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ANALYTICAL STUDY OF STOL AIRCRAFT IN GROUND EFFECT

PART II. NONPLANAR, NONLINEAR METHOD APPLICABLE TO THREE-DIMENSIONAL JETS OF FINITE THICKNESS

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FOREWORD

The results of an analytical investigation of nonlinear, nonplanar analysis methods applicable to both thin-jet modeling and thick-jet modeling of STOL aircraft ground-effect phenomenon are presented. The study consisted of two concurrent tasks which are reported on separately as Parts I and II.

Part I. Nonplanar, Nonlinear Wing/Jet Lifting Surface Method. The objective of this task was to extend the Douglas Nonplanar Lifting Systems program to include powered-lift wings having thin jets of varying strength for both part and full span arrangements and to analyze various configurations in ground effect.

Part II. Nonplanar, Nonlinear Method Applicable to Three-Dimensional Jets of Finite Thickness. The objective of this task was to apply the NASA Ames Research Center Potential Flow Analysis to power-off ground effect cases and recommend procedures for developing a thick-jet analysis method.

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The contributions of Mr. M. I. Goldhammer, who served as the principal investigator on Part I during the early stages of the study, are greatly appreciated. His previous work on the development of the Nonplanar Lifting Systems program contributed significantly to the present work. The assistance of Mr. D. H. Neuhart in preparing the input and running many of the cases is also appreciated.

The authors also gratefully acknowledge the contributions of Dr. R. T. Medan of the NASA Ames Research Center for his assistance and support in the application of the NASA Ames Research Center Potential Flow Analysis to aircraft ground effects prediction.

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c	reference chord
C_ℓ	section lift coefficient
C_L	total lift coefficient
C_{D_i}	total induced drag coefficient
C_{L_α}	lift curve slope
h	distance between wing leading edge and ground plane
ΔH	total pressure difference between two regions of flow
u	horizontal component of velocity
U	flow speed
$\overline{V}$	mean local flow speed
w	vertical component of velocity
α	angle of attack
$\Delta\alpha$	increment in angle of attack resulting from ground effect
γ	jet vortex strength, flight path angle
θ	attitude angle relative to ground
μ	doublet strength
ξ	coordinate parallel to local flow
ρ	fluid density

<u>Subscript</u>

∞	freestream value, out of ground effect value

1. INTRODUCTION

The influence of ground proximity on three-dimensional lift systems has been previously studied, as reported in Reference 1, using the Douglas Nonplanar Lifting Systems program. Reference 1 presents calculated steady and quasi-steady aerodynamic characteristics of various wings operating in ground effect. Selected configurations from Reference 1 have been analyzed in the present study using the NASA Ames Research Center Potential Flow Analysis (POTFAN) in order to examine POTFAN's applicability to ground effects problems and to provide a second evaluation of the importance of ground proximity on some basic wing planforms.

The commonly addressed aircraft ground effect problem considers a lift system in motion at a constant altitude above a ground plane. This steady-state representation, illustrated in Figure 1a, is an idealization of the approach or departure of an aircraft from a runway. The complete unsteady representation of aircraft motion near a ground plane, depicted in Figure 1c, includes the time history of the lift system which is manifested by varying strength shed trailing vorticity. Additionally, the unsteady model employs the proper geometric relationship between aircraft attitude, θ, aircraft angle of attack, α, and flight path angle, γ. The quasi-steady representation of Figure 1b includes the geometrical relationships of the unsteady representation but ignores the lift system time history. Therefore, compared with the steady representation, the quasi-steady model provides an improved description of the transient ground effect problem with only a minimal increase in computational complexity.

Results of two-dimensional vortex lattice calculations are presented in the next section to compare vortex lattice methodology, used in the present application of POTFAN, with exact results. Furthermore, the two-dimensional trends for quasi-steady ground effect cases are presented for contrast with predictions for three-dimensional cases. The principal emphasis of the present study is examination of the three-dimensional POTFAN results for wings operating in ground effect as reported in Section 3. Finally, development of the capability within POTFAN to analyze propulsive influences on lift systems has been investigated and is discussed in Section 4.

2. TWO-DIMENSIONAL VORTEX LATTICE CALCULATIONS

A simple airfoil analysis method employing discrete vortices and conventional vortex lattice collocation rules was constructed to supplement the three-dimensional ground-effect calculations. Although a two-dimensional analysis option is available within the POTFAN system, the present two-dimensional results were obtained from a rudimentary computer program written specifically for this task. The two-dimensional study was initiated to investigate the suitability of vortex lattice methodology used in the present three-dimensional POTFAN calculations to analyze wings operating in ground effect. A secondary objective of the two-dimensional calculations was determination of aerodynamic characteristics for quasi-steady ascent and descent relative to the steady-state values.

The two-dimensional analysis employed was a simple finite-element formulation with equal length elements distributed along the airfoil chord. Each element was represented by a point vortex at a location one quarter of the element length aft from the forward element edge. The inviscid condition of tangential flow was imposed at an element control point which was located three-fourths of the element length from each element forward edge. All nonplanar and nonlinear aspects of the airfoil geometry and velocity evaluation were included in application of the airfoil boundary conditions and force evaluation. Actual image airfoils were employed in the analysis, rather than image or symmetry options, to avoid any possible errors or ambiguity in simulating the ground plane. Airfoil loadings were determined by calculating the force on each elementary vortex through application of the Kutta-Joukowski Law for the force on a point vortex. The flow velocities employed in this evaluation were the local velocity at each point vortex excluding the self-induced contribution. Formulation of this two-dimensional analysis is closely analogous to the three-dimensional POTFAN method as applied in Section 3 to analyze wings in ground effect.

Calculated results obtained using the two-dimensional vortex lattice method are given in Figure 2 for steady and quasi-steady motion of a flat-plate airfoil near a ground plane. The quasi-steady cases are approximations to the complete unsteady ground approach or departure problem as described in the previous section. In Figure 2 the symbols indicate the actual cases computed during the study. Also, exact values of lift augmentation from Reference 2 are shown in Figure 2 for the steady flight case.

The lift augmentation ratios predicted by the vortex lattice method agree closely with the exact values of Reference 2 for the range of airfoil height above ground plane values considered. This agreement provides confidence that vortex lattice methodology is capable of predicting aerodynamic ground effect. There are no exact values for comparison with lift augmentation ratios calculated for quasi-steady flight. However, Figure 10 of Reference 1 indicates quasi-steady descent case exhibits greater lift augmentation than the steady case. This trend is in agreement with the present two-dimensional calculations. It is apparent from the present two-dimensional study that the quasi-steady ascent lift is generally predicted to be lower than the steady case for the flat plate airfoil.

3. THREE-DIMENSIONAL POTFAN CALCULATIONS OF WINGS IN GROUND EFFECT

This section presents aerodynamic characteristics predicted by the NASA Ames Research Center Potential Flow Analysis (POTFAN) for various wings operating near a ground plane. All of the presently considered configurations were previously analyzed using the Douglas Nonplanar Lifting Systems program as reported in Reference 1 and updated in Reference 3. (All results currently presented are from Reference 3.) Thus, the present results provide a comparison between the predictions of the two methods and an additional evaluation of the significance of ground effect on lift system characteristics.

The POTFAN method is a potential flow singularity, finite element analysis that is implemented by a series of modular computer programs which perform the various analysis functions. Two of the program modules are described in References 4 and 5. Additional POTFAN documentation is provided by the extensive use of comments within the program code. The POTFAN program structure is exceptionally general in many respects including geometry input, singularity type and distribution, image options, and equation solving techniques. In the present study only a small number of POTFAN's capabilities were employed.

All POTFAN calculations discussed in the present section used vortex lattice collocation rules for vortex filament and element control point locations. The potential singularity type selected for the POTFAN calculations was a lattice of discrete vortex filaments which can be equivalently formulated in terms of constant strength doublet distributions. The doublet formulation is employed within POTFAN and is a computationally efficient arrangement for application of vortex lattice rules. The element spacing over the wing systems analyzed using POTFAN was generally uniform except for configurations where flap geometry required unequal element sizes. Also, a one-fourth element tip inset option was selected to improve solution convergence with respect to the number of wing elements. The undeformed trailing vortex wake position specified in the POTFAN input was always parallel to the ground plane which is not necessarily in the same direction as the freestream velocity for quasi-steady ascent or descent cases.

In order to assure a sufficient number of elements were used to analyze each configuration, a series of calculations were performed for each wing with increasing numbers of analysis elements. The number of elements to be employed was selected on the basis of small variation in lift and drag predictions for increased number of analysis elements. The number of spanwise and chordwise divisions employed for POTFAN computations are indicated on each figure showing POTFAN results.

The lift augmentation resulting from steady motion near a ground plane is given in Figure 3 for a rectangular planform wing with aspect ratio equal to 6.0. Several methods were employed to analyze this configuration thereby providing an indication of the variation among predicted ground effect aerodynamic characteristics. The lift predicted by the Douglas Neumann Program (Reference 6) is taken from Figure 23 of Reference 1 and pertains to a 12-percent thick NACA 0012 airfoil section. All other results presented on Figure 3 are for zero thickness flat plate airfoil sections. The Douglas Nonplanar Lifting Systems results are the revised values of Reference 3. POTFAN calculations were generally conducted with ten spanwise and four chordwise divisions but some calculations were performed with a 15 by 6 distribution to evaluate element spacing sensitivity. Finally, the Douglas Jet Wing Fuselage Program described in Reference 7, was used to analyze the wing at two ground heights. The Douglas Nonplanar Lifting Systems, POTFAN, and Jet Wing Fuselage Program results for this aspect ratio 6.0 wing are all in close agreement and indicate smaller lift augmentation ratios than the Douglas Neumann Program results for all ground heights. In ground effect, the influence of section thickness (included in the Douglas Neumann Program calculations) is commonly assumed to produce a negative lift or "such down" compared to zero thickness wing section lift. However, this thickness effect is not a rigorous result which can be applied with confidence to all configurations. The Douglas Nonplanar Lifting Systems, POTFAN and Jet Wing Fuselage Program results indicate an unexpected opposite trend from the "such down" concept.

A second set of results for a rectangular wing operating in ground effect is presented in Figure 4 where lift curve slope is given as a function of leading edge height above the ground plane. The calculated lift slopes are for zero thickness airfoil sections (compared to the 22-percent thick experimental section) and are based on an assumption of a linear lift slope between zero and one degree angle of attack. As in the case of the aspect ratio 6.0 wing results of Figure 3, the Douglas Nonplanar Lifting Systems program predicts slightly higher lift than the POTFAN values for this aspect ratio 4.0 wing. Also Figure 4 indicates very close agreement between experimentally measured lift slope and the POTFAN predictions. It should be noted that the combined effects of wing thickness and fluid viscosity are not considered in either of the calculated results.

The POTFAN results for a third rectangular planform wing are given in Figures 5 and 6. These figures correspond to the Douglas Nonplanar Lifting Systems results given by Figures 14 and 15 of Reference 3. Figure 5 applies to a wing with flat plate airfoil section while Figure 6 corresponds to a zero thickness airfoil section with a 40-percent chord full-span flap which is deflected 60 degrees. Both figures include steady-state lift and drag values as well as quasi-steady ascent and descent values. The quasi-steady approximation to the fully dynamic transient ground effect problem employs the wing-ground plane geometry of the full dynamic case but ignores the lifting system motion time-history (see Figure 1).

Comparison of the present results with those of Reference 3 yields no substantial differences in predicted aerodynamic characteristics. The quasi-steady analyses indicate a greater lift augmentation than the steady-state case for descent and a smaller than the steady-state ratio for ascent. This trend in quasi-steady results are observed for both negative and positive lift increments due to ground effects. This ordering of the ascent and descent values of lift relative to the steady-case results is consistent with the two-dimensional vortex lattice results reported in Figure 2.

Lift induced drag predicted by POTFAN and the Nonplanar Lifting Systems program follows a regular trend and indicates that the quasi-steady ascent drag ratios are consistently higher than the steady drag values while descent drag ratios are less than steady values. Application of vortex lattice methods, such as the present use of POTFAN, to calculate drag on wings with highly deflected flaps requires care in ensuring solution convergence and, typically, vortex lattice methods overestimate drag magnitudes compared to experiments and other analytical methods. The presently employed POTFAN force evaluation method approximates the actual leading edge thrust term by a distribution of streamwise force resulting from local application of the Kutta-Joukowski Law for the force on a vortex filament. Although quite useful, vortex lattice induced drag calculations must be viewed with caution.

In order to examine POTFAN ground effect calculations for a more complex wing than the above examples, a typical transport wing was analyzed with takeoff flap deflection. Figure 7, which corresponds to Figure 18 of Reference 3, gives the increment in angle of attack resulting from motion near the ground as a function of wing lift coefficient. In this case the height of the wing above the ground is specified to be the height at which the aircraft main landing gear contacts the ground. Calculated POTFAN and Douglas Nonplanar Lifting Systems results are given in Figure 7 as well as unpublished wind tunnel data for this transport configuration. POTFAN predictions of increment in angle of attack are generally lower than the values estimated by the Douglas Nonplanar Lifting Systems program or the wind tunnel measurements except at low lift coefficients. POTFAN calculations with a larger number of chordwise wing elements produced substantially the same results as the 14 spanwise and 8 chordwise divisions used to obtain the results of Figure 7.

4. DEVELOPMENT OF THICK-JET ANALYSIS WITHIN POTFAN

Currently the NASA Ames Research Center Potential Flow Analysis (POTFAN) is applicable only to single energy flow and therefore it cannot directly estimate the mutual influence between aircraft propulsion and lift systems. Several development options are available to facilitate estimation of power effects by POTFAN. These options include replacement of propulsive jets by solid boundaries, deflected jet representations, jet flap techniques and jet with finite thickness models. Each of these options has proven useful for analysis of certain configurations but often have limited generality. The thick-jet model proposed in this section is a generally applicable jet representation within the finite element analysis, potential flow formulation of POTFAN.

Modeling of propulsive jets originated with propeller slipstream analyses such as References 9, 10, and 11. Typically these methods employ linearized boundary conditions at an assumed jet location. Refinement of propeller slipstream aerodynamic prediction methods involved improved solution techniques and greater complexity of configurations which could be analyzed within the framework of linearized theory. Achievement of STOL aircraft performance through application of strong interaction between propulsion and lift systems has stimulated new interest in jet interaction prediction beyond the scope of propeller slipstream analysis. Although models employing the jet flap idealization of Reference 12 have proven useful for estimating powered lift characteristics, the initial jet angle and momentum must be specified. Also, the jet flap model describes a thin high energy jet exhausting near the wing trailing edge and, therefore, is not directly applicable to some powered lift proposals such as upper surface blowing.

In an effort to obtain a more useful jet interaction analysis, a thick-jet model is discussed below which is based on the analysis of References 7 and 13. This jet model is compatible with the potential flow singularities available within POTFAN and will provide a basis for discussion of factors which will require attention regardless of the jet model ultimately selected. Since the purpose of the present study is to make general recommendations of procedures for developing a thick-jet capability within POTFAN, considerations which are specific to a particular existing method will be avoided.

The thick-jet model suggested presently is an inviscid, incompressible idealization of real jet flow. Corrections for real fluid effects, such as jet entrainment, can be incorporated into the model subsequently. The alternative to the present fluid assumptions is acceptance of a jet model with empirically derived characteristics which restrict the generality of the method. The area of interest of many thick-jet applications is the first few jet diameters downstream of the jet origin. In this region viscous effects may be secondary to the jet momentum influence on lift systems. Furthermore, jet models based on fundamental experiments can lead to inconsistencies such as flow through solid surfaces. Therefore, the perfect fluid assumption will be employed, at least initially.

A significant feature of finite element aerodynamic analyses, such as POTFAN, is the wide variety of configuration geometries that can be analyzed. Since the proposed thick-jet analysis is also a finite element technique, few restrictions on the type of problem which can be analyzed should be necessary. For example, arbitrary initial jet shapes and locations are feasible. Also, jets may originate at free actuator disks (modeling propellers which do not impart swirl to the flow) or at duct trailing edges (forming an idealized jet engine). These basic jet capabilities combined with a finite element solid body analysis, such as POTFAN, can be employed to analyze very general configurations including externally blown flaps, deflected slipstreams and upper surface blown wings.

The assumption of inviscid fluid in all flow regions implies that, except for special areas (wing trailing vortex sheets, jet boundaries, etc.) the flow is irrotational and, therefore, a velocity potential can be defined. Additionally, the incompressible fluid assumption requires this velocity potential to satisfy Laplace's equation and consequently all of the usual potential flow solution techniques are available for this multi-energy jet interaction problem. For example, since the Laplace equation is linear, potential flow singularities each individually satisfying Laplace's equation, may be superimposed to obtain solutions for complex cases.

Extension of POTFAN to multi-energy flow would not require alteration of the boundary conditions presently specified on solid bodies; however, application of the solid body boundary conditions would require inclusion of the jet induced velocities to account for the jet influence. The usual inviscid flow condition of tangential flow on solid surface boundaries would normally be applied for combined solid body and jet computations; but other conditions, such as a specified flow normal to the body surface, could be accommodated as at present in POTFAN.

Introduction of a thick-jet model into POTFAN will require boundary conditions to be specified on the jet boundaries which separate regions of different energy. Inviscid jet fluid does not mix with the ambient flow and, consequently, one jet condition prohibits flow normal to the jet boundary surfaces. (In subsequent development of the jet model, an empirically specified flow normal to the jet boundary could be imposed to simulate entrainment of fluid by the jet.)

In addition to the above jet kinematic boundary condition, a dynamic condition is necessary to insure that the jet boundary is unloaded. Since the jet boundary will not sustain a load, the static pressure is continuous across the boundary whereas the total pressure is discontinuous. These jet pressure conditions can be applied in numerous forms, but it is apparent from the Bernoulli equation that the flow speed tangential to the jet boundary is discontinuous. This velocity behavior implies that the jet boundary is a vortex sheet and, as shown in Reference 13, the jet pressure condition requires that the cross-stream component of jet vortex sheet strength, γ, to be given by

$$\gamma = \frac{\Delta H}{\rho \bar{V}}$$

where ΔH is the total pressure difference between the two regions of flow, ρ is the fluid density and $\bar{V}$ is the mean local flow speed at the jet boundary.

A doublet sheet is equivalent to a vortex sheet (see Reference 6, for example) and, therefore, can also be employed to represent a jet boundary. Then, as shown in Reference 7, the jet dynamic boundary condition can be expressed by

$$\frac{\partial \mu}{\partial \xi} = \frac{\Delta H}{\rho \overline{V}}$$

where μ is the doublet strength and ξ is the coordinate parallel to the local flow. The above two equations are just two of the many possible conditions on jet singularity strengths which express the jet dynamic condition.

As discussed above, the thick-jet boundary is a surface with discontinuous tangential flow speed which is characteristic of a vortex sheet or equivalently a doublet sheet. Therefore, either vortex or doublet distributions are appropriate potential singularities to represent the jet boundaries within POTFAN. Continuous singularity distributions are desirable from an accuracy viewpoint but are likely to require prohibitively large computation time for a preliminary analysis effort. Also, since POTFAN (as applied in the present study) employs discrete singularity distributions to represent solid surfaces, a compatible singularity type specification for jet boundaries is a discrete distribution. Reference 13 describes a jet representation employing vortex filaments while Reference 7 discusses the constant strength doublet distribution jet model illustrated in Figure 8. Either of these jet boundary representations are compatible with the basic POTFAN singularity types and distributions. Other possible applicable jet representations include ring or elliptical vortices such as used in Reference 14 or a linearized jet model such as Reference 15.

Within the proposed finite element analysis, the jet boundary surface is divided into numerous elements. On each element an appropriate potential flow singularity is placed to model the fluid behavior at the jet boundary. Additionally, a control point where the jet kinematic and dynamic boundary conditions will be applied, is located on each element. Specific examples which comply with these assumed characteristics are the jet representations of References 7 and 13.

Probably the most extensive modification to POTFAN required to facilitate multi-energy flow analysis involves development of a procedure for the application of the jet and solid body boundary conditions to obtain a combined flowfield solution. The principal difficulty to be anticipated in the solution process is introduced by the initially unknown jet boundary location. To overcome this difficulty, an iterative solution scheme is required which successively approximates the jet position while adjusting the strengths of the singularities representing the jets and solid bodies. The final result of the solution process is a jet boundary location and set of jet/body singularity strength values which simultaneously satisfy the boundary conditions prescribed above. Two iterative solution techniques will be discussed briefly. The first scheme divides the process of adjusting the jet location and redetermining the singularity strengths into separate steps. In contrast, the second technique attempts to both move the jet boundary and reevaluate the singularity values simultaneously.

The first iterative solution scheme, illustrated by the flow chart of Figure 9, is basically the procedure of Reference 13 and is initiated by an approximation or "guess" for the jet position and singularity strengths. The matrix of aerodynamic influence coefficients which express the solid body singularity distribution influence of every body element on each body control point is then evaluated. This matrix, when multiplied by the vector of body singularity strengths, yields the total body influence at each body control point. The influence coefficient matrix is next inverted (or equivalently triangularized) so that the equations expressing the body boundary conditions can be repeatedly solved in an efficient manner.

With these preliminary steps completed, the iterative process begins with calculation of the freestream and jet singularity influence at each body control point. The freestream and jet influence are the nonhomogeneous part of the equations expressing the body boundary conditions. The body singularity strengths are then determined by multiplying the inverted body influence coefficients matrix by the nonhomogeneous terms of the solid body boundary condition equation.

The newly determined body singularity strengths permit the flow velocities at each jet boundary element control point to be determined. Then the jet is repositioned by forcing each element to be tangent to local flow (jet kinematic condition) and the jet singularity strengths are re-evaluated to satisfy the jet pressure requirement (jet dynamic boundary condition). At this point in the solution cycle, one iteration has been completed and a convergence test to determine the change in jet/body properties is performed. If a significant change in these properties has occurred during the most recent cycle, the steps beginning with calculation of jet and freestream influence on wing control points are repeated. A converged solution, very closely satisfying all jet and body boundary conditions, is obtained when the variation of jet and body properties between successive iterative cycles becomes small. At this occurrence, the iterative process is terminated and the pressures, forces, and other desired flowfield qualities are calculated.

The second iterative solution procedure to be discussed is an adaptation of the method employed in Reference 16 to analyze wings with attached free vortex sheets. Bristow in Reference 17 applied a similar technique to calculate airfoil shapes with prescribed pressure distributions. Figure 10 gives a flow chart of this second procedure. Once again an initial starting solution or approximation is required to initialize the solution procedure. This starting solution must include the jet location as well as singularity strengths of each jet and body element. Next the Jacobian matrix of the equations expressing the solid body and jet boundary conditions is calculated. This Jacobian matrix when multiplied by the perturbations in the solution variables (singularity strengths and jet coordinates) is equal to the error between the present solution and the exact compliance with the boundary conditions.

The error between the desired and present solution is then evaluated permitting the perturbations in solution variables to be determined. This process determines updates to all singularity strengths and jet boundary coordinates in a single step. Next, these updates are employed to reposition the jet boundaries and evaluate the jet/body singularity strengths. A convergence test checks the progress of the solution to determine if additional iterative cycles are required. Finally, desired flowfield properties are calculated from the converged solution.

Either of these two solution schemes is suitable for incorporation into POTFAN for application of jet and body boundary conditions to obtain multi-energy flowfield solutions. The first scheme offers the following advantages compared to the second method:

1. Smaller matrices are involved since only the body boundary conditions are expressed in matrix equation form.

2. An efficient "inverse" matrix solution technique can be employed since the matrix of influence coefficients is only calculated once.

3. Most required calculated quantities (influence coefficients, flow velocities, etc.) are already evaluated within POTFAN.

The second iterative scheme possibly provides benefits in rate of convergence and assurance of obtaining converged solutions. The potential benefits of the second scheme appear most certain when the solution scheme is employed in conjunction with higher-order singularity distributions (such as employed in References 16 and 17) rather than with the relatively crude distributions currently used in most POTFAN applications. The low-order of POTFAN singularity distributions combined with the three advantages listed above suggest that the first solution technique is probably most suitable for jet analysis within POTFAN.

At the completion of the iterative solution process, the calculated results include the jet boundary positions and the strengths of singularities representing bodies and jets. These quantities are usually of secondary interest compared to the body pressures and flowfield velocities. However, the calculated jet position is useful for determining the realism of calculated solutions and indicating problem areas for solutions that fail to converge. Graphic presentation of the calculated jet location is a valuable aid in assessing solutions and would be a logical addition to the existing POTFAN graphics capability.

The flow velocity at any point in the jet/body flowfield can be evaluated from converged solutions by summation of the jet and body singularity induction with the freestream influence. Consequently, the pressures on bodies can be determined using the local velocity on the body surface including the jet influence. Presently, one POTFAN option determines the force on body elements by repeatedly applying the Kutta-Joukowski Law for the force on a vortex filament. In this procedure the velocity at each vortex filament midpoint is employed and numerical difficulties could be encountered if the filament midpoint is in close proximity to a jet boundary which is represented by discrete singularities. In Reference 7 this difficulty is avoided by using the velocity only at element midpoints which can usually be selected to avoid close encounters with concentrated jet singularities. Some care may be required within POTFAN to preclude numerical problems in the force evaluation procedure.

The above discussion described general properties of a thick-jet model with only minor emphasis on specific considerations relative to POTFAN. The remainder of this section will examine areas of POTFAN which will require modification to provide a thick-jet analysis capability.

Provisions will be necessary within POTFAN to describe the jet characteristics and the jet properties required to initialize the iterative solution scheme. The existing POTFAN input program is very general and can be simply adapted to include jet related input. Jet properties which must be input include the jet strength (probably characterized by the total pressure difference relative to ambient flow conditions), jet origin coordinates and whether the jet originates at a free actuator disk or at the trailing edge of a duct. Additionally, the finite element properties such as the number of circumferential and streamwise elements, the element spacing and the downstream extent of the jet calculation before a downstream representation is employed, must be specified. Also, the starting or "guess" values for jet singularity strengths and jet boundary locations must be approximated to initiate the solution process. Provision for optional use of linearized or simplified solutions to approximate the jet singularity strengths is desirable since these strengths are not easily determined intuitively by users. Ease in approximating the initial jet position is an important consideration in user acceptance of the multi-energy flow analysis. Finally, some input will be required to specify the functions to be performed and techniques to be applied during the iterative solution process. For example, the number of iterations to be performed, convergence criteria, relaxation of solution variables, and subiterative cycles must be specified.

Also, input provisions must be made for optional functions such as force evaluation, offbody velocity evaluation, graphic presentation of solutions or restart of the iterative process from a previous, partially converged solution.

Prior to entering the iterative solution cycle some preliminary calculations are required. The extent of these calculations depends on the iterative solution method selected. For example, for the scheme of Figure 9, the wing influence coefficient matrix is evaluated and provisions are made to solve the matrix equation enforcing the wing boundary conditions in an efficient manner (inversion or triangularization). Similarly, in the method of Figure 10 elements of the Jacobian matrix which are not altered by jet boundary position changes are calculated and stored. Many of these preliminary functions would be performed by the existing POTFAN influence coefficient evaluation and matrix solution programs with minor modification.

Upon completion of the preliminary steps discussed above, the main iterative process is entered. The functions performed during this process are highly dependent on the iterative scheme selected. Basically, steps must be provided to update body/jet singularity strengths and reposition the jet boundaries. The jet reposition perhaps introduces the greatest difficulty in modifying POTFAN for multi-energy flow analysis. Within the iterative scheme of Figure 9, the jet is repositioned using the jet kinematic boundary condition to align the jet surface with the local flow. In contrast, the method of Figure 10 requires the calculation of the elements of the Jacobian matrix which express the jet boundary conditions. In this case, the jet coordinates are part of the matrix equation solution.

Most functions within the iterative cycle, other than the jet reposition, are already available within POTFAN. For example, matrix solution, solid body boundary condition application, and velocity evaluation techniques are presently operational. However, some modification to existing program code will be required, such as inclusion of jet induction in the velocity calculations.

A necessary addition to the POTFAN structure for multi-energy flow analysis is an executive program to monitor and control the iterative solution process.

The executive program directs the functions requested by the user input and applies the numerical procedures specified. Integral to the executive program is calculation of appropriate convergence test parameters on which execution decisions are based. The convergence parameters reflect the rate of change of the solution between iterative steps as well as indicate when a solution with acceptable compliance with jet and body boundary conditions has been achieved. Also the executive program could apply relaxation of the solution variables (jet singularity strengths, body singularity strengths, jet boundary coordinates) to increase the rate of solution convergence or assist in obtaining convergence for difficult cases.

Since it is desirable to maintain POTFAN's present independence of machine type, the executive program should be written in FORTRAN rather than relying on manipulation of a particular machine control language. The modular POTFAN structure, with storage of the calculated result of each module in data sets, lends itself to control by an executive program.

The above discussion identifies factors which must be considered to provide a thick-jet analysis capability within POTFAN. This provides a basis to suggest a series of steps to undertake the modification to POTFAN. First, example computations should be completed using existing analysis codes with jet models, such as References 13, 14, and 15. These calculations would afford an examination of the potential usefulness and possible difficulties of the candidate jet models and solution techniques. Next, the analysis components (such as input modifications, jet reposition algorithm, and application of jet dynamic boundary condition) could be individually constructed and tested. Then it would be appropriate to incorporate into POTFAN the various analysis components along with an executive control program to direct the iterative solution process. Finally, the resultant method would require validation and documentation of the thick-jet analysis.

5. CONCLUDING REMARKS

Several conclusions are apparent from the present study on the applicability of the Ames Research Center Potential Flow Analysis (POTFAN) to predict ground influence and propulsive lift system aerodynamic characteristics. The most significant results are:

1. Calculations for a two-dimensional flat plate airfoil indicate that vortex lattice analysis is useful for evaluation of ground influence on aerodynamic characteristics.

2. Two-dimensional calculations employing the quasi-steady approximation indicate that a descending flat plate airfoil has greater lift augmentation, and an ascending airfoil has less lift augmentation, than the steady case.

3. POTFAN calculations performed in the present study are in close agreement with the Douglas Nonplanar Lifting Systems results. However, POTFAN generally indicated slightly lower lift augmentation, due to ground proximity, than the Douglas Nonplanar Lifting Systems method.

4. The three-dimensional quasi-steady lift predictions agree with the ordering of ascent, steady flight and descent values found for the two-dimensional calculations.

5. From the limited number of cases examined, the POTFAN and Douglas Nonplanar Lifting Systems predictions generally appear to agree equally well with experimentally determined ground effect aerodynamic trends. However, effects of wing section thickness and fluid viscosity introduce uncertainty in comparisons of theoretical and experimental ground effect results.

6. POTFAN is suitable for extension for multi-energy flow analysis. Required modifications have been identified and systematic development steps have been suggested to provide a capability within POTFAN to analyze interactions between propulsion and lift systems.

6. REFERENCES

1. Goldhammer, M.I., Crowder, J.P, Smyth, D.N., STOL Aircraft Transient Ground Effects — Part I. Fundamental Analytical Study. NASA CR 137766. November, 1975.

2. Tomotika, S., Tamada, K., Umemoto, H., The Lift and Moment Acting on a Circular Arc Airfoil in a Stream Bounded by a Plane Wall. The Quarterly Journal of Fluid Mechanics and Applied Mathematics. Vol. 4, pp. 1-22. 1951.

3. Shollenberger, C.A., Smyth, D.N., Analytical Study of STOL Aircraft in Ground Effect — Part I. Nonplanar, Nonlinear Wing/Jet Lifting Surface Method. NASA CR 152087. March 1978.

4. Medan, R.T., Bullock, R.B., NASA Ames Potential Flow Analysis (POTFAN) Geometry Program (POTGEM) — Version 1: NASA TM X-73,127. August, 1976.

5. Davis, J.E., Bonnett, W.S., Medan, R.T., NASA Ames Three-Dimensional Potential Flow Analysis System (POTFAN) Equation Solver Code (SOLN) — Version 1: NASA TM X-73,074. July, 1976.

6. Hess, J.L., Calculation of Potential Flow About Arbitrary Three-Dimensional Lifting Bodies. McDonnell Douglas Report No. MDC J5670-01. October, 1972.

7. Shollenberger, C.A., A Wing and Jet Interaction Analysis Based on a Doublet Singularity Formulation. McDonnell Douglas Report No. MDC J7421. August, 1977.

8. Saunders, G.H., Aerodynamic Characteristics of Wings in Ground Proximity. M.Sc. Thesis, Dept. of Aeronautics and Astronautics, Massachusetts Institute of Technology. 1963.

9. Koning, C., Influences of the Propeller on Other Parts of the Airplane. Aerodynamic Theory. Vol. IV, Springer-Verlag, Berlin. 1935.

10. Rethorst, S.C., Aerodynamics of Nonuniform Flows as Related to an Airfoil Extending Through a Circular Jet. J. of Aero. Sci. Vol. 25, No. 11. 1958.

11. Ribner, W.S. and Ellis, N.D., Theory and Computer Study of a Wing in a Slipstream. AIAA Paper No. 66-466. 1966.

12. Spence, D.A., The Lift Coefficient of a Thin Jet-Flapped Wing. Proceedings of the Royal Society. Series A. 238, 46. 1956.

13. Shollenberger, C.A., Three-Dimensional Wing/Jet Interaction Analysis Including Jet Distortion Influences. J. of Aircraft. Vol. 12, No. 9. 1975.

14. Mendenhall, M.R., Dillenius, M.F.E., and Spangler, S.B., Calculation of Aerodynamic Characteristics of STOL Aircraft with Externally-Blown-Jet-Augmented Flaps. AIAA Paper No. 72-63. January, 1972.

15. Lan, C.E., An Analytical Investigation of Wing-Jet Interaction. NASA CR 138140. 1974.

16. Weber, J.A., Brune, G.W., Johnson, F.T., Lu, P., and Rubbert, P.E., Three-Dimensional Solution of Flows Over Wings with Leading-Edge Vortex Separation. AIAA Journal. Vol. 14, No. 4. 1976.

17. Bristow, D.R., A New Surface Singularity Technique for Subsonic Analysis and Design. AIAA Paper No. 76-20. 1976.

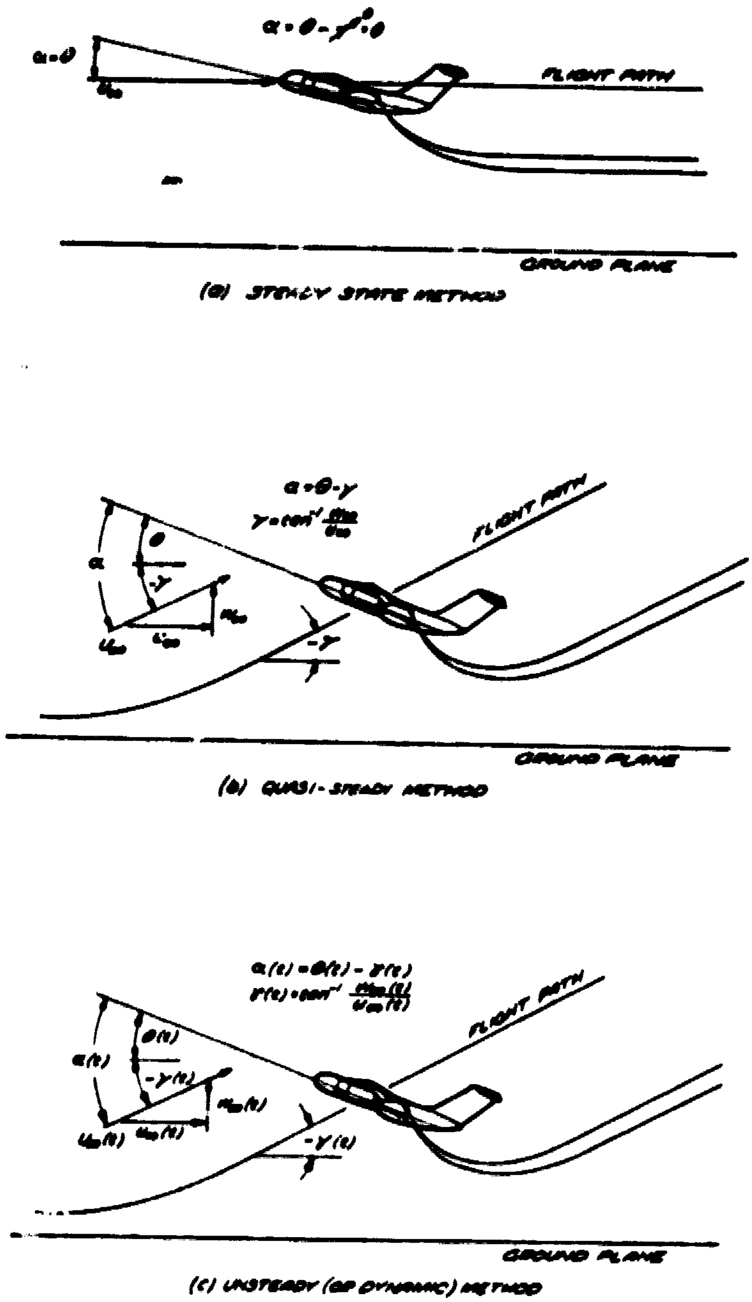

Figure 1. Steady State, Quasi-Steady and Unsteady Representation of an Aircraft Approaching the Ground.

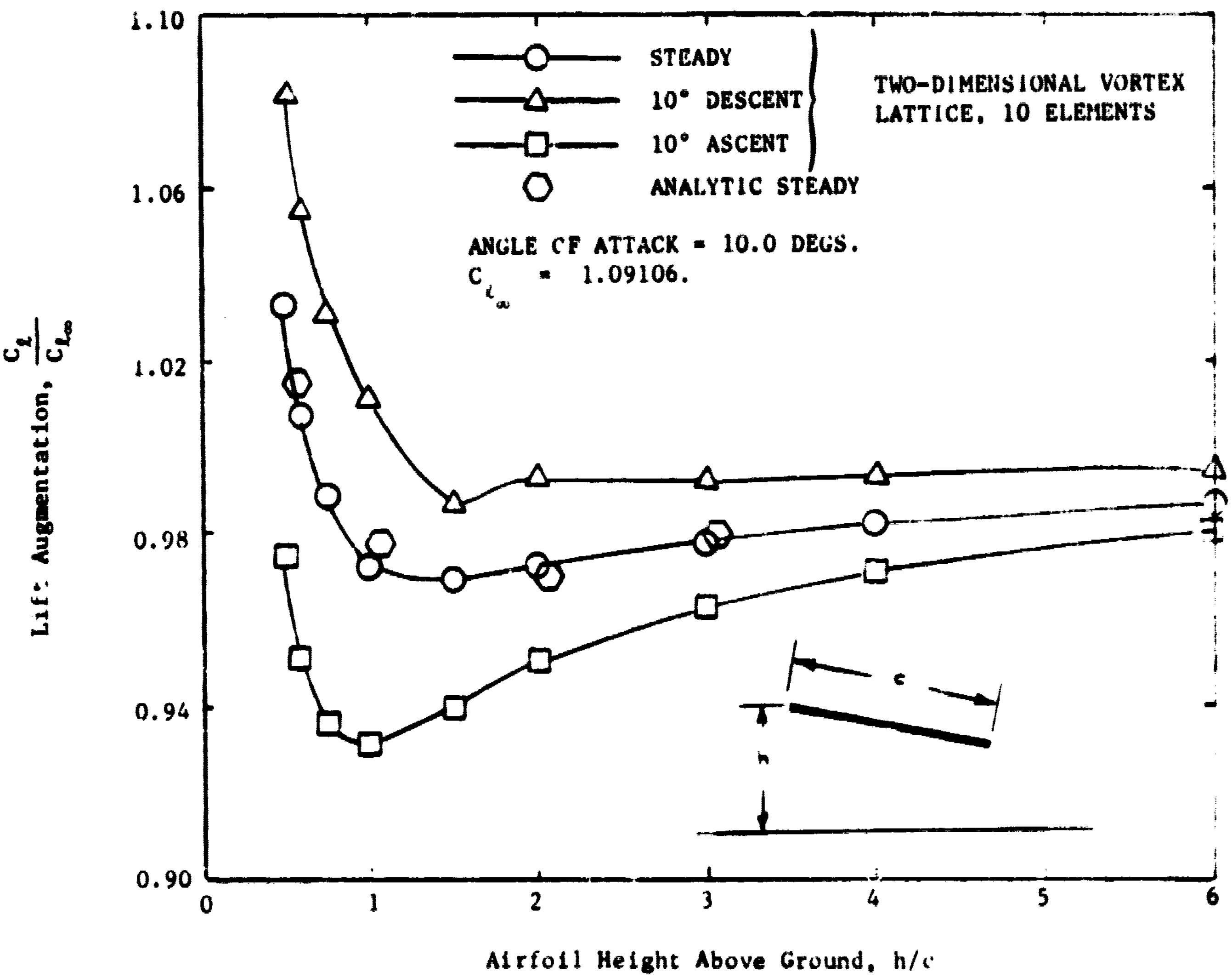

Figure 2. Calculated Lift of a Two-dimensional Flat Plate Airfoil in Ground Effect.

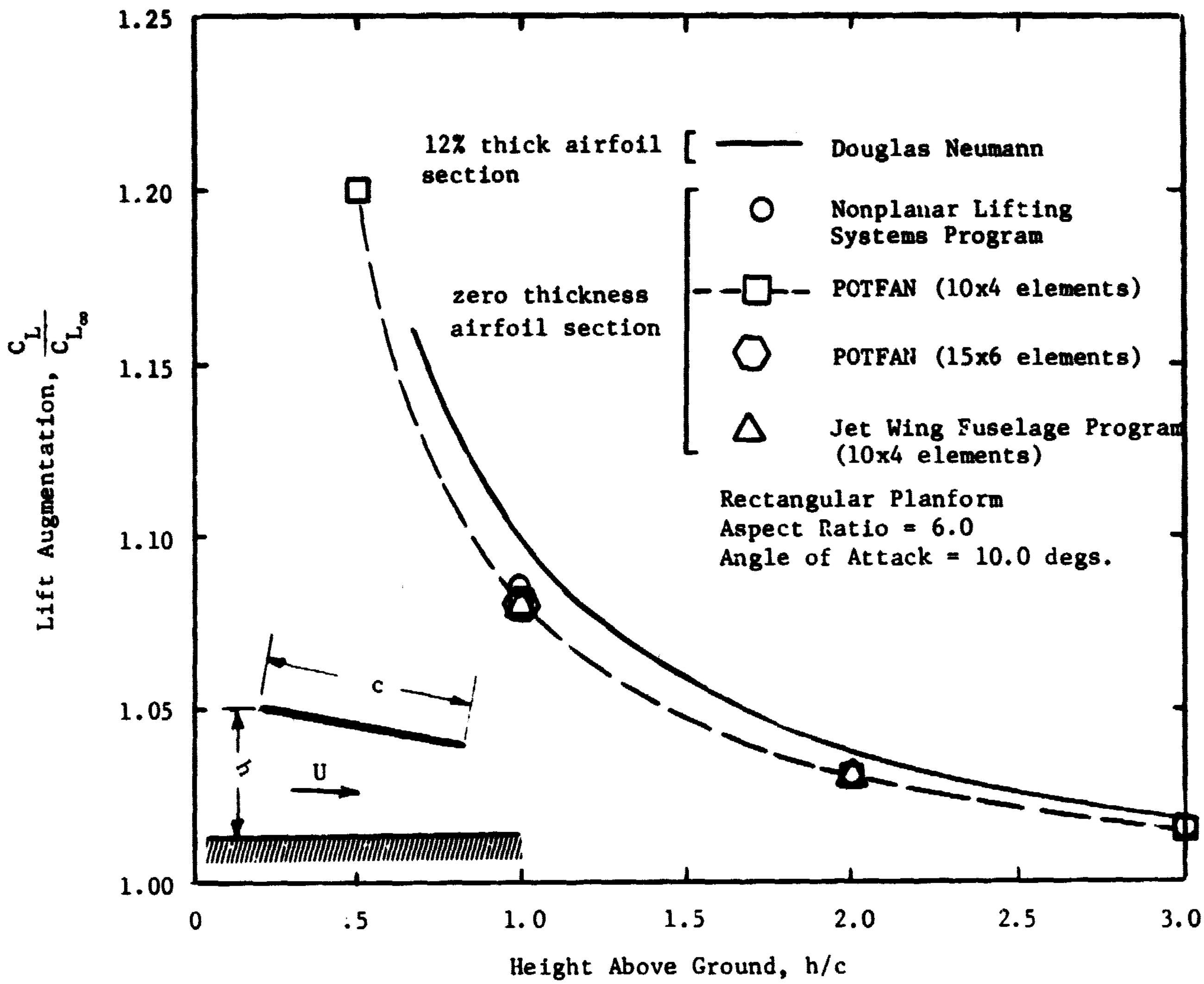

Figure 3. Predicted Lift Variation with Ground Proximity of Rectangular Aspect Ratio 6.0 Wing

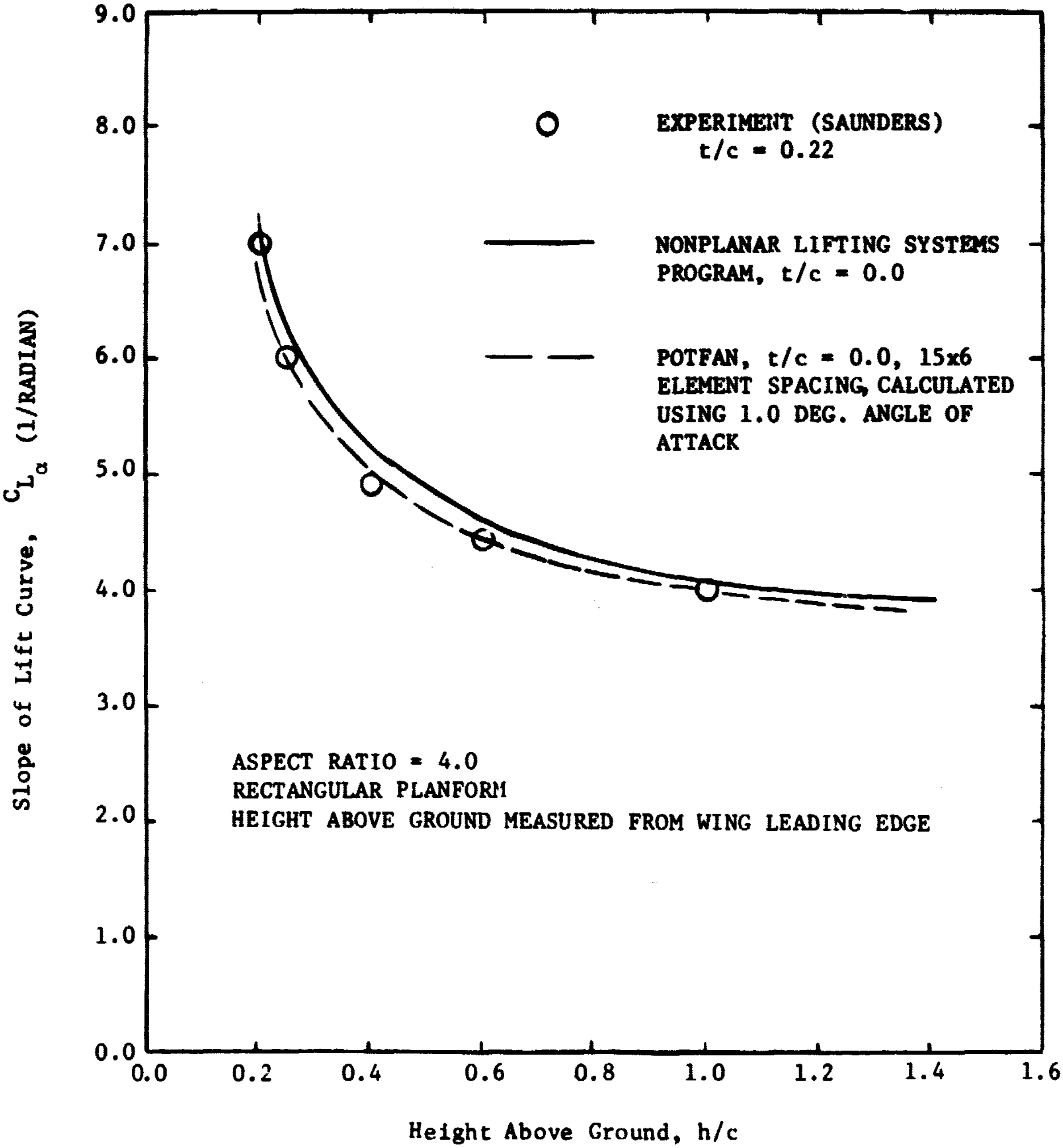

Figure 4. Experimental and Calculated Lift Slope Variation with Ground Height for Rectangular Wing.

RECTANGULAR WING
ZERO FLAP DEFLECTION
ASPECT RATIO = 7.0
ANGLE OF ATTACK = 10.0 DEGS.
HEIGHT ABOVE GROUND MEASURED FROM WING LEADING EDGE

—□— POTFAN 10x4 STEADY C_{L_∞} = 0.7662
- - △ - - POTFAN 10x4 10° QUASI-STEADY DESCENT C_{L_∞} = 0.7611
- —○— - POTFAN 10x4 10° QUASI-STEADY ASCENT C_{L_∞} = 0.7747

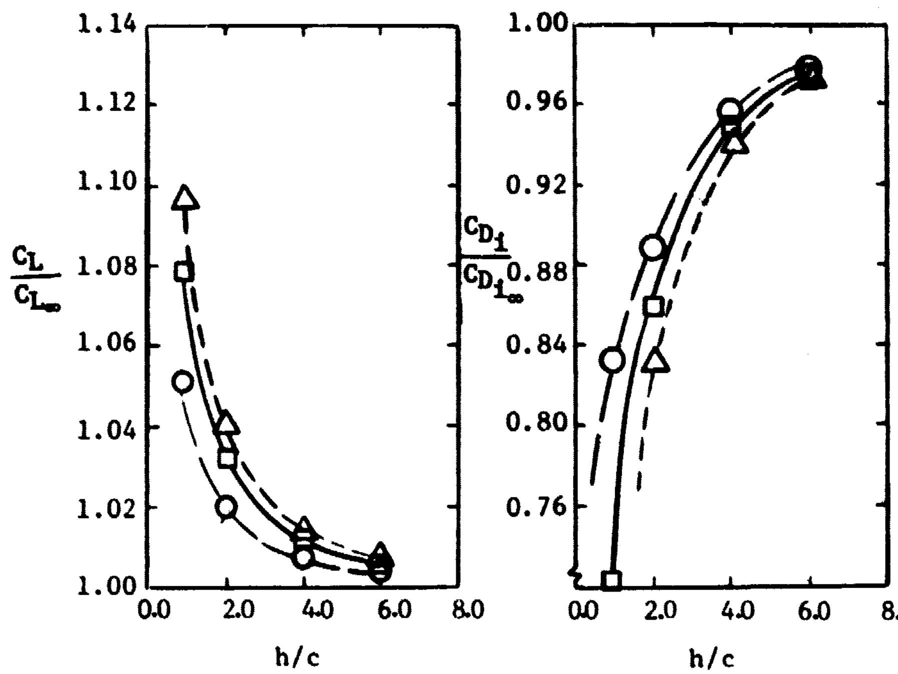

Figure 5. Lift and Induced Drag of a Rectangular Wing in Ground Effect Predicted by POTFAN for Steady and Quasi-Steady Flight.

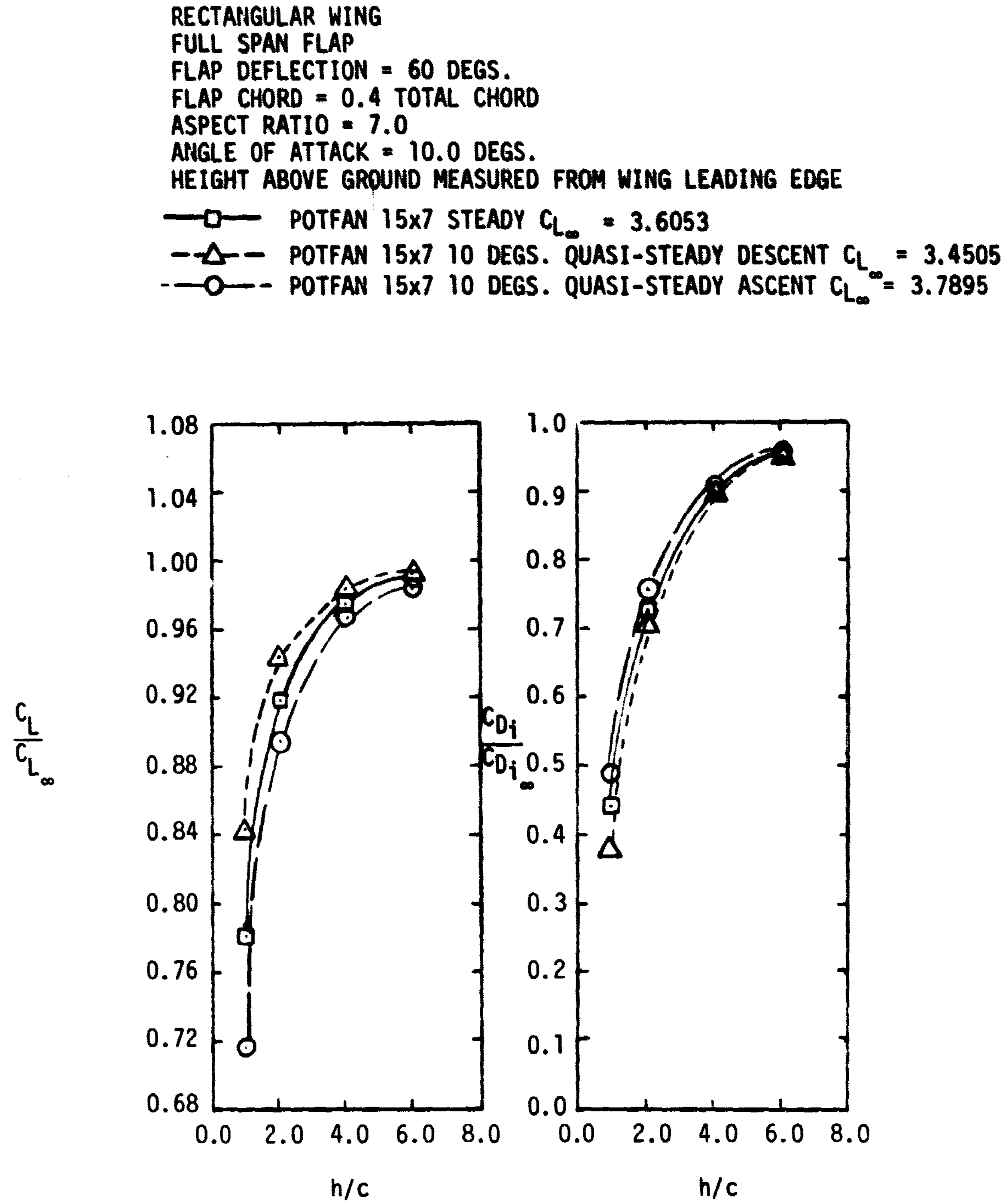

Figure 6. Lift and Induced Drag of a Rectangular Wing with 40-Percent Chord Flap in Ground Effect Predicted by POTFAN for Steady and Quasi-Steady Flight.

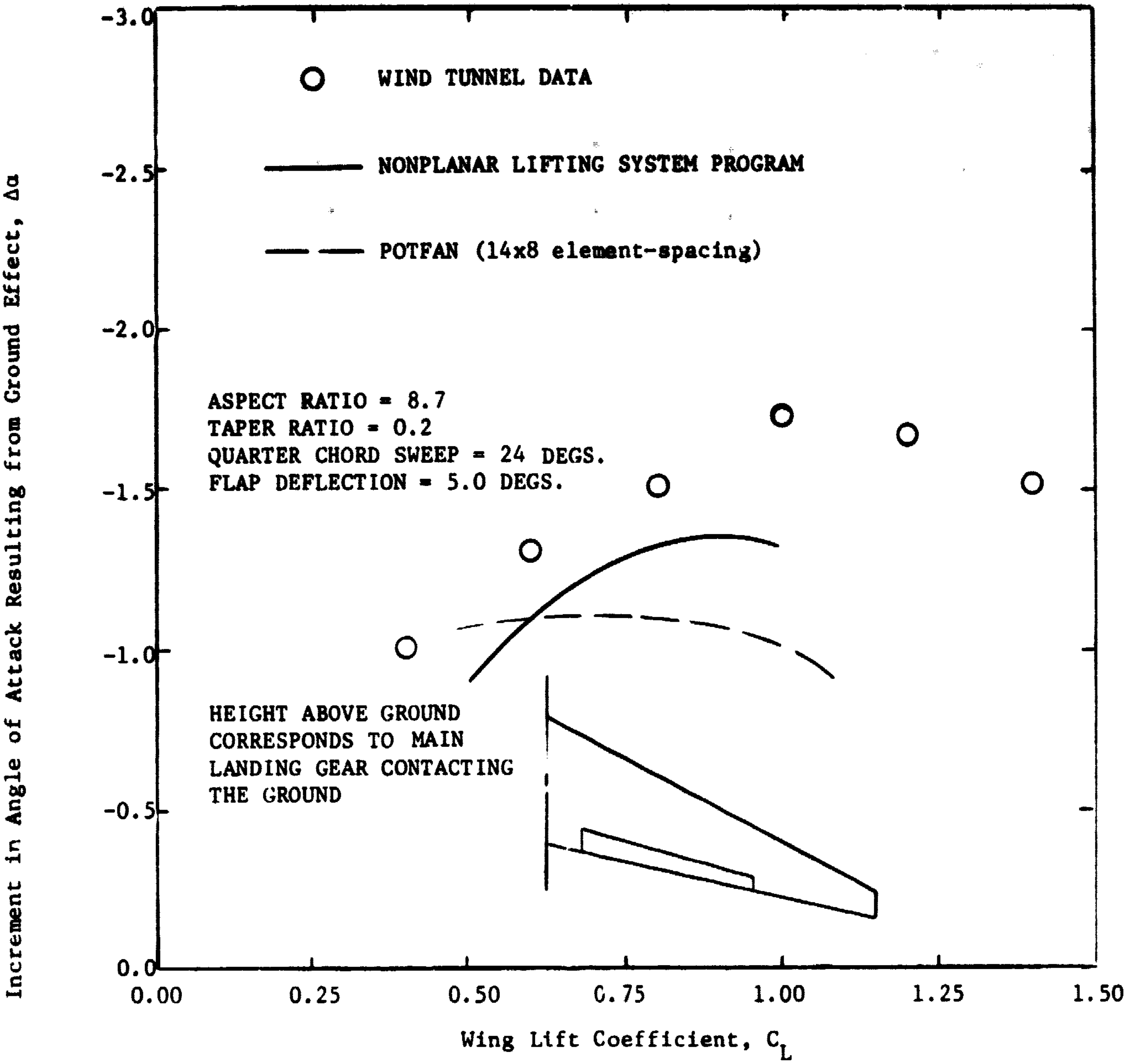

Figure 7. Predicted and Experimental Increments in Angle of Attack Resulting from Ground Effect for a Typical Transport Wing with Takeoff Flap Deflection.

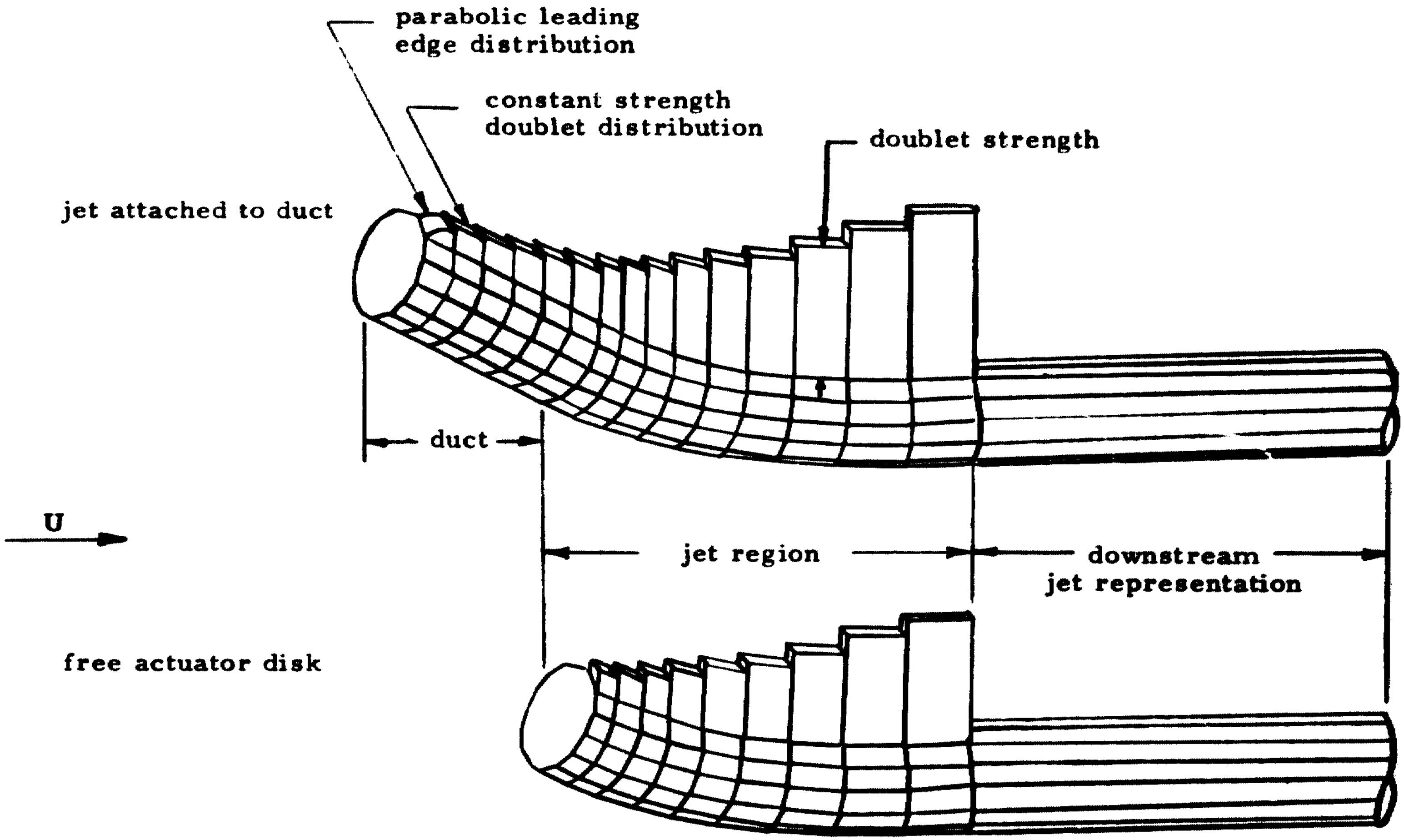

Figure 8. Jet Boundary Doublet Representation

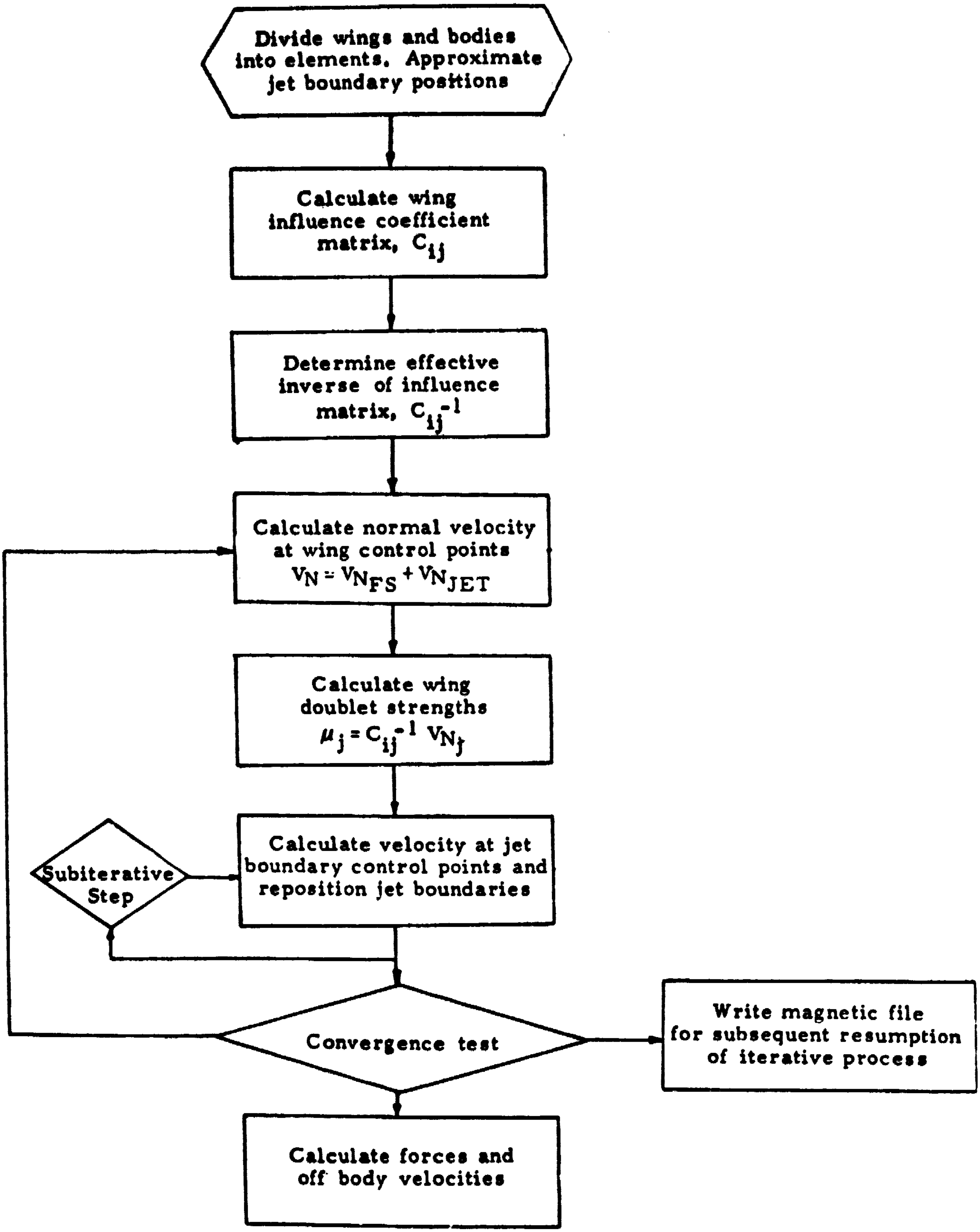

Figure 9. Jet Interaction Analysis Iterative Solution Scheme Number 1.

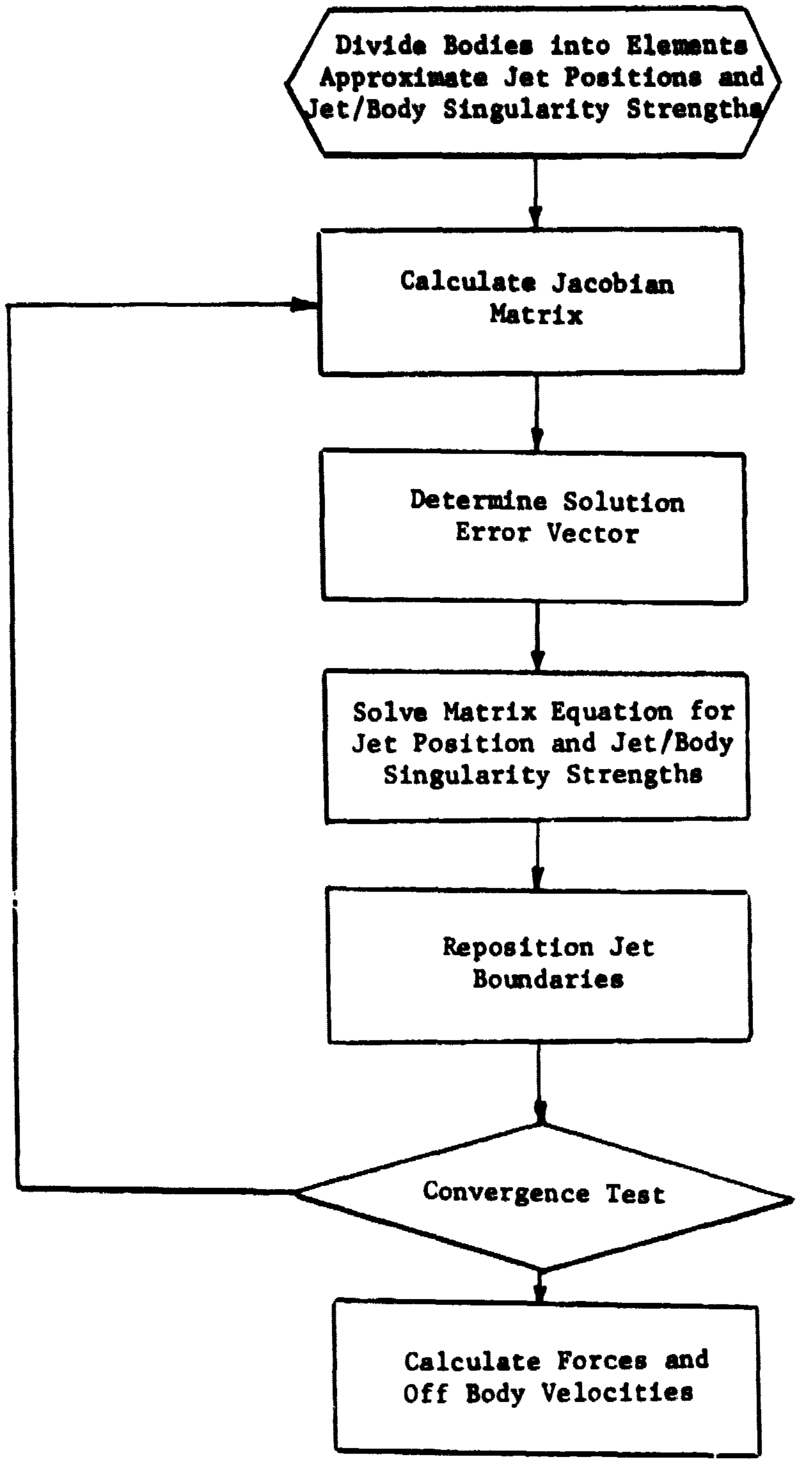

Figure 10. Jet Interaction Analysis Iterative Solution Scheme Number 2