A Theoretical Method for the Analysis and Design of Multielement Airfoils

J. G. CALLAGHAN* AND T. D. BEATTY†
Douglas Aircraft Company, Long Beach, Calif.

A theoretical method is presented for the computation of the two-dimensional high lift characteristics of multielement airfoils of arbitrary shape operating in a viscous incompressible fluid. This approach combines a geometry definition routine, a potential flow method based on a surface source distribution, and a finite-difference boundary-layer method to accomplish the ananlysis. An empirical method used for modeling separated flow is shown to work reasonably well for cases of moderate flow separation. Results obtained by this method are presented which show very good agreement with experimental data. It is shown that although the inviscid pressure distributions give a good qualitative representation of the flowfield, the viscous effects of adding the displacement thickness must be considered to obtain good quantitative results; however, the effects of merging boundary layers were not significant for these correlations. The ultimate objective of this method is the accurate calculation of the complete viscous flowfield about multielement airfoils through stall.

Nomenclature

C = reference chord length
C_l = section lift coefficient
C_p = pressure coefficient
R_x = Reynolds number, UX/ν
x = distance along chord line
X = distance along surface measured from stagnation point
α = angle of attack

Subscripts
SEP = separation
TR = transition

Introduction

PERFORMANCE requirements of aircraft dictate a variety of lifting conditions throughout the flight regime. The high-lift coefficient required during takeoff to reduce the ground run is constrained by the necessity of having high lift-to-drag ratios to permit adequate climb, particularly in the instance of power loss in multiengine aircraft. During landing and approach, considerably higher lift coefficients may be needed in order to reduce approach speeds and resultant landing ground roll.

To satisfy all of these requirements, some type of variable wing geometry is required. The nature of the high-lift problem demands that this variable geometry provide high trailing-edge camber, and depending on the extent to which the leading edge is loaded, additional leading-edge camber may also be needed. The resulting high-lift system is then highly cambered from leading edge to trailing edge. To approximate this shape structurally, several elements must be utilized. Many possibilities are open to the designer as to the shape, location, orientation, and number of these elements in a multielement high-lift system.

Until recently, the capability of theoretically analyzing two-dimensional multielement high-lift systems has not been available. Two-dimensional analysis, while obviously providing only a partial solution to the design problem, is nevertheless an extremely useful design tool. Moreover, before an understanding of the three-dimensional flowfield can be realized, the two-dimensional theoretical tools must be developed first.

In the past few years, well-proven methods have been developed at the Douglas Aircraft Co. which can provide the basis for extensive aerodynamic analysis of multielement airfoil high-lift systems. The Douglas Neumann Potential Flow Program[1,2] can determine the exact nonlinear inviscid flowfield about an arbitrary two-dimensional multielement airfoil. The potential flow pressure distribution can then be used as an input for the Douglas Finite-Difference Boundary-Layer Program[3,4] to obtain the complete boundary-layer characteristics, as well as transition and separation points for all components of the multielement system.

The present method integrates these existing theoretical tools, along with a geometry definition routine, into a flexible design tool which has been developed with the following objectives in view: 1) assist in a more fundamental understanding of the flowfield of multielement high-lift systems, 2) allow systematic studies of configuration variables, and 3) guide configuration development for wind-tunnel studies.

Method of Analysis

The method developed for the analysis and design of two-dimensional multielement airfoils operating in an incompressible viscous flowfield is comprised of three main components: 1) geometry definition routine, 2) potential flow analysis, and 3) boundary-layer analysis.

Description of Geometry Definition Routine

Presently, there are only two methods available for calculating the potential flow solution on a multielement airfoil consisting of more than two elements.[5–8] These methods are quite sensitive to the airfoil input geometry in that they require both the surface curvature to be smooth and the airfoil-defining coordinates to be distributed properly. These requirements are easily achieved on an analytical airfoil shape, since the input coordinates may be calculated exactly for any prescribed distribution. However, some method of determining accurate input coordinates for an arbitrary airfoil shape is necessary, since the airfoil geometry may not always be amenable to exact analytical definition. In addition, whenever two bodies are brought into close proximity, as in a multielement system, there is an interplay between the opposing surfaces which imposes certain other restraints on the input coordinates.

Presented as Paper 72-3 at the AIAA 10th Aerospace Sciences Meeting, San Diego, Calif., January 17–19, 1972; submitted January 3, 1972; revision received August 30, 1972. This paper summarizes work performed under the sponsorship of the Independent Research and Development Program (IRAD) of the McDonnell Douglas Corp.

Index categories: Subsonic and Transonic Flow; Airplane and Component Aerodynamics.

* Group Chief, High Lift Technology Development, Aerodynamics Subdivision.

† Engineer/Scientist-Specialist, High Lift Technology Development, Aerodynamic Subdivision.

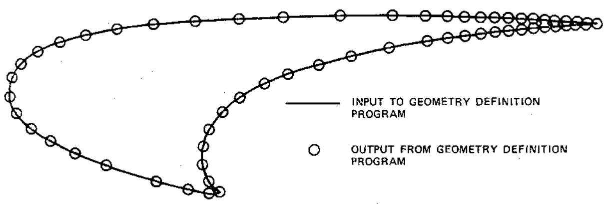

Fig. 1 Comparison of input and output from geometry definition program on representative shape.

A method was developed which converts coordinates that are unsmooth and irregularly distributed about any arbitrary airfoil into smoothed coordinates spaced appropriately for the Douglas Neumann Potential Flow Program. The leading-edge slat shape shown in Fig. 1 is an example of the type of solution generated.

The importance of this routine can be realized by examining Fig. 2. This graph shows a comparison of pressure distributions calculated by the Douglas Neumann Potential Flow Program using a nonanalytical airfoil whose coordinates were unsmoothed and smoothed.

Description of the Potential Flow Method

The Douglas Neumann method is used for calculating the potential flowfield.[1,2,9] A special characteristic of this very general method is that it can calculate the flowfield about virtually any body. There is no restriction, for example, to slender bodies. In fact, the "body" in question need not be a single body, but may be an ensemble of bodies, as shown in Fig. 3.

This method is especially well-suited for interference problems such as that of multielement airfoils. In principle, the calculated solution may be made as accurate as desired by suitably refining the numerical procedure. Accordingly, the Neumann method is designated an exact method in this sense.

The usefulness of potential flow, which does not account for viscosity or compressibility, is due to the fact that it is a good approximation to real flow under a wide variety of circumstances. The most important exception is the case of lifting airfoils, where a viscous correction is needed. These conclusions cannot be deduced from first principles, but have been established empirically. To verify the usefulness of potential flow as a prediction technique for real flow, results calculated by the Neumann program have been compared with experimental data. Over the years, approximately one hundred such comparisons have been made for a wide variety of configurations and flow conditions.[10,11] In a subsequent section, several recent comparisons between the Neumann solution and wind-tunnel test results are presented.

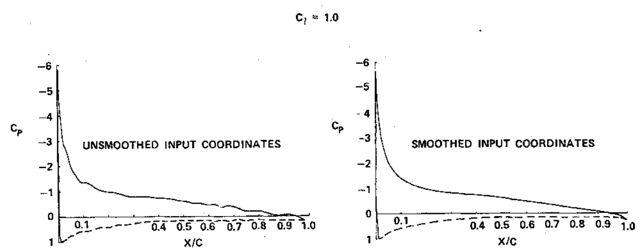

Fig. 2 Comparison of pressures generated from smoothed and unsmoothed input coordinates.

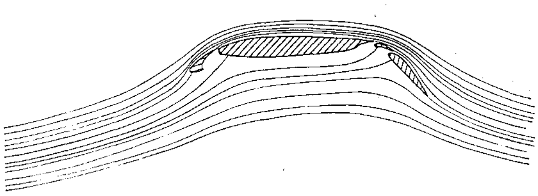

Fig. 3 Streamline flowfield for airfoil with leading-edge slat and double-slotted flap.

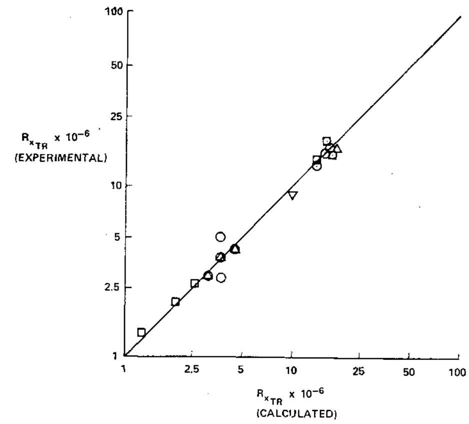

Fig. 4 Comparison of experimental and calculated transition points.

Description of the Boundary-Layer Method

The present method utilizes the recently developed Douglas boundary-layer method[3] which eliminates many of the disadvantages of the integral methods by solving the full partial-differential equations governing the flow, and is thereby classified as a differential method. For two-dimensional incompressible flows, turbulent boundary-layer equations contain terms involving time means of fluctuating velocity components known as Reynolds stress terms. At present, the exact relationship between these terms and the mean velocity distribution in the boundary layer still remains unknown. In the present method, a relation based on the eddy-viscosity concept is used, giving highly satisfactory results for a variety of flow conditions. This method is general, and is applicable to a wide variety of important flow problems.

The prediction of boundary-layer transition is a necessary part of any viscous analysis. The approach taken in this method is to use the transition correlation curve of Smith,[12] which is based on a large amount of experimental data over a wide Reynolds-number range. Figure 4 shows the extremely good results which are obtainable using this approach.

The boundary-layer separation point is another parameter which must be accurately predicted. Figure 5 shows the very good agreement between the separation point, as calculated by the present method, and experimental data for 67 different test cases.

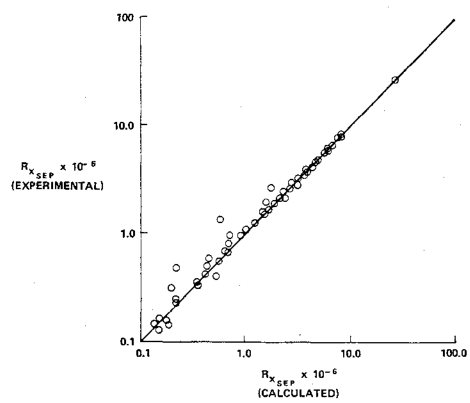

Fig. 5 Comparison of experimental and calculated separation points.

Calculation Procedure

The basic calculation procedure of this method consists of calculating the potential flowfield about a body that has been modified to account for viscous effects. The definition of the equivalent inviscid body for the potential flow calculations is obtained by the use of the boundary-layer displacement thickness from the boundary-layer analysis. There are several approaches for the definition of this equivalent inviscid body. One technique provides surface blowing which, when combined with the onset flow, creates a body which is thicker by an amount corresponding to the added boundary-layer displacement thickness. Another technique treats camber and thickness effects (resulting from the displacement thickness) separately and adds the two solutions.[8] The present method takes a more direct approach, in that the displacement thickness is added directly to the basic body geometry to form a new, thicker equivalent body. Since the displacement thickness is finite at the trailing edge, the new body does not close. This open trailing edge would present a problem if the potential flow method were not of the surface-source type. In Ref. 13, Hess shows that the ability to calculate flow about a body with an open trailing edge is inherent in the formulation of a surface-source method, whereas, in a distributed vorticity approach, some sources would have to be added to permit the analysis of an open trailing-edge body.

The three previously discussed components utilized in the present calculation procedure are combined under direct control of the Multielement Airfoil Design and Analysis Method computer program known as MADAAM.

The MADAAM Program utilizes these components, as shown in Fig. 6, in the following iterative manner: 1) precise geometry definition for input into the potential flow program, 2) calculation of the exact nonlinear potential flow for specified geometry and flow conditions, 3) calculation of the viscous flow characteristics based on the results of the potential flow program, 4) addition of boundary-layer displacement thickness to the basic geometry for each element, 5) recalculation of the pressure distribution utilizing the potential flow program, based on the redefined geometry, 6) recalculation of viscous flowfield based on recalculated pressure distribution from redefined geometry, if desired, and 7) iteration of the above scheme until convergence is achieved.

Experimental Correlations

To establish the validity of any theoretical method, correlations with carefully conducted experimental tests are required. The experimental data utilized for correlations with the calculated results of the present method were obtained from a two-dimensional high-lift development experimental program conducted in the McDonnell Douglas $8\frac{1}{2} \times 12$-ft low-speed wind tunnel. A 27-in. chord model, whose basic shape and high-lift geometry are similar to a typical transport wing, was mounted between two parallel floor-to-ceiling inserts that provided a $2 \times 8\frac{1}{2}$ ft two-dimensional test section. These inserts were provided with a suction system for purposes of removing the wall boundary layer, thereby minimizing any three-dimensional effects.

The method described in the previous section has been used in recent studies involving single and multielement airfoils, the results of which can be used to demonstrate the importance of including viscous effects in theoretical calculations. Figure 7 presents the calculated lift curves, with and without viscous effects, as compared to the experimentally-measured lift for a single element section. It is evident that the inviscid lift curve is high in both level and slope compared with the experimental value. This is also reflected in the attendant pressure distribution for a representative angle of attack at 10° (Fig. 8).

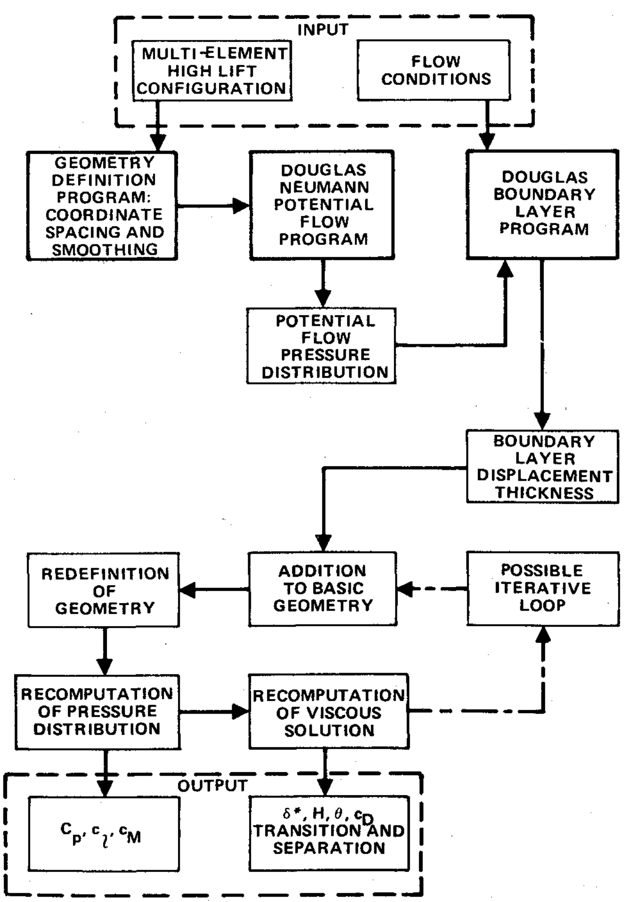

Fig. 6 Flow diagram of computer program for multielement airfoil design and analysis method (MADAAM).

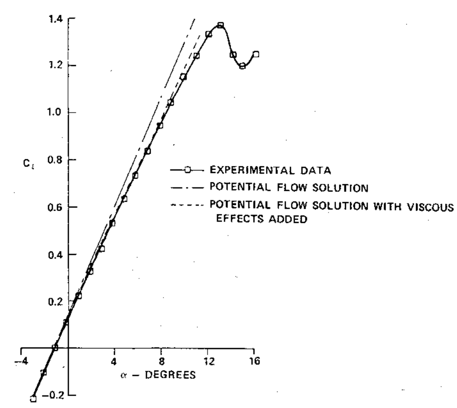

Fig. 7 Comparison of experimental and calculated lift curves for single-element airfoil.

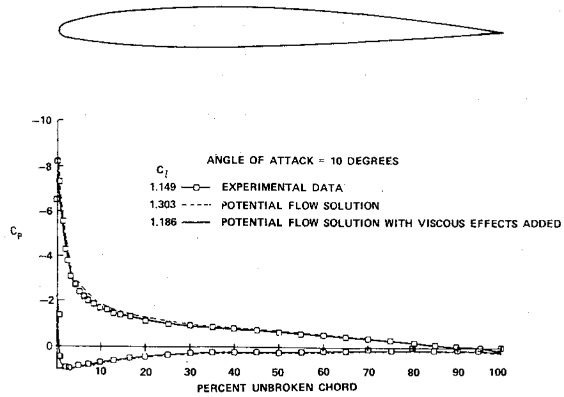

Fig. 8 Comparison of experimental and calculated pressure distributions for single-element airfoil.

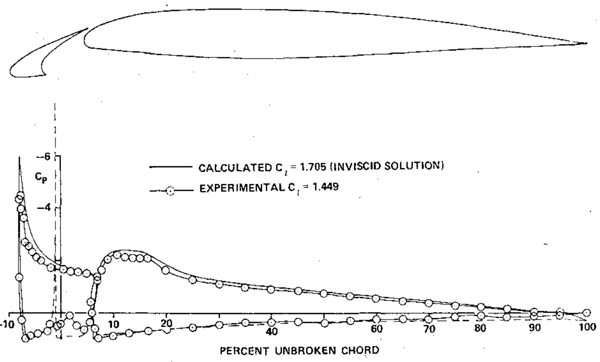

Fig. 9 Comparison of experimental and inviscid pressure distributions on airfoil with leading-edge slat.

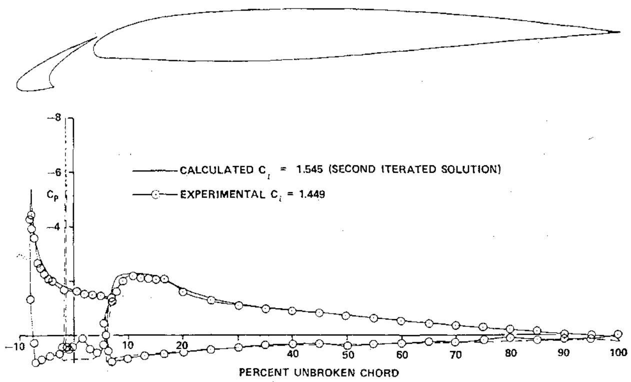

Fig. 11 Comparison of experimental and second viscous solution pressure distributions on airfoil with leading-edge slat.

The lift curve obtained by the present method, which includes the effects of viscosity, is seen to be in much closer agreement with experimental values. The pressure distribution shows remarkably good agreement. It is significant that for this case only one iteration was required, that is, two potential flow solutions and one boundary-layer solution.

Figure 9 compares test results with purely inviscid pressures on a transport-type airfoil with leading-edge slat deflected. The inviscid pressure distribution is seen to be in qualitative agreement with experiment, but is too high in loading and, correspondingly, in lift coefficient.

The first iteration on the viscous solution, as seen in Fig. 10, reduces the calculated lift coefficient from 1.71 to 1.58, bringing it into closer agreement with the experimental level.

Iterating a second time (i.e., recalculating the boundary-layer displacement thickness from the pressure distribution of Fig. 10, and adding it to the basic geometry, and calculating the pressures a third time) provides even closer agreement with test results, as shown in Fig. 11. The iterative process is converging, as seen by comparing the lift reduction on the first iteration of 0.13 to that for the second iteration of 0.03.

The lift coefficient difference in Fig. 11 is small, but still too large to be acceptable. The boundary-layer analysis revealed that turbulent separation was predicted at 98% chord on the wing. This is in agreement with the loss in pressure recovery shown in experimental pressures occurring between 95 and 100% of chord. The analytical description of separated flow regions is in an embryonic stage at best. However, some semiempirical models have been developed. One particular method developed at Douglas has been used to represent the separated region on the main airfoil of the current example. The results of this modeling are presented in Fig. 12. There is very little difference between experimental and calculated lift for this case, and the pressures are in close agreement.

The lift curves for the inviscid and viscous calculations are compared with the experimental lift curve in Fig. 13. At the lower angles of attack, two iterations on the boundary-laye solution provide very good agreement with test results. Where moderate amounts of flow separation are present, the separated wake model used provides good accuracy.

The analysis of an additional case for an airfoil with a double-slotted flap and leading-edge slat is presented. The

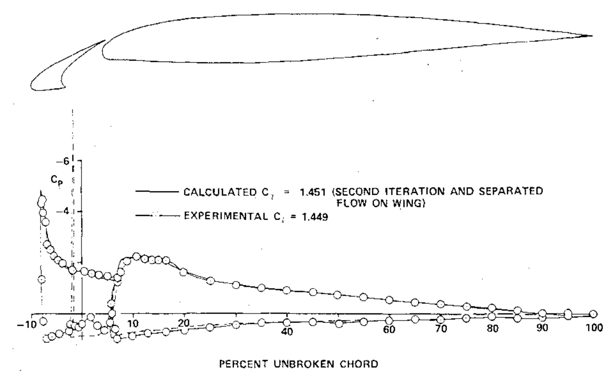

Fig. 12 Comparison of experimental and second viscous solution pressure distributions, including separation effects on airfoil with leading-edge slat.

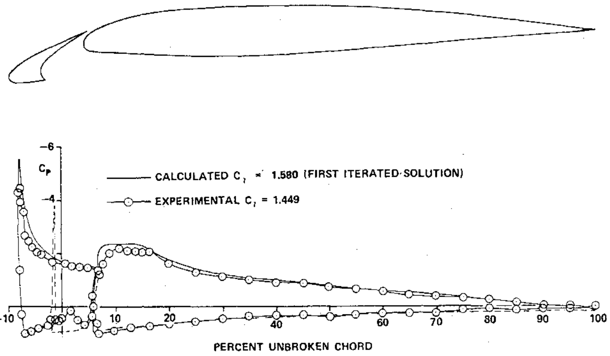

Fig. 10 Comparison of experimental and first viscous solution pressure distributions on airfoil with leading-edge slat.

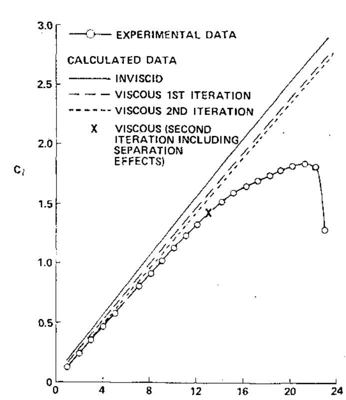

Fig. 13 Comparison of experimental and calculated lift curves for an airfoil with leading-edge slat.

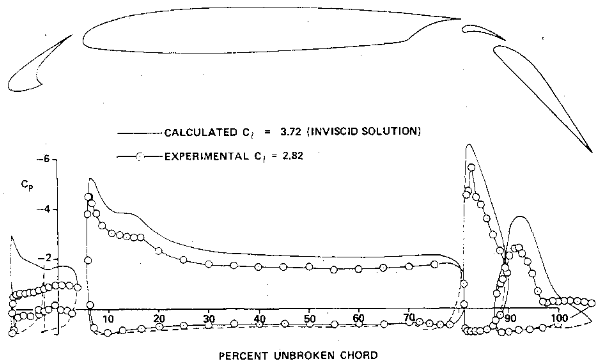

Fig. 14 Comparison of experimental and calculated pressure distributions on airfoil with leading-edge slat and double-slotted flap.

inviscid pressures for this airfoil are presented in Fig. 14, as compared with experimental data. As seen, there is a considerable difference in the pressure distributions and lift coefficients.

This four-body case was analyzed in a manner similar to the one used on the slatted airfoil. Two iterations on the viscous solution were generated, and the theoretical separation points for all bodies calculated. Separation was found on both the vane and flap, but the separation point on the flap was much further forward. In addition, another correction was made on this airfoil. The flow cannot negotiate the very steep gradient at the cusp of the slat lower surface; in fact, experimental evidence indicates that it separates, forming a trapped vortex in the cusp region and reattaching near the slat trailing edge. An equivalent shape for the slat was assumed which included an empirical representation of the separated region. The resulting pressures are shown in Fig. 15. As can be seen, the pressures on the wing and slat are in very close agreement. The calculated lift coefficient is now within 3% of the test data, whereas in Fig. 14, the inviscid value of C_l was over 30% in error.

Concluding Remarks

A method has been presented for the calculation of the viscous flowfield about multielement high-lift airfoils. Results obtained by this method have been presented which show very good agreement with experimental data. It has been shown that the inviscid pressure distributions, while generally over-predicting the level of lift, nevertheless give a good qualitative representation of the flowfield. The importance of including viscous effects has been shown, with rapid convergence on the solution being obtained after two or three iterations. While the theoretical results presented here have shown very good correlation with experimental results, the need for continued work in the theoretical analysis of multielement air foils is clear. The empirical method used for modeling the separated flow works reasonably well in cases of moderate flow separation, but has not proved an adequate model in cases of extensive flow separation. Further, the correlations presented here have been for configurations where the effects of merging boundary layers were not significant. In-house work, as well as work in other agencies, shows considerable promise in developing theoretical tools in the areas of both separated flow and merging boundary layers. Continued experimental correlations will demonstrate the extent of applicability of these theoretical tools to the end result that the complete viscous flowfield about multielement airfoils through the stall can be calculated.

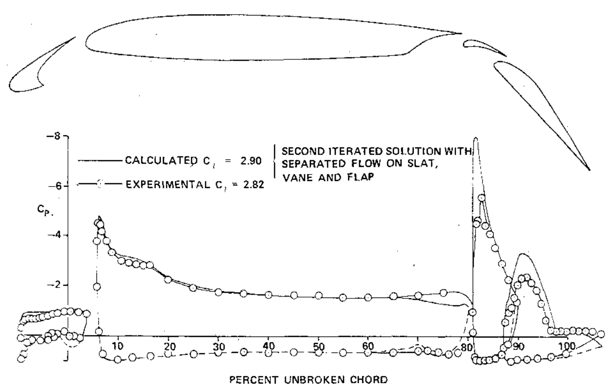

Fig. 15 Comparison of experimental and calculated pressure distributions on airfoil with leading-edge slat and double-slotted flap.

References

[1] Hess, J. L. and Smith, A. M. O., "Calculation of Potential Flow About Arbitrary Bodies," *Progress in the Aeronautical Sciences*, Vol. 8, edited by D. Kucheman, Pergamon Press, New York, 1966.

[2] Giesing, J. P., "Potential Flow About Two-Dimensional Airfoils," Pts. I and II, LB-31946, Dec. 1966, Douglas Aircraft Co., Long Beach, Calif.

[3] Cebeci, T. and Smith, A. M. O., "A Finite-Difference Solution of the Boundary-Layer Equations," Pt. I, DAC 67131, 1968, Douglas Aircraft Co., Long Beach, Calif.

[4] Cebeci, T. and Smith, A. M. O., "A Finite-Difference Solution of the Incompressible Turbulent Boundary-Layer Equations by an Eddy-Viscosity Concept," *Computation of Turbulent Boundary Layers, AFOSR-IFP—Stanford Conference*, Vol. 1, Stanford University Press, Stanford, Calif., 1968, pp. 346–356.

[5] Foster, D. N., "Note on Methods of Calculating the Pressure Distribution Over the Surface of Two-Dimensional Cambered Wings," TR 67095, April 1967, Royal Aircraft Establishment, Farnborough, Hampshire, England.

[6] Jacob, K. and Riegels, F. W., "The Calculation of the Pressure Distribution Over Aerofoil Sections of Finite Thickness With and Without Flaps and Slats," Z.F.W. 11, Pt. 9, 1963, p. 357; translated as *Library Translation* No. 1101, 1965, Royal Aircraft Establishment, Farnborough, Hampshire, England.

[7] Wilkinson, D. H., "A Numerical Solution of the Design Problems for the Flow Past One or More Aerofoils or Cascades," R. and M. 3545, 1968, Aeronautical Research Council, England.

[8] Stevens, W. A., Goradia, S. H., and Braden, J. A., "Mathematical Model for Two-Dimensional Multi-Component Airfoils in Viscous Flow," CR-1843, July 1971, NASA.

[9] Smith, A. M. O. and Pierce, J., "Exact Solution of the Neumann Problem. Calculation of Plane and Axially Symmetric Flows About or Within Arbitrary Boundaries," ES-26988, April 1958, Douglas Aircraft Co., Long Beach, Calif.

[10] Faulkner, S., Hess, J. L., and Giesing, J. P., "Comparison of Experimental Pressure Distributions with Those Calculated by the Neumann Program," LB-31831, Dec. 1964, Douglas Aircraft Co., Long Beach, Calif.

[11] Bauer, A. B., Smith, A. M. O., and Hess, J. L., "Potential Flow and Boundary Layer Theory as Design Tools in Aerodynamics," *Canadian Aeronautics and Space Journal*, Vol. 16, No. 2, Feb. 1970, pp. 53–69.

[12] Smith, A. M. O., "Transition, Pressure Gradient, and Stability Theory," *Proceedings of the 9th International Congress of Applied Mechanics*, Vol. 4, 1956, p. 234.

[13] Hess, J. L., "Numerical Solution of the Integral Equation for the Neumann Problem With Application to Aircraft and Ships," *Proceedings of SIAM Symposium on Numerical Solution of Integral Equations with Physical Applications*, edited by B. Noble, to be published; also Engineering Paper 5987, Douglas Aircraft Co., Long Beach, Calif.