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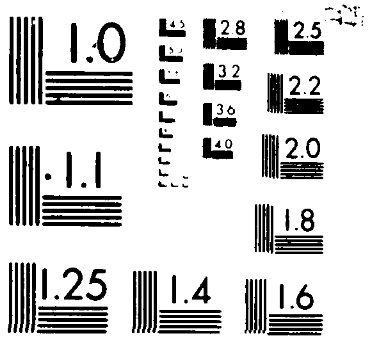

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A research program in non-linear unsteady aerodynamics carried out at the Georgia Institute of Technology between 1982 and 1986 is summarized. New computational and theoretical methods ideally suited for viscous unsteady aerodynamic problems are described. Improved understanding of important physical processes involved in non-linear unsteady aerodynamics are discussed. Results are presented for three focal problems: (1) the Weis-Fogh problem, (2) the concept of trapping vortices and (3) the vortex-airfoil interaction.

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STUDIES IN NON-LINEAR UNSTEADY AERODYNAMICS

FINAL REPORT

AFOSR GRANT NO. 82-0108

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I. INTRODUCTION

This report reviews a research program in unsteady aerodynamics carried out at the Georgia Institute of Technology. This program is an outgrowth of a long-range research effort at Georgia Tech dealing with various aspects of unsteady flows. This long-range effort, initiated in the early 1970s, produced new computational and theoretical (non-computational) approaches which have a broad range of applications and which are ideally suited for studies of unsteady aerodynamics problems. The research program reviewed in the present report employed these new approaches in studies of problems in the non-linear domain, where viscous separation and strong unsteady effects are such that the linearization of flow equations are not justifiable.

The present research program was initiated in March of 1982. The overall objectives of the present research program are (1) the establishment of a body of knowledge and a precise understanding of the difficult interactive fluid dynamic elements which dominate the aerodynamics of unsteady flows in the non-linear domain and (2) the establishment of a rational framework for the prediction and utilization of large aerodynamic forces generated from large amplitude unsteady motions of lifting bodies. It was recognized that these objectives were challenging and would require extensive and persistent research efforts over many years to achieve. Accordingly, the present research program was planned to be carried out in several phases. The first-phase of the present research program was completed in March of 1986. Research results obtained during this first phase are summarized in this report. Much of the findings of this research have been documented in a series of reports, Ph.D. theses, conference proceeding papers, journal articles and chapters of specialist books. For this reason, only brief descriptions of research accomplishments that, in the opinion of the principal investigator, represent new and significant contributions to the subject of unsteady aerodynamics are given in this report. Chronological lists of publications and Ph.D. theses are provided in Section 4 of this report for additional information.

The present research program encompasses a theoretical aspect and a computational aspect. The scientific approach utilized in the present research program is briefly reviewed in this report. Throughout the tenure of this research, the theoretical and the computational aspects of the program were made to interact with one another. The close interplay of these two aspects made it feasible to develop improved understanding of various physical processes contributing to the generation of unsteady aerodynamic force. This close interaction further reinforced the further development of theoretical and computational techniques for unsteady aerodynamic problems. At the present, the development and utilization of these approaches in two-dimensional applications have reached a stage of maturity. A highly efficient procedure for routinely predicting unsteady aerodynamic forces associated with large amplitude motion of two-dimensional lifting bodies has been created. A good understanding of important physical processes involved in two-dimensional non-linear unsteady aerodynamics has been obtained.

Current research interest in non-linear unsteady aerodynamics can be divided, in accordance with the types of applications involved, into at least three major areas. In turbo-machines, marine propellers, helicopter rotors, etc., strong flow unsteadiness leads to large adverse effects (e.g., Reference 1). The alleviation or minimization of these adverse effects is of primary concern in these applications. In the area of biofluiddynamics, (Reference 2), non-linear unsteady aerodynamics clearly plays a dominant role in the locomotion of aquatic and aerial animals. Studies of locomotion of these animals in recent years include problems of propulsion and of control. Parallel to the two types of applications just stated, during the past few years, the opportunity of utilizing non-linear unsteady aerodynamic forces advantageously in the design of future aircraft has received considerable attention. The present research was motivated by this opportunity in aeronautics. Consistent with this motivation, three focal problems were selected for theoretical and computational investigations under the present research program. These focal problems are: (1) Unsteady aerodynamic forces acting on airfoils encountering passing vortices, (2) Unsteady aerodynamic force, moment and power expenditure associated with the Weis-Fogh motion, and (3) Concepts of anchoring, or trapping, vortices near lifting bodies. These focal problems involve two-dimensional lifting bodies. Each problem represents an important facet of non-linear unsteady aerodynamics.

Studies of the three focal problems were completed. Extensive information was obtained not only about the focal problems themselves but also about the anatomy of unsteady flows and the major contributors to unsteady aerodynamic forces in general. This information is briefly described in this report.

2. SCIENTIFIC APPROACH

The theoretical and computational approaches employed in the present research possess several distinguishing features. Several of these features are particularly important to studies of non-linear unsteady aerodynamics and are reviewed briefly here.

A lifting body undergoing unsteady motion in a fluid is in general surrounded and trailed by a flow region containing vorticity where viscous effects are important. For brevity, this region is referred to as the vortical region. This vortical, or viscous, region is surrounded by potential flow regions where the vorticity fields, and hence the viscous effects, are negligibly small. The vortical region is, in general, composed of attached boundary layers and detached vortical zones. The detached zones include recirculating flows (separation bubbles), wakes and starting vortex assemblies. For flows at high Reynolds numbers, the thickness of the attached boundary layer is drastically smaller than the length scale of the detached vortical zones. The length scale of the detached vortical zones, in turn, is drastically smaller than that of the potential flow. The physical and mathematical characteristics of the various flow components present are greatly different from each other. The *simultaneous presence of these diverse length* scales and diverse flow characteristics has led to serious theoretical and computational difficulties.

The theoretical and computational approaches employed in the present research program have in common two distinguishing attributes:

(1) They permit aerodynamic analyses to be confined to the vortical part of the unsteady flow. The potential flow components need not be evaluated. Only the vortical components enter the process of analyses.

(2) They permit the contributions of the several vortical flow components to the aerodynamic load to be identified and evaluated individually. Through this ability, important contributors to non-linear unsteady aerodynamic load can be identified and their relative importance can be assessed.

These two attributes removed the serious theoretical and computational difficulties associated with the simultaneous presence of diverse length scales and diverse flow characteristics in non-linear unsteady flows.

Long before the emergence of computational aerodynamics, remarkable advances in aerodynamics were brought about by researchers who perceived theoretical approaches that predict aerodynamic forces and moments acting on lifting bodies while avoiding, as much as possible, entanglement with details of the fluid motion around the bodies. In particular, the well-known circulation theory is known to predict steady lift forces accurately for certain types of lifting surfaces, e.g., thin airfoils with sharp trailing edges, under certain flow environments, e.g., small angles of attack. Earlier investigators successfully extended the circulation theory to studies of several important unsteady aerodynamic problems in the linear domain (e.g. Reference 3). These earlier studies are facilitated by the fact that, within the context of the linear theory, the various vortical components present can be represented by discrete vortices or vortex sheets. The contributions of these vortex elements to the aerodynamic load can be evaluated individually. The linear addition of these individual contributions then yields the total aerodynamic load. These earlier investigations, however, are subject to a number of serious restrictions and are based on the concept of an inviscid fluid. Uncertainties and conceptual difficulties were encountered in past attempts to extend the circulation theory to the non-linear domain and to viscous flows. It is generally assumed that contributions of the different flow components to the total aerodynamic load cannot be evaluated individually. It is further believed that, even if the contributions can be individually evaluated, the linear addition of these contributions does not yield the total aerodynamic load because the flow is in the non-linear domain. For this reason, comparatively little emphasis has been given by the aerodynamics community to theoretical (non-computational) studies of non-linear unsteady aerodynamics.

Contrary to these beliefs, results of the present research program conclusively demonstrated that the contribution of each flow component to the total aerodynamic load can be clearly identified and individually evaluated theoretically even for viscous flows in the non-linear domain. Moreover, the linear addition of the individual contributions yields the total aerodynamic load for both linear and non-linear flows. Indeed, under certain circumstances, closed form analytical expressions for each individual contribution can be obtained for both rigid and non-rigid lifting bodies.

A general viscous theory of aerodynamics (Reference 4) developed previously by the principal investigator is used in theoretical studies in the present research. This theory is derived mathematically rigorously from the full viscous flow equations. This theory is valid and ideally-suited for flows in either the linear or the non-linear domain. No simplifying assumptions are introduced other than those contained in the familiar Navier-Stokes equations. The theory relates the aerodynamic force and moment acting on a lifting body, rigid or flexible, to its vortical environment. The mathematical statements of this theory are integral expressions of the aerodynamic force and the moment of the aerodynamic force. The expression for the aerodynamic force $\vec{F}$ is:

$$\vec{F} = -\frac{\rho}{d-1}\frac{d}{dt}\int_R \vec{r} \times \vec{\omega}\, dR + \rho \frac{d}{dt}\int_{R_S} \vec{v}\, dR$$

where ρ is the density of the fluid, t is the time coordinate, $\vec{r}$ is a position vector, $\vec{\omega}$ and $\vec{v}$ are respectively the vorticity vector and the velocity vector, d is the dimensionality of the problem, i.e., d = 2 and 3 respectively for two- and three-dimensional flows, R is the unlimited infinite region occupied jointly by the fluid and the solid, and R_S is the region occupied by the solid alone.

The integral expression for the aerodynamic force shows that the total aerodynamic force is linearly dependent upon the first moment of the vorticity field. As a consequence, it is permissible to confine the analysis to the vortical region of the flow in theoretical studies of aerodynamic loads. The potential region of the flow does not contribute to the vorticity moment integral, since the vorticity is zero in the potential region. Further, the integral of vorticity moment is replaceable by a sum of zonal integrals, each zonal integral covering a vortical flow component in the flow. Thus, each individual contribution of a flow component to the total aerodynamic force is readily identifiable and determinable once the time-dependent vorticity distribution of the flow component is known.

The integral expression for the moment of aerodynamic force is in a form similar to that just given for the aerodynamic force. It is obvious from the above discussion that the general viscous theory of aerodynamics does possess the two distinguishing features stated earlier.

Under certain circumstances, the general viscous theory of aerodynamics permits non-linear unsteady aerodynamic load to be determined approximately without the need to compute the detailed unsteady flowfield. Closed form or analytical expressions are obtainable under special circumstances, as discussed later in this report. Under general circumstances, computations of the unsteady flowfields are necessary to determine the time-dependent vorticity distribution accurately. Once this vorticity distribution is known, the aerodynamic performance of the lifting body associated with the flow can be determined using the theory.

During the past several years, the aerodynamic community has intensified its search for computational methods capable of predicting non-linear aerodynamic loads acting on lifting bodies. At present, a variety of computational procedures are being developed and utilized for such predictions. These procedures deal with various levels of approximation of the full viscous flow equations, ranging from linearized surface singularity techniques coupled with a non-linear vortex sheet roll-up model (Reference 5) to Euler equation solver (Reference 6), parabolized Navier-Stokes solvers (Reference 7) and full Navier-Stokes solvers (Reference 8). These procedures are mostly based on familiar finite-difference and finite-element concepts. They do not possess the two distinguishing features described earlier. Researchers at Georgia Tech have been actively developing and utilizing these procedures for many years. In the course of this long-term research effort, a zonal computational approach was conceived and subsequently developed (Reference 9, 10). This zonal approach possesses the two distinguishing features described earlier and is totally compatible with the general viscous theory of aerodynamics.

The zonal approach is developed on the basis of an integral formulation of the full viscous equations. Using the concept of fundamental solutions of partial differential equations, the viscous equations are recast into integral forms mathematically rigorously. No simplifying assumptions are introduced other than those contained in the familiar Navier-Stokes equations. The integral formulation is ideally suited for computing flows in either the linear or the non-linear domain. In aerodynamic studies, the integral formulation permits the computation field to be confined to the vortical region. The potential component of the flow is removed from the computation procedure. For unsteady flows, each vortical flow component can be computed individually. In particular, the unsteady boundary layers can be computed separately from the detached vortical flow components without iteratively matching the viscous components present (References 9, 10).

A number of highly important attributes of the general viscous theory of aerodynamics and of the zonal computational procedure have been uncovered, calibrated, refined, and utilized in the first phase of the present research. It has been found that the zonal computation procedure is easily hybridized (Reference 11). Through hybridization, unique attributes of the zonal procedure are combined with advantageous features of more conventional approaches to achieve superior computational efficiency and accuracy. In this connection, the extensive experience of Georgia Tech researchers in developing and utilizing other, more conventional, computational approaches has played a significant role in the present research.

Beginning in the early 1970s, extensive wind tunnel and water tunnel studies of different types of non-linear unsteady flows have been carried out in several research laboratories at different points of the world (e.g. References 12 through 16). These studies have identified some of the prominent flow features important to non-linear unsteady aerodynamics. It has been observed, for example, that unsteady systems of vorticity, often referred to as "vortex-like disturbances," are usually present in unsteady flowfields associated with the production of large unsteady aerodynamic forces. Theoretical and computational approaches used in the present research are well-suited for the interpretation of available experimental data. Such interpretation during the present research has produced a reasonable understanding of many physical mechanisms associated with the generation of large unsteady aerodynamic forces in two-dimensional flows.

3. WORK ACCOMPLISHED

The ability of the general viscous theory of aerodynamics to identify and to separately evaluate the individual contributions of each of the vortical flow components to unsteady aerodynamic load has been conclusively demonstrated in studies of the vortex-airfoil encounter problem and the Weis-Fogh problem.

For the vortex-airfoil encounter problem, in the case where no massive flow separation is induced by the encounter, the major contributors to unsteady aerodynamic load have been identified to be the unsteady boundary layer activities surrounding the airfoil, the unsteady wake activities trailing the airfoil and the distortion of the trajectory of the external vortex passing by the airfoil. In this case, the unsteady aerodynamic load has been determined theoretically using the following approximations: (1) the boundary layers and the wake layer are approximated by vortex sheets, (2) the velocity of the wake is approximated by the freestream velocity and (3) the external vortex trajectory is approximated by a streamline of a steady state potential flow around the airfoil.

With these approximations, closed formed analytical expressions have been obtained for the unsteady lift, unsteady drag and unsteady moment experienced by the airfoil during the encounter. These analytical expressions show that the unsteady aerodynamic load is approximately proportional to the strength of the passing vortex. The contributions of the unsteady boundary layer, the unsteady wake and the trajectory of the passing vortex appear as separate terms in the analytical expressions. Using these analytical expressions, the effects of the airfoil shape, angle of attack of the airfoil, separation distance between the airfoil and the passing vortex on each individual contribution and on the total unsteady aerodynamic load are determined analytically.

Theoretical results show that the main contributors to unsteady lift during the encounter are the unsteady boundary layer and the unsteady wake activities. The trajectory of the passing vortex has only a minor effect on unsteady lift. This trajectory, however, has a major effect on unsteady drag. All these theoretical conclusions have been confirmed by computations discussed later in this report.

The simplifications listed earlier have been incorporated into theoretical analyses not as idealizations but as justifiable approximations based on physical reality. For example, the representation of a boundary layer by a vortex sheet does not imply an inviscid fluid (or inviscid flow) assumption. Rather, the fact that boundary layers are very thin in high Reynolds number flows is utilized and the exact location of vorticity across the boundary layer is compromised in an approximation. According to the general viscous theory of aerodynamics, the lift force is dependent on the component of moment of vorticity associated with the freestream direction. Consequently, in a theoretical evaluation of unsteady lift, the approximation of a boundary larer by a vortex sheet is expected to yield highly accurate results. The theoretical evaluation of unsteady drag using this approximation, however, is expected to introduce significant errors.

The approximation of the velocity of the wake vortices by the freestream velocity is reasonable in the far wake. In the near wake, however, the magnitude of the wake velocity is known to be substantially lower than the freestream speed. Furthermore, in non-linear unsteady flows, the direction of the wake velocity can differ from the freestream direction substantially. In consequence, the approximation of the wake velocity by the freestream velocity is expected to introduce significant errors in theoretical evaluations of both the unsteady lift and the unsteady drag. The errors in unsteady lift, however, can be minimized through the use of estimated wake velocities. Details of the theoretical analyses of the vortex-airfoil encounter problem are presented in References 17, 18 and 19.

The Weis-Fogh problem involves the motion of two identical wings relative to one another. During the "fling" phase of the Weis-Fogh motion, the two wings, with their trailing edges joined together and their leading edges initially near each other, fling open by rotating about their trailing edges. Theoretical and experimental results for the circulation generated on each wing during the fling have been obtained by previous investigators representing the two wings by two straight line segments (References 2, 16 and 20). Problems of unsteady aerodynamic force generated and power expenditure required during the fling were not studied either theoretically or computationally. Under the current program, these problems have been investigated using the general viscous theory of aerodynamics.

Major contributors to the aerodynamic performance of the Weis-Fogh wings during the fling have been identified to be unsteady boundary layers created by the fling motion and the vortical wakes shed from the leading edges of the wings. Theoretical studies have been carried out in two steps. In the first step, the contributions of the unsteady boundary layers to the aerodynamic performance of the wings in the absence of the vortical wakes have been obtained. In the second step, additional contributions due to the presence of the vortical wakes have been obtained.

Closed-form analytical expressions have been obtained for the circulation, the unsteady lift force, the total force and the power expenditure of each wing. In these expressions, contributions of the unsteady boundary layers and the wakes are represented individually. Furthermore, each of these individual contributions is represented by several terms, each term is associated with a different parameter of the problem.

For example, the lift force experienced by each wing during the fling phase has been expressed in the form $L = L_b + L_c$, where L is the total lift, L_b is the contribution of the unsteady boundary layers to the total lift and L_c is the contribution of the wakes. The term L_b is given by

$$L_b = \rho c^3 f(\alpha) \frac{d\Omega}{dt} + \rho c^3 \frac{df}{d\alpha} \Omega^2$$

where ρ is the density of the fluid, c is the chord of the wing, α is half angle of opening between the two wings, Ω is the angular velocity of the wing, and the function $f(\alpha)$ is given by

$$f(\alpha) = \frac{\pi}{3} \left(\frac{\alpha}{\pi}\right)^{1-3\alpha/\pi} \left(1 - \frac{\alpha}{\pi}\right)^{-2 + 3\alpha/\pi} \left(1 - \frac{2\alpha}{\pi}\right) \csc 2\alpha$$

In the above expression for L_b, the effect of the wing's acceleration, represented by the first term, is directly proportional to the acceleration. The effect of the wing's angular velocity, represented by the second term, is proportional to the square of the angular velocity. Both effects are dependent on the angle of opening α. The functions $f(\alpha)$ and $df/d\alpha$, on which these effects depend, are easily calculated.

The contribution L_c of the wake to the lift force has also been expressed in two terms. Both terms are dependent on the angle of opening α. One of the two terms is proportional to the product of the vorticity moment and the angular velocity of the wings. The other term is proportional to the rate of change of the vorticity moment. It has been demonstrated that this wake contribution can be determined independently from L_b, the boundary layer contribution. The linear addition of the two contributions give the total lift. This unique attribute has rendered the theoretical analyses of Weis-Fogh problem particularly revealing.

There existed some controversy concerning the importance of the wake effect on the aerodynamic performance of the Weis-Fogh mechanism (Reference 20). The present research has shown conclusively that the wake effects are important and they should not be omitted in aerodynamic analyses. Also, previous investigators estimated the performance of certain insects in hover on the basis of steady state aerodynamics and concluded that the required lift coefficients are too high. The present research has successfully explained the ability of such insects to hover on the basis of non-linear unsteady aerodynamics. Detailed discussion of theoretical results for the Weis-Fogh problem are presented in References 21 and 22.

Theoretical studies carried out under the present program reveal a number of techniques for computing unsteady aerodynamic flows under various circumstances. These techniques drastically improve computational efficiency and yet yield accurate results for unsteady aerodynamic load. More importantly, based on theoretical observations, sources of computational error are identified, estimates of the magnitude of errors are made, and procedures for minimizing the error are devised. For example, a procedure for accurately evaluating the strength and direction of the vortical wake leaving the trailing edge of an airfoil in unsteady flow has been established (Reference 19). Sample theoretical results are discussed in conjunction with computational results.

The present research thoroughly demonstrated that the zonal procedure is ideally suited for the computation of non-linear unsteady viscous flows at high Reynolds numbers. Under general circumstances, when flow separation is an important feature, the zonal method allows the computation field to be confined to the viscous region. The several viscous zones present in the flow can be computed separately. Because the zonal procedure successfully resolves computational difficulties resulting from the simultaneous presence of flow zones with diverse length scales and vastly different physical characteristics, computation results obtained using the zonal method are highly accurate and are free of spurious results (Reference 10). For cases where no appreciable separated regions are present, the zonal method simplifies to a time-dependent boundary layer computation procedure.

The zonal procedure has been fully developed, calibrated, and applied to a variety of non-linear laminar and turbulent unsteady two-dimensional flows. An efficient, accurate and user-oriented computer program has been prepared for two-dimensional incompressible unsteady viscous flows using the zonal procedure. Full documentation of this program is in progress. Under a separate program, finite-difference codes have been prepared for the numerical solution of two-dimensional time-dependent Euler and compressible Navier-Stokes equations and three-dimensional time-dependent Euler equations. These finite-difference codes are state-of-art programs based on the concept of approximate factorization. Compressible flow computations have been carried out parallel to incompressible flow computations as an additional calibration of the zonal procedure. Experience in treating three-dimensional flows has been acquired in computing compressible flows.

Extensive numerical results have been obtained for the three focal problems under investigation. For the vortex-airfoil encounter problem, computations have been carried out under circumstances where the encounter induces unsteady flow separation as well as under circumstances where the unsteady boundary layers remain attached throughout the encounter. For cases with attached unsteady flows, the contributors to the unsteady aerodynamic load have been identified as the unsteady boundary layers, the wake and the passing vortex (Reference 19). Theoretical studies suggest that the boundary layers and wake layers are justifiably approximated by vortex sheets and filaments in computing unsteady lift forces. An extremely efficient numerical procedure, similar to the vortex panel-lattice method, has been developed using this approximation. This approximate procedure has been utilized in computing unsteady lift and unsteady drag experienced by the airfoil during the encounter. In Figure 1 computed lift history obtained using the approximate method is compared with that obtained by solving the full viscous equations. The airfoil is a NACA 0012 airfoil at zero angle of attack and a Reynolds number of one million. The passing vortex has a strength equal to -0.2 times the product of the freestream velocity and the chord length. The vortex is initially spaced 0.26 chord length below the airfoil and 6 chord lengths upstream of the airfoil's leading edge. A two layer model (Reference 23) is used to model flow turbulence in the full viscous computation. The boundary layers are found to remain attached throughout the encounter. Excellent agreement between the results of the approximate computation and the full-viscous computation is observed.

In carrying out the approximate computation, the question of "unsteady Kutta condition," which represents a major conceptual uncertainty in previous panel-lattice type of methods, has been critically examined. A method for determining the strength and location of the nascent wake vortices has been established on the

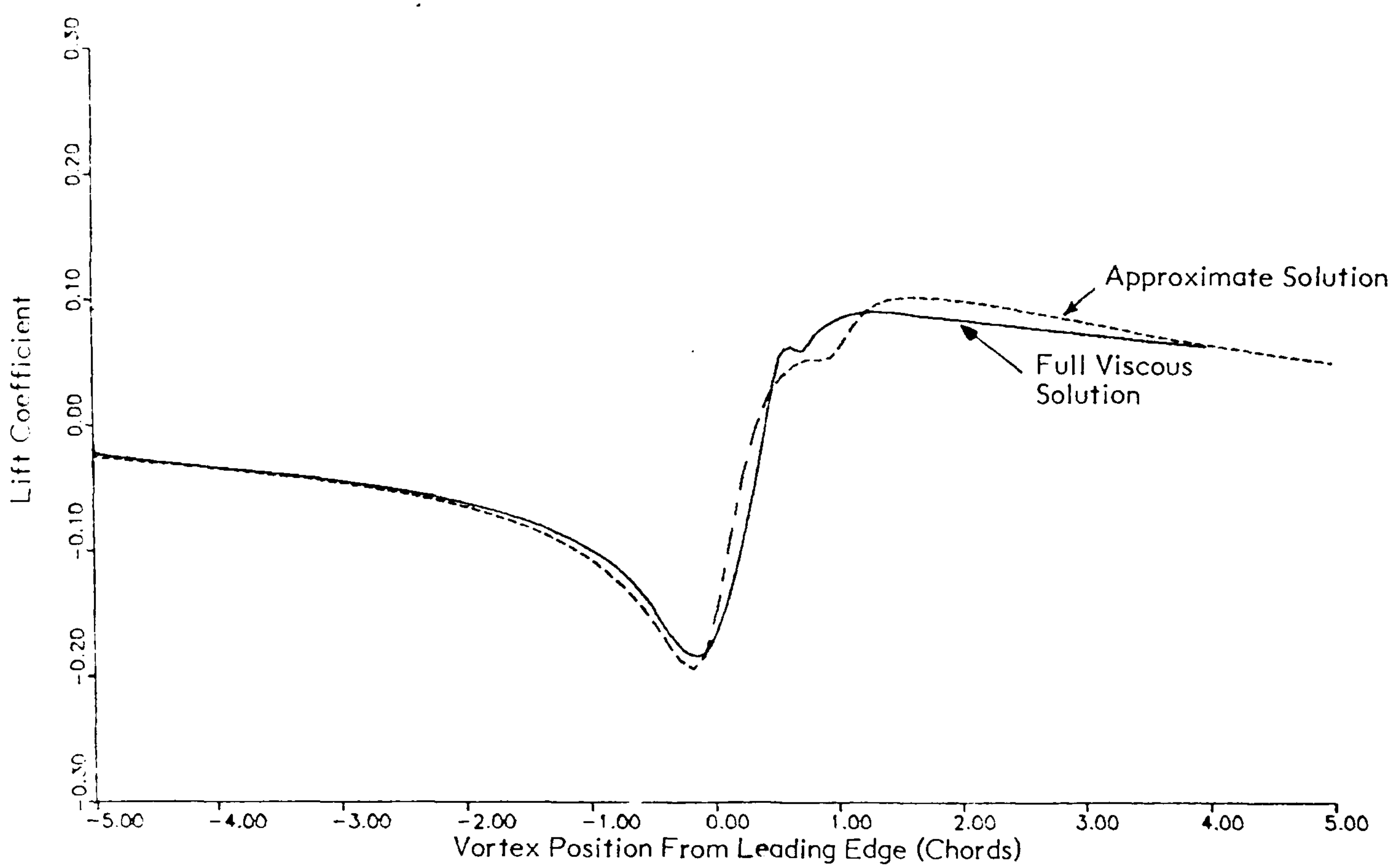


Figure 1. Unsteady Lift Force During Vortex-Airfoil Encounter

basis of physical characteristics of unsteady boundary layers leaving the trailing edge of the airfoil and feeding into the wake. It has been demonstrated that this method correctly represents the physical flow near the trailing edge (Reference 19).

As discussed earlier, the approaches used in the present research permit the contributions of the several flow components to the unsteady aerodynamic load to be evaluated separately. In Figure 2, the computed contributions of the unsteady boundary layers, the unsteady wake and the trajectory of the passing vortex to the unsteady lift coefficient are shown individually for the case just described. The contributions shown are obtained using the approximate method and are nearly equal to those obtained by solving the full viscous equations.

For cases with encounter-induced stall, the unsteady aerodynamic load computed using the approximate method, as expected, differs substantially from that obtained by computing the full viscous equations. In Figure 3 is shown a comparison of the lift history obtained from these two computations for a case involving encounter-induced flow separation. The flow parameters for this case are identical to those just described for the attached flow case, except that the angle of attack is 12° and the vortex strength is 0.5. The departure of the full viscous result from the approximate result is correlated theoretically to the appearance, growth and subsequent shedding of a well-structured vortex-like disturbance which is produced by the encounter. Detailed computational results are presented in References 18 and 19.

Theoretical studies have identified the unsteady boundary layers and the wakes as major contributors to unsteady aerodynamic force

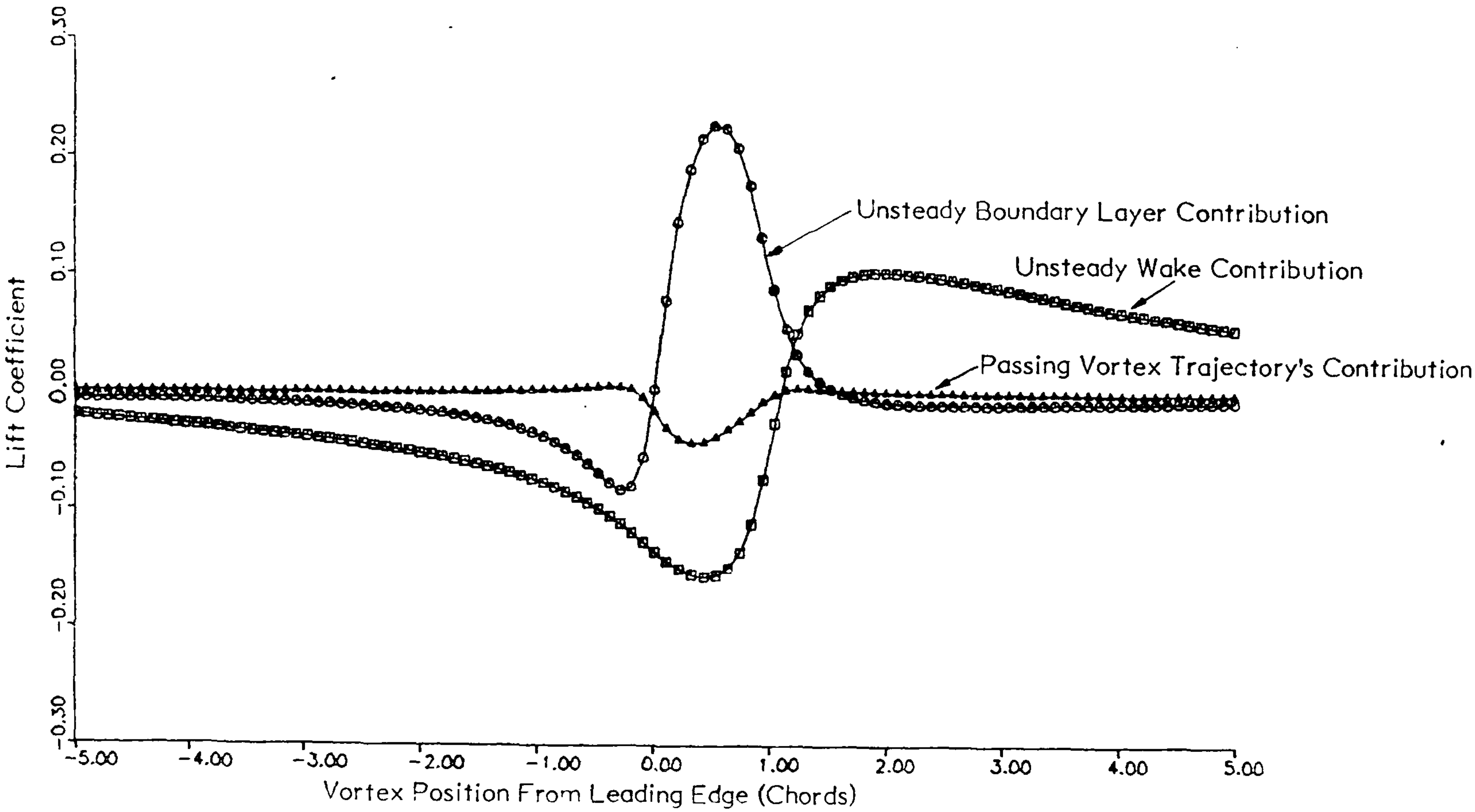


Figure 2. Contributions of Different Vortical Zones to Unsteady Lift

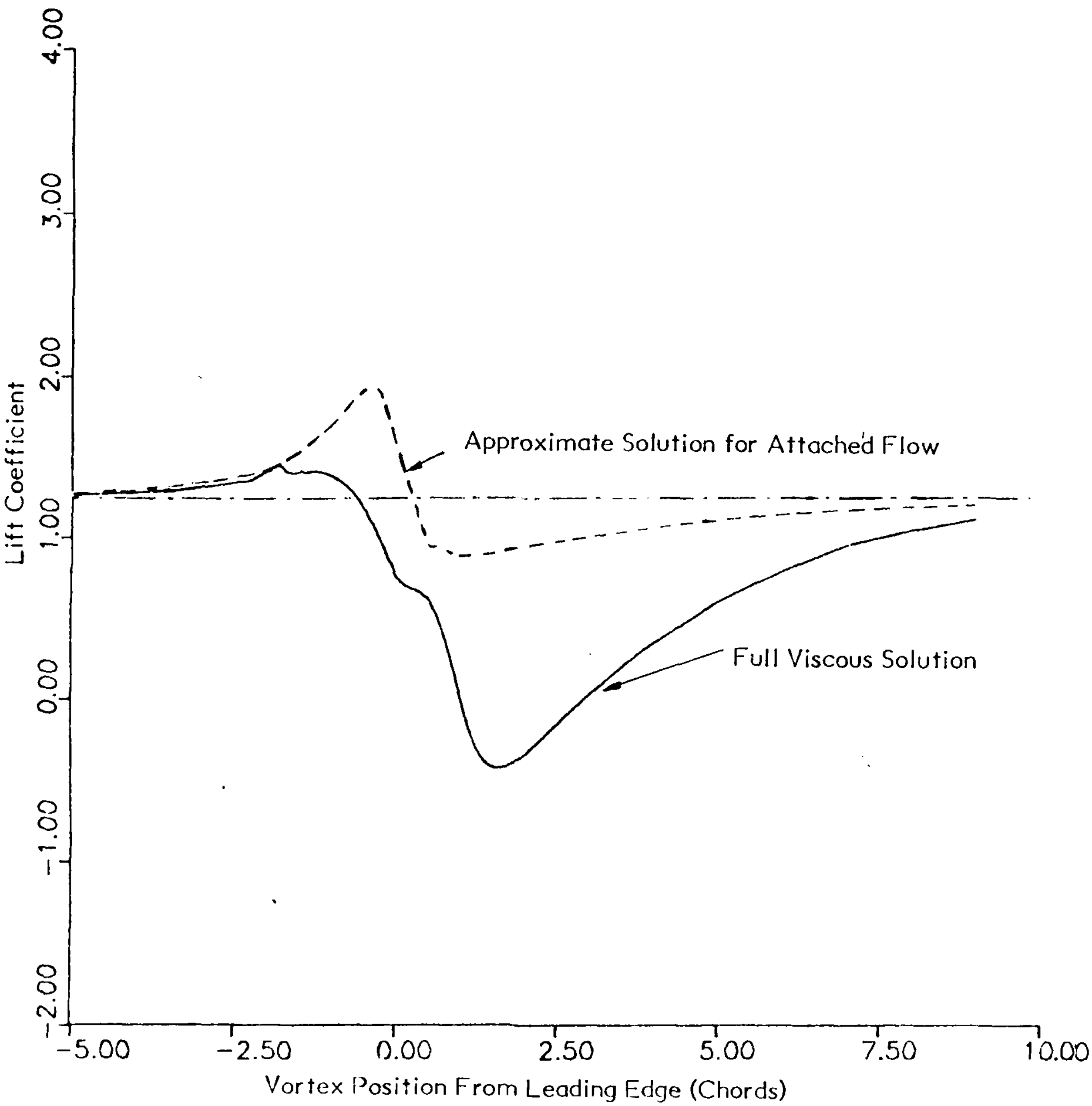


Figure 3. Unsteady Stall Due to Vortex-Airfoil Encounter

experienced by Weis-Fogh wings during the fling phase of the wings' motion. Closed form analytic expressions have been obtained for the aerodynamic force and the power expenditure of the wings. Experimental observations (Reference 16) show well-structured wakes with specific trajectory. An extremely efficient procedure for evaluating the circulation, the lift, and the power expenditure of the Weis-Fogh wings has been developed using the theoretical expressions and approximating the wakes by single vortices.

Time-dependent circulations around the Weis-Fogh wings have been computed using the approximate procedure. The computed results, shown in Figure 4, are in reasonable agreement with experimental data presented in Reference 16. Experimental data shown are for a Reynolds number of 13,000. This Reynolds number is defined as the average angular velocity of the wing multiplied by the square of the chord length and divided by the kinematic viscosity of the fluid.

The full viscous equations are solved to determine the flowfield surrounding the Weis-Fogh wings and the aerodynamic performance of the wings during the fling phase. The computations are carried out using the experimental parameters of Maxworthy's experiment (Reference 16). In Figure 5 are shown computed streamlines compared with flow patterns observed experimentally (Reference 16) for flow Reynolds numbers of 32 and 13,000. The agreements between the computed and experimental results are excellent.

No aerodynamic data are presented in Reference 16. It is, however, possible to estimate the power expenditure experienced by the wings based on the description of the experimental apparatus given in Reference 16. In Figure 6 are shown computed power expenditure, obtained by solving the full viscous equations, compared with

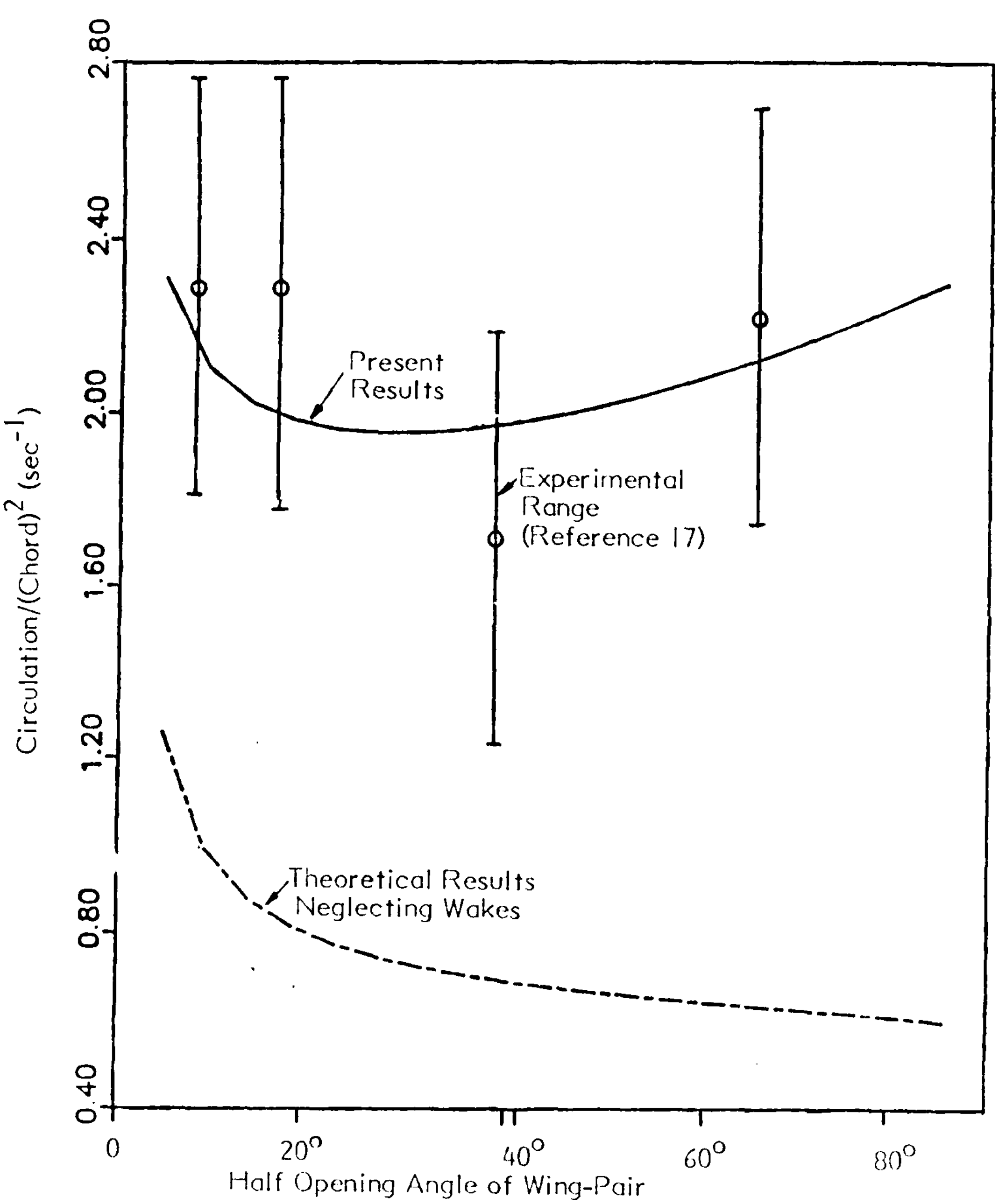
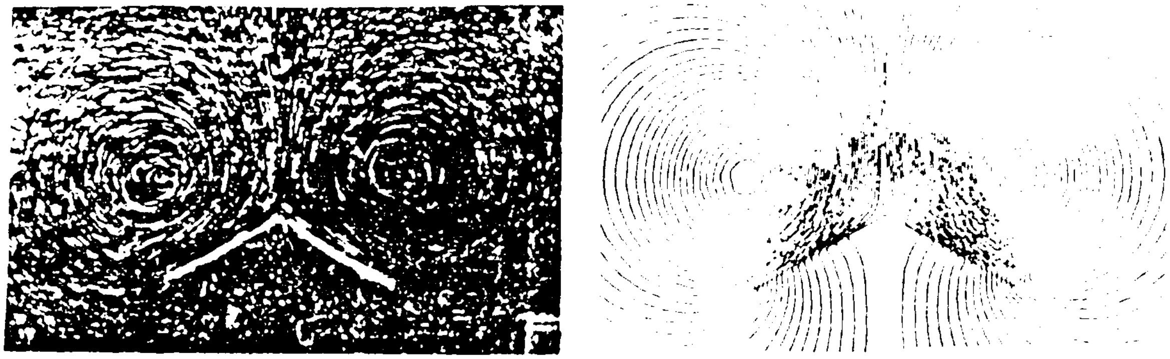
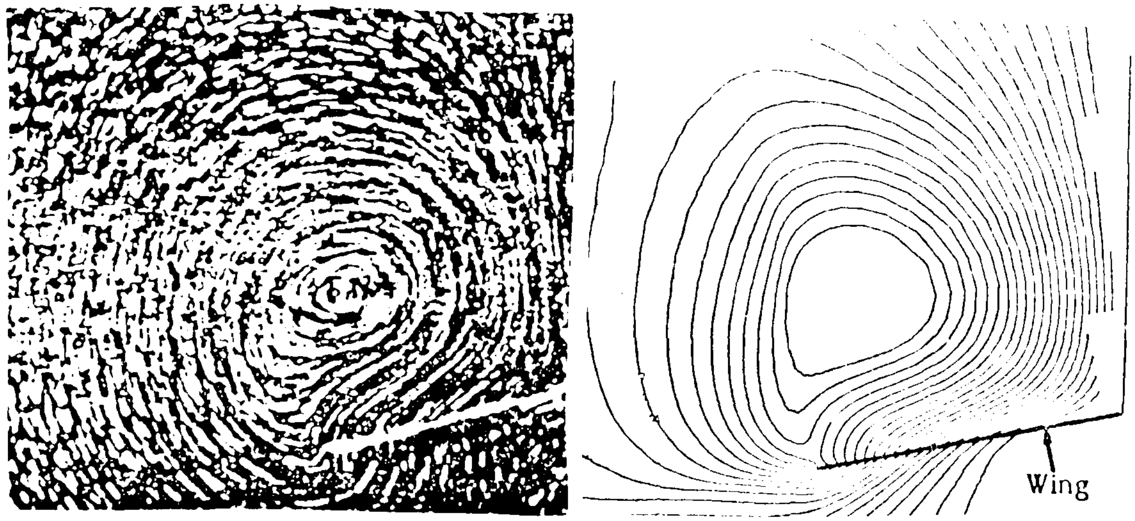


Figure 4. Circulation Around a Weis-Fogh Wing



Reynolds Number 13,000



Reynolds Number 32

Computed Streamlines Experimental Streaklines

Figure 5. Flow Around Weis-Fogh Wings

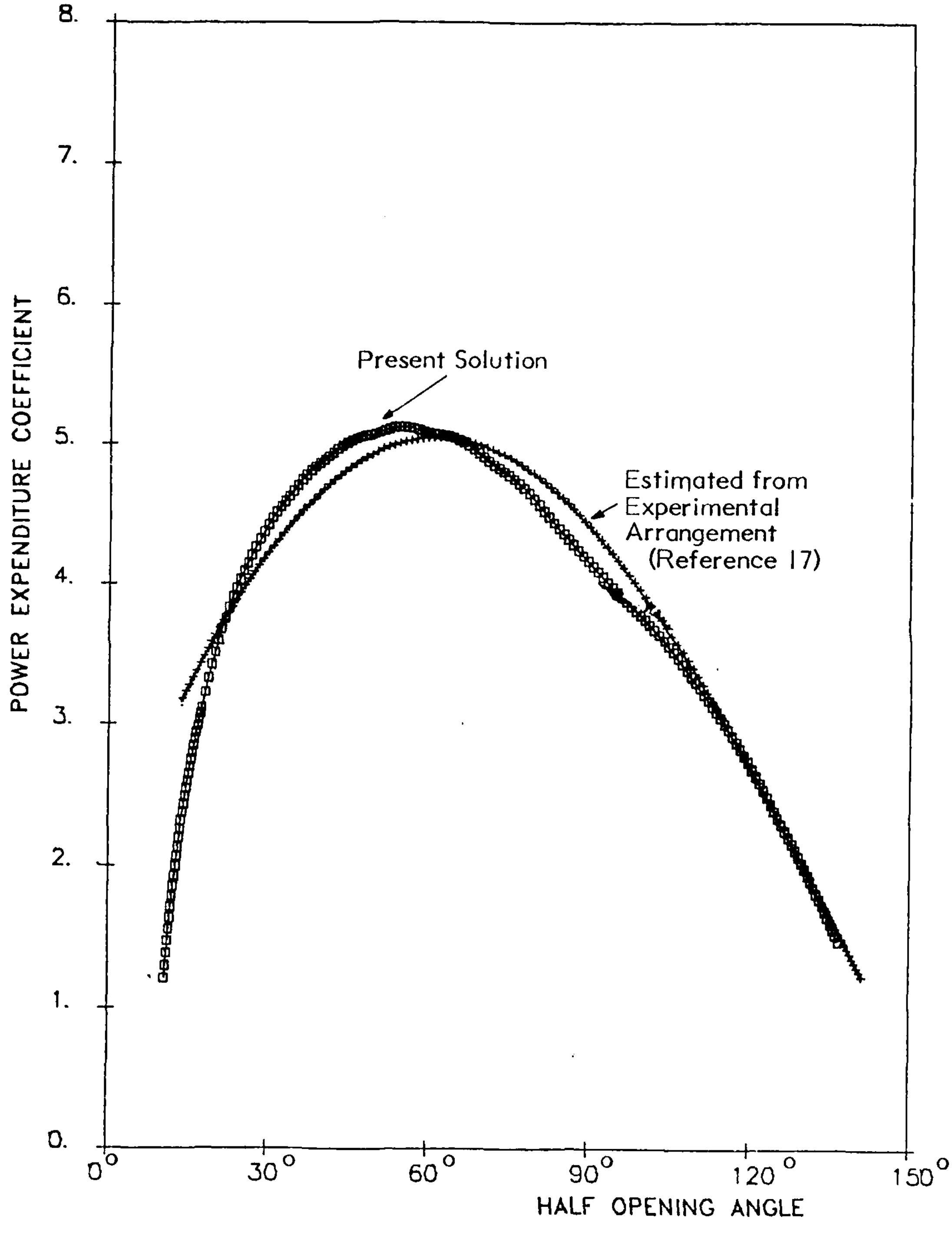


Figure 6. Power Expenditure of Weis-Fogh Wing

estimated experimental values for a Reynolds number of 13,000. Reasonably good agreement between the computed results and the estimated experimental values are observed. It is noted, however, that in the absence of certain information about the experimental apparatus, assumptions are made to deduce the "experimental" curve shown in Figure 6. There is no assurance that these assumptions are in agreement with the experiments. It is of interest to note, however, in a recent article, Spedding and Maxworthy (Reference 26) presented new experimental results on the lift history of a Weis-Fogh wing. The new lift data are in good agreement with the results obtained by Wu and Hu-Chen (Reference 21) in this program which is based on Reference 26.

In Figure 7 are shown computed streamlines and equi-vorticity lines around a 9% thick airfoil with an upwind facing flap approximately 1/4 chord in length at an angle of attack of 15° and a flow Reynolds number of 1000. The streamlines and the equi-vorticity lines are computed using the zonal procedure and they show a separation bubble temporarily being trapped upstream of the flap.

In addition to the three focal problems originally planned for the present research, the problem of a rapidly pitched airfoil has also been studied. In Figure 8 are shown measured unsteady lift coefficients experienced by a rapidly pitched NACA 0012 airfoil with a chord length of 6" in a flow with a freestream velocity of 33.2 fps. The center of rotation is located at 1/4 chord from the leading edge of the airfoil. The angular motion of the airfoil is shown in Figure 8a. The computed lift history is in excellent agreement with the experimental data of Reference 15. Excellent agreement between computed and measured unsteady drag and moment coefficients have also

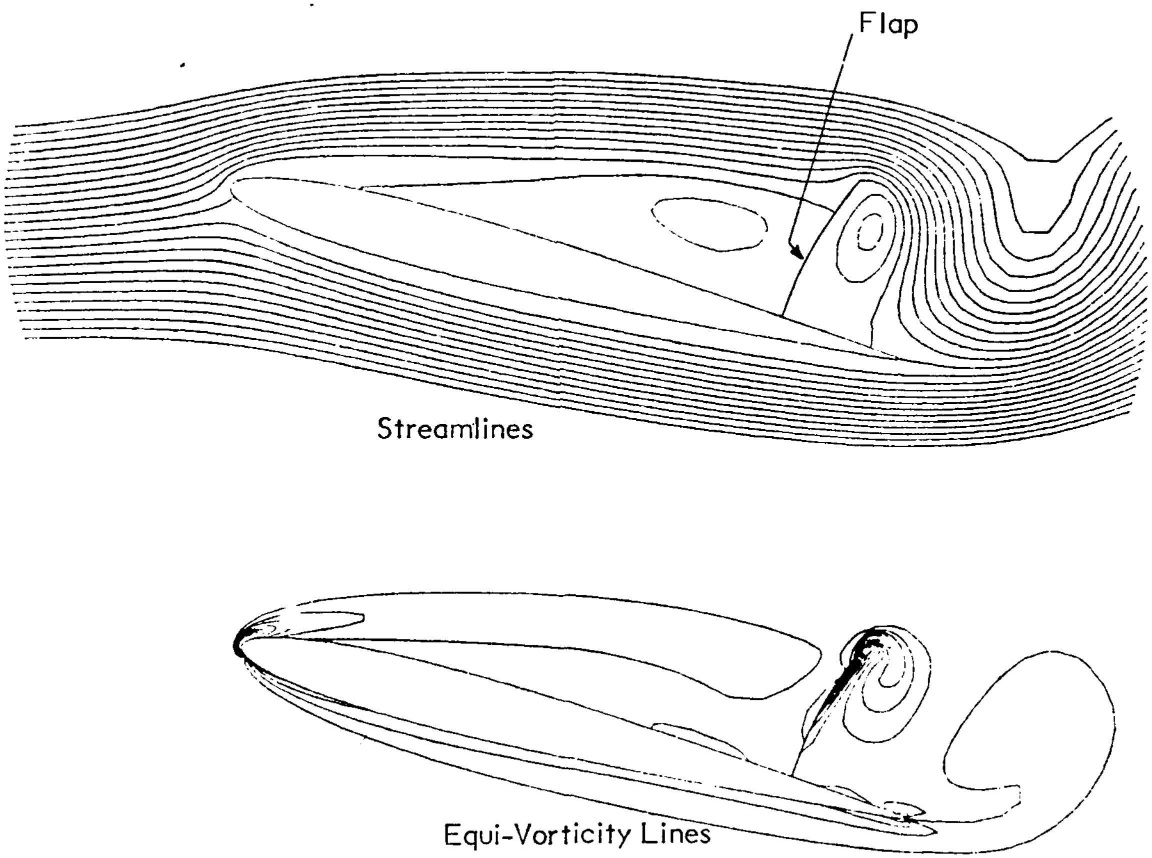
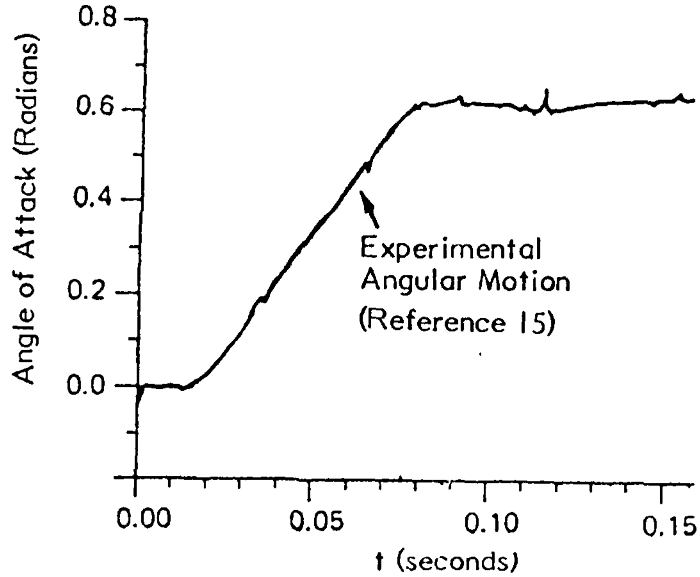
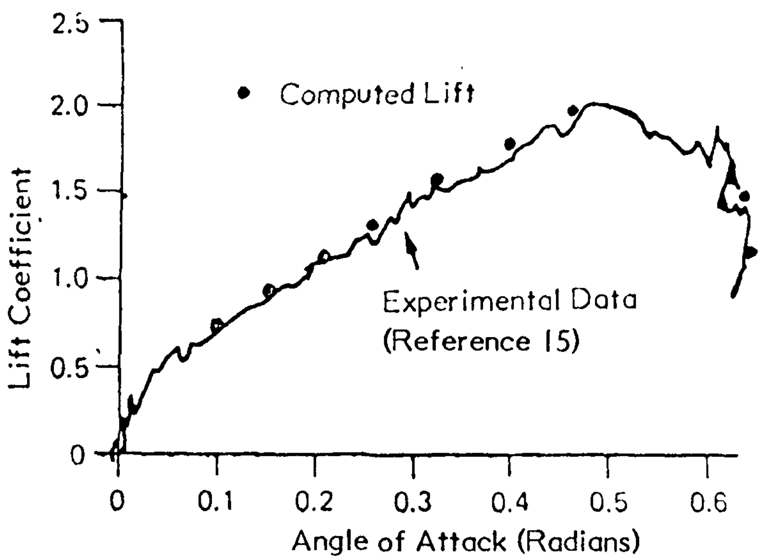


Figure 7. Vortex Trapping



(a) Angular Motion of Airfoil



(b) Unsteady Lift

Figure 8. Rapidly Pitched Airfoil

been observed. Computations were carried out by I. Tuncer, a doctoral student in his initial phase of dissertation research utilizing an available zonal code. About ten hours of programming time was spent in adapting the code for the present problem. The total computer time used was approximately 15 minutes of CYBER 855 CPU time.

In Figure 9 is shown a computed flow pattern around a NACA 0012 airfoil oscillating in pitch about quarter-chord at a Reynolds number of 5,000, a reduced frequency of 0.5, with the angle of attack varying between 0° and 20°. The computations were carried out using the existing zonal code under a separate research program. Experimentally observed leading edge stall and trailing edge stall phenomena have been simulated computationally. Figure 10 demonstrates the agreement between computed and experimentally observed (Reference 12) flow patterns and shows a leading edge separation bubble as well as a trailing edge bubble.

In Figure 11 is shown a computed lift hysteresis for a NACA 0012 airfoil oscillating in and out of dynamic stall. The computations were carried out using a compressible flow (non-zonal) code for a Reynolds number of 3.8 million, a freestream Mach number of 0.3, a reduced frequency of 0.15 and the angle of attack varying between 0° and 5°. The computed results are in reasonable agreement with experimental data. Three-dimensional transonic flow computations have been carried out using a time-dependent Euler code. In Figure 12 are shown computed pressure distributions on a F-5 fighter wing with a freestream Mach number of 0.95 and a zero angle of attack. The computed results are compared with test results (Reference 25).

Results shown in Figures 9, 10 and 11 were obtained by the present investigators under other, parallel, research projects. These

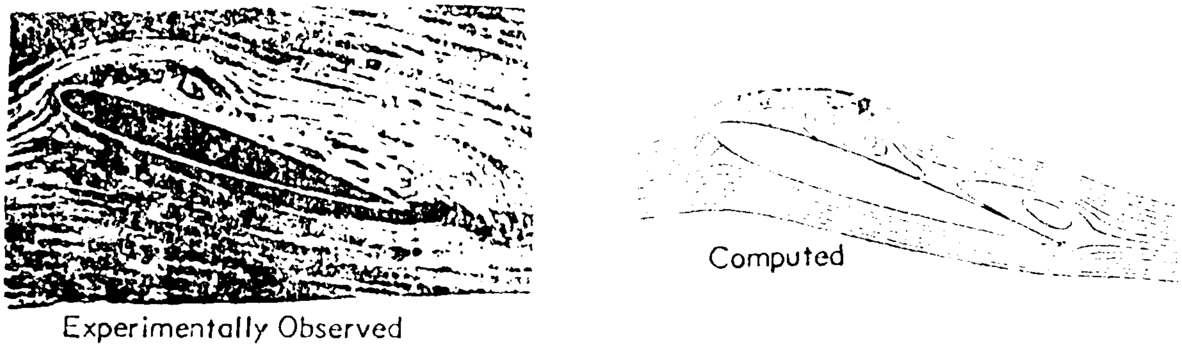


Figure 9. Flow Pattern Around Oscillating Airfoil, $\alpha = 20^{\circ}$

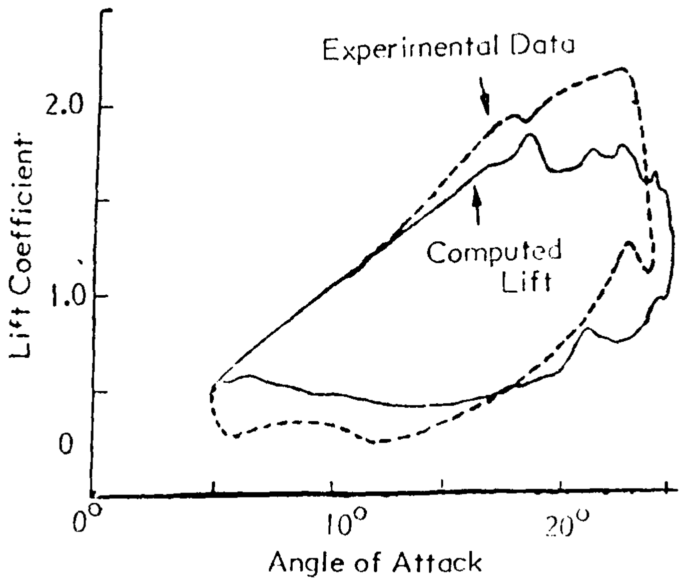


Figure 10. Lift Hysteresis

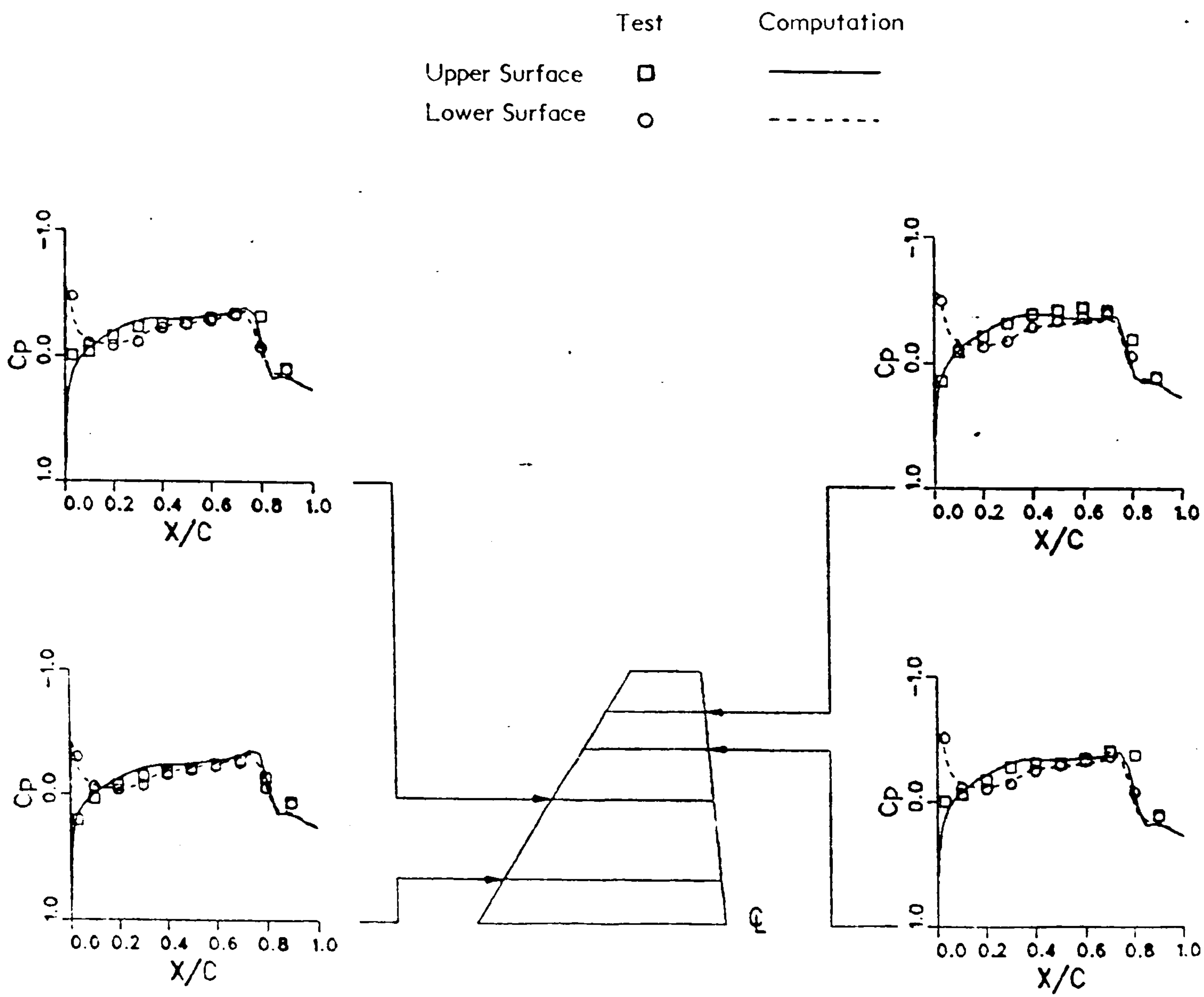


Figure 14: Surface Pressure on a Wing

results illustrate the mutual stimulus between the present program and other on-going research programs conducted by the present researchers. They also illustrate the ability currently available for computing various types of complex flows.

4. PUBLICATIONS

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4. R. Reilman, "A Theoretical and Numerical Study of the Weis-Fogh Problem including Wing-Separation," expected completion in 1987.

5. J. Singh, "A Computational Study of the Vortex Trapping Phenomena," expected completion in 1987.

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5. CONCLUDING REMARKS

The overall objectives of the present research program, as stated in Section 1 of this proposal, are the establishment of a body of knowledge and a precise understanding of the difficult interactive fluid dynamic elements which dominate the aerodynamics of unsteady flows in the non-linear domain and the development of a rational framework for the prediction and utilization of large unsteady aerodynamic forces generated by large amplitude unsteady motions of lifting bodies. The present research demonstrated that these overall objectives are not as difficult to reach as they once appeared to be. A reasonable understanding of the viscous and inviscid processes that contribute significantly to the unsteady aerodynamic performance of two-dimensional lifting bodies has already been established. Theoretical and computational methods ideally suited for analyzing linear and non-linear unsteady aerodynamic performance of two-dimensional lifting bodies have already been set up. A substantial amount of experience has been accumulated in the use of the theoretical and computational methods. Work is now in progress under a new research program to study unsteady aerodynamic problems involving flexible lifting surfaces and three-dimensional bodies undergoing large amplitude unsteady motions.

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