogous to tangential velocity) for a small change in span loading indicates that alleviation can be accomplished by balancing the wake vortex distribution so that favorable interactions occur [10].

Note that Rossow's theoretical works are inviscid, but his experimental paper is involved in real fluids with some viscosity.

Hackett showed that when the tip vortex was split into several vortices, "significant reduction of rotational energy was obtained" [12]. (He also concluded that vanes should be set at maximum C_L , not maximum C_L/C_D . Fins below the wing line were not efficient.)

This leads one to think that the viscous interaction of multiple vortices enlarges the core of the merged trailing vortex, reducing the induced drag. Especially interesting is that Cone [5] mounted a vulture wing in a wind tunnel and could detect no trailing vorticity behind it when the tip feathers were loaded. Upon depressing the leading feather he immediately detected a large trailing vortex.

Out-of-Plane Effects

Cone also produced a classic paper on non-planar wings in which, both by mathematics and an electrical potential analogy, he shows that a non-planar wing can

have a lower induced drag than an elliptically loaded planar wing of the same span. This is for inviscid, incompressible flow. Several configurations are analyzed. Those that had frontal view configurations resembling the curving tip feathers of a bird were quite efficient.

Cone states in his general conclusions [4]:

For the forms investigated here, it appears that modifications which tend to release the major portion of the vorticity near the tip and over an appreciable vertical area result in the greatest increases in k . For the forms considered, it appears that increases in k of 30 to 50 percent are possible . . . where k is the efficiency factor related to induced drag and its relationship to the lift/drag ratio is

$$\frac{L}{D} = \frac{C_L}{C_{D0} + \frac{C_L^2}{\pi k A}}$$

An example is shown in Figure 10. Note how this resembles the soaring bird's tip feather pattern.

It should be noted that some experiments have been conducted at UTSI which bear a relationship to these effects. Discrete jets at the tip (spanwise blowing) have produced marked improvements in wing performance [13,14, 15] (see Figure 11). The improvement is attributed to the secondary vortices produced by the jet in the local crossflow. These vortices are located out of the plane of the main wing, in a manner similar to the non-planar wings previously described.



Figure 10. One of Cone's Optimized Wing Configurations.

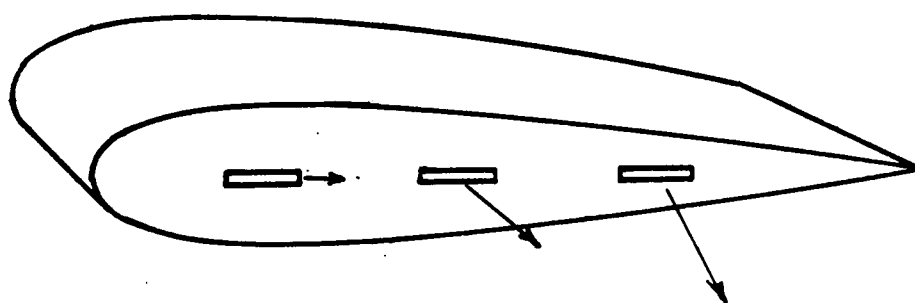


Figure 11. Wing Tip Model Illustrating Discrete Wing Tip Blowing as Done by UTSI.

Studies of Bird Flight

Cone's work was cited in a paper [3] on man-powered flight written by Mitrovich in 1970 (before the Kremer prize was won). The advantage of a geometrically low aspect ratio producing a high aerodynamic aspect ratio would have saved weight in a man-powered aircraft. Therefore, Mitrovich notes Cone's references to vultures, hawks, etc., as being good soarers with "modest aspect ratio" compared to those of the albatross and seagull.

Cone's work may give us a lead in determining just how wing tip "sails" or feathers should be configured. His description of the Black Vulture wing tip follows:

The effective wing-tip consists of seven long slender primaries which, considered as individual airfoils, have very large aspect ratios ($A = \text{about } 14$). In the circling phase of flight these pinions are always held fully extended and present somewhat the appearance of a fan as they radiate out from the main wing. This spreading out separates the pinions from one another and leaves large gaps or slots between successive feathers. The pinions are also spread out vertically due to their bending or curving upward under the air load they carry. The leading pinion bends upward strongly, with its tip almost vertical. The second pinion also has a strong curvature, but less than the first, and so on until the sixth and seventh pinions actually curve downward in flight. The first three pinions are all heavily loaded; the fourth through the seventh are not nearly so curved. A good idea of the three-dimensional disposition of the pinions in flight can be obtained by fully spreading the fingers on the hand and then raising the thumb as high as possible while twisting the hand so that the little finger is turned down.

In this way each succeeding feather lies below the plane of the one in front of it so that each pinion is essentially operating as an individual airfoil. Flight photographs of the pinion spread of condors appear in plates 9 and 11 in Koford (1953) and of vultures in Storer (1948:70). (In these photographs the pinions are only moderately loaded.)

In flight, the curvature of these pinions is automatic. That is, they assume their proper curvature automatically due to their elastic deformation under the air loading and not because of direct control by the bird. I have shown this by testing a rigid vulture wing in a wind tunnel. At angles of attack below stall and at speeds equal to the usual flight speed of the bird (20-25 miles per hour) the pinions automatically spread out vertically in exactly the same pattern as that photographed in soaring birds. Different degrees of pinion spread and curvature can be obtained by varying the wind speed while holding the angle of attack of the main wing constant or by varying the angle of attack while holding the air speed constant. In actual flight, of course, the angle of attack uniquely determines the equilibrium air speed of the bird, so that this natural combination we might call the "design" flight conditions. Each pinion has a carefully tailored structure to give a specific elasticity gradient and twist so that it will attain a precise curvature for the specific angle of attack being flown. When not under an air load the pinions all curve strongly downward at the tips. The leading pinion has an appreciable geometrical twist near its tip so that it presents a rather large angle of attack to the airstream, and hence, in flight, the heavily lifting tip produces a sharp curvature of the pinion. The second pinion is also twisted but to a lesser extent. The third pinion has only a slight twist, while the others have none. However, in flight, the fourth pinion still has some span curvature just due to the elasticity of the feather. In flight the tips of the first four pinions have been bent from the strong downward curvature to an upward curvature. The force necessary to do this is appreciable and for large birds like the condor the force may amount to a pound or so for bending a single pinion. At lower lifts the feather curvature automatically decreases and the wing assumes a more conventional tip shape. As the pinions bend or curve under the

air load, stresses are set up in the vanes of the feather which cause it to become more and more cambered as it bends. Such cambered airfoils are capable of producing much more lift than flat sections, and this explains why the pinions become so highly curved at low flight speeds. Here we have the ultimate in aerodynamic design: the use of aeroelasticity for automatic geometry control [5].

This quotation is included because it is so authoritative; Cone having tested a vulture wing; and because any other factual description of bird tip feather configuration is unknown. In addition to position, span-wise camber, and articulation of the feathers, he notes the twist of the leading ones. This will be referred to at the conclusion of the present work. From Cone's description, one would think that the incidence angle among the tip feathers was higher toward the front ones.

Mitrovich cites in his paper another study which might have bearing on the incidences of the feathers. In 1936, Nenadovitch did work on biplane configurations [16]. He shows that there is an optimum biplane interplane distance and stagger and incidence angle between the airfoils. The resulting wing combination has lower drag and higher lift than the equivalent monoplane. Figure 12 is reproduced from this work. Figure 13 is also from Mitrovich's paper, as he suggests that the incidences may reduce toward the front. Plate 9 in Koford [17] seems to support this geometry.

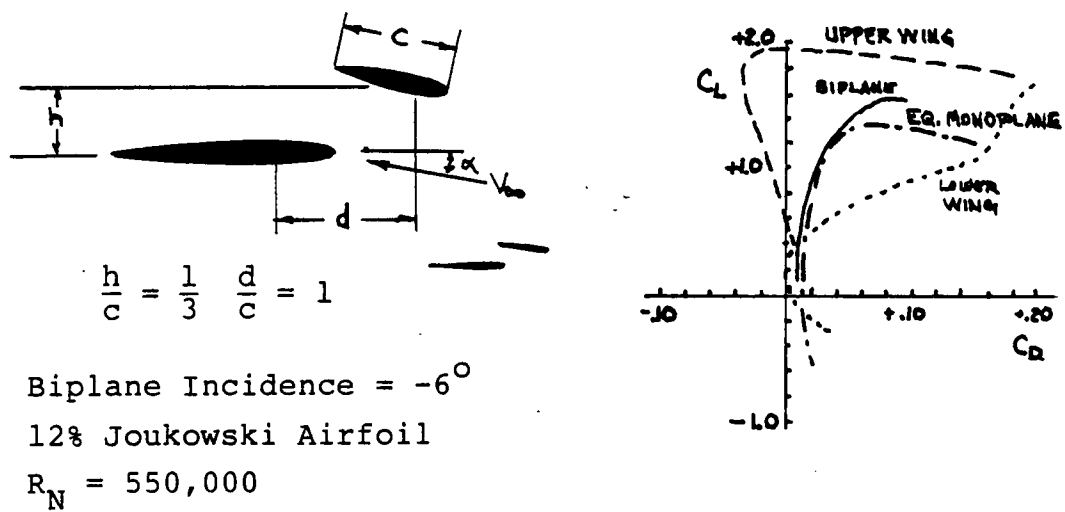


Figure 12. Nenadovitch's Optimum Biplane Configuration [3].

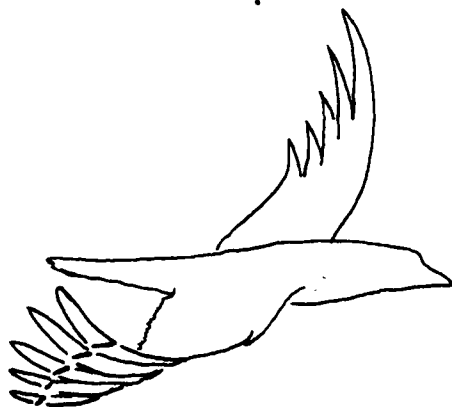


Figure 13. Illustration from Mitrovich's Paper [3].

Following are some bird pictures (Figure 14). The feathers appear to have equal incidences and do not support this geometry. One of the pictures is of ornithoptic (flapping) motion, where contributions due to unsteady flow become important. This is outside the realm of the present study, as we shall be concerned only with steady flow. It is interesting that the tip feathers are spread in this motion also.

Based on these references and the Cranfield wing tip flow data, it is suggested that for future work, the root sections of the sails decrease toward the front. It is believed that, under low loads, the front pinions of a bird are twisted such that the tips have higher incidences toward the front. Under loading the front feathers decrease their incidence relative to the rear feathers. This also will be referred to at the conclusion of the present study.

In 1950, Raspet of Mississippi State University published a paper on performance measurements of a Black Vulture [18]. His measurements (made by flying behind the birds in a sailplane) show a change in C_L^2 versus C_D when the bird closed his wing tip slots (feathers). The effective aspect ratio went from 3.18 to 4.7. This is shown in Figure 15.

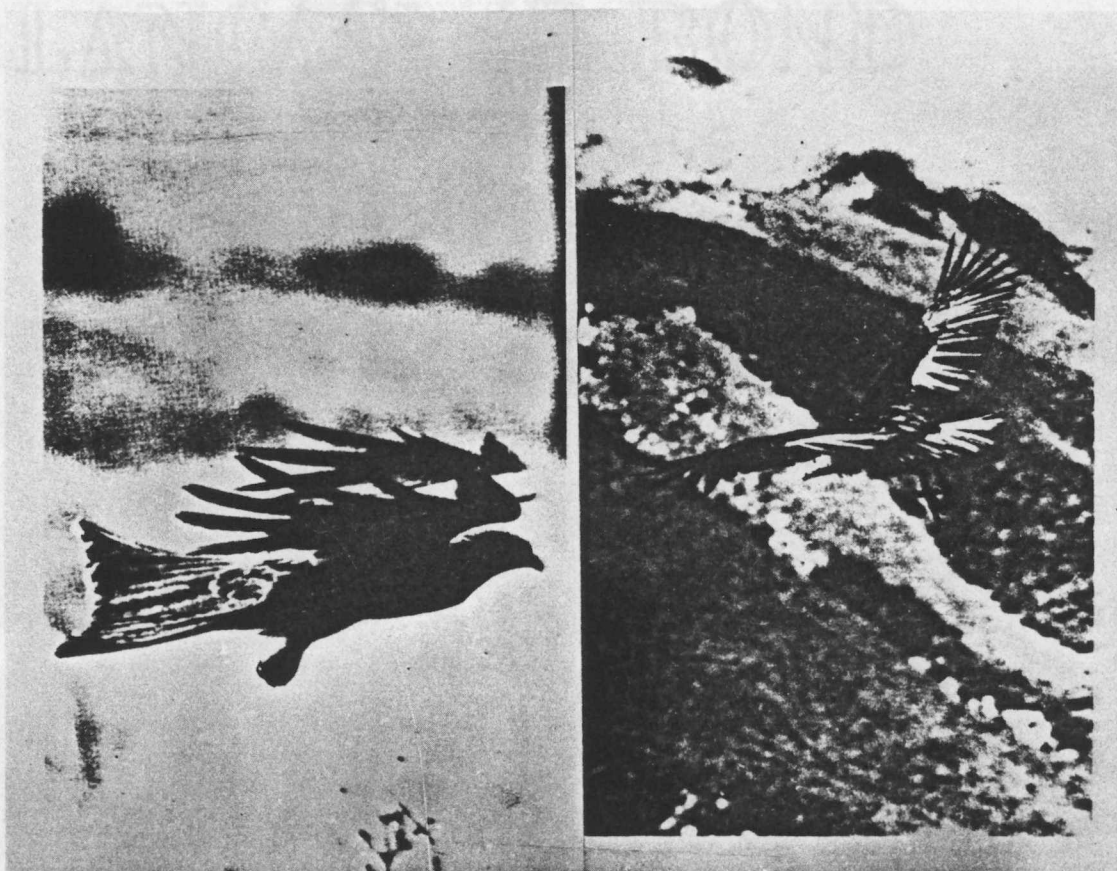


Figure 14. Photographs of Birds which May Indicate Incidence Variation for the Tip Feathers.

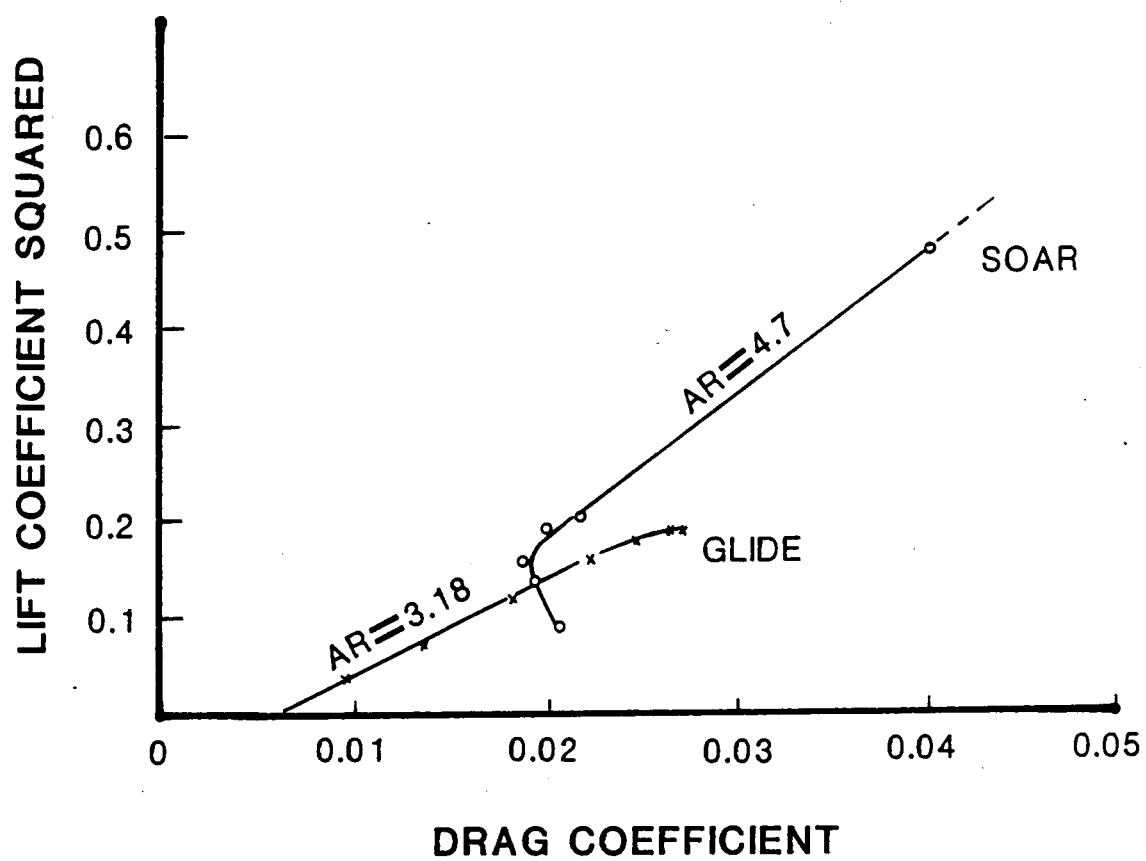
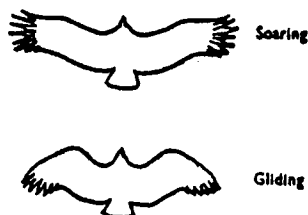


Figure 15. Drag Polar for Black Vulture [18].

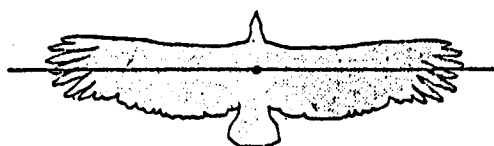
Newman [19] in 1957, disagreed with Raspet. He felt that the changes in performance were due to actual physical changes in aspect ratio due to the bird pulling its wings into its body. He reproduces two sketches from Aymar [20]; they are identically traced below.



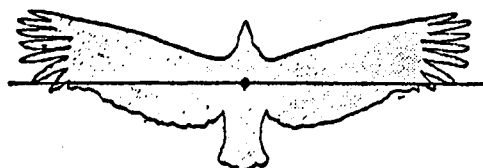
Observations do not substantiate that birds always make such a large change in span as they close the primaries. The sketches and subtitles shown in Figure 16 are taken from Hankin (1913) [21], who spent much time in observation. Note that Newman's sketches match those of Hankin's "effort to gain height" and "fast flex-gliding"--the most extreme cases.

In plate 10 of Koford's book [17] there are photographs of California Condors with primaries open and closed. There does not appear to be a wingspan change. Obviously, there is room for Raspet's contention.

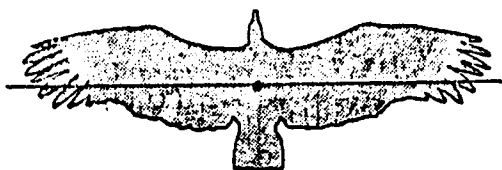
Newman also uses a mathematical proof to show that two wings in tandem produce the same vortex drag as an equally loaded monoplane.



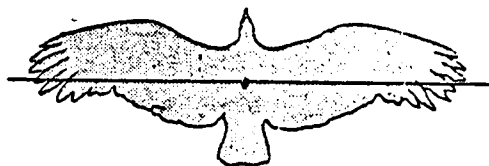
a. Outline of a Vulture Circling in Air Not Fully Soarable, or Circling in Fully Soarable Air without Effort to Gain Height



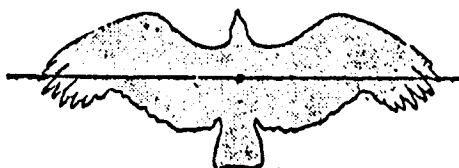
b. Outline of a Vulture Circling in Fully Soarable Air and with Effort to Gain Height



c. Outline of a Vulture Slow Flex-Gliding (8 meters per second)



d. Outline of a Vulture Flex-Gliding at Medium Speed (12 meters per second)



e. Outline of a Vulture Fast Flex-Gliding (22 meters per second)

Figure 16. Soaring Bird Planforms Observed by Hankin [21].

Cone had trouble with this mathematical model. He first offers his main explanation of the drag reduction mechanism and then states:

An alternative explanation of the drag reduction mechanism of the pinioned wing is to consider it as a multiplane system in which the planes (the pinions) merge to form the main wing. If we apply Munk's results (1921) on multiplanes, it is easily proved that the pinioned wing must reduce the induced drag over that of a single wing. Newman (1958) has concluded that the pinions do not reduce the induced drag, as a result of a simple analysis of tandem airfoils to which he compares the bird wing. It follows, of course, directly from Munk's Stagger Theorem that merely splitting a flat airfoil into several separate foils arranged one directly behind the other has no effect at all on the total induced drag. However, the vertical arrangement or gap of the individual foils has a critical effect which Newman failed to consider: a multiplane system with gaps always has less induced drag than a monoplane of equal span and lift [5].

Von Karman showed this mathematically [8, pp. 201-222]. He developed tables by which one can calculate the reduction in induced drag for biplanes and triplanes.

The Newman paper is considered to be in error.

Before leaving bird studies, we should go back and present Cone's primary explanation for what is going on:

Now when the bird is operating at a high lift coefficient, as in circling, if the wing-tip were one continuous piece, the lift would go rapidly to zero at the tip, thus producing a strong vortex sheet behind it. However, the tip is actually broken into seven smaller, high aspect ratio vanes which are strongly curved upward and inward as discussed. In order that these vanes remain curved in this manner, a component of the airload must act in a spanwise direction, and this means that the pinions must be throwing air outward, away from the center

of the wing. This outward flow prevents air from sweeping in from the tip over the upper surface of the main wing, as it would otherwise do, and thus prevents the formation of a trailing vortex sheet behind the main wing. The total wing circulation is of course shed in very weak vortex sheets from the high aspect ratio pinions, but due to the spreading of the vorticity over a large area instead of confining it to a single tip vortex, the kinetic energy of the flow field is appreciably reduced as is the associated induced drag. In effect, therefore, the pinions can considerably reduce the overall intensity of the trailing vortices in exactly the same manner as would a large endplate. In fact, each pinion may be considered as a small endplate, eliminating its portion of the induced drag [5].

Figure 17 illustrates what Cone has said here.

Experimental Investigations

The following discussion will highlight what, in my opinion, are some of the best quantitative reports on wing tip devices. The works come from the Cranfield Institute of Technology [22,23], Virginia Polytechnic Institute and State University [2], George Washington University [24], and NASA Langley Research Center [25].

In addition to the work cited in Chapter I, the Cranfield Institute of Technology recently published two more reports--both having to do with multiple "sails." In the first, full-scale wake tests were done with one aircraft obtaining readings of the wake by use of a vane mounted on a nose boom [22]. The data is shown in Figure 18. The difficulty of flying through the center of the wake and the response of the vane caused so much

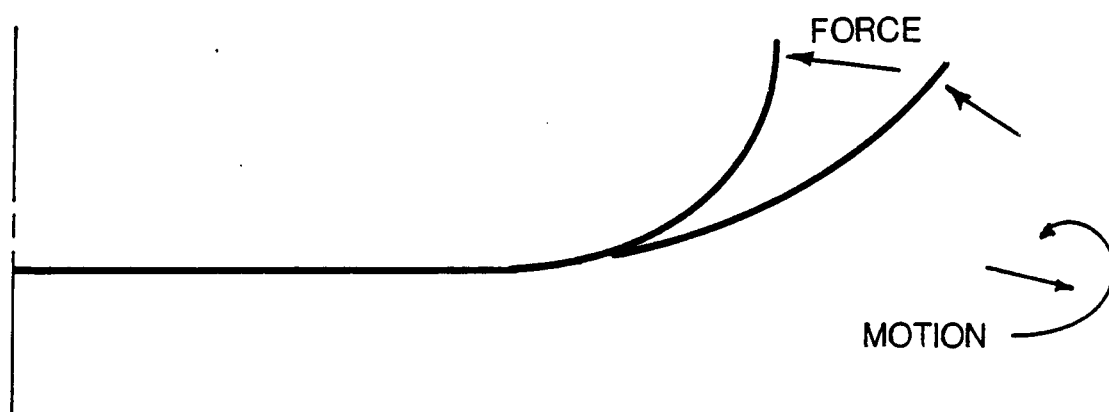


Figure 17. Illustration of Shed Vortex Lateral Motion.

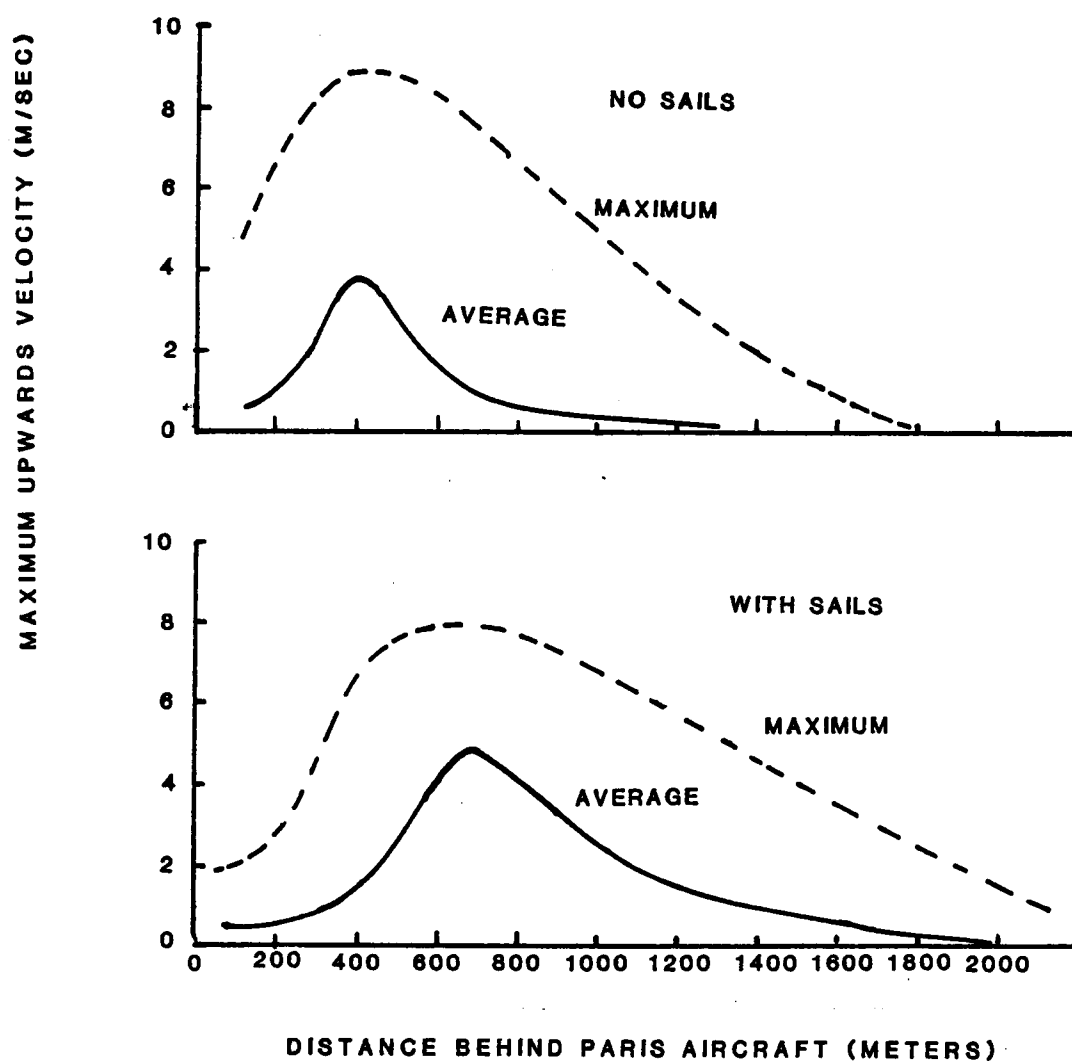


Figure 18. Wake Data from Cranfield's Full-Scale Flight Test [23].

scatter in the data that little is conclusive. Sensibly looking at the data causes one to believe that sails do indeed reduce vorticity up to 1,500 meters behind the wing. The wing tip was of the original Cranfield type: three bladed, one vertical, one at 45° , and one horizontal (from mid-chord to trailing edge).

In the second paper [23], a 1/10 scale model aircraft was tested in a wind tunnel with both multiple sails and a winglet similar to Whitchomb's. Multiple sails used both cambered (at the root, as in [1]) and uncambered airfoils. There were four sails per tip with 5° dihedral between them. The third one was horizontal. The cambered sails invariably had flow separation at the root. At high angles of attack this appeared on the top surface at the sail-wing junction. At low angles of attack the camber caused separation on the underside. The uncambered sails had separation at the root for most incidences, particularly the fore sail.

The model was small; sails were 1-inch span, approximately. The single winglet was 12% of semi-span. The multiple sails were 3% of semi-span. The single winglet could have been optimized at a lower C_L and shortened.

With this in mind, the multiple sails had better L/D than the single winglet for small angles of attack

(up to 5°), as shown in Figure 19. Also, the sails gave less increase in root bending moment of the wing.

In the VPI report [2], several mono-wing tip configurations were tested along with Whitcomb winglets. These are shown in Figure 20. Looking along the chordline (rear view), the pointed tip caused a 27% decrease in maximum tangential velocity in the vortex and a 6% reduction in core size (even with a 9% increase in shed circulation). Also, although several different types showed axial velocity deficits at the core, all except the pointed tip show an excess just outside the core. The pointed tip shows less energy both tangentially and axially, and, as cited in the present study, is probably due to the high shear gradient imposed at the sharp pointed tip. This is extremely interesting when compared to bird tip feathers (multiple sharp points).

The Whitcomb winglet produces two vortices wrapped around each other, in the same direction as their rotation, and the sum of their velocities is 50% of that of the pointed tip (estimated by this author from their graph). As shown in the VPI report [2, p. 26], in tow tank studies with dye, when the winglet and main wing vortices finally merged, the winglet vortex "eventually diffused so that only the main wing vortex remained, and even it looked

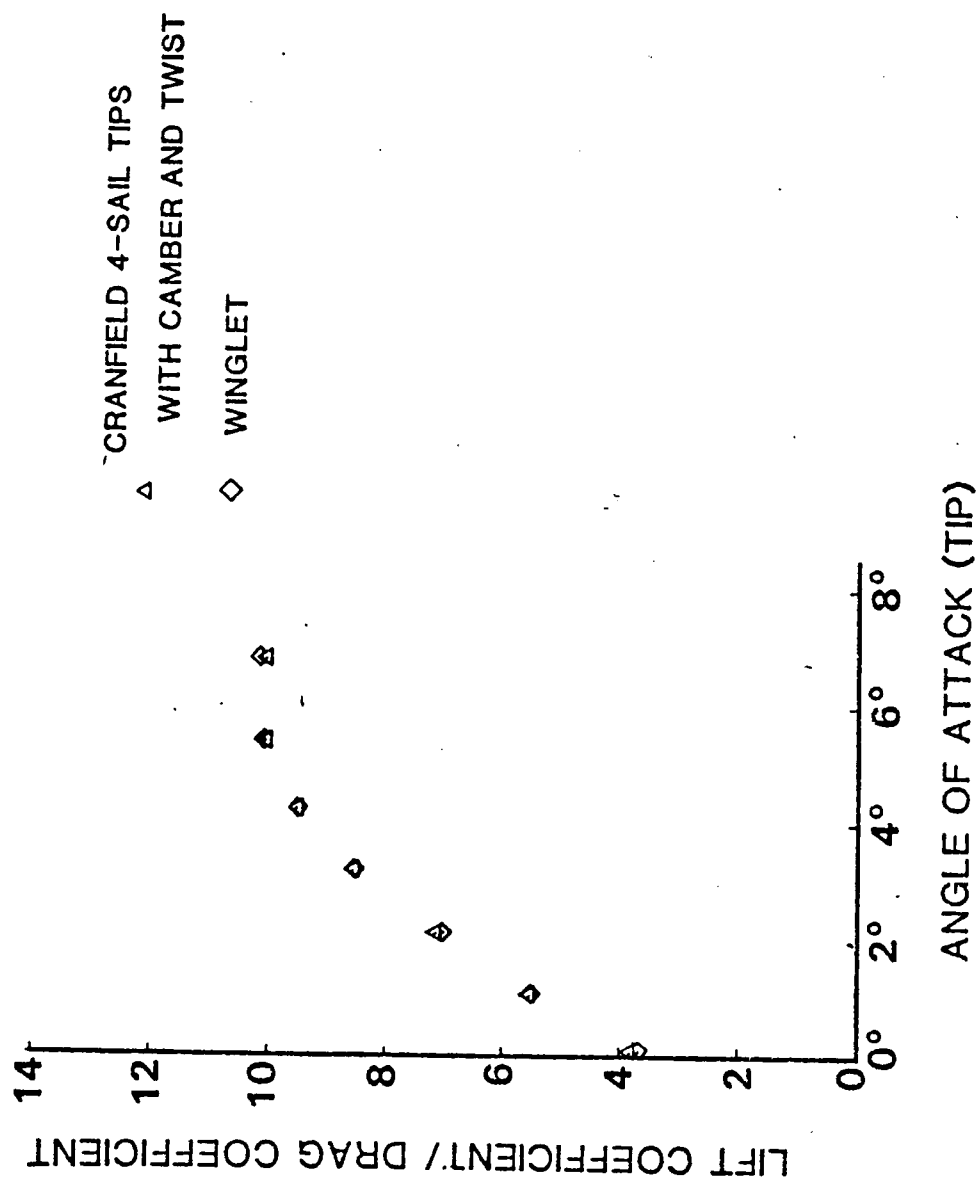


Figure 19. Cranfield's Wind Tunnel Test with Four-Sail Tips [22].

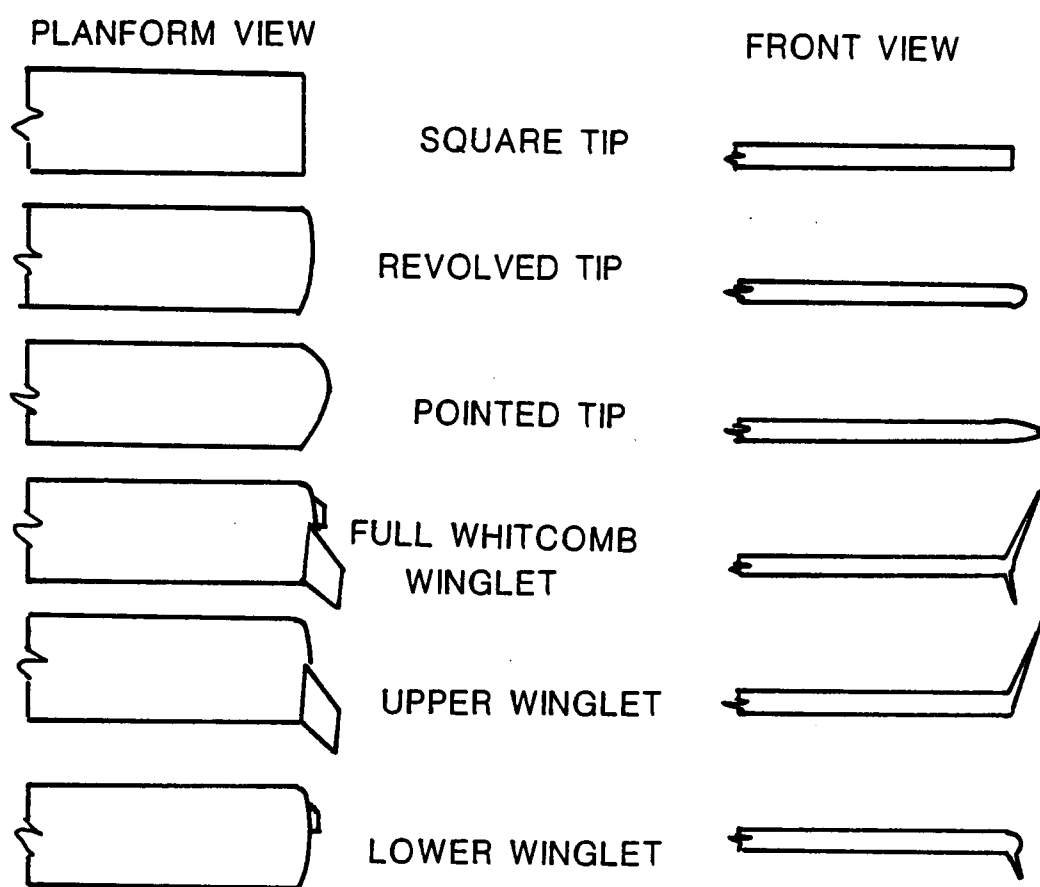


Figure 20. VPI Wing Tip Test Configurations [2].

somewhat dissipated." They estimated 50% reduction in wake vorticity. Axial deficits (which the Whitcomb displayed) near the wing are therefore associated with tangential reductions further downstream.

For the Whitcomb winglet, L/D improvements were not found until the angle of attack was above 3° . Figure 21 is reproduced from this work [2] and shows L/D for the several tips.

Note also, on the subject of load profiles:

A comparison of these (spanwise) pressure distributions with the vortex profiles clearly indicates that a reduction in maximum swirl velocity appears to be linked to a span load increase near the tips [2, p. 25].

Vulture planform is almost rectangular, which should give a higher loading, near the tips, than an elliptical distribution would.

In 1974, Yuan and Bloom presented some results of blowing downward from a tube placed, spanwise at the wing tip near the trailing edge [24]. It is referenced here because the results on circulation and kinetic energy are similar to that of multiple sails. A full span model of 69-inch span was used and velocity measurements were made at one-half and five chord positions downstream with a hot film probe. Rolling moments (indicative of tangential velocity) were taken with a small rectangular wing placed in the wake. Also, lift and drag of the test model were measured.

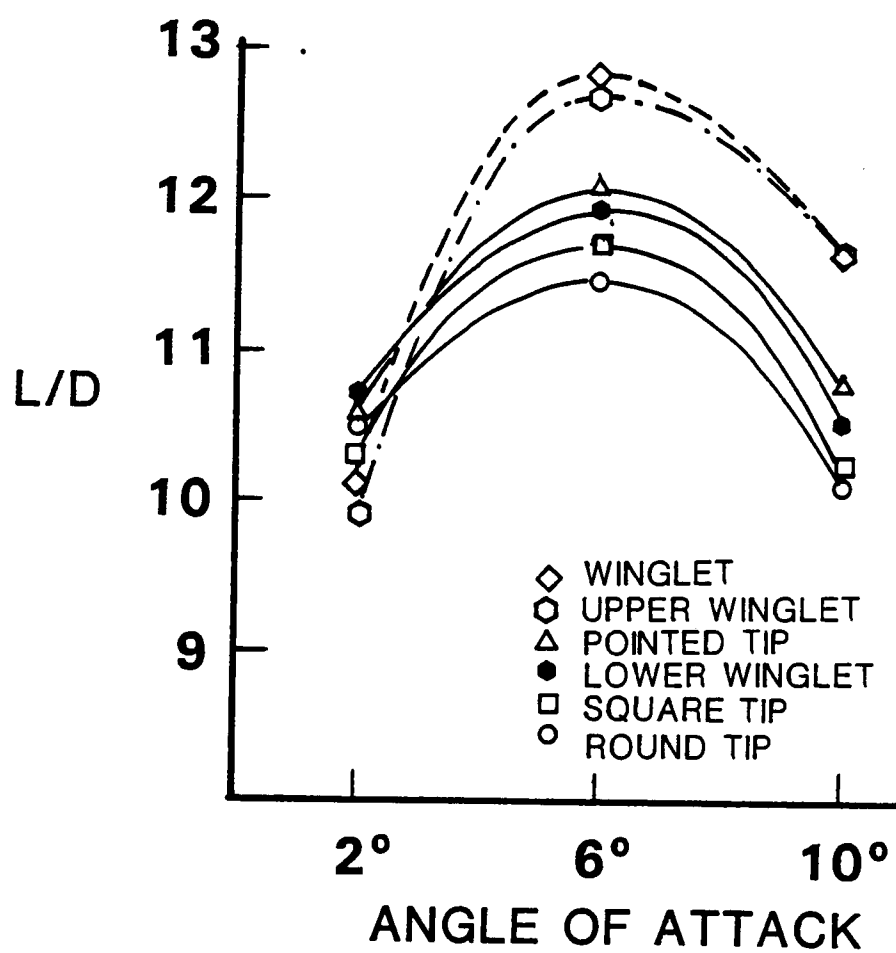


Figure 21. VPI Wing Tip Test Results [2].

In 1976, Dunham of NASA Langley Research Center presented wake data from tests on an ogee tip [25]. The planform is shown in Figure 22.

Data from all the above sources [2,22-25] are shown in Chapter III in comparison with our own experiments.

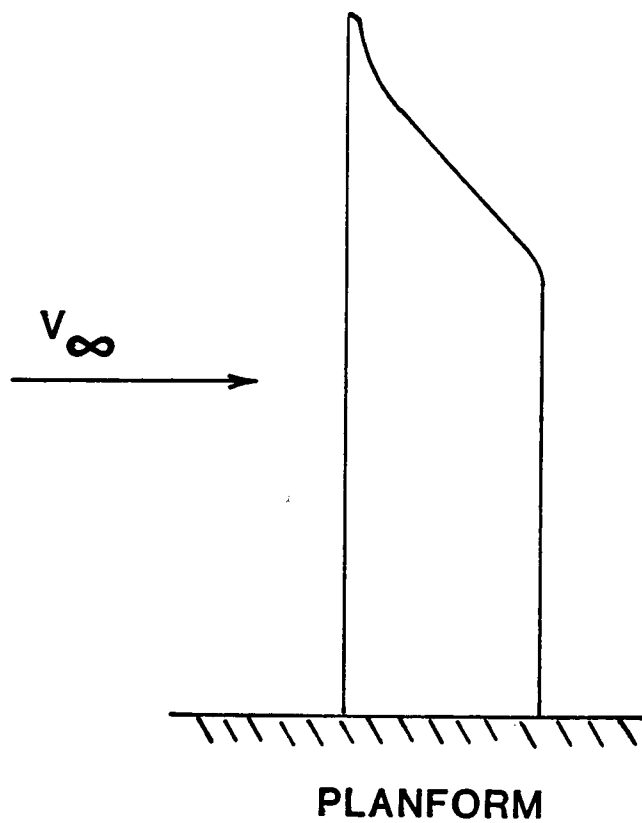
DUNHAM'S OGEE TIP

Figure 22. Dunham's Ogee Tip Configuration [25].

CHAPTER III

THE UNIVERSITY OF TENNESSEE SPACE INSTITUTE
EXPERIMENTS

Water Tunnel Wake Investigation

The first experimentation done at UTSI was a study of the wake vorticity in a water tunnel. Our objective was to determine what, if any, were the changes in the velocities in the Y-Z plane when sails were added to a wing. Our test setup in the UTSI 12-inch by 18-inch water tunnel is shown in Figure 23.

After some experimentation with dye injection and other methods, hydrogen bubbles were used to show the tangential velocity vector in the Y-Z plane. A crosswire (horizontal and vertical) of 0.003-inch diameter platinum wire was placed two and three and one-third chord lengths behind a 6-3/8-inch chord by 10-inch semi-span rectangular wing with a NACA 0012-64 airfoil. The tip of the wing was square in the Y-Z plane. The tunnel speed was 1.6 in./sec. The Reynolds number was 5,600.

Sails were made of wood, 2.75-inch in span, patterned after the Cranfield sails. One configuration utilized three of these sails at 90° , 45° , and 0° dihedral, equally spaced from model and test plane. Our other model

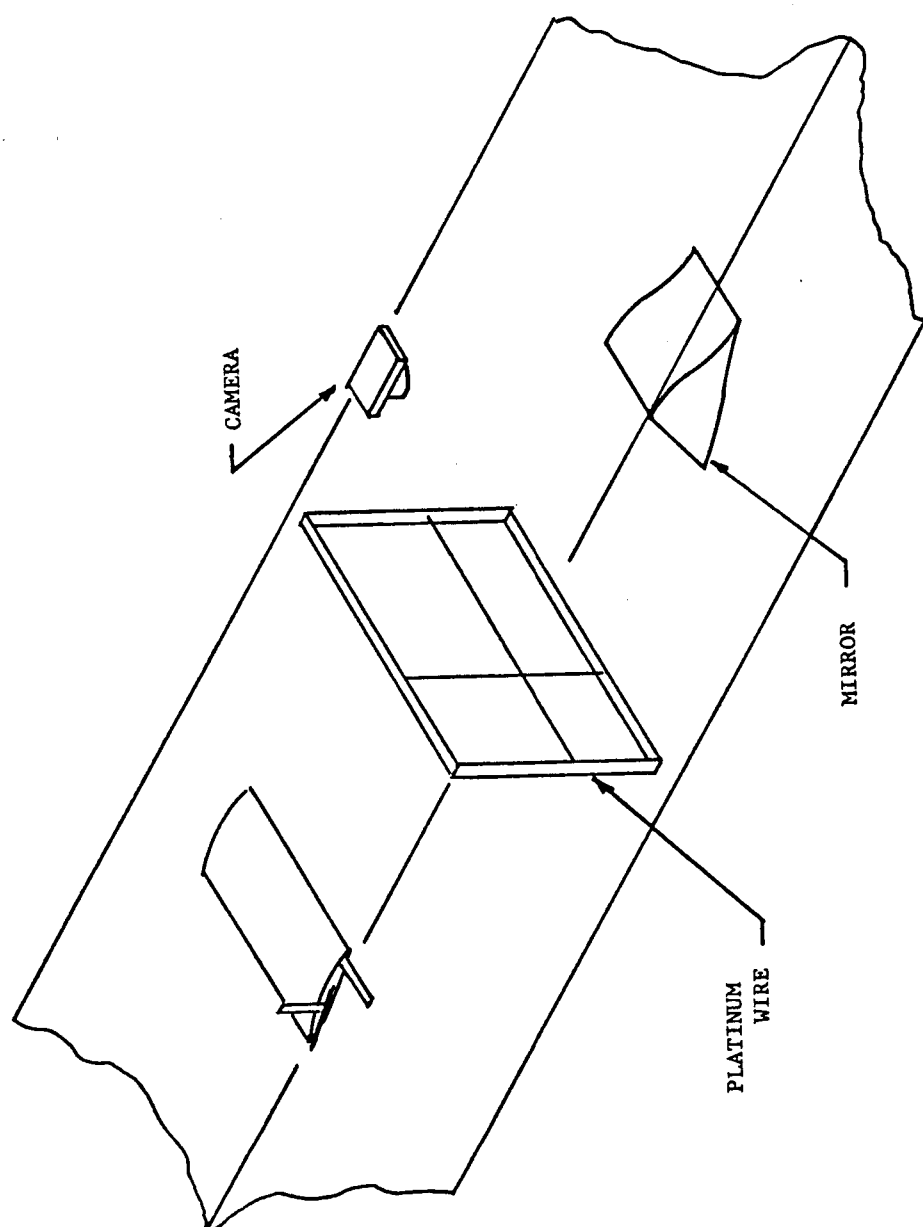


Figure 23. Illustration of UTSI Water Tunnel Test Setup.

had five sails equally spaced along the tip chord, ranging from $+16^\circ$ dihedral for the front sail, to -8° for the rear. These are shown in Figure 24.

A mirror set at 45° to the horizontal was placed approximately 36 inches downstream of the wing. Photographs were taken from overhead at a set delay time after a narrow pulse was applied to the wire. Best results were obtained with fresh water (no salt added) and about 70 to 80 volts d.c. (negative) applied to the crosswire. The voltage was adjusted to be just under a value that caused bubbles to form which were large enough to be buoyant. The platinum wire was "burned in" prior to taking data by allowing it to generate bubbles for several minutes. The circuit used for the pulse time and the photographic delay time is shown in Figure 25. Originally the circuit was to strobe light with the camera shutter open. It did not supply enough light. Instead, the output was used to trigger human response to trip the shutter. Our procedure was to trip the circuit and manually actuate the camera when one heard the firing of the strobe. Ideally, a slave solenoid should be in the output side to drive the shutter. It is estimated that the human response could produce errors of 5%. Our results seemed consistent and no problems were encountered with response time.

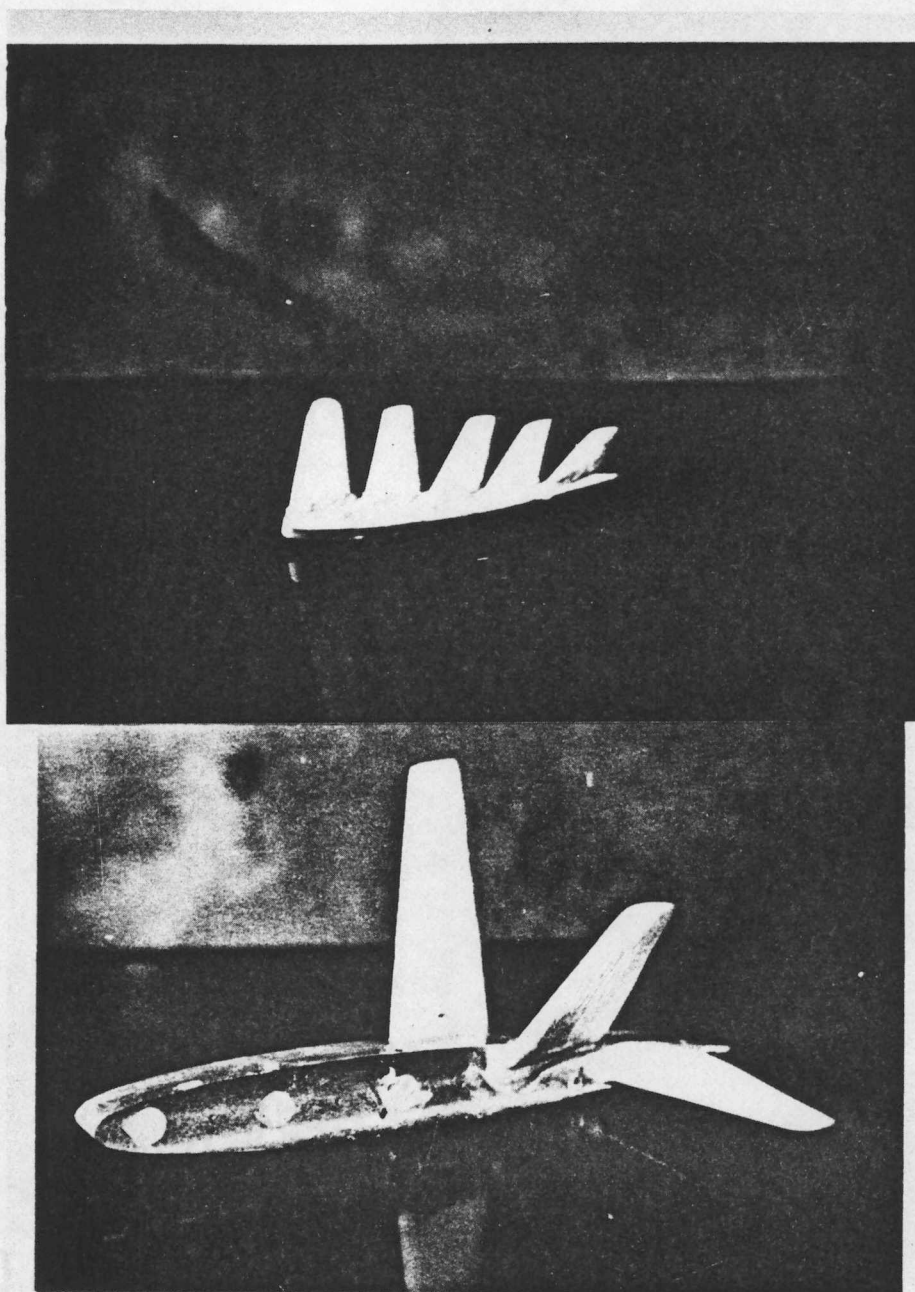


Figure 24. Models for UTSI Water Tunnel Experiment.

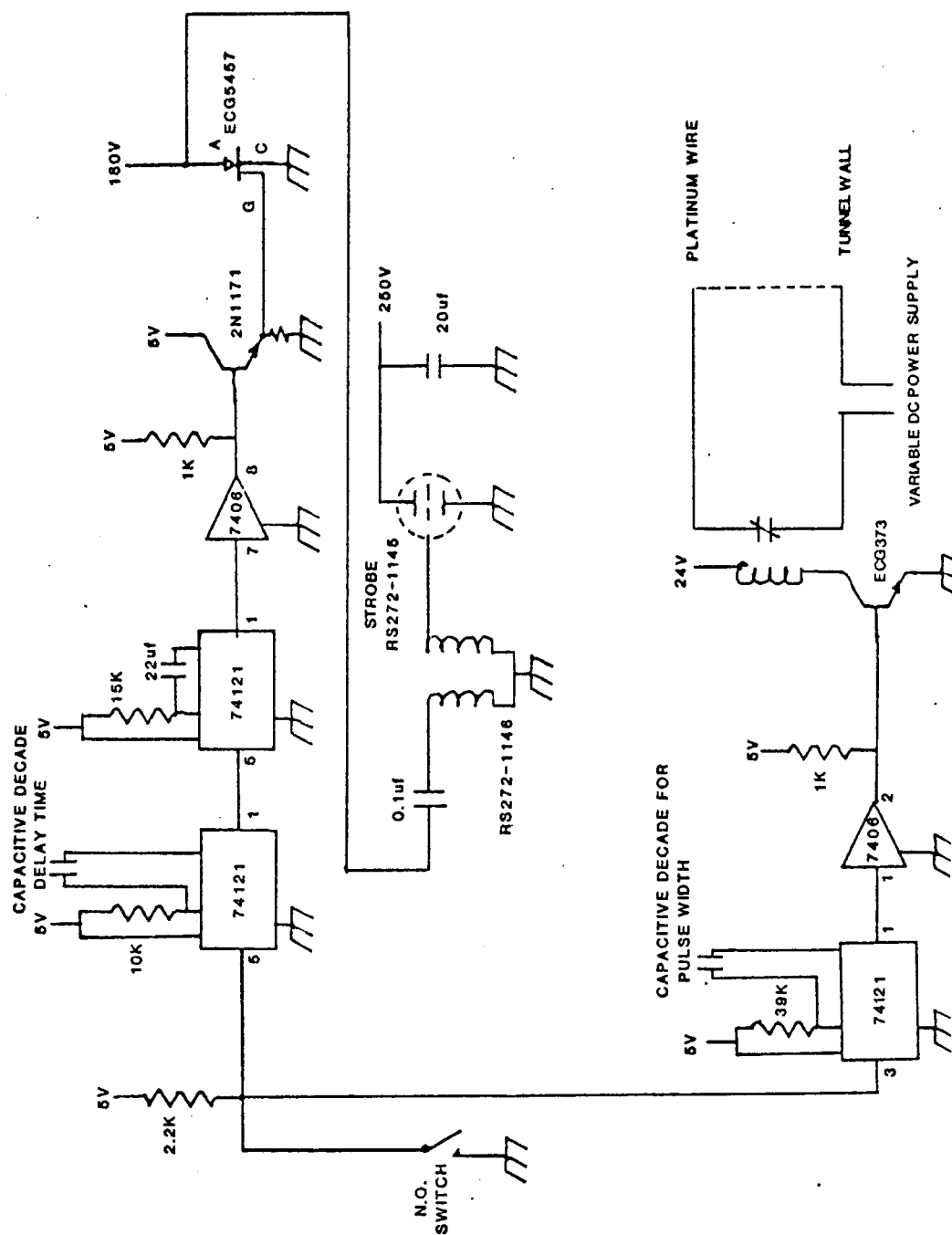
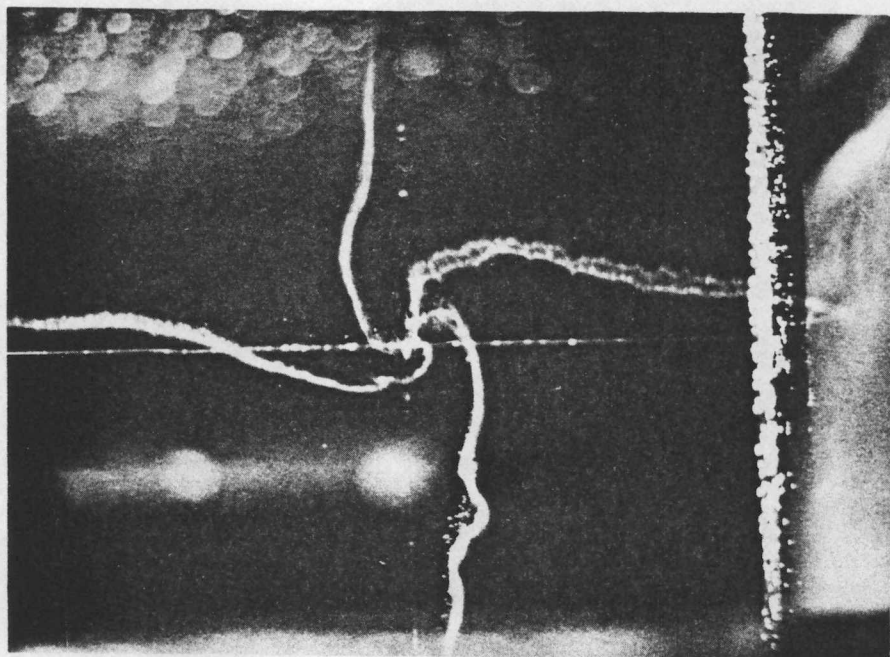


Figure 25. Schematic of Electrical Circuit for Hydrogen Bubble Generation and Photography.

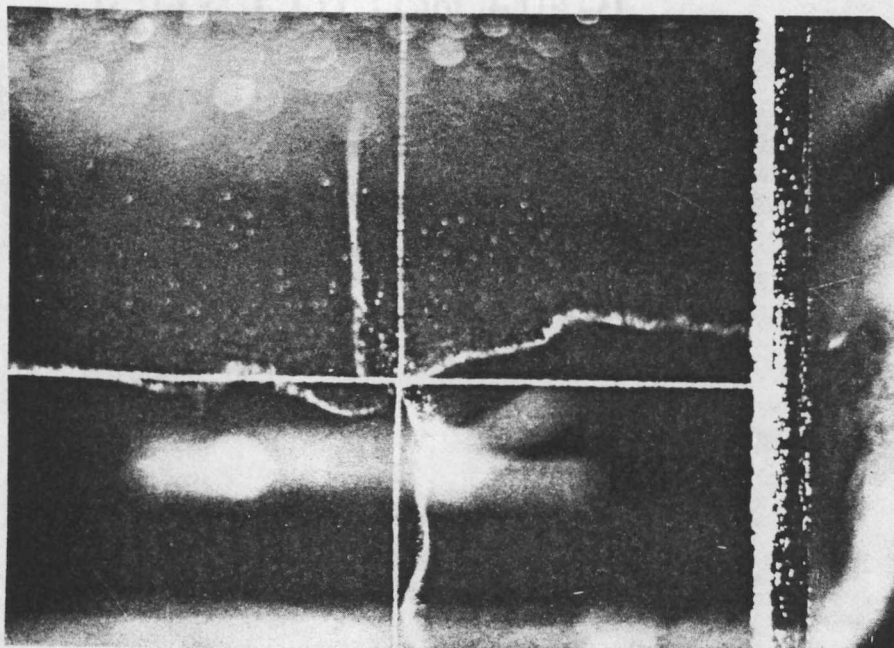
By knowing the dimensional scale and the delay time, the position of the bubbles was converted to velocity. (It was assumed that the radial component was negligible in comparison.) The biggest problem was finding the center of the vortex due to the fact that the presence of the mirror caused instability in the flow upstream. Several photographs would be taken, and the ones when the center did not move appreciably would be used. A set of sample photographs is shown in Figure 26. The photographs were expanded and traced into a more usable form by use of a Bausch & Lomb Zoom Transfer Scope®. A set of sample tracings is shown in Figure 27.

The results are qualitatively repeatable. Because some runs were shifted somewhat for the same configuration, the data are not averaged from run to run. Rather, cases which were run close to each other in time are compared. In some instances, all three configurations were tested in a matter of minutes. These results present such a strong case it seems a shame to lump them with sets which had been run on differing days. The cause of the shifts is unknown. As experimentation progressed during the summer of 1983, our water temperature varied. (The water is taken from a lake.) Also, the wires seemed to respond differently sometimes to the amount of current used. Due to these factors and any other unknown parameters, the data were



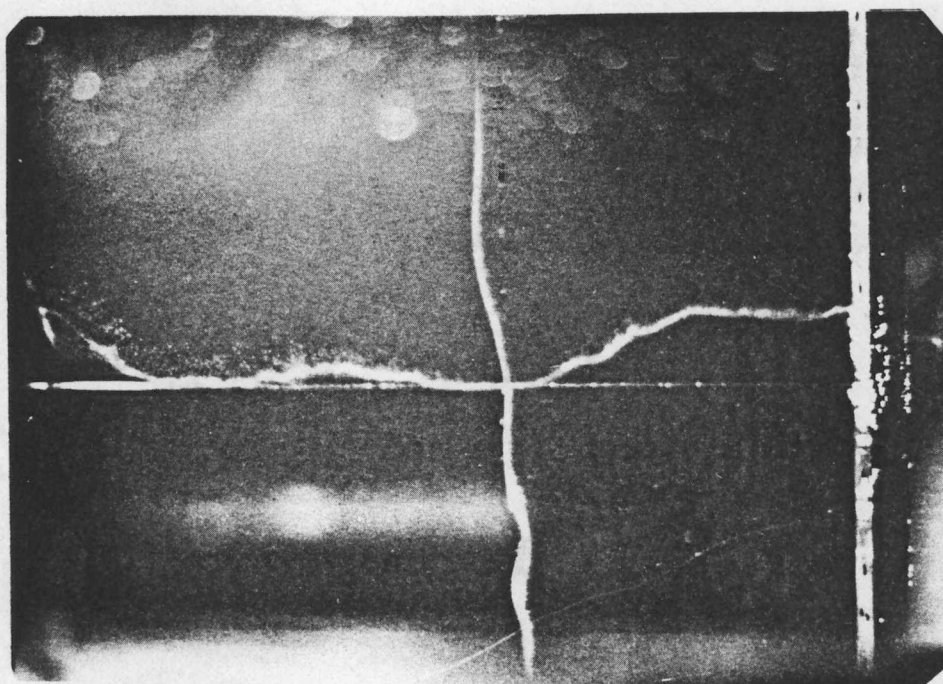
a. Plain Wing Tip

Figure 26. Photographs of Hydrogen Bubbles in the Y-Z Plane of Trailing Vortices.



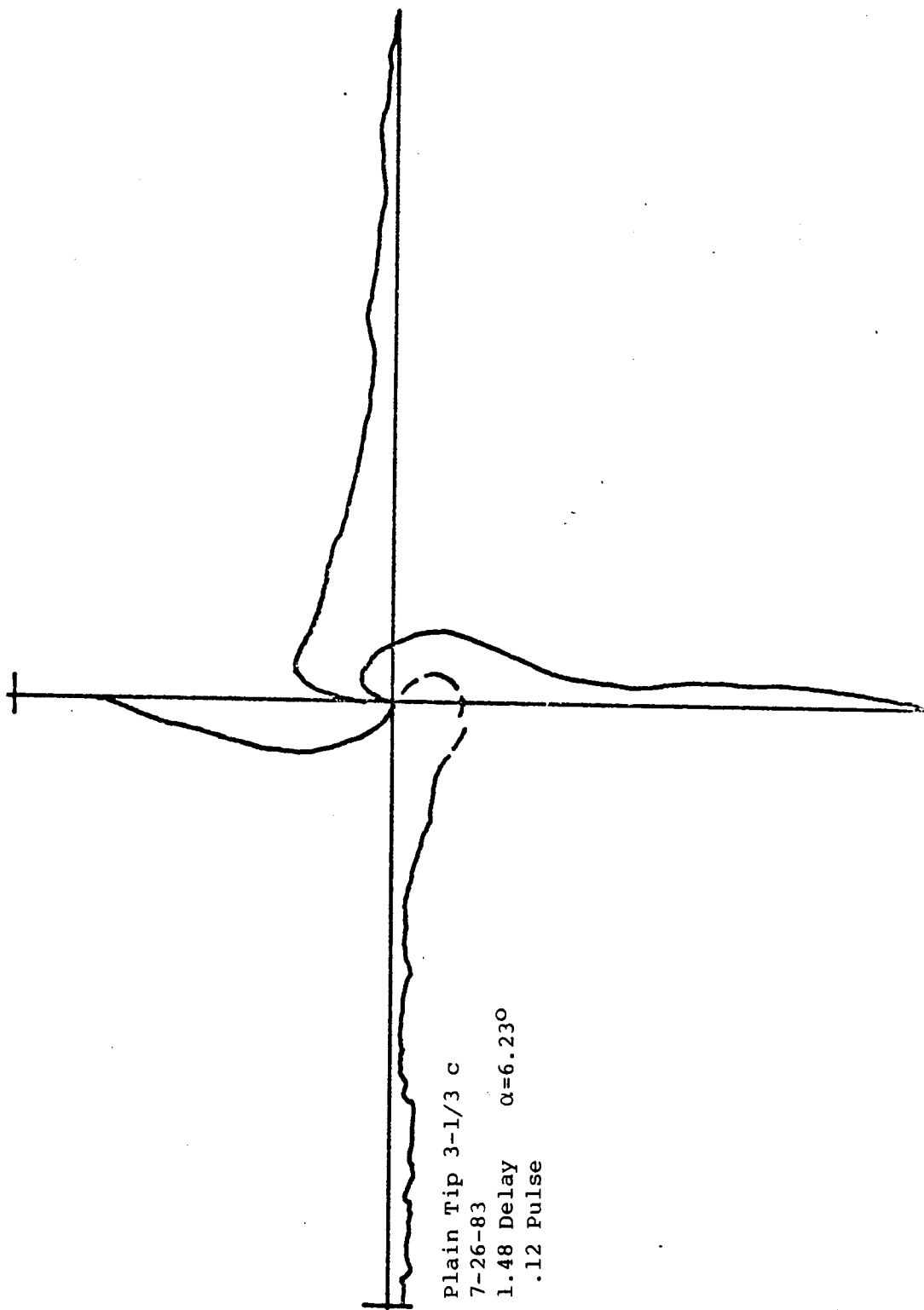
b. Three-Sail Configuration

Figure 26. (Continued)



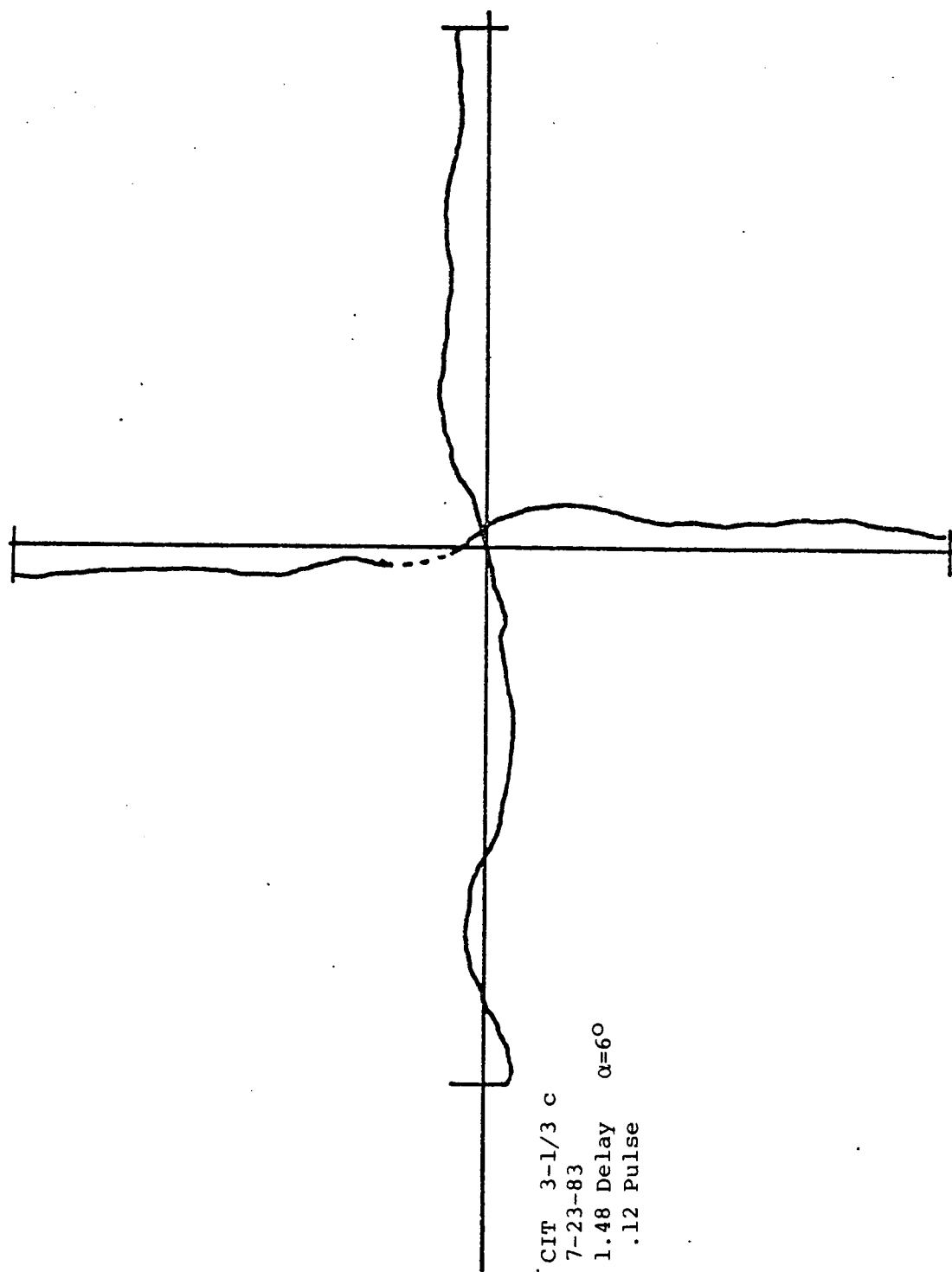
c. Five-Sail Configuration

Figure 26. (Continued)



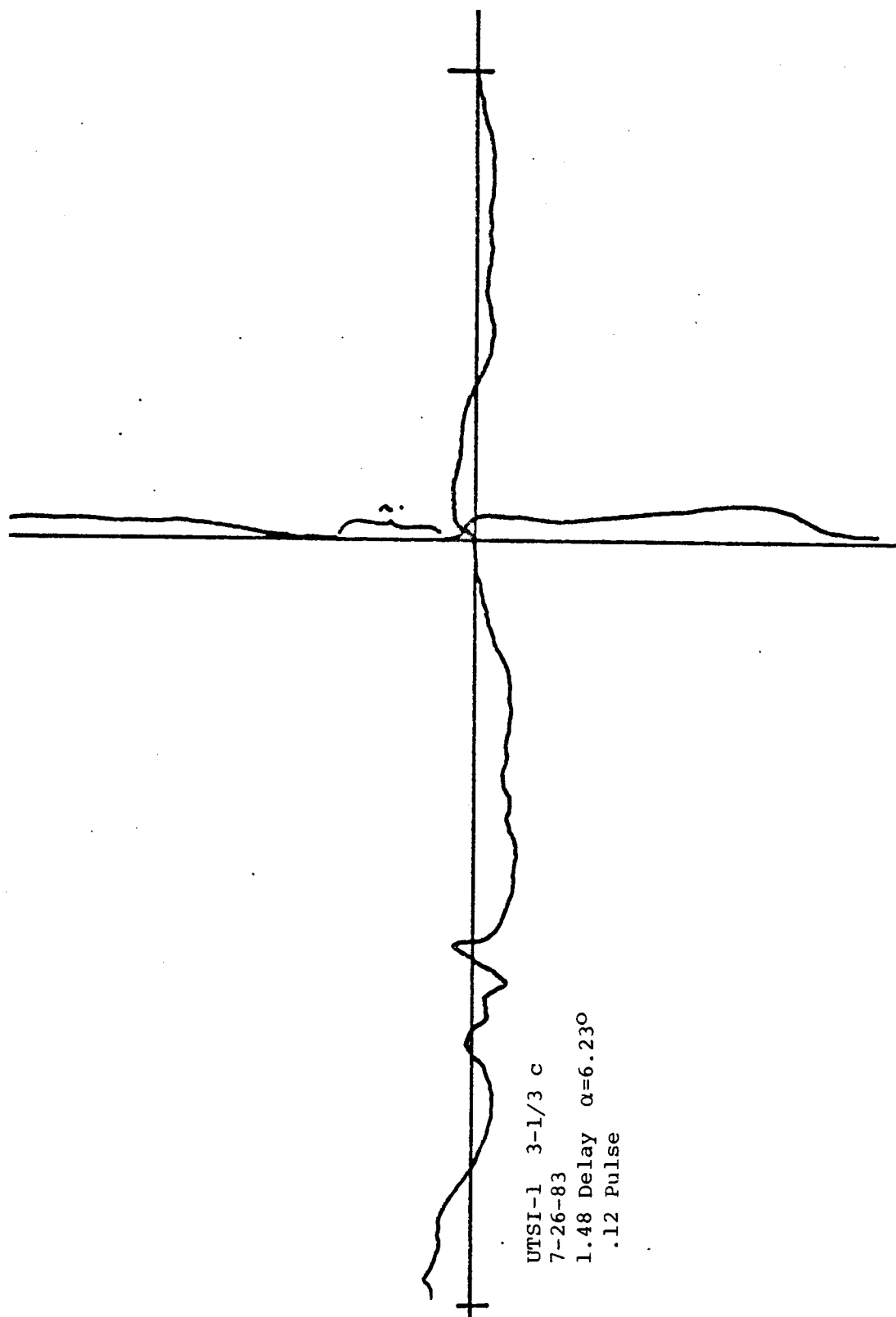
a. Plain Wing Tip

Figure 27. Tracings from Hydrogen Bubble in the Y-Z Plane.



b. Three-Sail Configuration

Figure 27. (Continued)



c. Five-Sail Configuration
Figure 27. (Continued)

not averaged, but presented in raw form. The shifts do not change the general trends. Groups of data are shown in Figures 28, 29, and 30. Both classes of comparisons are shown--those of the same day and those of differing days. The data is an average of all four legs of the crosswire.

The results specifically show that below 1.5 inches from the center of the vortex, the addition of sails reduces the velocity profile. Beyond 1.5 inches from the center, the results are inconsistent. The data points were also multiplied by the radius values and summed for each curve. This gives some measure of the angular momentum. These values were consistent, reducing as sails were added. There is no doubt that core velocities are reduced, just as in our simplified model of Figure 8, page 15.

Comparison of Data with Data from Similar Investigations

Let us compare the preceding wake vortex tangential velocity data with: (a) Rossow's work on vortex generators on a B747 [10]; (b) VPI's wake study using Whitcomb wing-lets [2]; (c) Dunham's ogee tip wake results [25]; and (d) Yuan and Bloom's results with vertical tip blowing [24]. Let us nondimensionalize the abscissae on percentage of semi-span. The ordinates are nondimensionalized on the maximum tangential velocity in the wake for the plain wing.

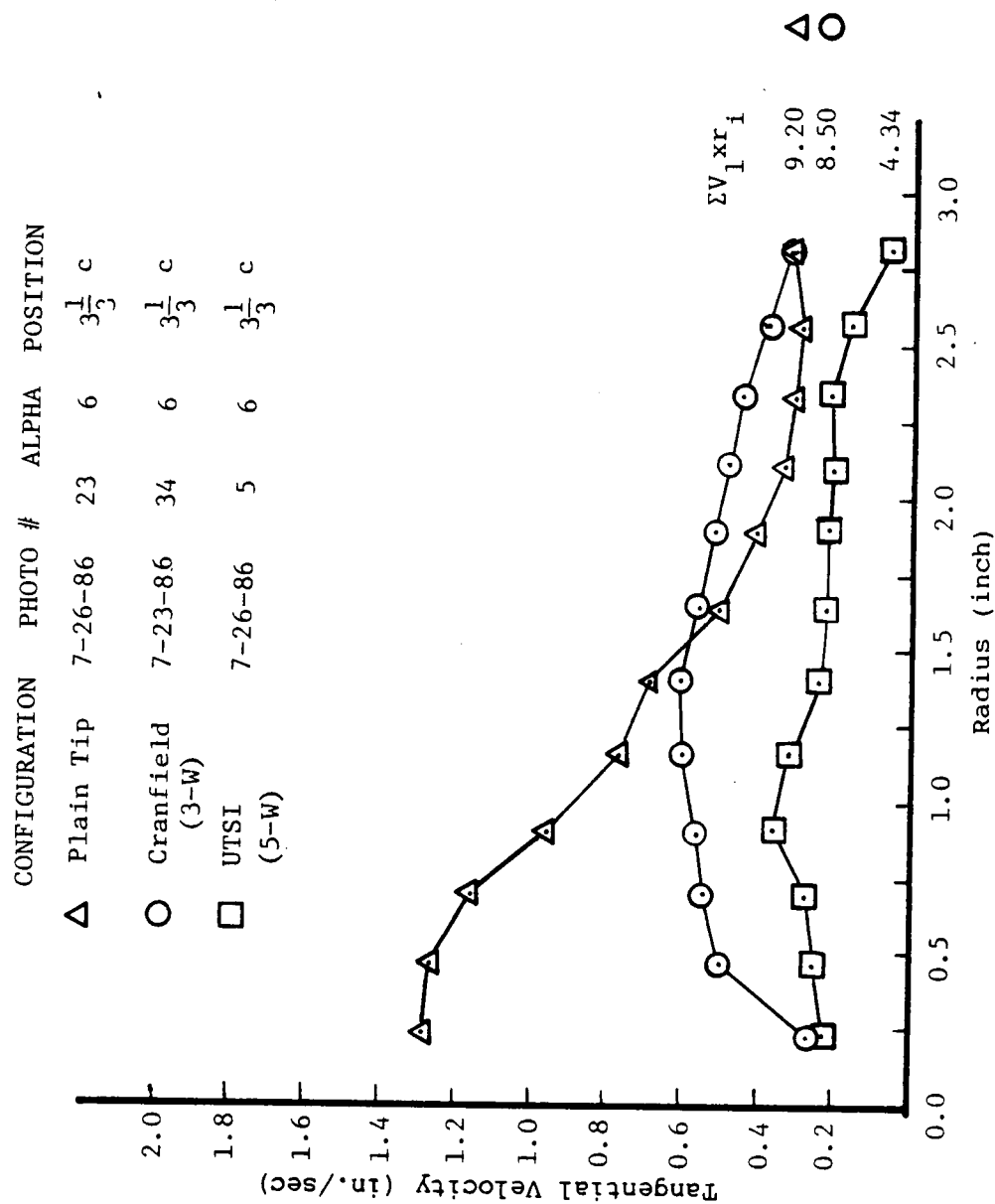


Figure 28. Vortex Profile (UTSI Water Tunnel) Group 1.

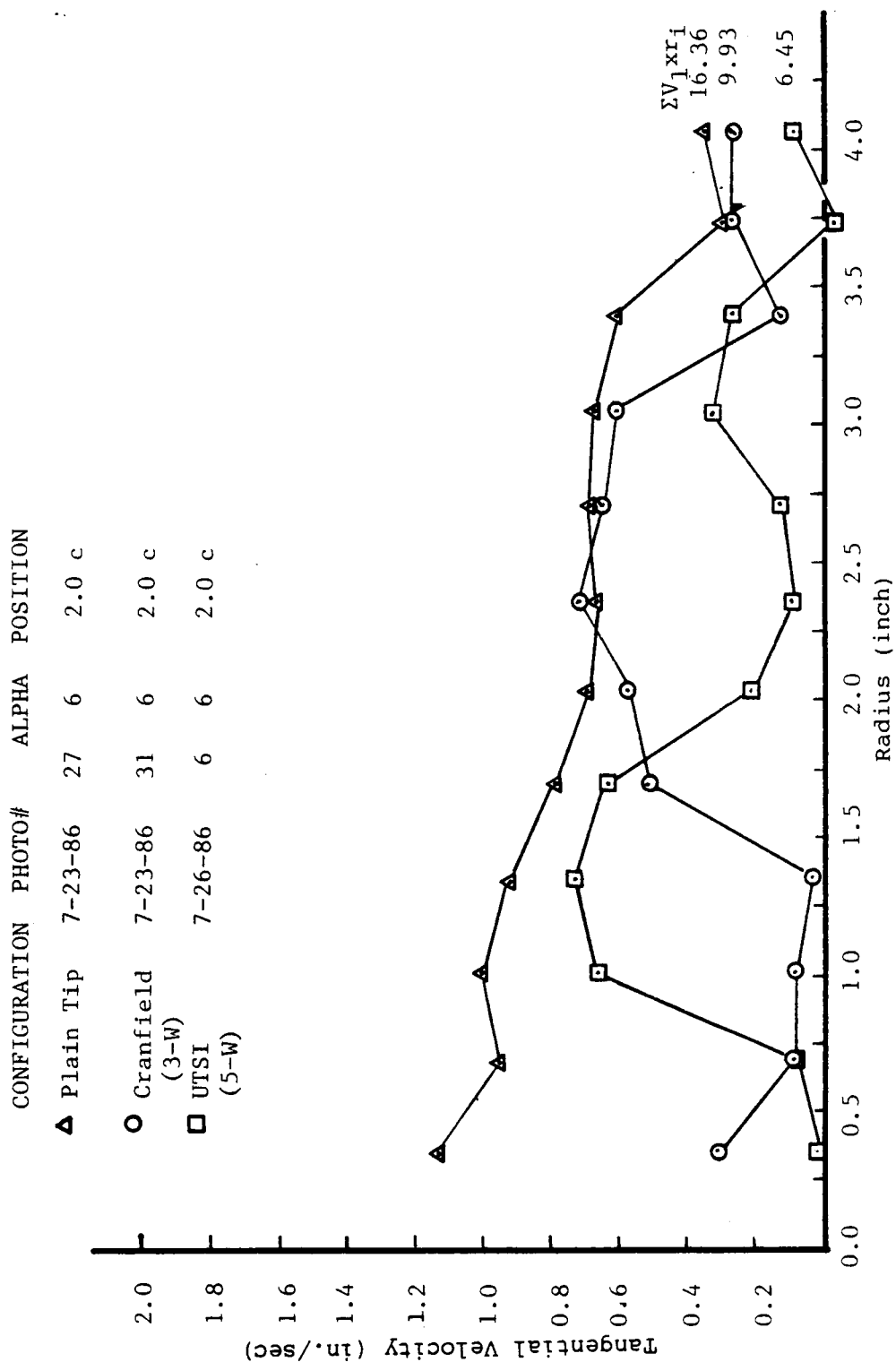


Figure 29. Vortex Profile (UTSI Water Tunnel) Group 2.

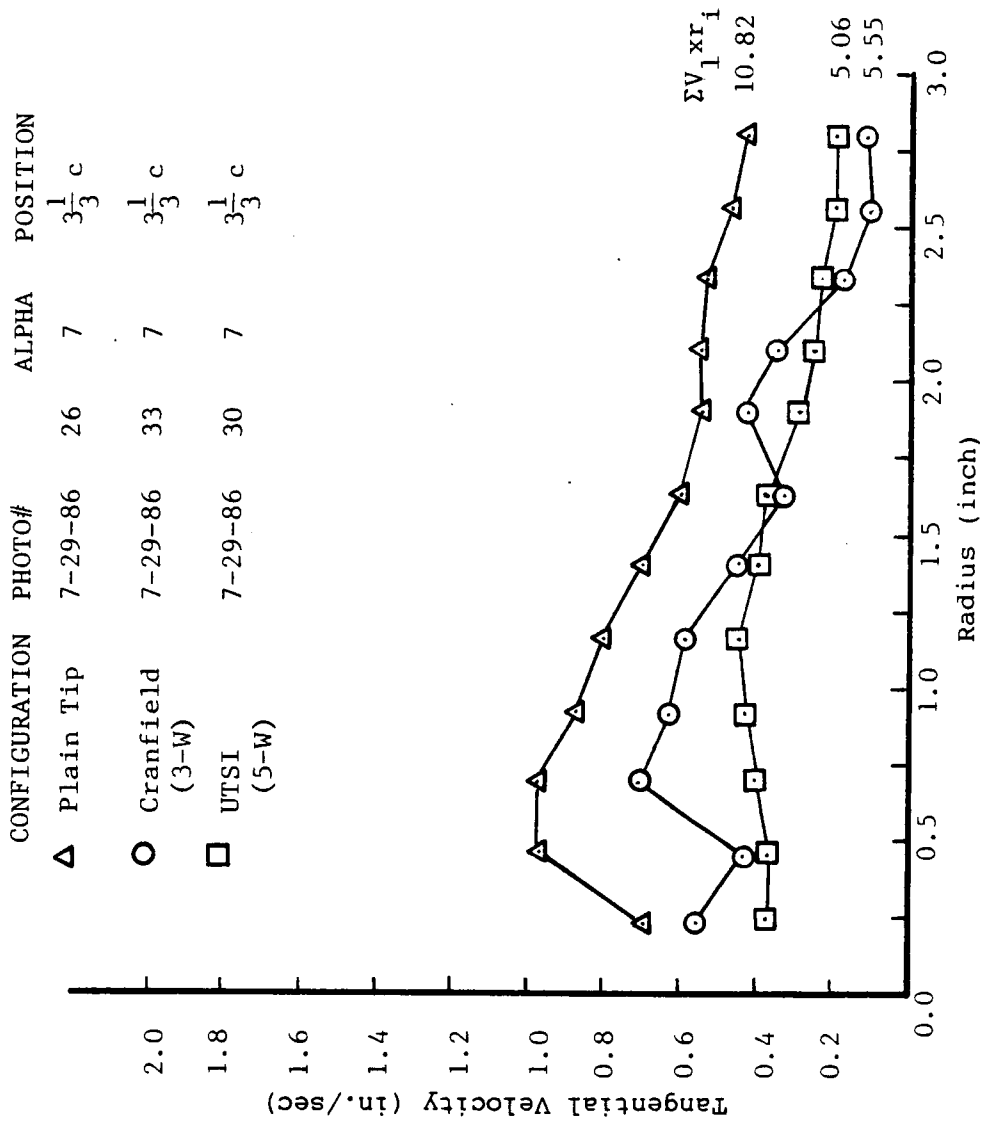


Figure 30. Vortex Profile (UTSI Water Tunnel) Group 3.

Linear interpolations were made on cuts parallel to the abscissa and ordinate of Rossow's contour plots of velocity and, similarly, Yan and Bloom's contour plots of rolling moment. Rossow's results (done this way) are shown in Figure 31. Yuan and Bloom's results are shown in Figure 32. Both of these show a velocity reduction similar to our water tunnel data inboard of 1.5 inches (15% semi-span). They both show a marked reduction for values of radius much larger, percentage-wise, than ours.

For the VPI data, the two velocity profiles from the two distinct vortices of the Whitcomb winglet were added to get a measurement of total wake energy for comparison purposes. This is compared with the results from their square tip case in Figure 33. Again there is a marked reduction of the core velocity, but outboard of 4% semi-span the Whitcomb reverses and has greater velocity than the square tip.

Dunham's ogee tip data is compared in Figure 34 to a rectangular tip case he also ran. It has extreme reduction of the core velocity and shows the reversal pattern outside of 12% semi-span.

In conclusion, it is found that all of these methods reduce the vortex core velocities. However, it cannot be determined that overall L/D is enhanced without doing force testing.

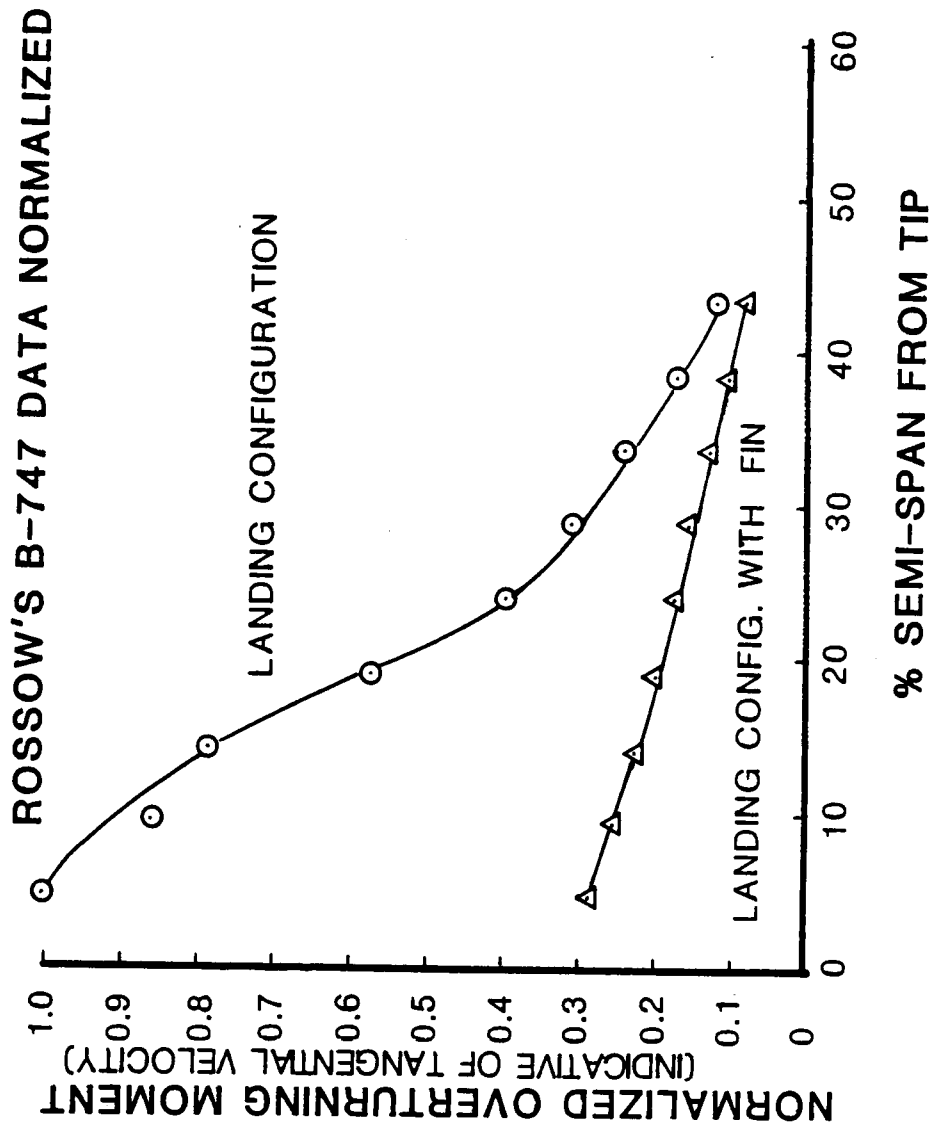


Figure 31. Wake Vortex Results of Rossow's Experiment.

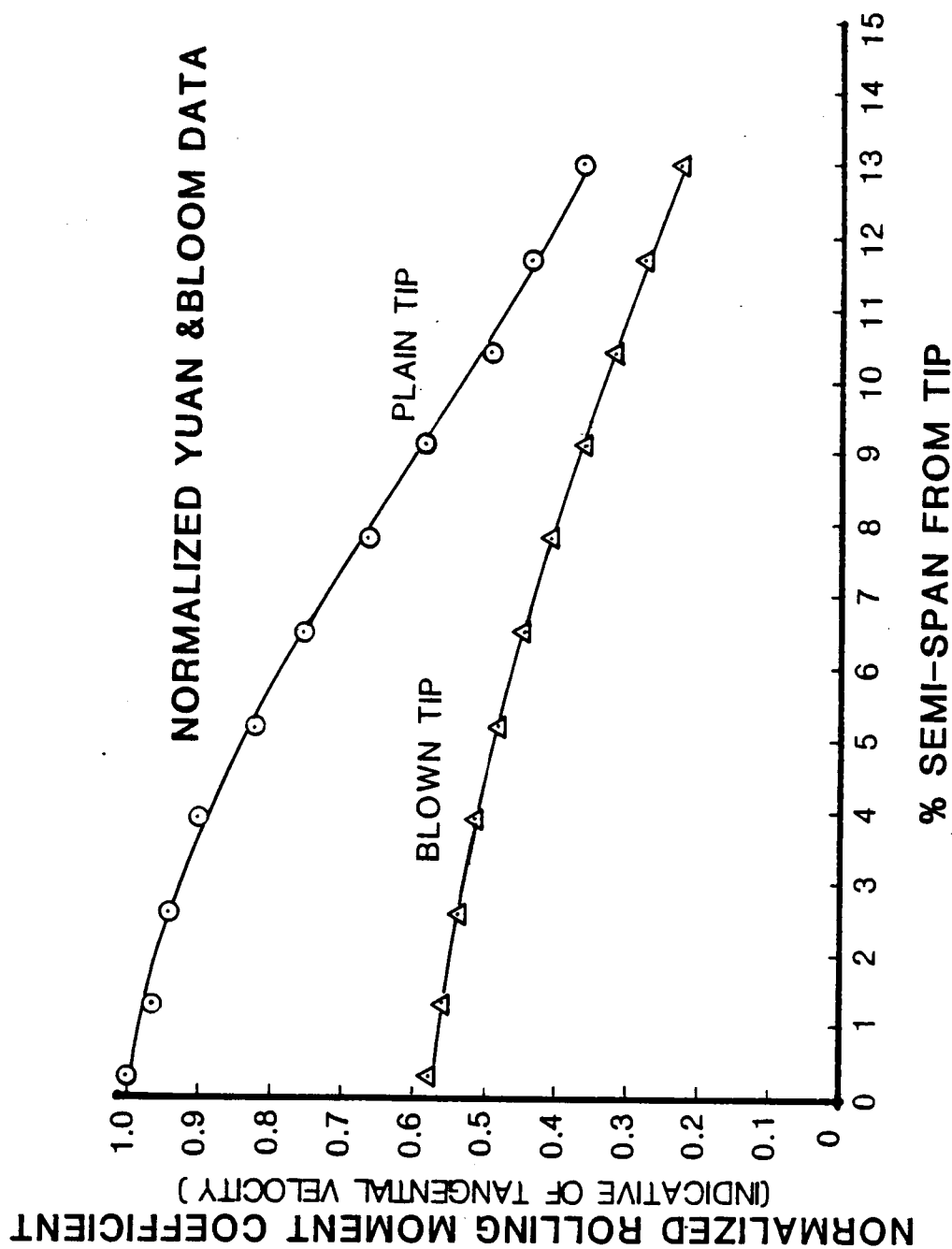


Figure 32. Wake Vortex Results for Yuan and Bloom's Experiment.

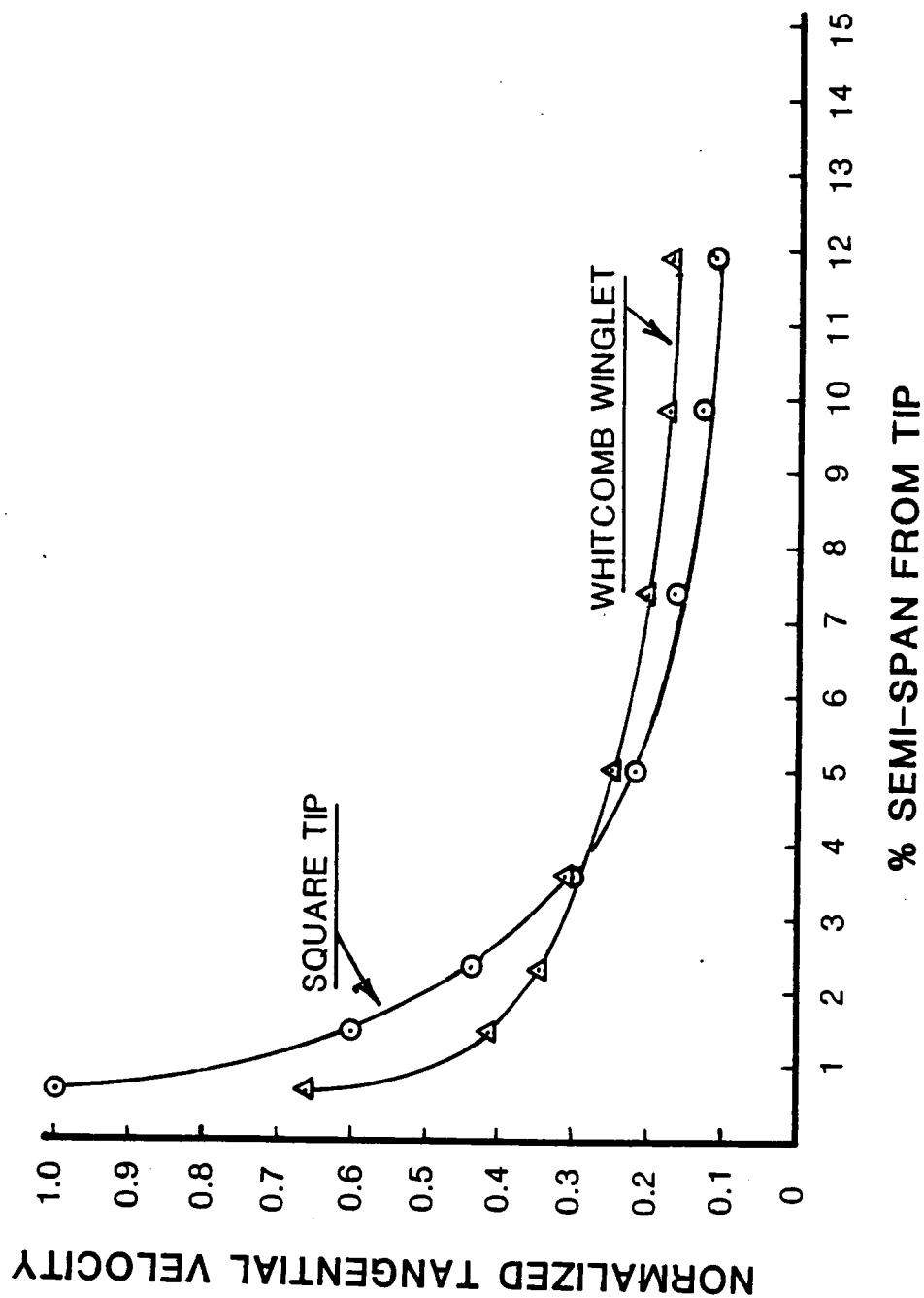


Figure 33. Wake Vortex Results for VPI Winglet.

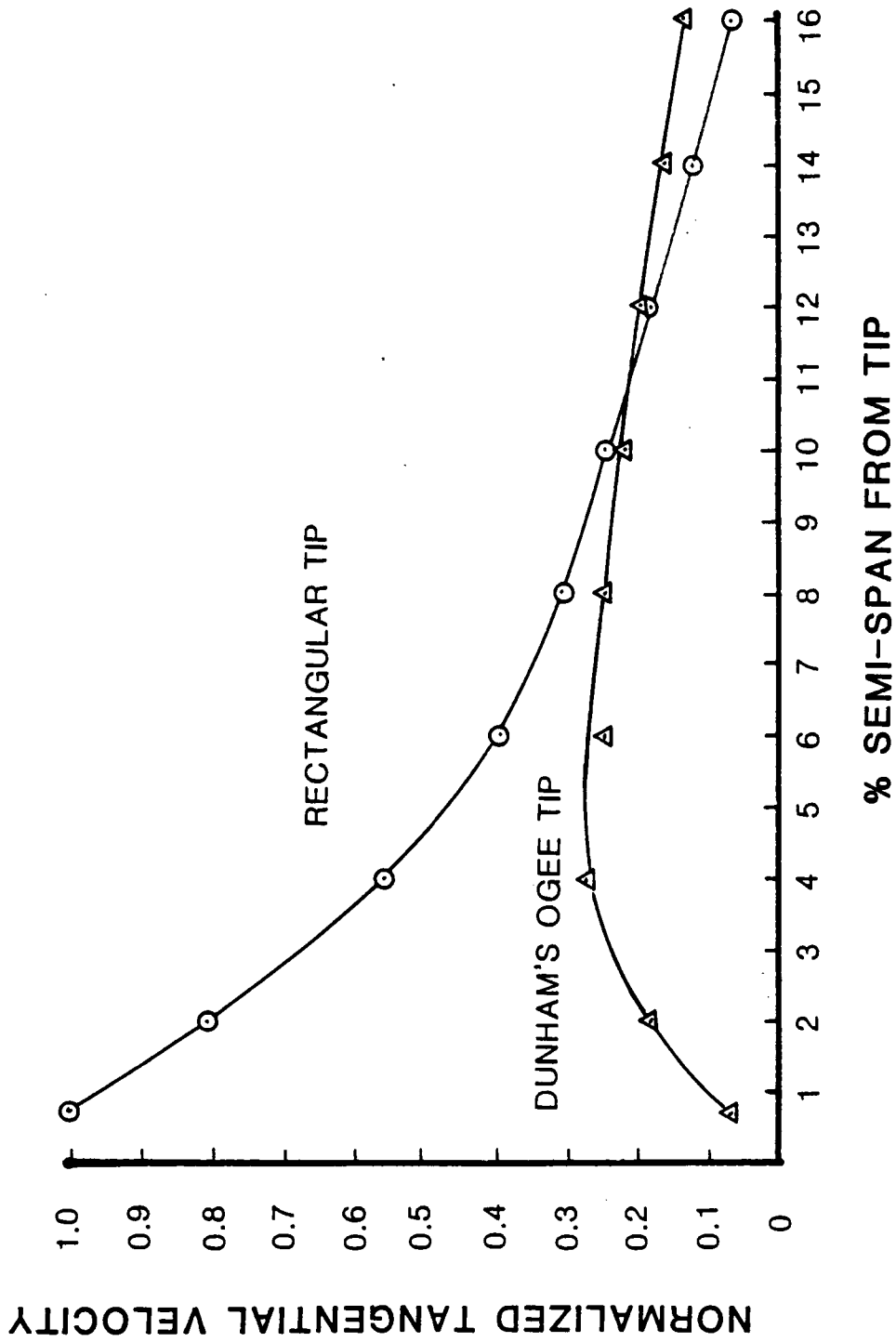


Figure 34. Wake Vortex Results for Dunham's Ogee Tip.

Wind Tunnel Lift and Drag Investigation

A second set of experiments was run to determine what influences the sails had on the forces on a finite wing. The same configurations which were run in the water tunnel were run in the UTSI 14-inch by 20-inch Low Speed Wind Tunnel. The tunnel has a 10:1 contraction ratio and is powered by a 5-hp centrifugal fan. The same sails were used as in the first experiment, even though the wing was 7 inches by 12 inches versus the water tunnel's 6-3/8-inch by 10-inch wing. The airfoil remained a NACA 0012-64. The planform and tip shape were the same as that tested in the water tunnel. The Reynolds number, based on chord length, was 235000.

A six-degree-of-freedom force balance was used to measure forces. Data were gathered while keeping the manometer reading at 60 ft/sec during angle-of-attack excursions from 4° to 13° . It is felt that better data would have resulted if the power setting had been left at the initial position during each excursion and the manometer had been left free to drift. The data were recorded on floppy discs using the UTSI laboratory micro-computer, then inverted by matrix algebra into lift and drag forces using a VAX 11/780 computer.

The results are shown in Figures 35, 36, and 37. Stall occurred at 13° angle of attack. The five-sail

○ PLAIN WINGTIP
 △ 3 SAIL CONFIGURATION
 ◇ 5 SAIL CONFIGURATION

NACA 0012-64

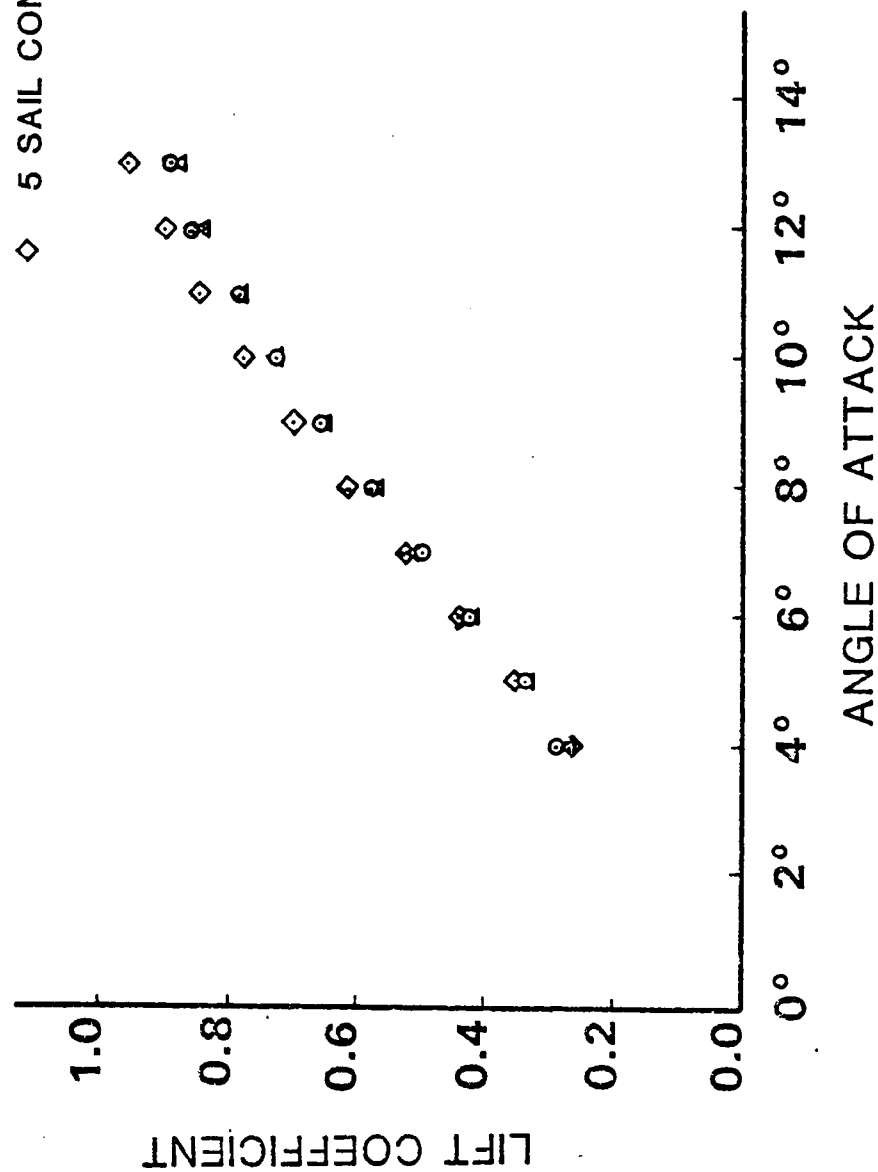


Figure 35. Lift Coefficient versus Angle of Attack for UTSI Wind Tunnel Test.

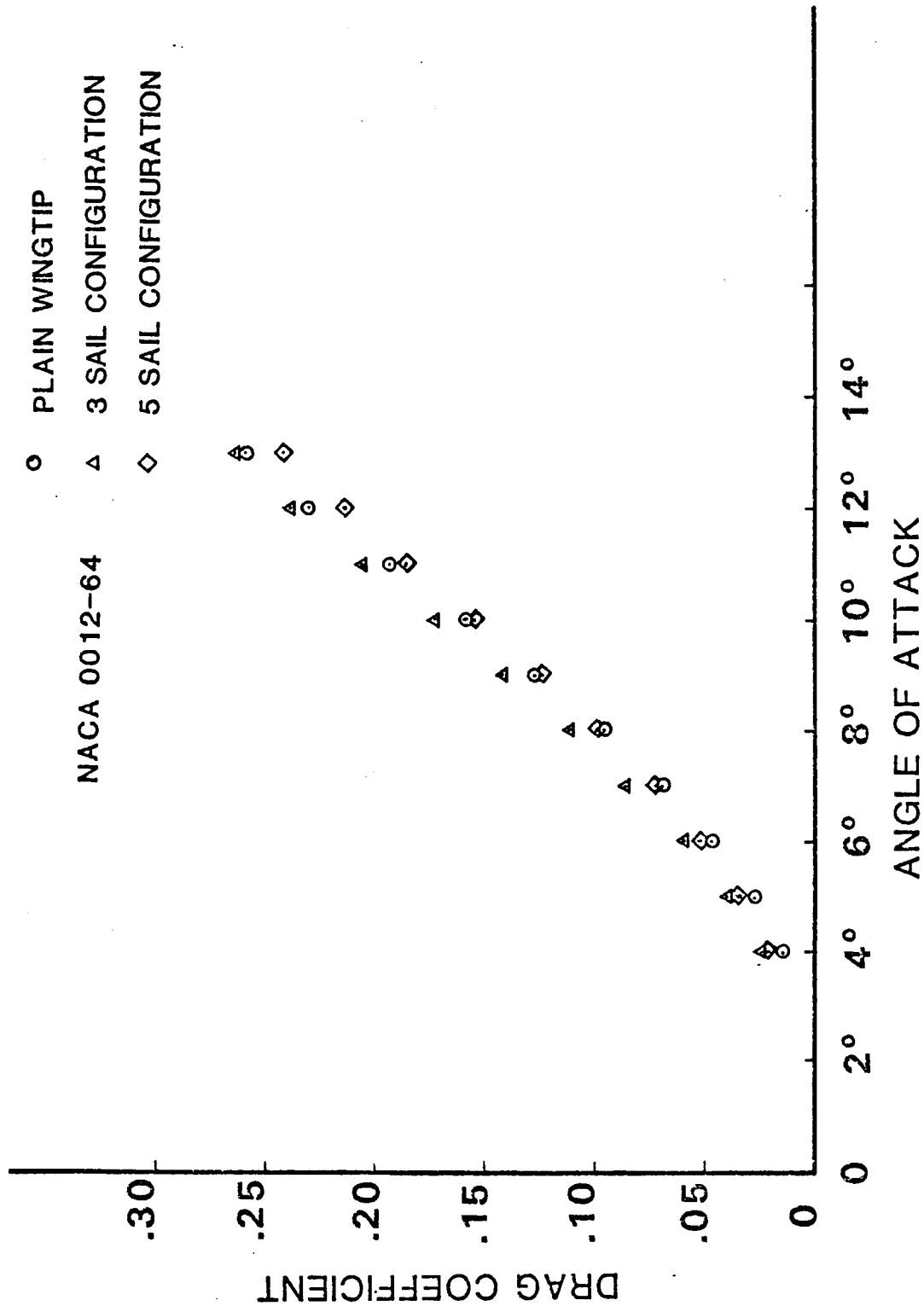


Figure 36. Drag Coefficient versus Angle of Attack for UTSI Wind Tunnel Test.

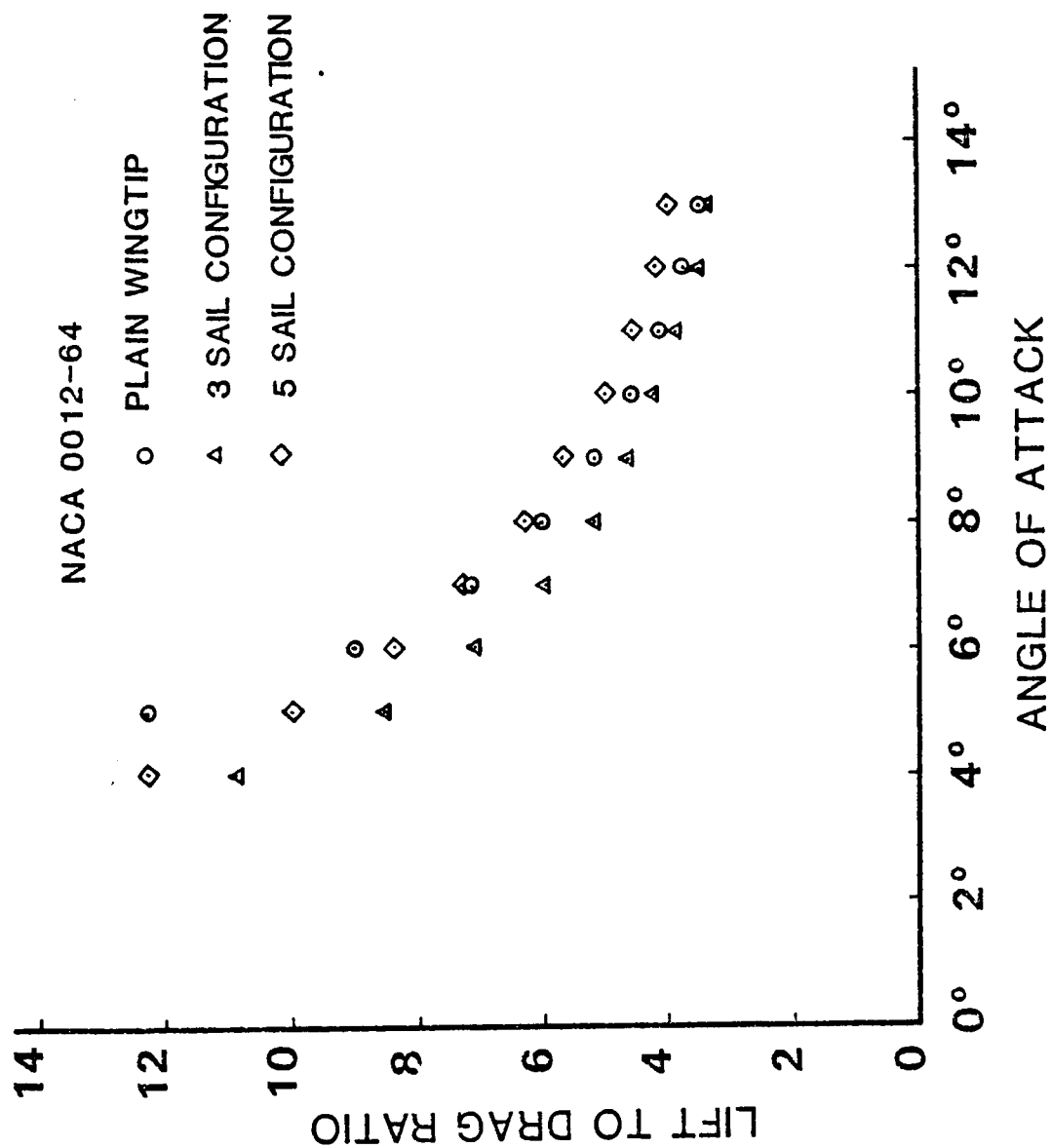


Figure 37. Lift to Drag Ratio versus Angle of Attack for UTSI Wind Tunnel Test.

configuration began to give better lift than the plain wing above 5° , and it gave less drag than the plain wing above 8° angle of attack. The three-sail configuration gave poorer lift and increased drag everywhere. The UTSI five-sail configuration has a better C_L/C_D than the plain wing above 6° angle of attack.

It could be argued that a fairer comparison would be to have had a higher wingspan for the plain model. If we use aspect ratio as

$$A = \frac{b^2}{S} ,$$

where b is the wingspan and S is the actual area, we have:

	<u>Plain Wing</u>	<u>Three-Sail Configuration</u>	<u>Five-Sail Configuration</u>
Aspect Ratio	3.368	4.841	4.623

Because of the extension in span with little area change for the three-sail case, it would have been the worst case for comparison, and neither of the sail cases would have really had a fair chance if the data for the plain wing had been adjusted to these new aspect ratios. It was decided to adjust the plain wing data to that for an extension of the wing to the same span (i.e., allow for the 2-7/8-inch length of the sails). This causes the area number to be larger than in the previous cases. An

extension of span to 25.75 inches gives an aspect ratio of 3.895. We need to adjust C_L and C_D to new values associated with this new aspect ratio. The subscript N will designate values associated with the new aspect ratio.

We know

$$C_D = C_{D_O} + C_{D_i} = C_{D_O} + \frac{C_L^2}{\pi A} .$$

Therefore,

$$C_{D_O} = C_D - \frac{C_L^2}{\pi A} .$$

If we let the new C_{D_O} be the same as the original,

$$C_{D_{O_N}} = C_{D_O} .$$

We know

$$C_{D_{i_N}} = \frac{C_L^2}{\pi A} \left(\frac{A}{A_N} \right) = \frac{C_L^2}{\pi A_N} .$$

Thus we transform the plain wing coefficient of drag to the new equivalent,

$$C_{D_N} = C_{D_{O_N}} + C_{D_{i_N}} = \left(C_D - \frac{C_L^2}{\pi A} \right) + \frac{C_L^2}{\pi A_N} .$$

For lift curve slope we use the Helmbold equation,

$$C_{L\alpha} = C_{\ell\alpha} \frac{A}{2 + \sqrt{4 + A^2}},$$

where $C_{\ell\alpha}$ is the sectional slope.

Since the $C_{\ell\alpha}$ does not change for the extended wing,

$$C_{L\alpha} \left(\frac{2 + \sqrt{4 + A^2}}{A} \right) = C_{L\alpha N} \left(\frac{2 + \sqrt{4 + A_N^2}}{A_N} \right).$$

Since $C_L = C_{L\alpha} \alpha$; for the same α ,

$$\left(\frac{C_L}{C_{L\alpha}} \right) = \left(\frac{C_{LN}}{C_{L\alpha N}} \right),$$

and substitution gives,

$$C_L \left(\frac{2 + \sqrt{4 + A^2}}{A} \right) = C_{LN} \left(\frac{2 + \sqrt{4 + A_N^2}}{A_N} \right).$$

The new C_{LN} is thus,

$$C_{LN} = C_L \left(\frac{A_N}{A} \right) \left(\frac{2 + \sqrt{4 + A^2}}{2 + \sqrt{4 + A_N^2}} \right).$$

The resulting data are plotted in Figures 38, 39, and 40. It would appear that with the five-sail configuration we have not helped L/D at all; C_D looks like it might have begun to go below that of the reference at the highest alphas, but the effect is marginal. Perhaps the configuration, chosen without a good knowledge of Cone's work, is too planar.

The three-sail configuration shows up in even poorer light. It offers only losses in lift and increase in drag, when compared to this equal span wing.

Keep these results in mind, both for the original model data and the equal span, theoretically adjusted data. Later, we shall submit both to a computer simulation of wing vortex shedding and roll-up.

Similar Aerodynamic Data from Other Investigators

Cranfield Institute of Technology

Even though they had better results with uncambered symmetric airfoils at -5° incidence, the cambered, twisted airfoils at -5° incidence (ours were at 0° incidence) more closely match our five-sail configuration.

Plots of C_L/C_D for the entire aircraft are shown in Figure 41, made to the same scales as plots of our data. These are for comparative purpose only because tare forces

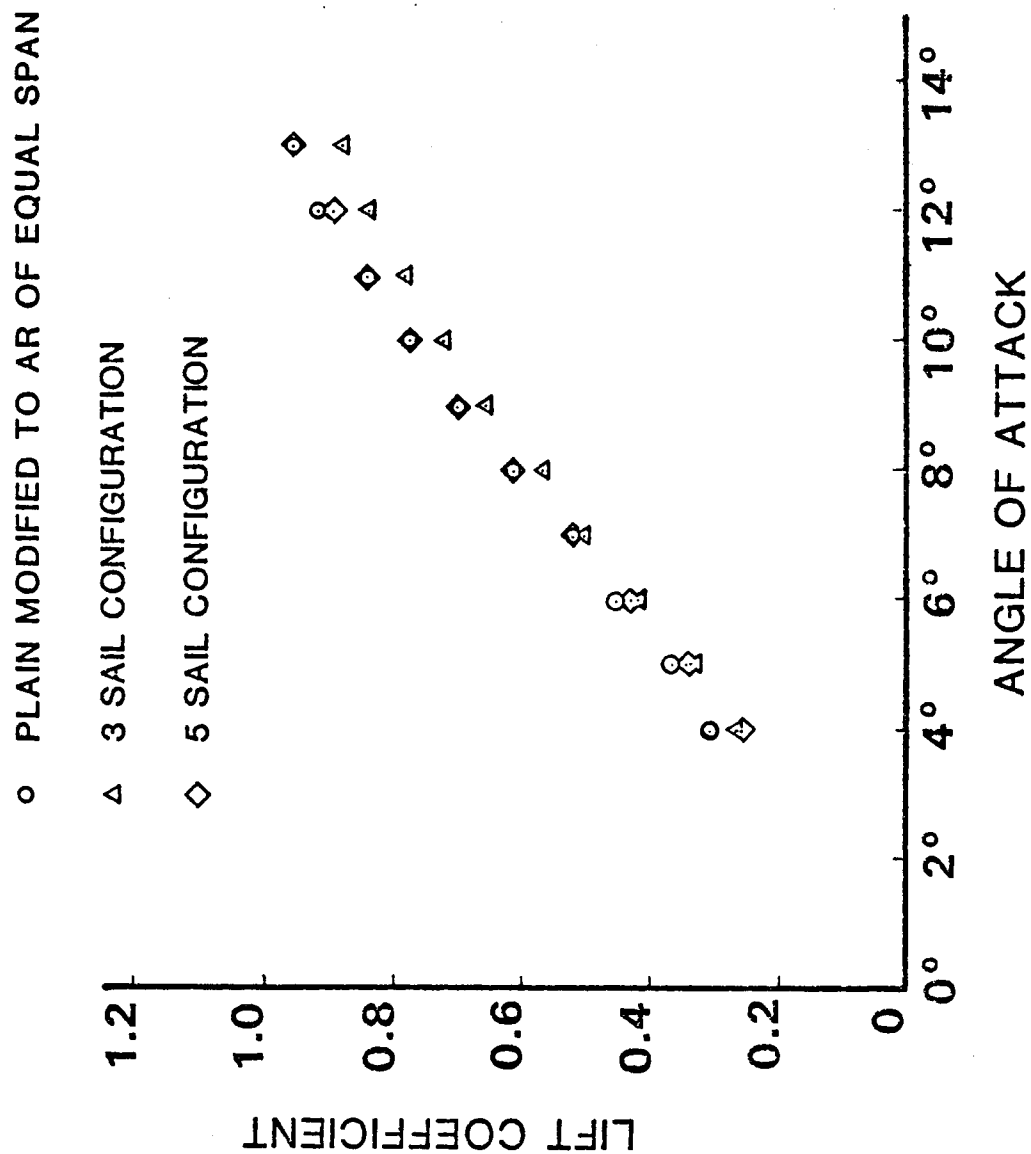


Figure 38. Lift Coefficient versus Angle of Attack for UTSI Wind Tunnel Data Compared to Modified Plain Tip Data.

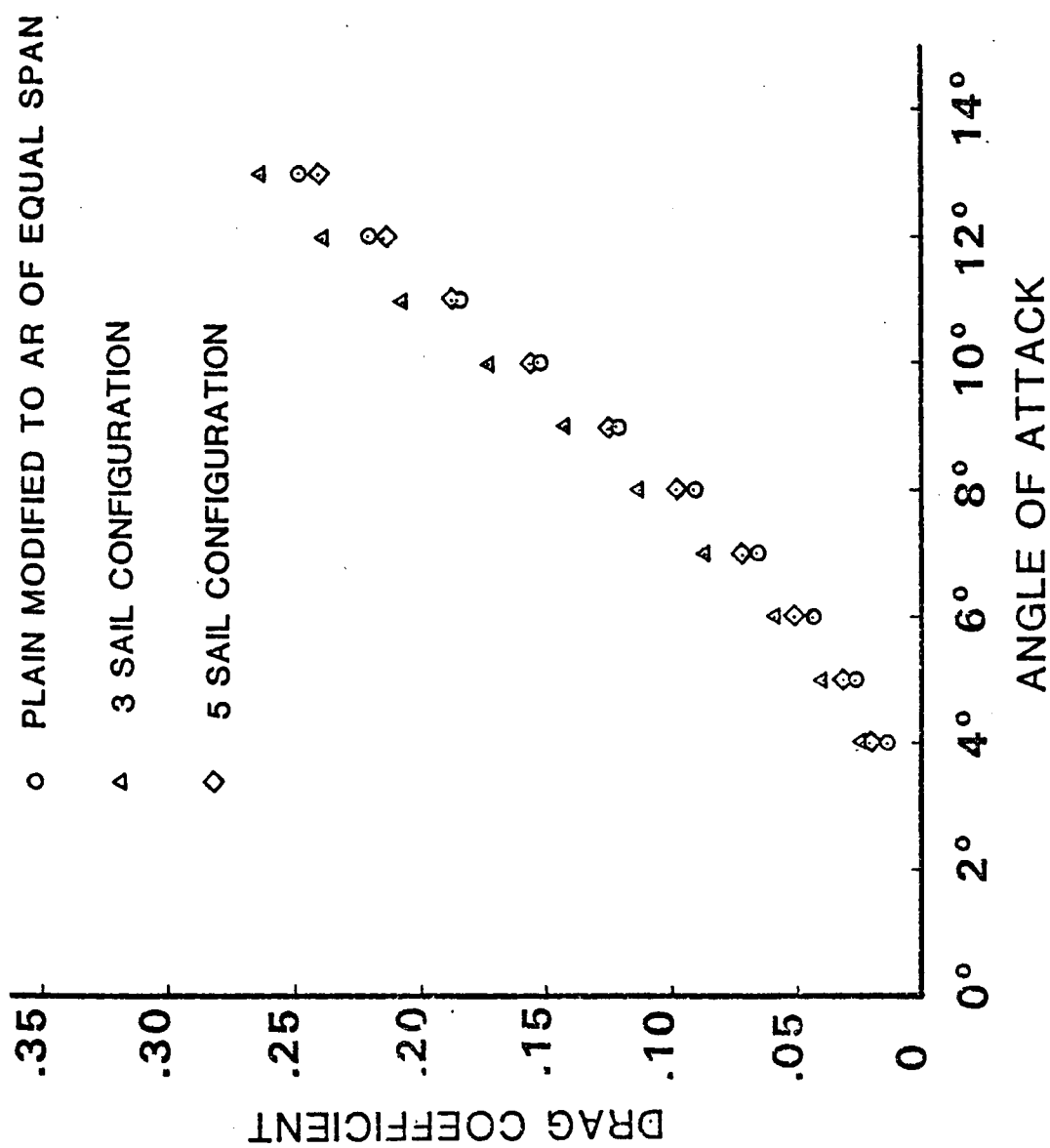


Figure 39. Drag Coefficient versus Angle of Attack for UTSI Wind Tunnel Data Compared to Modified Plain Tip Data.

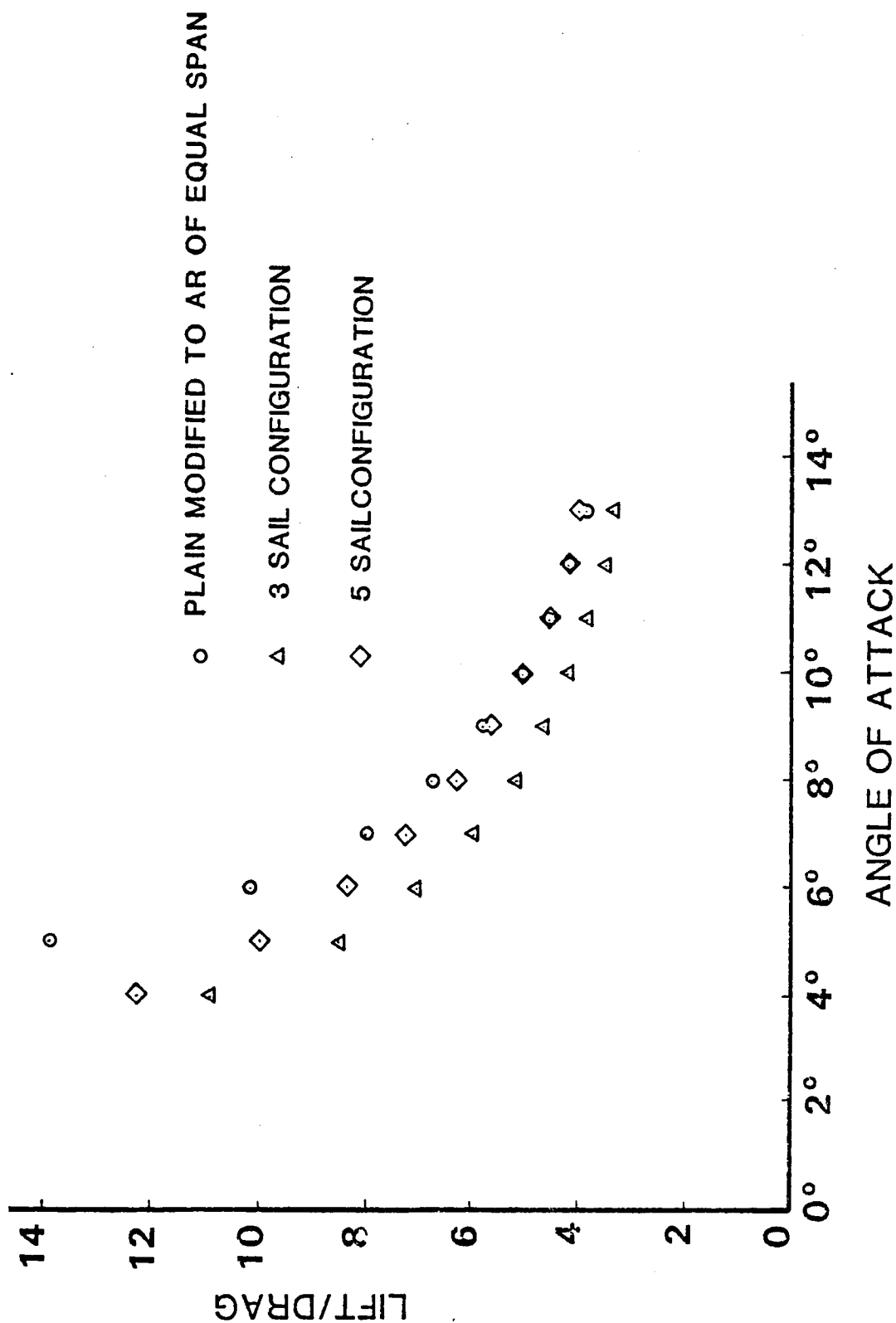


Figure 40. Lift to Drag Ratio versus Angle of Attack for UTSI Wind Tunnel Data Compared to Modified Plain Tip Data.

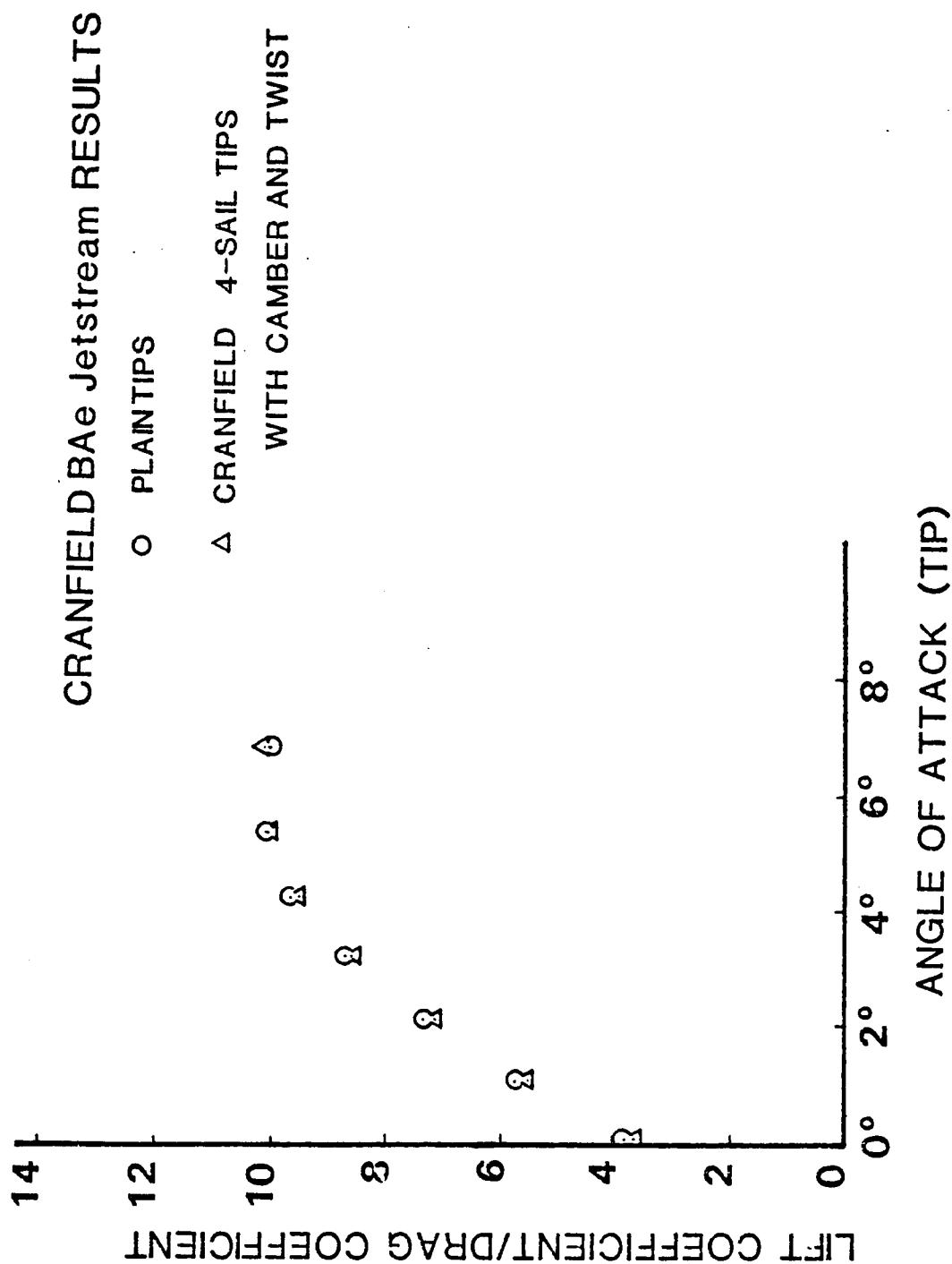


Figure 41. Lift to Drag Ratio versus Angle of Attack for Cranfield Wind Tunnel Test.

are not subtracted out. The data are shown in Table 1. It shows that the multiple sails were beginning to give a performance gain at the last data point--above 6° angle of attach for the tip (8° for the root). This is the same result that our data indicated.

Virginia Polytechnic Institute

The VPI results are shown in Figure 21, page 41. Note that the Whitcomb winglets are effective above about 3° angle of attack.

Computer Simulation

The University of Tennessee Space Institute has developed a program to simulate off-wing vortices and their effect on the trailing wake of a wing [26]. It is based on a program by Chow in Introduction to Computational Fluid Mechanics [27]. It has been modified to simulate a planar wing and out-of-plane vortices placed arbitrarily in the wing tip vicinity. the circulation is simulated by equally spaced vortices of varying strengths. We input the out-of-plane vortex strengths. We chose to assume that the tip vortex shed by a sail was proportional (based on the geometric scale factor; e.g., span) to the tip vortex shed by the whole wing.

Table 1. Results of Cranfield BA_e
Jetstream Test

α	(C_L/C_D) Plain Tips	(C_L/C_D) Cambered Sails (-5° Incidence)
-1.0	1.91	1.86
0	3.86	3.73
1.07	5.70	5.55
2.14	7.30	7.18
3.21	8.67	8.59
4.28	9.65	9.54
5.4	10.06	10.02
6.8	10.05	10.08

The out-of-plane vortices were located so that they simulated the three-sail tip tested and the five-sail tip. The results are shown in Figures 42 and 43. These plots show the positions of the shed wing vortices (not including the out-of-plane vortices) at some nondimensional time equal to 0.15. Also shown on the plot are the positions of where the vortices would have been located had there not been any out-of-plane vortices (i.e., for a plain wing of same span).

The plots reflect the same trends as that of the LSWT theoretically adjusted data. The five-sail tip gives almost the same result as the equivalent span airfoil, when viewing downwash and "sidewash." The three-sail tip is poorer than the equivalent span.

The results were also compared with a plain wing with no increase in span. This would be the same as the original data from our LSWT test. These results are shown in Figures 44 and 45. Again these results show the same trend as the force data. The three-sail configuration is somewhat better than the plain wing; the five-sail one about doubles the margin of improvement.

Because a clearer understanding of the reference material was obtained after the experimentation in the LSWT and water tunnel had ceased, it was decided to input into the computer a configuration resembling that of Figure 10, page 20. The "tip feather" section of Figure 10 was scaled

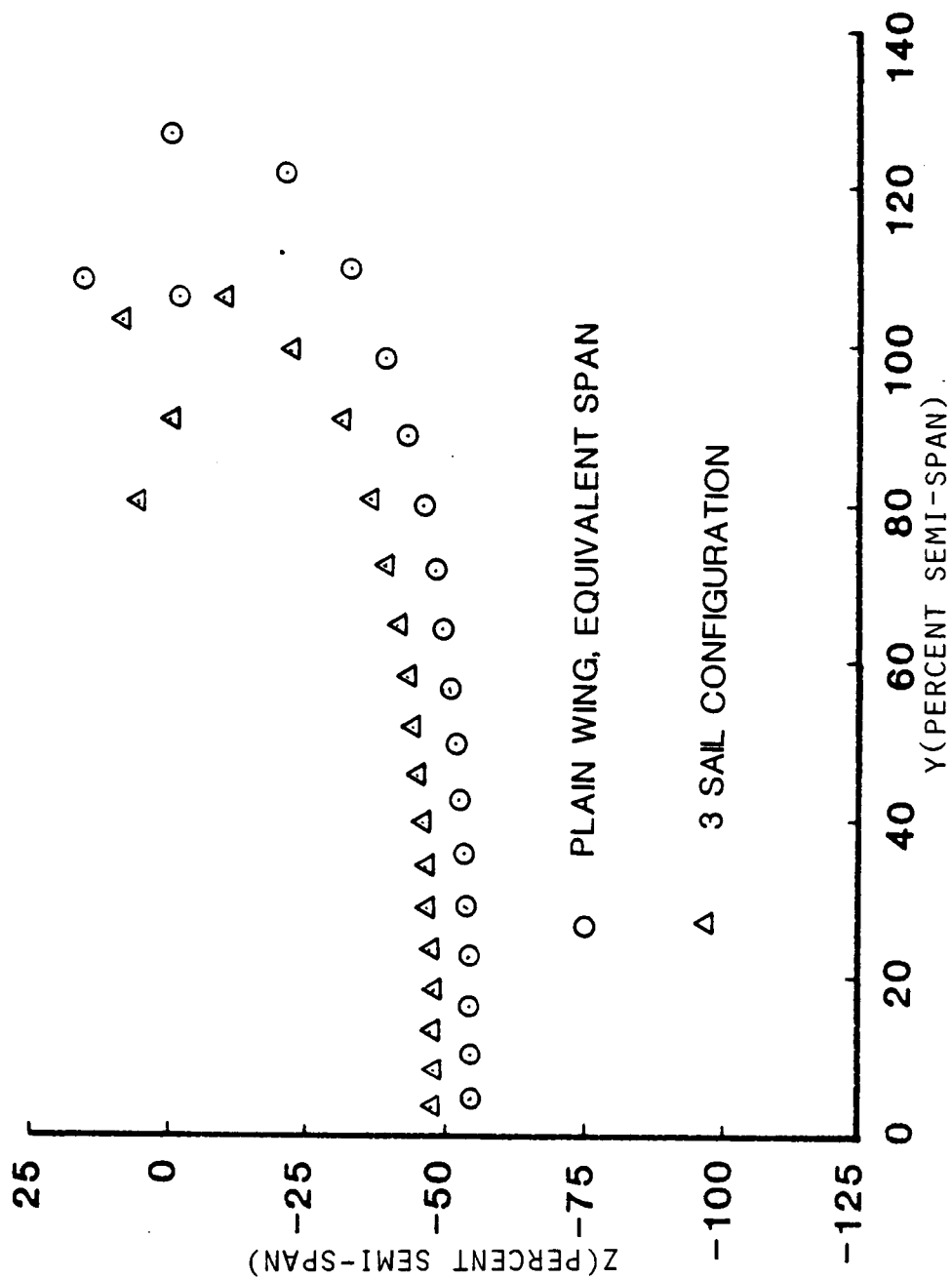


Figure 42. Position of Shed Vortices from Computer Model, Plain Wing of Equivalent Span versus Three-Sail Configuration.

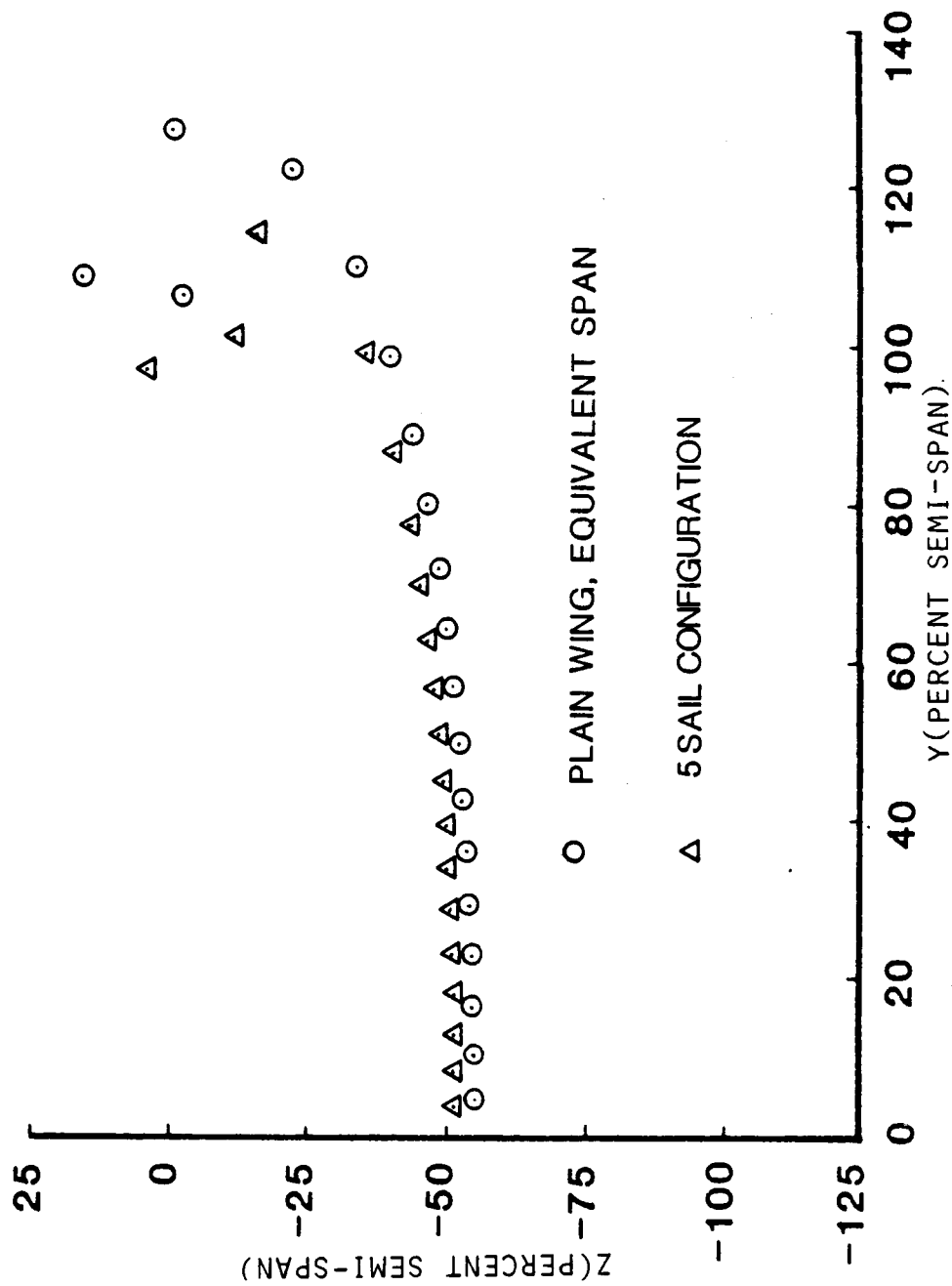


Figure 43. Position of Shed Vortices from Computer Model, Plain Wing of Equivalent Span versus Five-Sail Configuration.

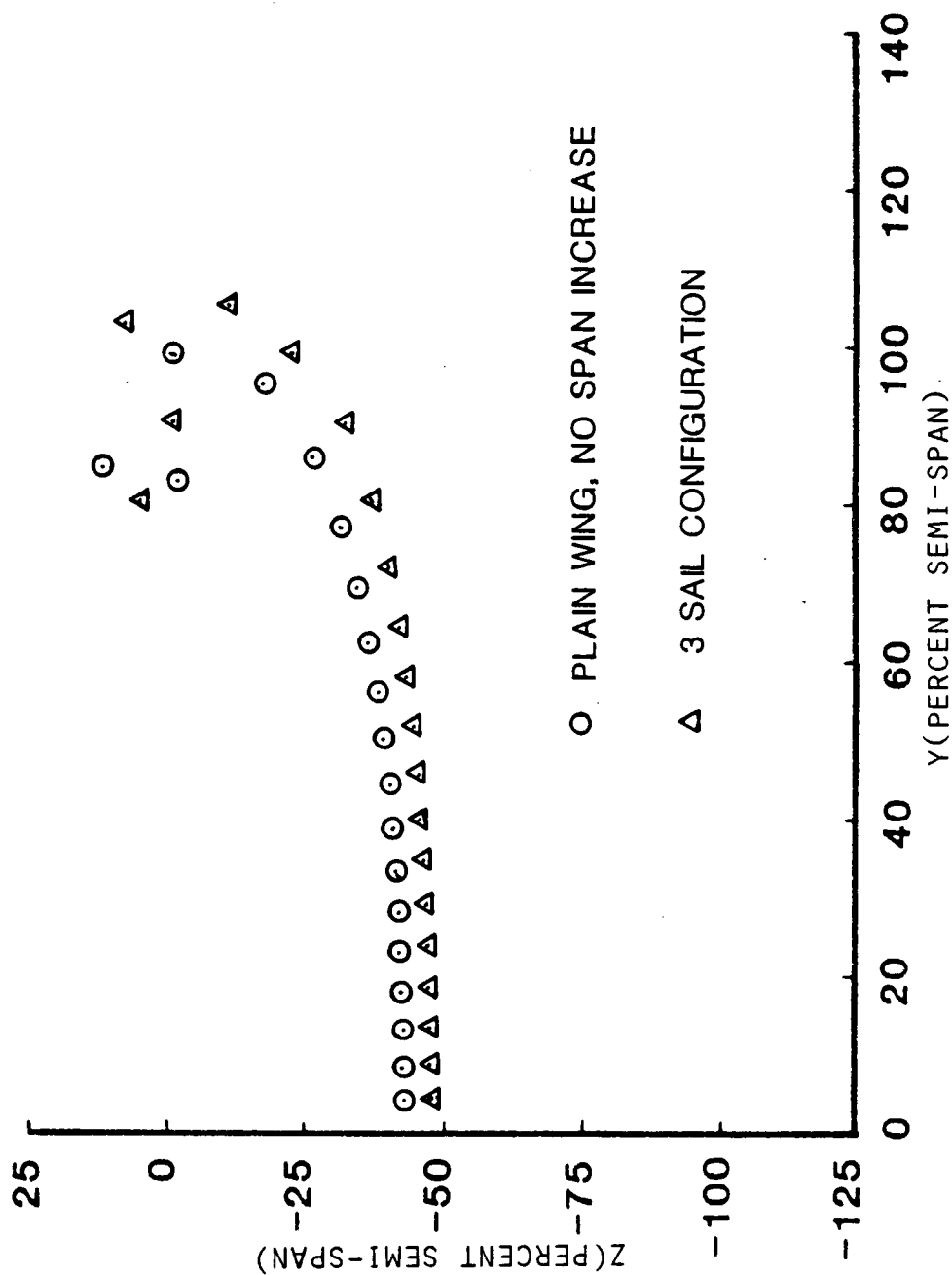


Figure 44. Position of Shed Vortices from Computer Model, Plain Wing with No Span Increase versus Three-Sail Configuration.

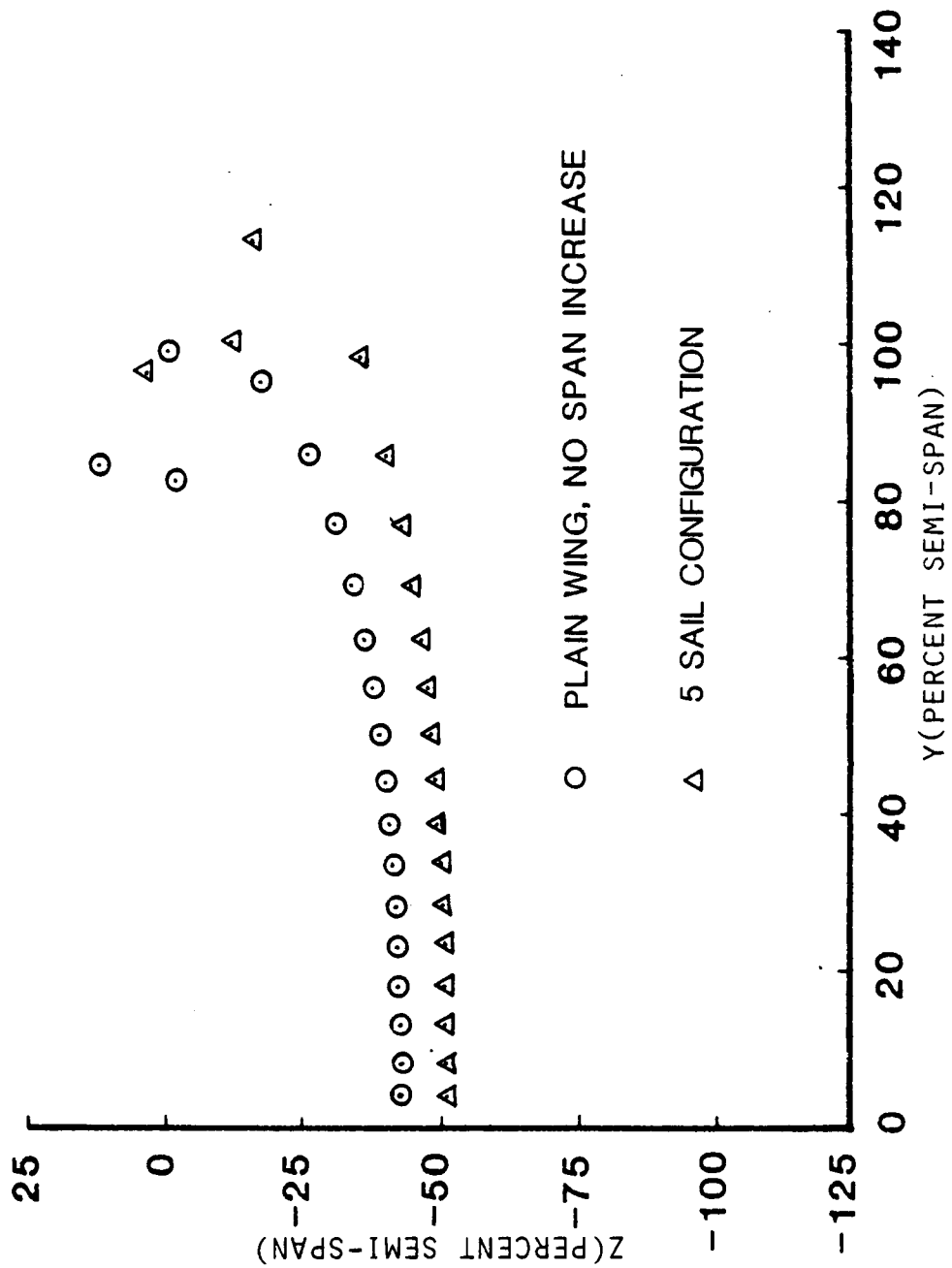


Figure 45. Position of Shed Vortices from Computer Model, Plain Wing with No Span Increase versus Five-Sail Configuration.

down (in Cone's, it was 50% of the semi-span) to the same percentage of semi-span we were allotting to sails (19%). The results are shown in Figure 46. The bird-like configuration of Figure 10, page 20, produces a pattern very close to the five-sail case. The "sidewash" is slightly increased inboard, but is slightly less outboard. The downwash is less outboard. The overall effect is equal, it would seem; and any advantage is difficult to discover. The smaller percentage allotted to the "feather" section, and the fact that we only used one tip vortex to simulate each feather (sail), should be remembered when comparing these computer results to birds.

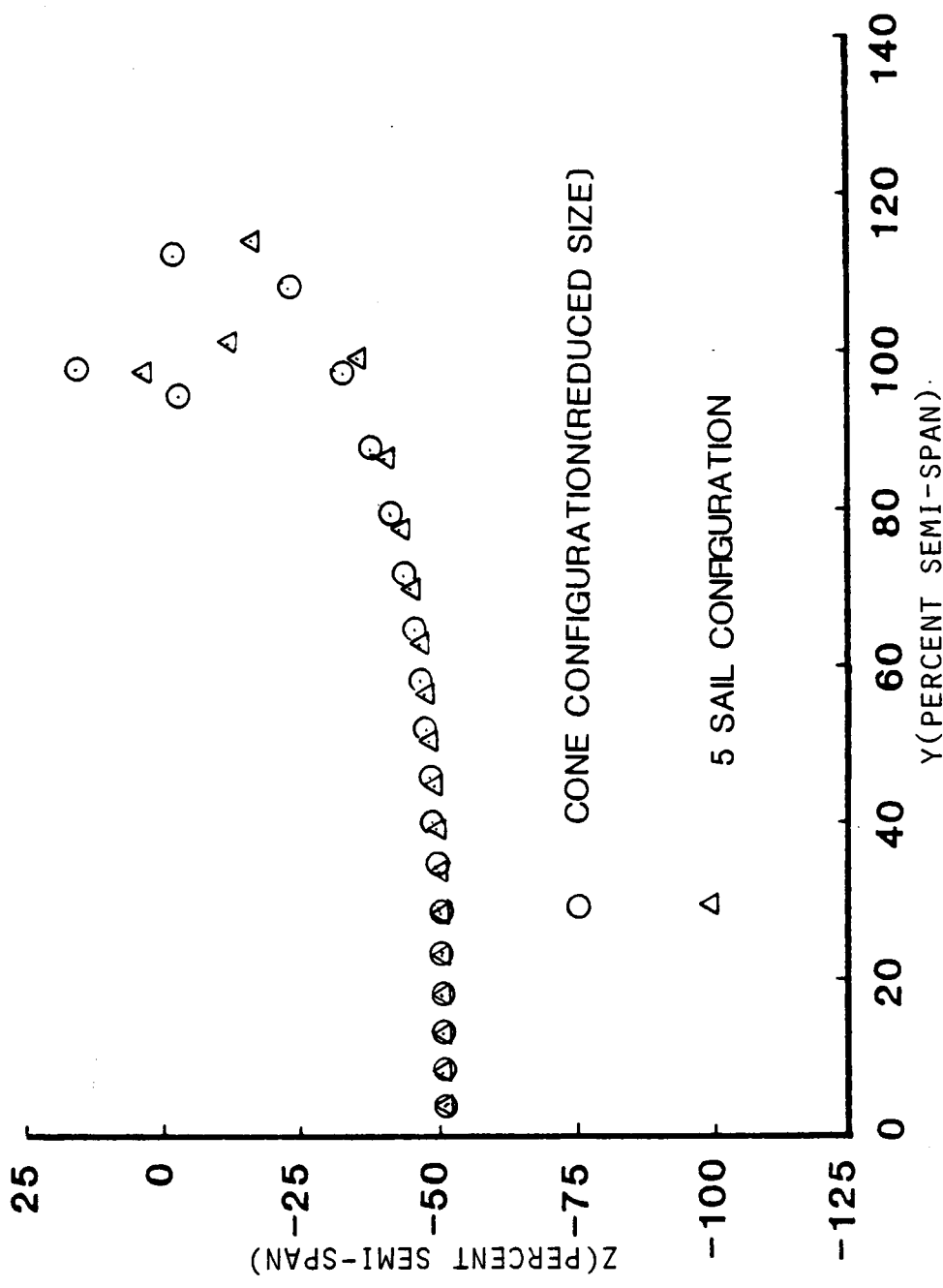


Figure 46. Position of Shed Vortices from Computer Model, Bird Tip Feather Configuration versus Five-Sail Configuration.

CHAPTER IV

THEORIES AND PROPOSED FUTURE RESEARCH

Theories on Bird Tip Feather Action

The Cranfield Institute data [6] suggest that the swirl angle ϕ increases with distance along the tip chord from leading edge to trailing edge. This means the aft tip feathers should have lesser angles of attack than the front ones.

I propose that this action--call it main wing action--dominates at the tips of the feathers at low main wing angles of attack.

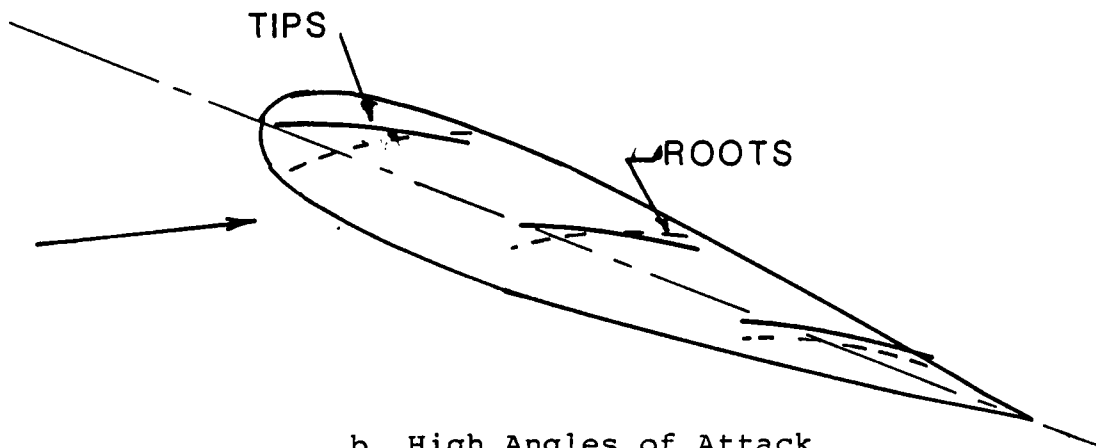
However, at high main wing angles of attack, the tips become more heavily loaded; the downwash from preceding feathers affects the tip flow, and causes the feathers to see more nearly the same local flow angle. As the main wing rotates the front feather should twist to a lesser incidence relative to the wing chord, because it was already at a higher incidence than the aft feathers. This is illustrated in Figure 47.

If one examines bird tip feathers, one will find that the front feathers are built in such a way that loading causes them to twist in the manner previously described. A sketch is shown in Figure 48. The "spar" is

SAIL (FEATHER) TWIST

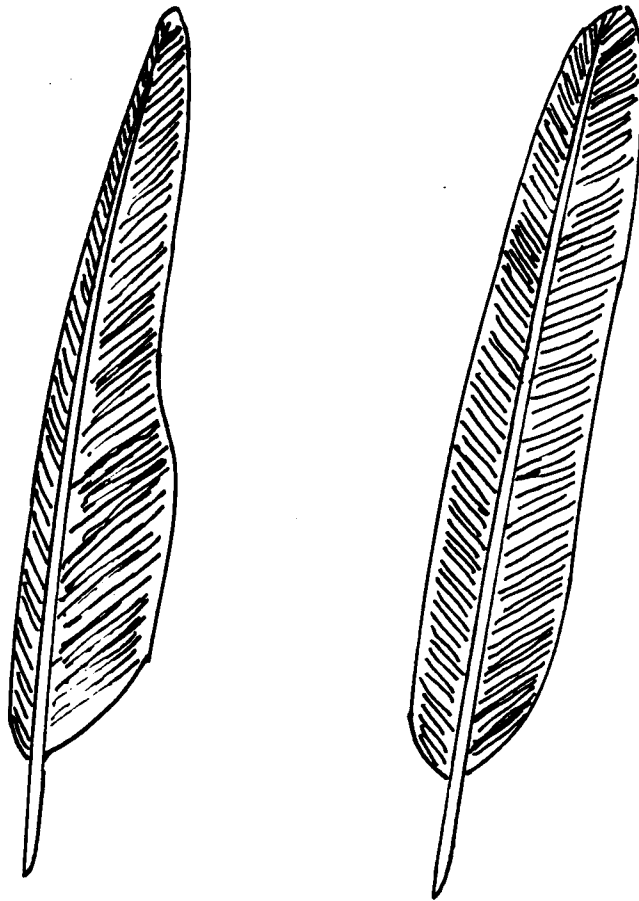


a. Low Angles of Attack



b. High Angles of Attack

Figure 47. Proposed Sail Configuration for Future Research.



a. Front Primary

b. Rear Primary

Figure 48. Configurations of Primary Feathers of Soaring Birds.

closer to the leading edge in the front feathers. However, at the feather root, which is now away from wing tip action, a configuration similar to Nenadovitch's [16] may be desirable.

Recommendations for Future Research

The following cases should be run in a wind tunnel and perhaps in a water tunnel for wake study.

1. The front sails should be cambered along their span (from Cone's work and bird pictures). Incidence angles should be reduced from one sail to the next (4 to 6°) at the root, moving forward from the aft sail. Twist should be such that at the tips all have the same angle of attack. This case should be run with the wing at high angles of attack.
2. A case should also be run with less spanwise camber and with twist in the sails such that the forward tips have greater incidence than the aft tips. This means that the forward sails will be very twisted. This configuration should be run at low angles of attack.

Again, these configurations are based on Nanadovitch's angles, Cone's verbal description of pinions, Cranfield's wing tip flow data, and the effects of downwash

from a feather tip on the succeeding tip. For designing these sails one should also consider Hackett's recommendation for using the highest C_L , not L/D for the wing tip device [12].

These should be compared against other possibilities, but they are proposed as techniques for optimization and may simulate the tip feathers of soaring birds.

CHAPTER V

CONCLUSIONS

In this study, I have tried to define the interacting mechanisms between vortex wake attenuation and improved L/D ratio so as to make the thought patterns natural. I have also re-displayed the data from the few investigators in a similar format for easy comparison.

Based on this study, we conclude:

1. Enlarging the wake vortex core (reducing core velocities in the Y-Z plane) increases the overall L/D ratio for a finite wing.
2. Several different wing tip devices yield similar changes in the wake vortex structure, reducing core velocities in the Y-Z plane.
3. High aspect ratio tip sails are an effective device for reducing core velocities in the Y-Z plane.
4. Five sails are more effective than three.
5. A wing with an upward curved wing tip can have performance as good as one with wing tips in the plane of the wing, increasing the span.
(Nature says it should be better!)

6. There is much study and experimentation to be done to optimize multiple wing tips to possibly produce greater performance than the equivalent wingspan.

It may be that the sails can be optimized further as noted above, giving even greater performance gains; but even this is going to give a best one-point design (on angle of attack) for fixed sails. To duplicate the birds would require a structural study in aeroelasticity. However, for aircraft not cruising over a wide range of angle of attack, the aerodynamic benefits of fixed sails exist. It may be possible to have a variable design by mechanically rotating (around the Y axis) the front one or two sails.

There are benefits other than improved aerodynamic performance which we have not mentioned. The attenuation of the trailing wing tip vortices can produce wider spraying patterns for agricultural application aircraft. Also, reducing the vortices will improve safety for operations at high traffic density airports.

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Mr. Hull spent the year 1975 in Nigeria, West Africa, teaching high school mathematics and preaching for churches of Christ. Upon return to the United States, he labored at various civil and mechanical engineering positions in the middle Tennessee area. In 1982 he began full-time study at The University of Tennessee Space Institute, where he was awarded the Master of Science degree in Aerospace Engineering in 1984.