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Final Report

ONR HULL PROPULSOR INTERACTION ARI

Contract No. N00014-86-K-0058

Work Unit No. 432a - 004

Project Director William S. Vorus

from

The University of Michigan
Department of Naval Architecture
and Marine Engineering

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I. INTRODUCTION

The University of Michigan, Department of Naval Architecture and Marine Engineering, participated in The ONR Hull-Propulsor Interaction ARI for the last four years of the five year program, with abbreviated funding in the second and fifth years. The total research funds received under the program was $445,000., out of $475,000. initially allocated.

The program officially ended for the University of Michigan at the end of CY 1989. The reason for the delay in submitting this report was an interest in waiting for all of the PhD students supported under the program to finish. However, with one thesis still outstanding, it was decided that this report best not be late by more than one year after program expiration.

The focus of the work of the Michigan segment of the ARI was in "Real Flow Effects in Propeller Hydrodynamics." Its organization was as depicted in Figure 1. Initially, the parallel efforts indicated on Figure 1 were set with four PhD students each under Professors W. S. Vorus and T. E. Brockett. Professor Brockett left The University in mid-1989, which has contributed to the delay in completing the work. Of the eight PhD students involved initially, five have finished, and the sixth and final one will finish in the next few months. A list of the names of the students and the titles of their theses constitute a following section.

A total of 7 journal and symposium papers have been published on the work, and three additional are in preparation at this time. A list of the publications also constitutes a following section of the report.

The report concludes with three selected excerpts describing technically what is considered to have been some of the more important results of the research effort.

II. PhD DEGREES AWARDED ON THE RESEARCH

The following is a list of PhD degrees awarded to students supported by the ARI, their thesis titles, and the dates of degree award:

Dinavahi, S.P., "A Streakline Method for Computing Vortical Flows in Two Dimensions", 1988

Statement "A" per telecon Dr. Edwin Rood.
Office of Naval Research/code 1132F.

VHG 1/16/91

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Korpus, R.A., " A Fully Relaxed Vortex Sheet Model for Propeller Analysis in a Sheared Onset Flow," 1989

Suh, J.-C., " Unsteady Analysis for a Two-Dimensional Foil in a Uniformly Sheared Onset Flow, " 1990

Kirschner, I.N., "A Flat-Cavity Analysis of Leading-Edge Vortex Separation from Slender Wings, " 1990

Chen, L., "Application of a Vortex Method to Free Surface Flows," 1990

The following degree will be awarded in 1991:

Kim, M.-H., " Analysis of Superseparation of High Aspect Ratio Foils Using Second Order Free Streamline Theory ."

III. JOURNAL AND SYMPOSIUM PAPERS PUBLISHED ON THE RESEARCH

The following is a list of papers published by the investigators and students during the course of the research. It must be kept in mind that the bulk of the publication of the research work necessarily follows the completion of the work. Three of the six theses were not finished until this year, and the final one will not be completed until sometime next year. The publications listed below represent, by in large, the results of secondary, albeit important, supportive investigations off the two main streams of the research program (Figure 1)·

Brockett, T.E., and Korpus, R.A., "Parametric Evaluation of the Lifting-Line Model for Conventional and Preswirl Propulsors," Proceedings of the INternational Symposium on Prepellers and Cavitation, Wuxi, China, (1986), 136-145.

Brockett, T.E.,"Propeller Interaction with an Axisymmetric Sheared Onset Flow," 16th Symposium on Naval Hydrodynamics, University of California, Berkeley, (1986).

Vorus, W.S.,"Ambient Supercavities of Slender Bodies of Revolution," Journal of Ship Research, vol 30, no 3, (1986).

Brockett, T.E., and Korpus, R.A., "Marine Propulsors for Minimum Shaft Horsepower," 21st ATTC, Washington, D.C., 1986.

Vorus, W.S., and Chen, L., "An Extension of the 'Malkus Hypothesis' to the Separated Base Flow of Blunt Sections," Journal of Fluid Mechanics, 184 (1987), 555-569.

Brockett, T.E., "Limiting Forms of Surface Singularity Distributions When the Field Point is on the Surface," Journal of Engineering Mathemnatics, 23 (1989), 53-79.

Vorus, W.S.," A Solution to Burger's Equation for Sinusoidal Excitation at the Upstream Boundary," Journal of Engineering Mathematics, 23 (1989) 219-237.

IV. IMPORTANT RESEARCH RESULTS

Referring back to Figure 1, the total ARI program at Michigan was divided into 'On-Blade Flows,' under the direction of W.S. Vorus, and 'Off-Blade Flows,' under the direction T.E. Brockett. The objectives in these two areas, as implied by Figure 1 and specifically defined in the original project proposal, have been largely achieved. However, in that the more important results are just now surfacing in the completing PhD theses, their publication is still in the future. As an alternative to providing reference to final publications, brief outlines of important results achieved in three selected areas are given in the following.

Effect of Variable Bernoulli Head on the Configuration of Propeller Blade Trailing Vortex Sheets, from the thesis of R.A. Korpus.

This work falls under the 'Vortex Wake Outflow' sub-topic defined on Figure 1.

For irrotational flow propeller models, the total head in the Bernoulli equation for the fluid pressure is constant everywhere. In Korpus' work, the propeller is assumed to be operating in an ideal, but rotational inflow, so that the Bernoulli head is not spatially constant. But it is assumed to be known as a function of position at the blade leading edge.

The pressure difference developed across the blade produces a distortion of the streamlines along which the variable Bernoulli head fluid is convected over the two blade surfaces. But the streamlines are distorted differently on the blade face and back surfaces. The result is that at any point along the blade trailing edge a jump in Bernoulli head occurs as two different streamlines from the two sides of the blade meet.

By the usual requirement of continuity of static pressure at the blade trailing edge, Korpus derived the following relation applicable on the vortex sheet shed at the blade trailing edge:

$$H^{+} - H^{-} \triangleq \Delta H = \rho \mathbf{V}_{m} \cdot \delta \mathbf{V}$$
$$= -\rho \mathbf{V}_{m} \cdot (\mathbf{n} \times \gamma) = -\rho \left|\gamma\right| \mathbf{V}_{m} \cdot (\mathbf{n} \times \mathbf{t}) \quad .$$

This relation states that the jump in Bernoulli head across the vortex sheet is the product of the fluid density, the magnitude of the sheet vortex strength, and the scalar product of the mean sheet velocity and the radially directed unit tangent vector lying in the sheet. For the conventional irrotational flow model the mean velocity is streamwise directed for continuity of pressure, so that the scalar product is zero, implying constancy of the Bernoulli head.

Korpus used the above relation to establish a boundary conditions on the sheet vortex strength, and sheet position, in terms of the head jump, which is presumed to be known. A propeller lifting surface model was then adapted to obtain a first order solution of the non-linear problem; iteration was used to establish the altered vortex sheet geometry.

The main conclusion of the work was that a typical variation of Bernoulli head significantly alters the strength of the vortex sheet, but has less effect on its pitch and contraction, except for heavily loaded, low pitched rotors.

From an engineering standpoint, the effect of spatially variable Bernoulli head can be important, theoretically, to establishing the correct pitch of propeller blades, but is currently not included in any propeller design procedure.

A First-Order Model for Leading Edge Separation from Lightly Loaded Lifting Surfaces; from the thesis of I.N. Kirschner.

This work, representing the "tip vortex roll-up and leading edge separation" research identified on Figure 1, was aimed at developing a model for predicting propeller blade leading edge separation, in the sense of the characteristic delta-wing flow, Figure 2. This type of secondary flow is particularly pronounced on propellers with highly swept (skewed) leading edges operating at off-design conditions.

Kirschner used slender body theory like the traditional approaches of the past, but simplified the problem substantially by side-stepping the more serious non-linearities with first order free-streamline theory, where all boundary conditions are all satisfied on the axis. As shown by Tulin (1964), this model completely avoids the troublesome details of vortex sheet roll-up. Its validity requires that the separation cavities formed by the separating vortex sheets are relatively thin, in some sense.

Figure 3 shows the predicted separation cavity on the half-span of a delta-wing of half-apex angle 10 degrees at 10 degrees incidence. The cavity opening admits the flow ingested from the outer field, which provides the feed for the growth of the vortex cavity downstream.

Figure 4 is a comparison of the differential pressure coefficient for the same delta wing at 5 degrees incidence. The comparison with Fink's experimental data is better than that of Mangler and Smith's highly acclaimed non-linear model. Kirschner's model is not as superior to Mangler and Smith at high incidence; the 10 degree incidence case is shown on Figure 5. The propeller blade off-design effective incidence level of interest is 2 to 3 degrees at the most.

Figure 6 shows the predicted cavity offset distribution along the leading edge for an elliptical wing of aspect-ratio 1.0 operating at a lift coefficient, for attached flow, of .2; this C_L is typical for a propeller blade section. Here the stream is in the + zeta direction. Figure 7 shows the distribution of lift amplification for this wing as a function of position along the chord; C_{La} represents the lift distribution for fully attached leading edges.

This model is believed to have significant potential value in propeller off-design performance analysis. Unfortunately, the budget cuts in the final year of the ARI did not allow its rather straightforward adaptation to the propeller analysis problem.

A Model for Turbulent Super-Separation from High Aspect Ratio Foils, from the thesis of M.-H. Kim.

The second separation type of interest on propeller blades is the closed type which can be characterized as approximately 2-dimensional in sectional planes of high-aspect-ratio lifting surfaces, Figure 8. It typically occurs near the inner radii of propellers where the leading edge gradients are not sufficient to provide relief through the 3-dimensional leading-edge separation process and where high cavitation number suppresses sectional sheet cavitation.

Here, Tulin's free-streamline perturbation theory has again been applied, Tulin (1964), but supplemented by a closure condition for turbulence based on the 'maximum dissipation' hypothesis of Malkus (1956). The initial work on this model is published in Vorus and Chen (1986), listed in Section III above. The Vorus and Chen (1986) work applied the technique to base separation of symmetric foils using first order free streamline theory. Figures 9 and 10, from that work, are for a symmetric wedge with half-apex angle of 15 degrees. The theory predictes the mean separation cavity configuration shown on Figure 9; note the large negative pressure coefficient of -1.19. Figure 10 compares predictions of base pressure drag with the Lindsey experimental data for wedges of varying apex angle. The classical Kirchhoff prediction for the wedge, for zero base pressure coefficient and an open cavity of infinite length, is included on Figure 10 as a reference basis.

Kim is extending this work to second order, as is theoretically required because of the high negative pressure coefficient developing within the separation cavity. Kim is also extending the theory to the lifting case.

This work, while not yet fully completely, is currently being applied as an engineering tool in propeller performance analysis by interest at the University of Michigan.

Mr. Kim is completing his thesis work self-supported.

V. REFERENCES

Vorus, W.S., and Chen, L., "An Extension of the 'Malkus Hypothesis' to the Separated Base Flow of Blunt Sections," Journal of Fluid Mechanics, 184 (1987), 555-569.

Malkus, W.V.R.,"Outline of a Theory for Turbulent Shear Flow," Journal of Fluid Mechanics, 1 (1956), 521-539.

Tulin, M.P.,"Supercavitating Flows - Small Perturbation Theory," Journal of Ship Research, 16 (1964).

ONR PROP-BODY INTERACTION ARI
AT THE UNIVERSITY OF MICHIGAN

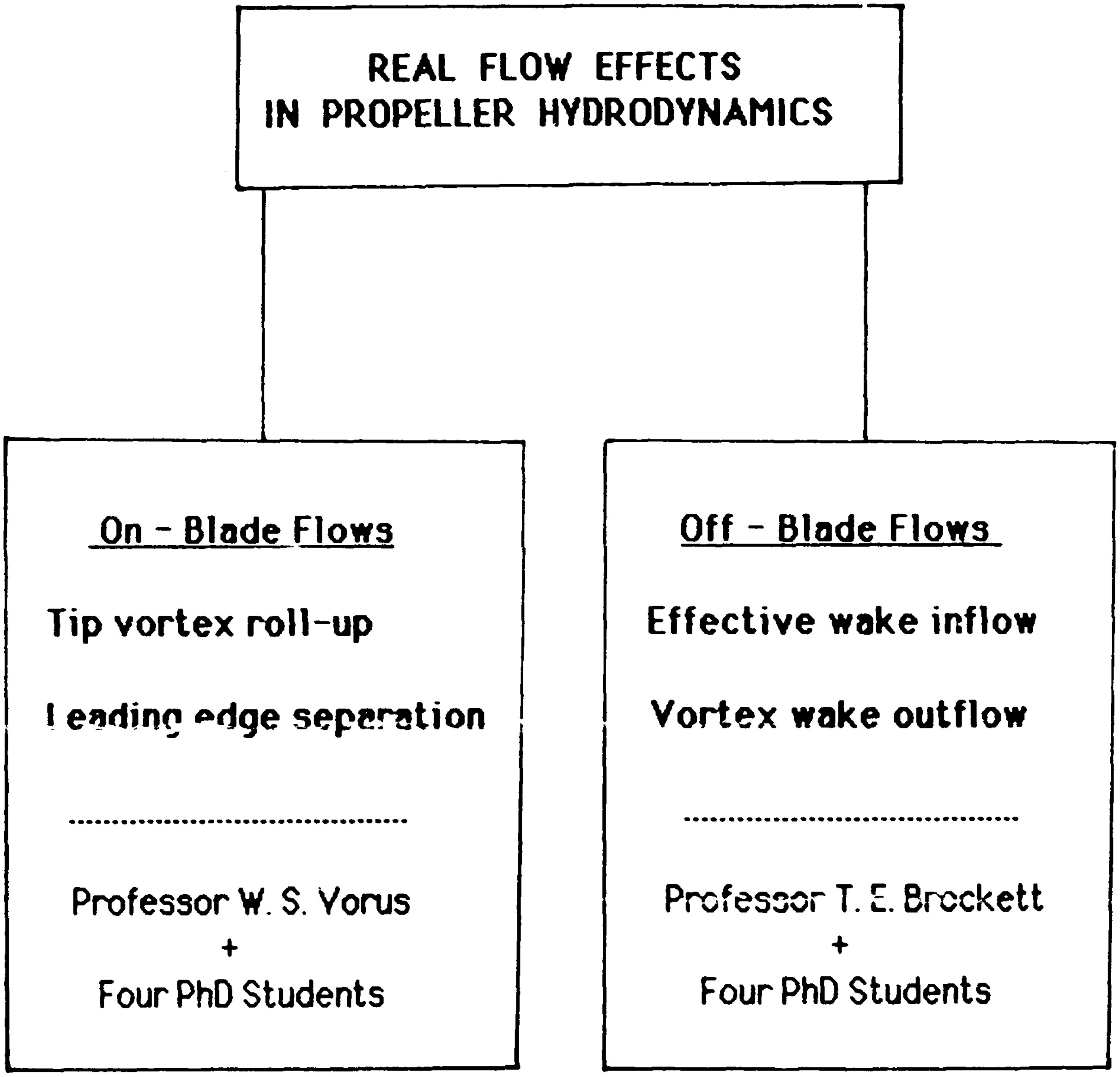
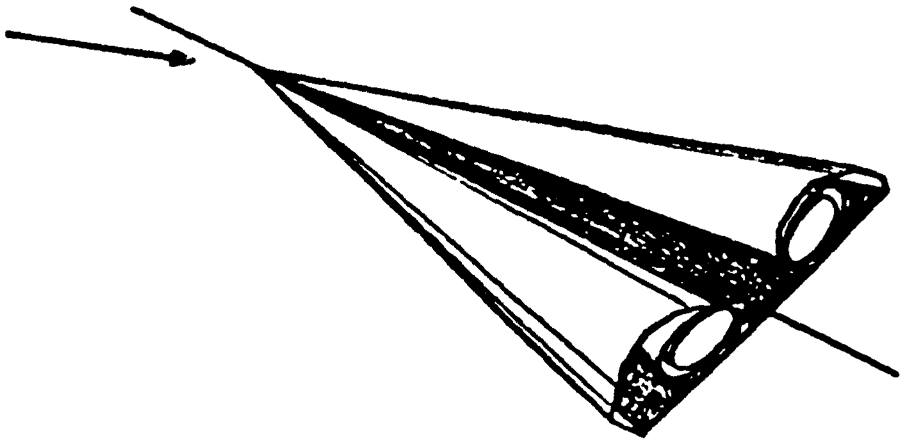


FIGURE 1



Open (Leading Edge Vortex) Separation

FIGURE 2

Separation Cavity Conto
Delta-Wing
$\beta = 10°, \alpha = 10°$

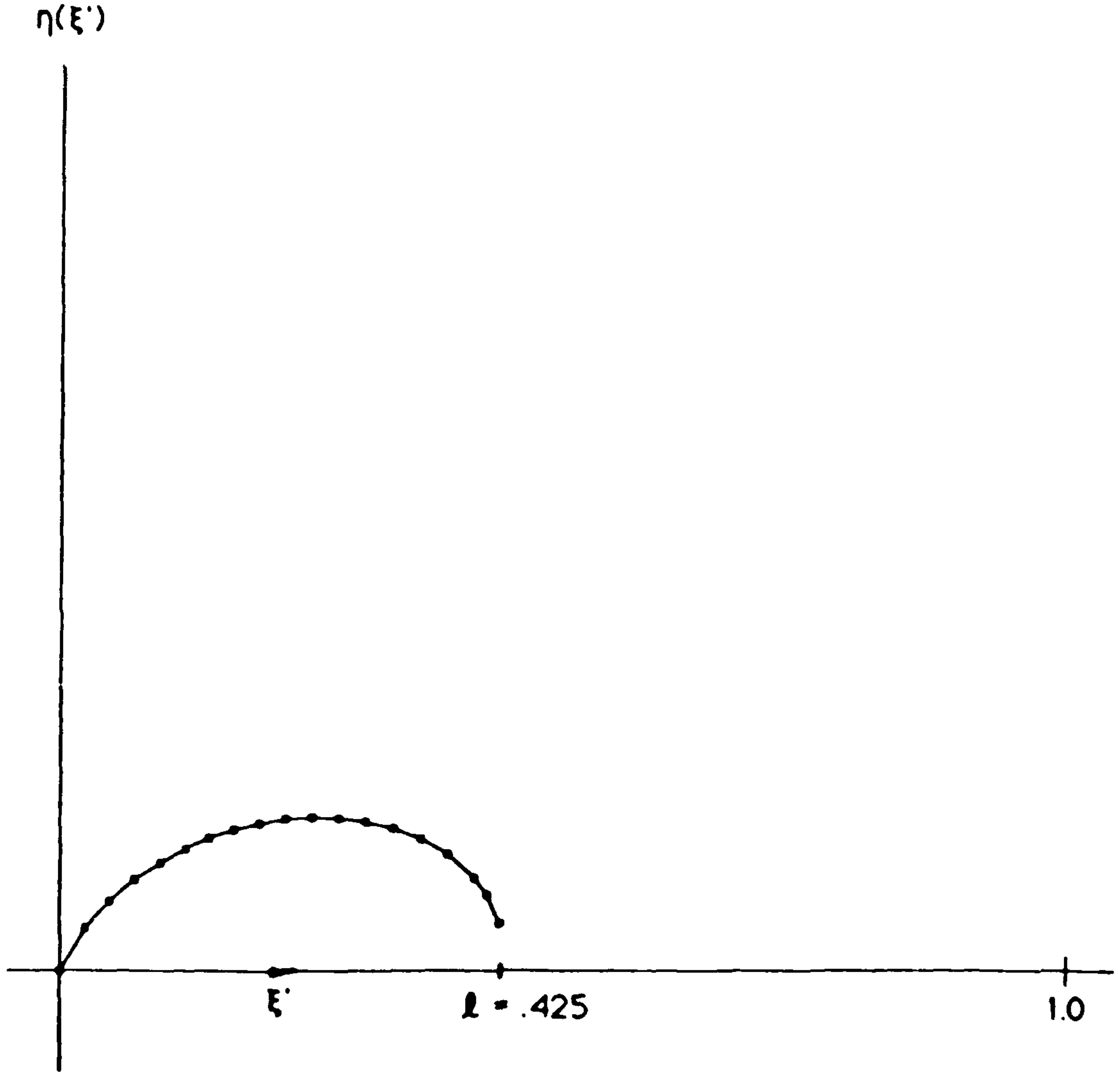


FIGURE 3

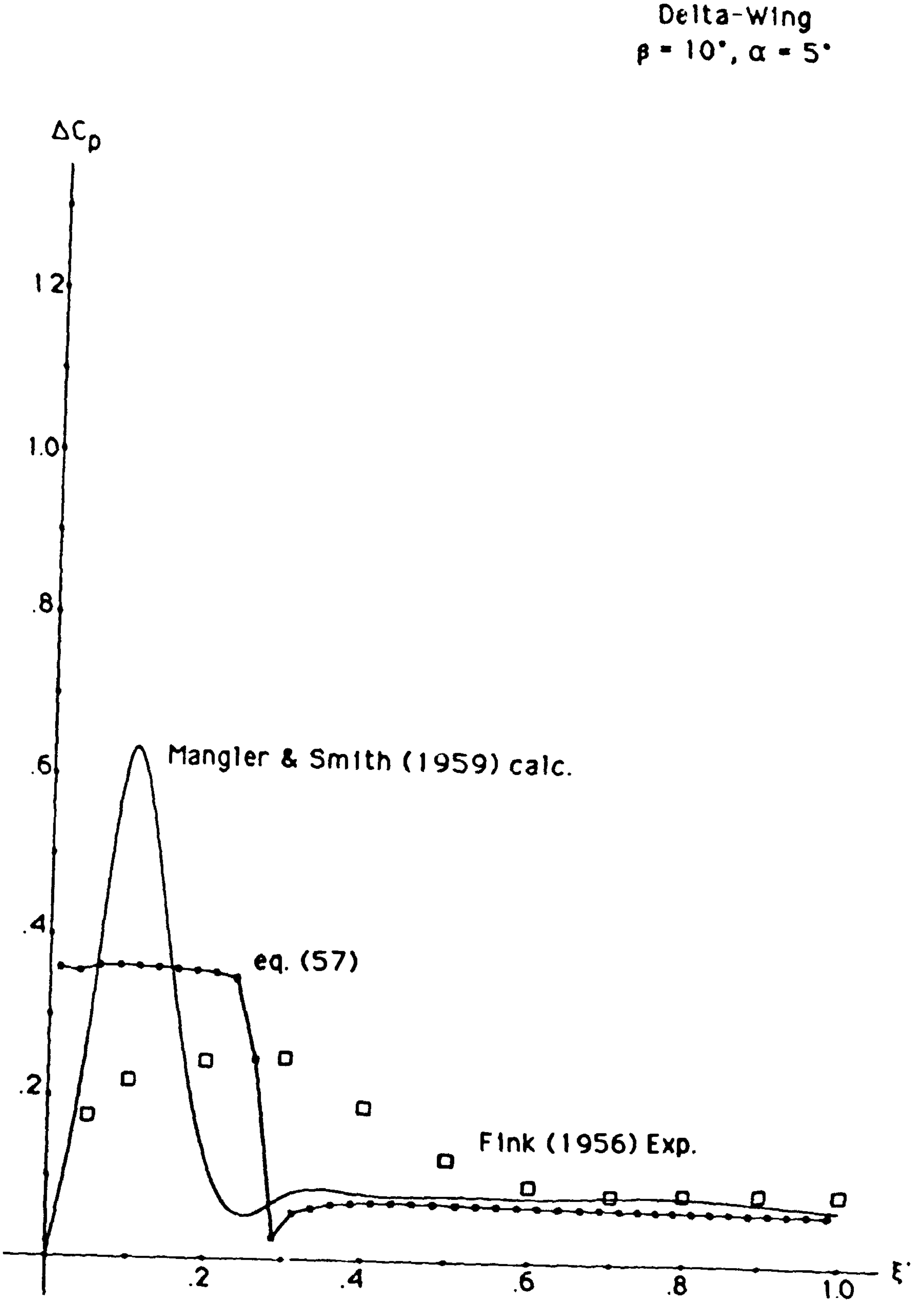

Delta-Wing
β = 10°, α = 5°
ΔC_p
1.2
1.0
.8
.6
.4
.2
Mangler & Smith (1959) calc.
eq. (57)
Fink (1956) Exp.
.2
.4
.6
.8
1.0
ξ'

FIGURE 4

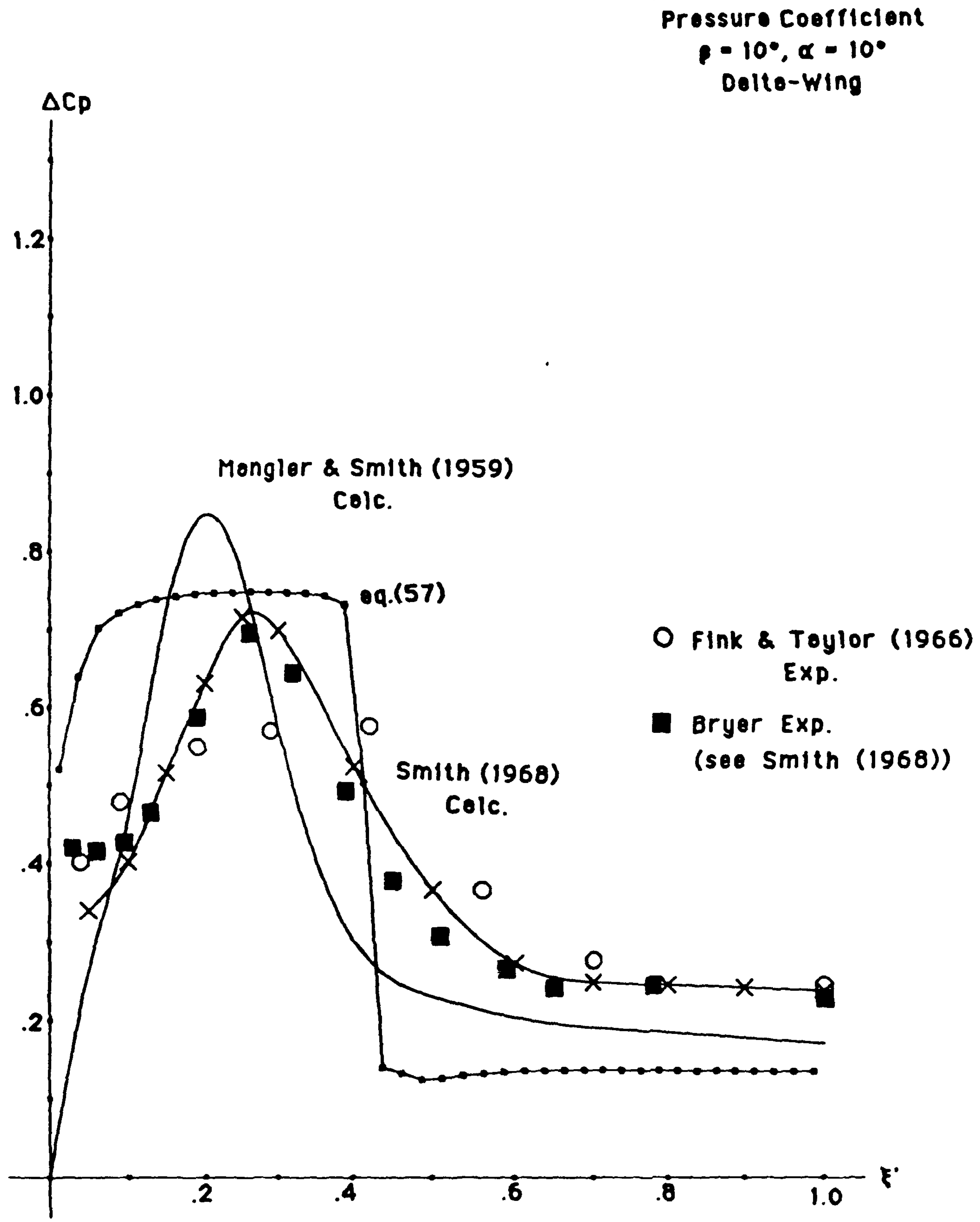
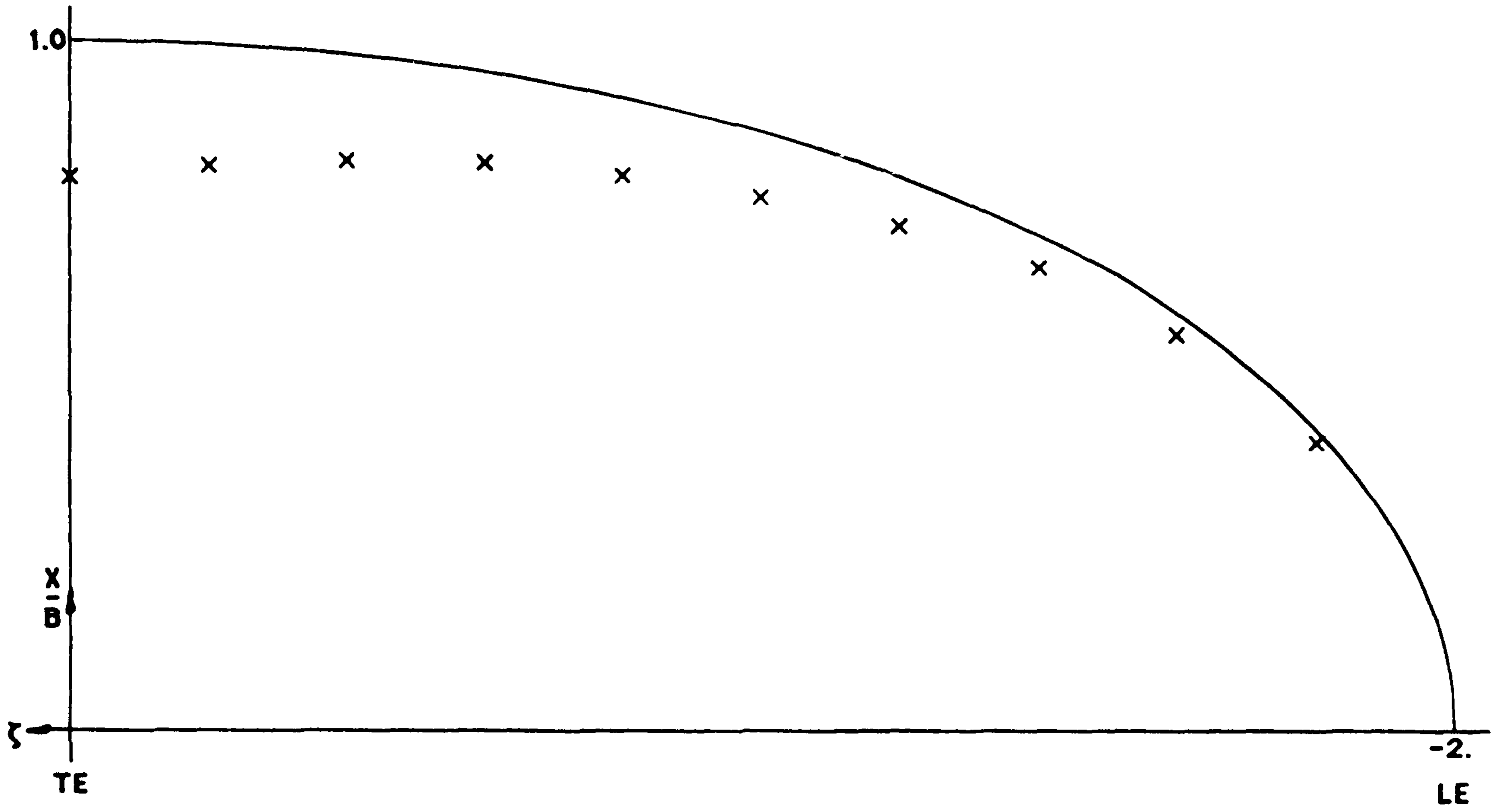

Pressure Coefficient
β = 10°, α = 10°
Delta-Wing
ΔCp
1.2
1.0
.8
.6
.4
.2
.2
.4
.6
.8
1.0
ξ'
Mengler & Smith (1959)
Calc.
eq.(57)
Smith (1968)
Calc.
○ Fink & Taylor (1966) Exp.
■ Bryer Exp. (see Smith (1968))

FIGURE 5

FIGURE 6

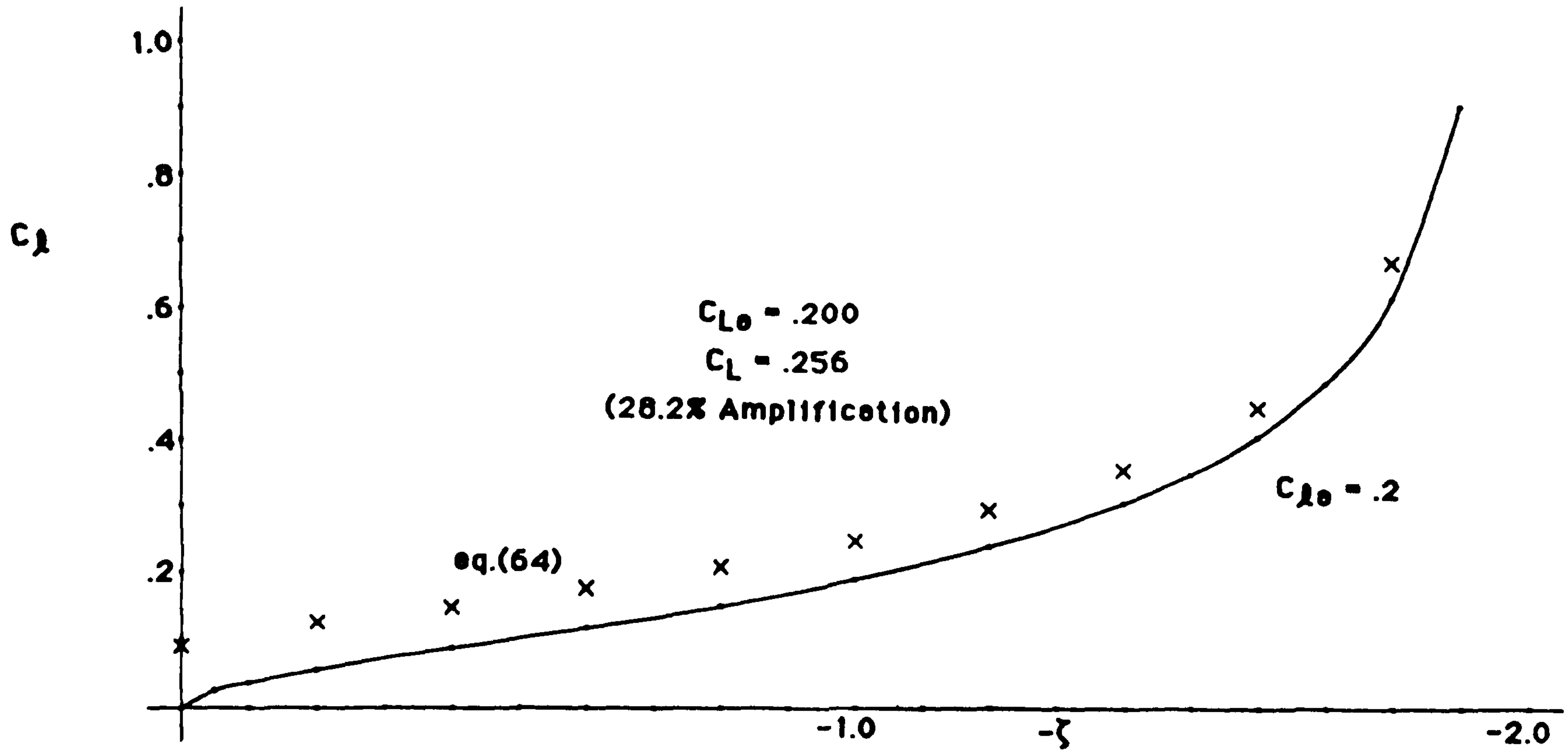


Semi-elliptical Wing

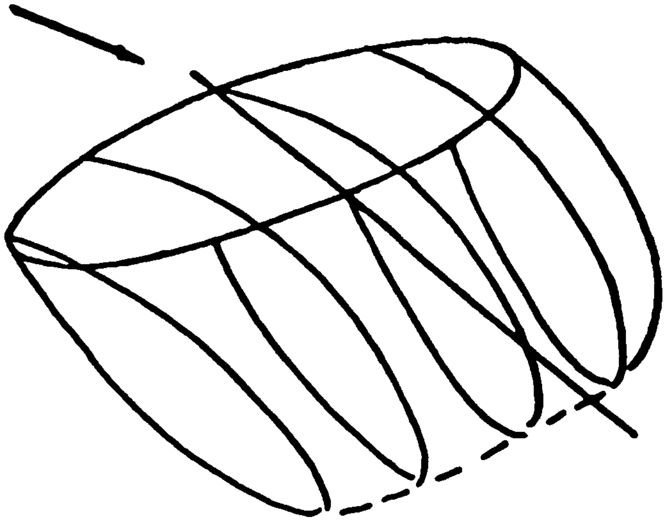
AE = 1.0, C_{Lo} = .2

Separation Cavity Width

FIGURE 7



Semi-elliptical Wing
AE = 1.0, $C_{Lo} = .2$
Lift Amplification Due to Separation



Closed Separation

FIGURE 8

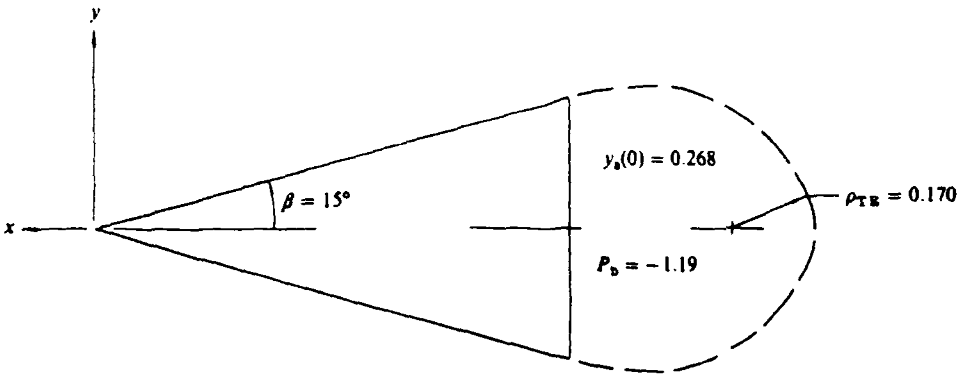


FIGURE 9 Wedge and separation cavity, half-apex angle = 15°.

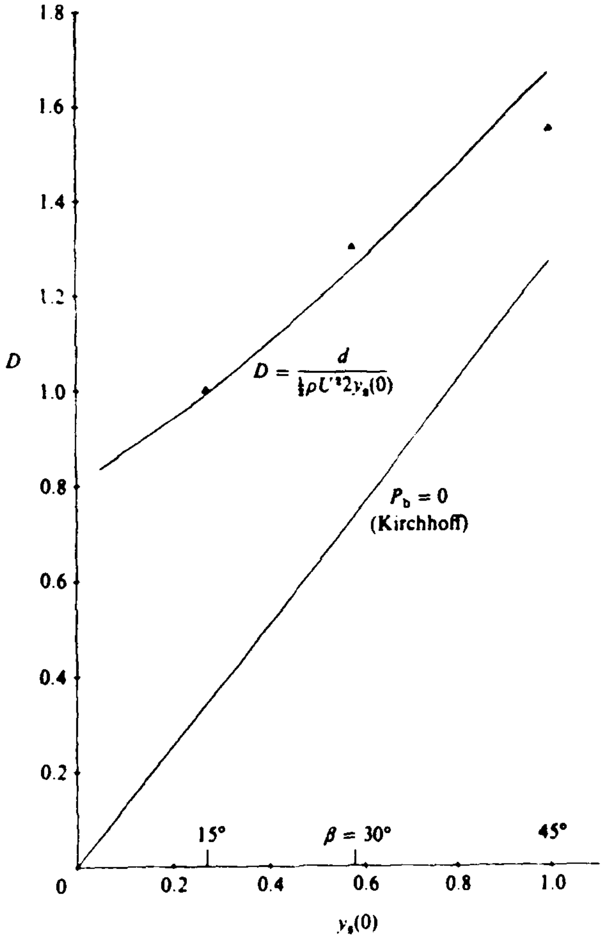


FIGURE 10 Drag coefficient versus wedge base offset; ▲, data from Lindsey (1938).