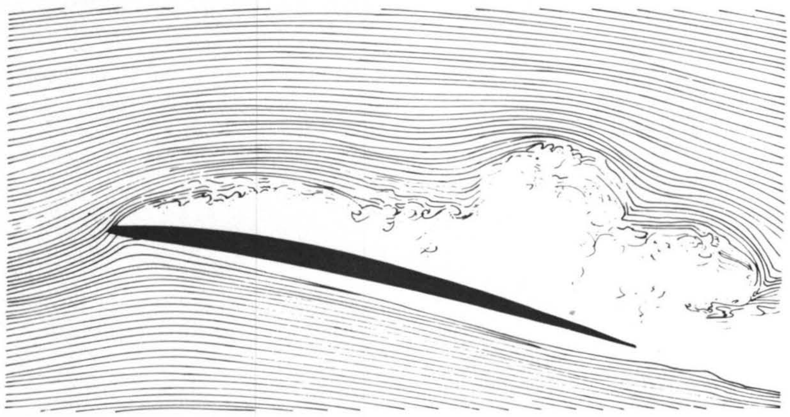
PROCEEDINGS OF THE CONFERENCE ON LOW REYNOLDS NUMBER AIRFOIL AERODYNAMICS

Edited by
Thomas J. Mueller

UNDAS-CP-77B123
June 1985



Sponsored by

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER
HAMPTON, VIRGINIA

AND

U.S. NAVY
OFFICE OF NAVAL RESEARCH
ARLINGTON, VIRGINIA

AND

THE UNIVERSITY OF NOTRE DAME
DEPARTMENT OF AEROSPACE AND MECHANICAL ENGINEERING
NOTRE DAME, INDIANA

LOW REYNOLDS NUMBER AIRFOIL DESIGN

Mark D. Maughmer
The Pennsylvania State University
University Park, PA

Michael S. Selig
Princeton University
Princeton, New Jersey

ABSTRACT

Due to the dependency of airfoil performance at low Reynolds numbers on the location of the laminar separation bubble, the design philosophies of such airfoils are considerably different than those employed at higher Reynolds numbers. While a great deal of current research is directed toward furthering the understanding of the flow behavior in the Reynolds number range of 50,000 to 500,000, for the most part, the results of these efforts have yet to be adequately implemented into the design process. To facilitate the design of low Reynolds number airfoils using existing methods, a first step in developing design philosophies has been undertaken by correlating analysis results obtained using the Eppler and Somers computer code with experimental data. From this study, it is found that the velocity distributions of the airfoils for which the method produces reasonable performance predictions can be characterized by particular features. By specifying velocity distributions incorporating these features, a number of new profiles having anticipated performance levels superior to existing sections have been designed. One of the airfoils obtained in this manner is examined. In addition to the velocity distribution features suggested by the correlations of calculated and experimental results, another aspect which appears to benefit low Reynolds number airfoil performance is the implementation of a condition which forces the pressure gradients occurring at the trailing edge, which are generally unbounded, to be finite. The potential benefits of using such a condition are discussed, and an example airfoil designed by an appropriately modified version of the Eppler and Somers code is presented.

INTRODUCTION

While the design and analysis of airfoils for Reynolds numbers above 500,000 can be accomplished with a high level of confidence that the resulting aerodynamics will be as predicted, this is not the case for airfoils intended to operate at lower Reynolds numbers. As discussed in Refs. [1]-[4], the occurence of laminar (transitional) separation bubbles can have a dominating influence on the aerodynamic characteristics of an airfoil. At the present time, the capability of satisfactorily accounting for the effects of such bubbles is limited. Thus, the difficulties in achieving reliable performance predictions for airfoils operating at low Reynolds numbers, particularly below about

200,000, are due primarily to the inability of determining the location and behavior of the separation bubble and its effect on the downstream boundary layer development.

Although experimental programs, such as those of Refs. [4]-[5], have resulted in significant progress toward the understanding of laminar separation bubbles, and there are numerous contributions toward the development of analytical prediction methods, including those of Refs. [6]-[9], considerable work remains before adequate engineering methods for the design and analysis of airfoils at low Reynolds numbers result. In fact, it has been demonstrated that the aerodynamics of low Reynolds number flows are so sensitive to external influences not under the control of a designer, such as free-stream turbulence, surface contamination, and so-forth, it may be that improving the analytical prediction capability for particular flow conditions is only of limited value in that an actual design must perform over the wide range of flow environments encountered operationally. Thus, from the standpoint of airfoil design, the most beneficial result of researching the behavior of flows at low Reynolds numbers may prove to be the understanding which facilitates the specification of velocity distributions that minimize the impact of environmental factors on the separation bubble and airfoil performance.

In order to carry out the design of low Reynolds number airfoils between now and the time that reliable predictions are possible, there is a need for design philosophies which, when used in conjunction with existing methods, will result in airfoils having actual characteristics close to those intended. In this regard, it is necessary to define the relationship between the velocity distribution on an airfoil and the development of laminar separation bubbles. As a design goal, it is desired to minimize the impact on the airfoil aerodynamics caused by the sensitivity of the laminar bubble to angle of attack changes and variations in the flowfield environment. The work discussed in this paper represents a first step in determining what features and characteristics of the velocity distribution on an airfoil lead to desirable and predictable low Reynolds number airfoil performance.

CORRELATION OF THEORETICAL AND EXPERIMENTAL RESULTS

In order to gain insight into the types of velocity distributions well suited for airfoils operating at low Reynolds numbers, analysis results obtained using the Eppler and Somers computer code [10] have been correlated with wind tunnel results of Althaus [11]. While the details are reported fully in Ref. [12], some of the important observations of this comparison will be briefly recounted here.

Among the airfoils for which wind tunnel test results were considered, in addition to examples having no hysteresis in the lift and drag characteristics, there are sections demonstrating hysteresis at relatively high angles of attack as is normally associated with short bubble or leading edge stall, as well as examples exhibiting hysteresis in the middle angle of attack range with behavior similar to that normally associated with long bubble or thin airfoil stall. In the case of short bubble hysteresis, as represented in Fig. 1, a short laminar separation bubble is formed near the leading edge of the airfoil. As the angle of attack is increased, a point is reached for which the airfoil stalls either by a bursting of the leading edge bubble, or by a trailing edge stall in which the upper surface turbulent separation point moves sufficiently far upstream to stall the airfoil. As the angle of attack is decreased from that of stall, hysteresis is caused by the short bubble reattaching at an angle less than that which caused stall for increasing angles of attack. From the experimental results examined, this type of hysteresis largely disappears when the Reynolds number is increased to values greater than 200,000.

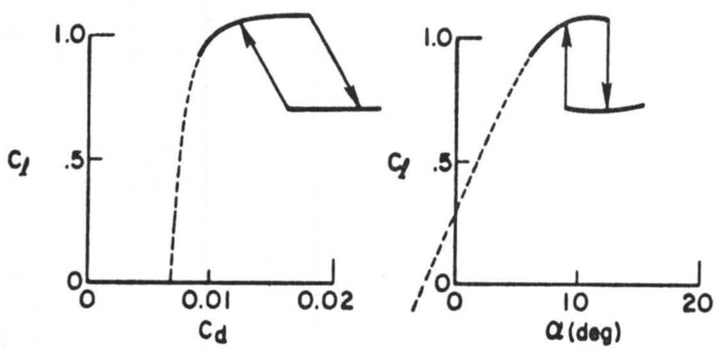


Fig. 1 Typical leading edge (short bubble) stall hysteresis.

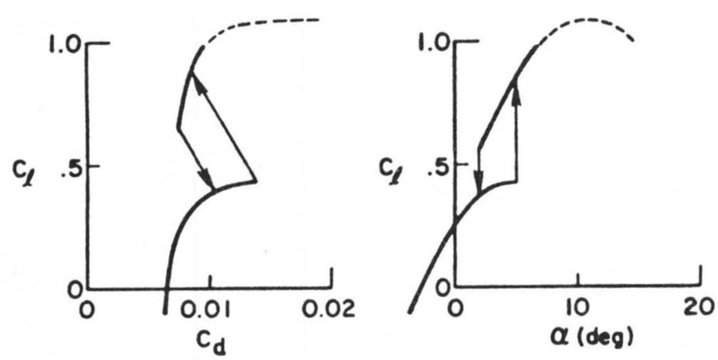


Fig. 2 Typical mid-polar (long bubble) hysteresis.

For the wind tunnel results considered, the long bubble type hysteresis, as depicted in Fig. 2, is confined to Reynolds numbers below 100,000. In this case, a laminar separation bubble is formed near the midchord and grows larger with increasing angles of attack. This causes the lift curve to flatten out and the drag to increase significantly until, at some point, the bubble collapses into a short bubble near the nose of the airfoil. Upon collapse of the bubble, the drag coefficient is decreased markedly and is accompanied by a jump in the lift coefficient. Upon decreasing the angle of attack, the reformation of the long bubble occurs at a lower angle of attack than that at which collapse occurred with increasing angles. Thus, airfoils exhibiting long-bubble type hysteresis tend to have a high drag knee which extends through the middle-range of the drag polar. It should be noted that a number of the airfoils considered display both long and short bubble hysteresis behavior.

To a large extent, the hysteresis effects caused by laminar separation bubbles can be eliminated by the use of artificial turbulation [1], [11]. As expected, however, because of the sensitivity of separation bubble behavior to flowfield variations, the design and placement of turbulators to achieve desired effects is extremely critical and benefits are confined to a relatively narrow range of operating conditions. Consequently, any performance gains achieved at one operating condition are largely offset by the drag increase which accompanies the use of turbulators away from the intended angle of attack and Reynolds number. For these reasons, the concentration of the effort discussed in this paper has been on the design of low Reynolds number airfoils which do not require the use of turbulators.

In attempting to predict the aerodynamic characteristics of airfoils at low Reynolds numbers, in its current form, the Eppler and Somers code is unable to fully account for the effects of laminar separation bubbles. In particular, the program execution is such that if laminar separation is predicted before an empirically developed transition criterion is satisfied, then an immediate transition is assumed and the calculations continue using a turbulent boundary layer model. While such treatment is reasonable for a short separation bubble which generally has little effect on the aerodynamic characteristics of an airfoil, this is not true in the case of a long separation bubble which can extend over most of the airfoil upper surface. This difficulty is addressed briefly by the code in that if a separation bubble is predicted to be longer than three percent of the chordlength, a warning is generated that the predicted sectional characteristics may not be indicative of the actual characteristics. As expected, this warning commonly appears for airfoils analyzed at low Reynolds numbers.

In spite of the limitations of the Eppler and Somers code regarding separation bubbles, through the experience of correlating predicted aerodynamic characteristics to those obtained experimentally, it can still be very useful for the design of low Reynolds number airfoils. Most simply, this usefulness is achieved by specifying velocity distributions which tend to suppress the formation of the long laminar separation bubbles which are not handled by the code. Because the short bubble type hysteresis generally occurs near the stalling angle of attack, its impact on aircraft flight mechanics can be eliminated simply by restricting the operation of the aircraft to angles of attack less than those for which stall hysteresis occurs. The erratic flight behavior which would be caused by the long bubble type hysteresis near the middle of the operational angle of attack range, as well as the degradation in aerodynamic performance, are both unacceptable. Thus, a primary goal in the design of airfoils for low Reynolds numbers is to prevent the formation of long separation bubbles.

In examining the potential flow velocity distributions of the airfoils considered, it is observed that airfoils demonstrating long bubble hysteresis are characterized by concave upper surface pressure recoveries. Airfoils not exhibiting long bubble hysteresis, on the other hand, are characterized by linear or convex upper surface recoveries. With a concave recovery, the flow separates upon entry into the adverse pressure gradient at the beginning of the recovery and, since the gradient is steep, reattachment is difficult and a long bubble forms. Increasing the angle of attack further aggravates the situation in that the bubble length steadily increases until the bubble eventually collapses. In the case of the convex recovery distribution, the pressure gradients are not as steep as those of the concave recovery and reattachment is not as difficult. As the angle of attack is increased, both the separation and reattachment points move forward toward the leading edge and, as the reattachment point moves forward at a slightly greater rate than does the separation point, the length of the bubble decreases. Thus, the bubble does not collapse in this case and hysteresis does not occur.

An additional observation resulting from the comparison of the computational and experimental results, which has also been noted by other researchers (Refs. [3] and [7]), is that the short bubble type hysteresis appears to be dependent on both the leading edge shape as well as the severity of the adverse pressure gradient on the upper surface following a pressure peak near the leading edge of an airfoil. Further, as has also been concluded by others and is discussed in Ref. [13], the agreement between predicted and experimental results is much better for airfoils in which steep adverse pressure gradients in the vicinity of the trailing edge, as caused by upper surface aft loading, are avoided.

Low Reynolds Number Airfoil Design Example

By making use of the observations noted in the preceding section to facilitate the specification of design velocity distributions, it is possible to design airfoils for use at low Reynolds numbers. In so doing, it is hoped that the actual performance of the airfoil is not significantly different from that predicted using the Eppler and Somers code. A number of airfoils designed in this manner, intended for use on radio-controlled model sailplanes, are presented in Refs. [12] and [14].

An example of an airfoil based on the observations noted is the

S2027, presented along with its calculated velocity distributions in Fig. 3. This section, which originally appeared in Ref. [14], is intended for the FAI/F3B model sailplane competition event. Although this event requires tasks in duration, distance, and speed, it is the speed task, along with the structural demands for a large thickness ratio to withstand the loads imposed by winch launching, which dictate the design requirements. Consequently, the design goal of the S2027 is to have low drag in the range of lift coefficients required for high speed, while still maintaining reasonable performance for duration and climb at moderate lift coefficients. The aerodynamic characteristics of this airfoil obtained using the analysis capability of the Eppler and Somers code are shown in Fig. 4. Theoretically, this design demonstrates a number of advantages over other sections commonly used for this event. More significantly, reports from users of the section indicate that its design goals have been met successfully.

APPLICATION OF FINITE TRAILING EDGE PRESSURE GRADIENTS

The potential flow velocity distribution for any airfoil having a non-zero trailing edge loading is characterized by the presence of unbounded normal and streamwise pressure gradients at the trailing edge. These singularities give rise to strong viscous-inviscid interactions which lead to the break-down of conventional boundary layer theory in the vicinity of the trailing edge. As fully discussed in Ref. [13], these interactions can cause the velocity distribution on an airfoil in the actual flow to differ significantly from that predicted by the potential flow methods often used in the design process.

By including the effects of normal pressure gradients in the vicinity of the trailing edge, wake thickness, and wake curvature, Melnik, et al. [15] have developed a boundary layer theory able to account for the strong viscous interactions due to the singularities in the inviscid flow solution. This fully self-consistent boundary layer theory has been incorporated into the viscous, compressible airfoil analysis code, GRUMFOIL [16]. As an alternative approach, a method is introduced in Ref. [13] for which the singularities at the trailing edge are eliminated. The resulting designs represent a class of airfoils for which the strong viscous-inviscid interactions in the vicinity of the trailing edge are minimized. For such airfoils, which have finite trailing edge pressure gradients, the potential flow design velocity distribution is in much better agreement with that developed in the real flow than is generally the case. In addition, conventional boundary layer theory is sufficient for predicting the viscous flow behavior of such airfoils. Perhaps of most importance, however, by forcing the trailing edge pressure gradients to be bounded, it is expected that the real flow will be able to pass off the airfoil and into the wake as smoothly as is possible. In so doing, not only are the critical pressure recoveries used in modern airfoil design more likely to be realized without unpredicted flow separations, but the possibility exists for some significant gains in airfoil performance.

As fully reported in Ref. [17], the design of airfoils having finite trailing edge pressure gradients can be accomplished using an

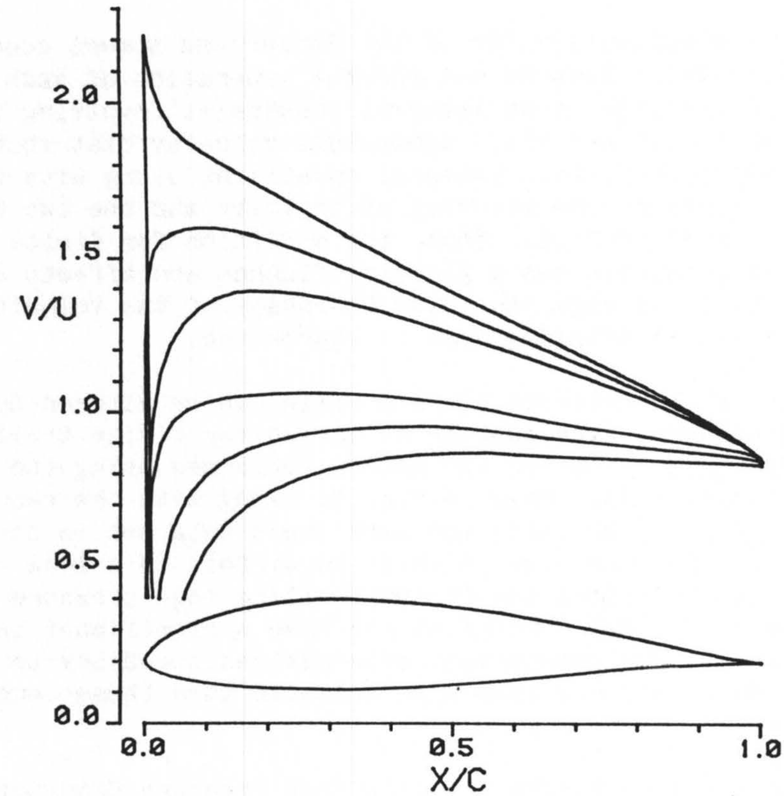


Fig. 3 The S2027 airfoil and calculated velocity distributions. Alpha = 4, 8 and 12 deg. relative to the zero-lift line.

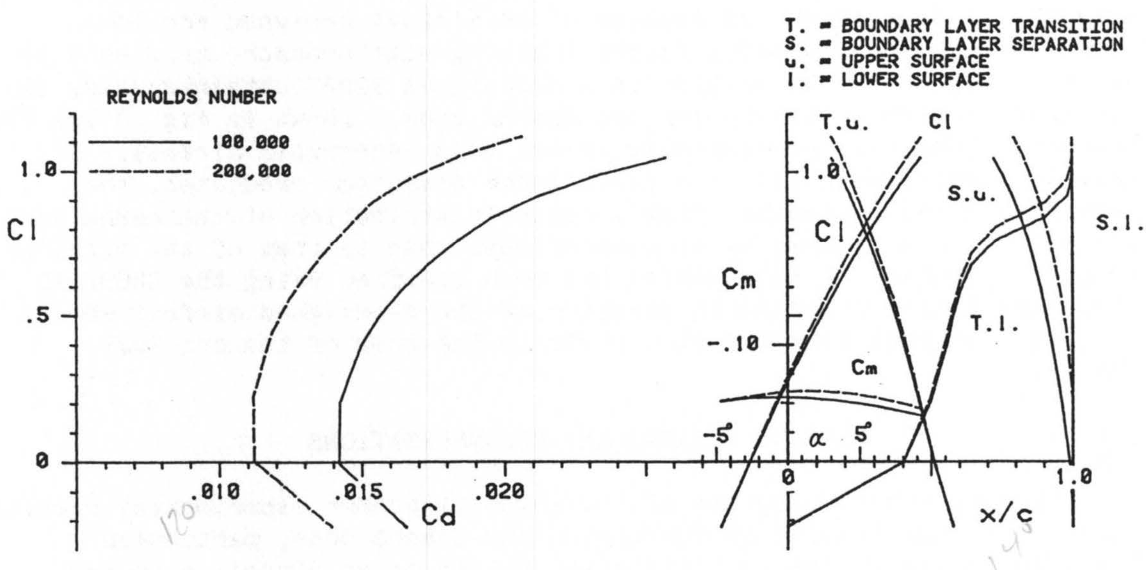


Fig. 4 Theoretical section characteristics for the S2027 airfoil obtained using the Eppler and Somers code.

appropriately modified version of the Eppler and Somers code. One of the conditions which must be met for the generation of such airfoils is manifested in the code as an integral constraint involving the velocity at each point on the airfoil. Admissible velocity distributions must simultaneously satisfy this integral constraint along with that which insures uniformity of the velocity at infinity and the two that guarantee a closed profile. Thus, the condition for finite trailing edge pressure gradients has a global influence and effects not only the flow at the trailing edge, but also the shape of the velocity distribution as the trailing edge is approached.

In order to demonstrate how a profile can be altered by the integral constraint which must be satisfied for finite trailing edge pressure gradients, consider the airfoil obtained using the unmodified Eppler and Somers code, shown in Fig. 5, along with the result, presented in Fig. 6, of using the same input data set in the modified code. Clearly, for the case in which an airfoil is a long way from satisfying the conditions for finite trailing edge pressure gradients, imposing the additional constraint can have a significant influence. In general, however, the geometrical alternations necessary to satisfy the additional constraint are much less dramatic then those demonstrated by this example.

Design Example Having Finite Trailing Edge Pressure Gradients

Because the influence of viscous effects on the flow over an airfoil become relatively more important as the Reynolds number is decreased, the use of finite trailing edge pressure gradients should be increasingly beneficial as the Reynolds number at which the airfoil operates is decreased. An example of an airfoil designed for low Reynolds numbers and having finite trailing edge pressure gradients is given in Fig. 7. This section is a redesigned S2027 obtained using the modified version of the Eppler and Somers code. Shown in Fig. 8 are the theoretical section characteristics for this redesigned airfoil. Of greater significance than the performance advantage predicted, the specified design potential flow velocity distribution of the redesigned airfoil is less altered by viscous effects than is that of the original section. Because of this, which has been verified using the GRUMFOIL code, the actual aerodynamic behavior of the redesigned airfoil should be closer to that expected than it is in the case of the original design.

CLOSING REMARKS AND RECOMMENDATIONS

Through the correlation of low Reynolds number experimental results with analytical results of the Eppler and Somers code, particular characteristics of the velocity distribution on an airfoil have been identified which lead to acceptable agreement between the actual and predicted aerodynamics. By specifying design velocity distributions which have these characteristics, it is hoped that airfoils for use at low Reynolds numbers can be developed whose actual performance and behavior is close to that anticipated. In addition, given the

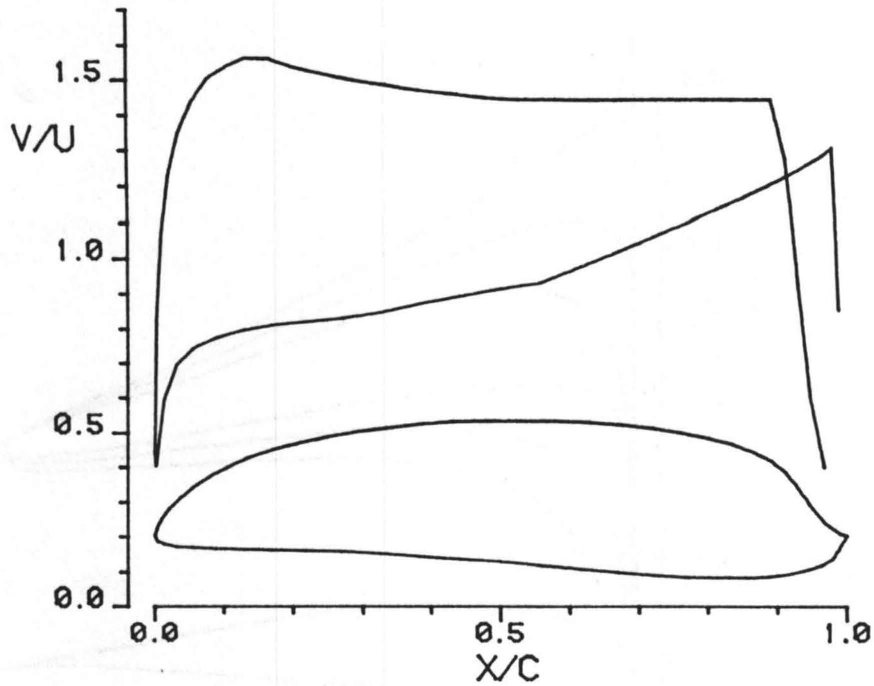


Fig. 5 Airfoil and velocity distribution obtained using the Eppler and Somers code. Alpha = 8 deg. relative to zero-lift line.

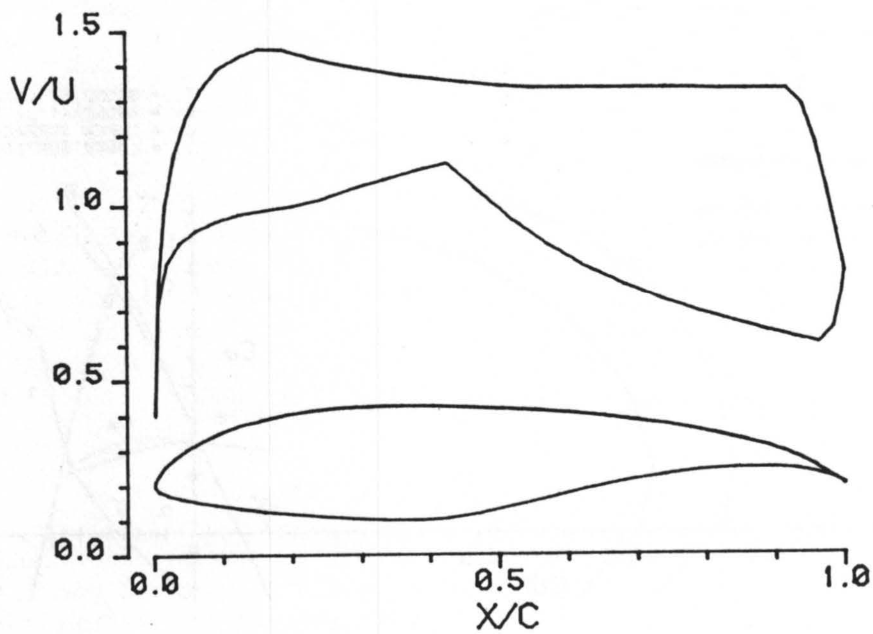


Fig. 6 Airfoil and velocity distribution obtained using the Eppler and Somers code modified to generate airfoils having finite trailing edge pressure gradients. Alpha = 8 deg. relative to the zero-lift line.

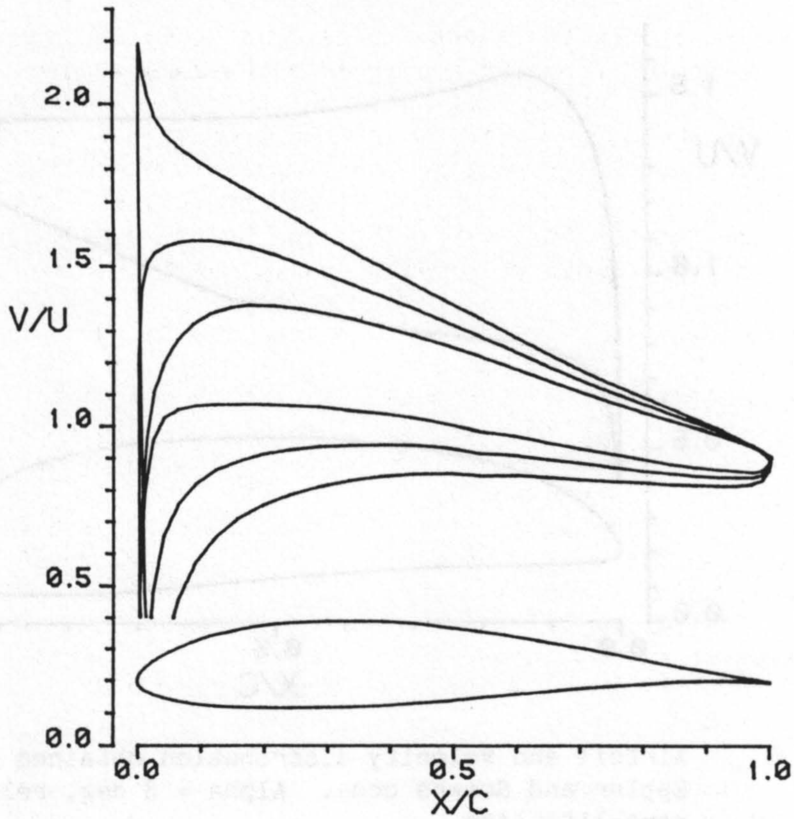


Fig. 7 The redesigned S2027 airfoil and calculated velocity distributions. Alpha = 4, 8 and 12 deg. relative to the zero-lift line.

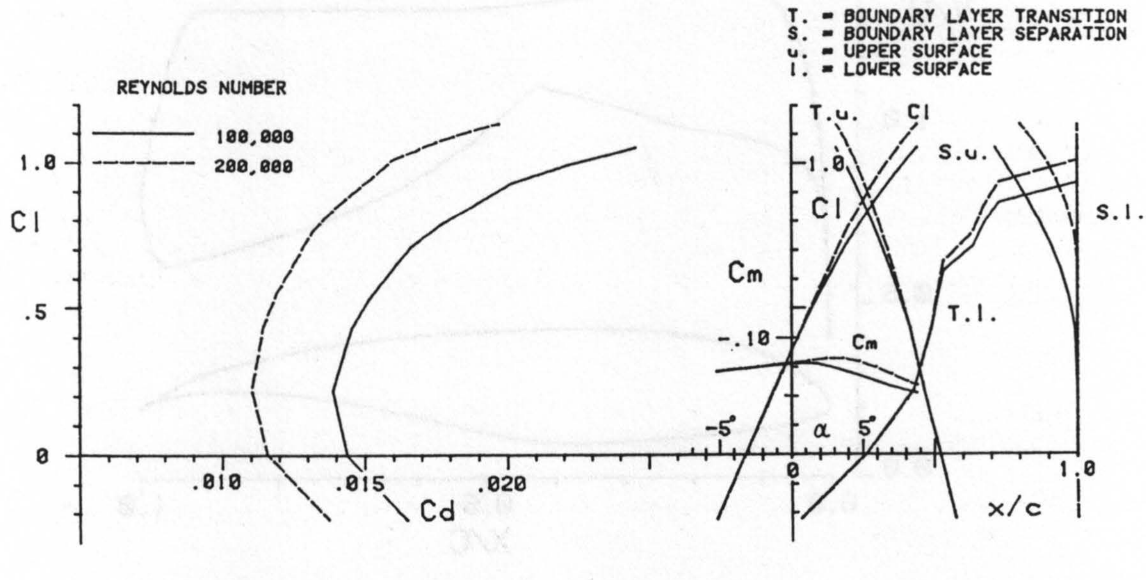


Fig. 8 Theoretical section characteristics for the redesigned S2027 obtained using the Eppler and Somers code.

significant influence of viscous effects on flows at low Reynolds numbers, the use of finite trailing edge pressure gradients can further increase the likelihood of obtaining the predicted aerodynamic behavior by minimizing the strong viscous interactions in the vicinity of the trailing edge. As a consequence, while more research is needed to experimentally verify that the benefits demonstrated computationally are possible, the use of finite trailing edge pressure gradients offers the potential for achieving some significant gains in airfoil performance.

A clear extension of the correlation between experimental and predicted low Reynolds number airfoil data would be the consideration of data from facilities other than that of the Laminar Wind Tunnel at Stuttgart [11]. The number of different airfoils which have been tested by the few facilities which have undertaken low Reynolds number testing is very limited. Consequently, both the empirical and purely analytical approaches to developing methods for predicting the aerodynamics of low Reynolds number airfoils could greatly benefit from additional experimental data. It is important that such results include the details of laminar separation bubble formation such as the locations of laminar separation and turbulent reattachment. In addition, it is important that the flow environment in which these data are taken is fully documented.

Until such a time that the flow over an airfoil at low Reynolds numbers can be adequately treated analytically, the design of airfoils for these flow conditions must be accomplished by means of empirical approaches such as that which has been described. In fact, even after rigorous analytical solutions are available for use in design, it is likely they will be costly and time consuming in terms of computer usage. Consequently, given the iterative nature of the design process, the speed and low cost of empirical approaches will justify their continued development and application for some time. Thus, in considering modifications to the Eppler and Somers code to make it more suitable for the analysis of low Reynolds number airfoils, it is likely that improvements could be gained by including a more detailed separation bubble calculation, such as those developed in Refs. [6]-[7], than is presently employed. Finally, due to the increased relative importance at low Reynolds number of viscous effects, the inclusion of displacement thickness-potential flow iteration might ultimately prove necessary.

REFERENCES

1. Carmichael, B. H., "Low Reynolds Number Airfoil Survey, Volume I," NASA CR-165803, Nov. 1981.

2. Lissaman, P.B.S., "Low-Reynolds-Number Airfoils," Annual Review of Fluid Mechanics, Vol. 15, 1983, pp. 223-239.

3. Ward, J. W., "The Behavior and Effects of Laminar Separation Bubbles on Aerofoils in Incompressible Flow," Journal of the Royal Aeronautical Society, Vol. 67, Dec. 1963, pp. 783-790.

4. Mueller, T. J., "The Influence of Laminar Separation and Transition on Low Reynolds Number Airfoil Hysteresis," AIAA Paper No. 84-1617, June 1984.

5. Mueller, T. J., Pohlen, L. J., Conigliaro, P. E. and Jansen, B. J., Jr., "The Influence of Free-Stream Disturbances on Low Reynolds Number Airfoil Experiments," Experiments in Fluids, Vol. 1, pp. 3-14, 1983.

6. Van Ingen, J. L., "On the Calculation of Laminar Separation Bubbles in Two-Dimensional Incompressible Flow," AGARD CP-168, 1975, pp. 1-16.

7. Roberts, W. B., "Calculation of Laminar Separation Bubbles and Their Effect on Airfoil Performance," AIAA Paper No. 79-0285, Jan. 1979.

8. Kothari, A. P. and Anderson, J. D., Jr., "Flows Over Low Reynolds Number Airfoils-Compressible Navier-Stokes Numerical Solutions," AIAA Paper No. 85-0107, Jan. 1985.

9. Cheng, H. K. and Lee, C. J., "Laminar Separation Studied as an Airfoil Problem," Third Symposium on Numerical and Physical Aspects of Aerodynamic Flows, Jan. 1985, pp. 39-61.

10. Eppler, R. and Somers, D. M., "A Computer Program for the Design and Analysis of Low-Speed Airfoils," NASA TM 80210, August 1980.

11. Althaus, D., Profilpolaren fur den Modellflug, Neckar-Verlag Vs-Villingen, 1980.

12. Selig, M. S., "The Design of Airfoils at Low Reynolds Numbers," AIAA Paper No. 85-0074, Jan. 1985.

13. Ormsbee, A. I. and Maughmer, M. D., "A Class of Airfoils Having Finite Trailing Edge Pressure Gradients," AIAA Paper No. 85-0206, Jan. 1985.

14. Selig, M. S., "The Design of Airfoils at Low Reynolds Numbers," Soartech 3, July 1984 (available c/o H. A. Stokely, 1504 Horseshoe Circle, Virginia Beach, VA, 23451).

15. Melnik, R. E., Chow, R. R., Mead, H. R. and Jameson, A., "An Improved Viscid/Inviscid Interaction Procedure for Transonic Flow Over Airfoils," Grumman Aerospace Corporation, Report RE-682, March 1984.

16. Mead, H. R. and Melnik, R. E., "GRUMFOIL - A Computer Code for the Viscous Transonic Flow Over Airfoils," Grumman Aerospace Corporation, Report RE-681, March 1984.

17. Ormsbee, A. I. and Maughmer, M. D., "Trailing Edge Flow Conditions as a Factor in Airfoil Design," University of Illinois Technical Report AAE 84-1, UILU-ENG 84 0501, Jan. 1984.