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THE FURTHER DEVELOPMENT OF CIRCULATION CONTROL AIRFOILS

N. J. Wood
Stanford University

INTRODUCTION

During the last decade a significant amount of information has been obtained from wind tunnel tests, full scale experiments and numerical analysis regarding the factors which affect the performance of circulation control airfoils. The design of the present family of airfoils being applied to stopped rotor vehicles is predominantly a legacy of the early experiments where elliptic sections were used to facilitate the transformation for inviscid pressure distribution calculations. Whilst elliptic sections have many interesting mathematical properties it remains to be shown whether they are aerodynamically the optimum shape for circulation control. It is important to recognize that aerodynamic efficiency should take precedence over design simplicity in this instance.

The recent paper by Wood and Nielsen[1985] has summarised the global performance characteristics of two-dimensional circulation control airfoils including the effects of Reynolds number, Mach number, angle of attack, etc.. This improved understanding, coupled with the observations of some less successful experiments, should permit the isolation of design guidelines to satisfy the requirement for improved airfoil performance. Perhaps the most notable reason for the lack of second generation airfoils is the absence of a reliable analytical code which would allow the effects of variations in geometry to be examined. Apparently, the development of the analytical procedures is progressing to a point where the timing is appropriate to begin a more thorough examination of the design concepts of circulation control airfoils.

This paper will review the performance trends of circulation control airfoils and make observations as to where improvements in performance and expansion of the flight envelope may be feasible. A new analytically defined family of airfoils will be suggested, all of which maintain the fore and aft symmetry required for stopped rotor application. It is important to recognize that any improvements in section capabilities may not be totally applicable to the present vehicle operation. It remains for the designers of the rotor system to reappraise the three-dimensional operating environment in view of the different airfoil operating characteristics and for the airfoil definitions to be flexible while maintaining satisfactory levels of performance.

PERFORMANCE REVIEW

Figure 1 illustrates the performance trends of a typical circulation control airfoil for a fixed free stream Mach number. With regard to a discussion of future developments, it is of interest to observe the limitations to performance with respect to the lift coefficient. The most obvious of these limitations is of course the stall points, both alpha stall and jet stall. The alpha stall has been identified as a consequence of small separation bubbles at the leading edge of the airfoil which result from the ever increasing pressure gradients imposed by the increasing circulation. For thin airfoils, this phenomenon may occur at negative angles of attack. The jet stall remains an unidentified phenomenon although some correlation with the occurrence of C_p^* has been previously observed. The precursor to the alpha stall is a progressively reducing lift augmentation with increasing angle of attack, resulting from the increasing boundary layer thickness approaching the slot. Indeed, the thickness of the boundary layer approaching the slot has been identified as the prime factor in most performance effects, Mach number, Reynolds number and the effects of airfoil thickness and camber. The effect of increasing Mach number on lift generation is shown as figure 2 for a typical airfoil in the absence of leading edge separation. A further reduction in lift augmentation is observed if shocks exist on the upper surface of the airfoil. This again corresponds to the increased boundary layer thickness which results from the shock/boundary layer interaction. Experiments have also indicated two further performance limitations exhibited by thick, highly cambered airfoils and by airfoils with curvature discontinuities on the Coanda surface. For the first case, the boundary layer prematurely detaches from the upper surface just ahead of the slot causing a massive reduction in lift augmentation. The situation may in some cases be overcome by sufficiently high blowing momentum. For the second case, a feature labelled 'premature jet detachment' was observed. This phenomenon exhibits usual lift augmentation up to a point, whereupon the lift coefficient attains a constant value independent of increasing blowing momentum. The jet has separated from the Coanda surface at the point of discontinuity and is now acting like a jet flap. Figure 3 illustrates the characteristics of these two phenomena.

This raises two highly important, although seldom recognised, performance limitations. First the ability to simply modify a current airfoil to obtain a different slot location. Second, the discontinuities in surface curvature which result from the present techniques for Coanda surface definition and the blending of those surfaces into the elliptic profile.

AREAS FOR AIRFOIL MODIFICATION

It has become apparent that there are two mechanisms whereby the characteristics of circulation control airfoils may be improved. First, the geometrical definition of the airfoils could be modified such that arbitrary slot locations may be chosen and that all surfaces would have smooth and continuous second derivatives. This would certainly allow a more thorough appraisal of such important parameters as slot location, assuming of course that a reliable code becomes available or some controlled experiments are performed. Second, the basic form of the airfoils' thickness distribution should be modified in order to delay the growth or separation of the upper surface boundary layer. In this way, airfoils could be designed to avoid or delay alpha stall, Mach number effects and even may be able to successfully include high degrees of camber at high speeds. The assumption is that modification of the thickness distribution may delay the occurrence of these performance limiting effects. Thus the primary objectives for this research are twofold:

1. To simplify and improve the geometrical definition of circulation control airfoils.

2. To delay the thickening of the upper surface boundary layer by modification of the thickness distribution of the airfoil.

This should yield airfoils which exhibit linear performance characteristics over a wider performance envelope.

The simplest mechanism to improve the overall performance of circulation control airfoils would, of course, be to improve the attainable lift augmentation level. Unfortunately, this parameter appears to be closely linked to the Coanda geometry, the slot height and the slot position in such a manner that precludes a simple redefinition. The present work will be confined to observing that the Coanda surface be smooth and free of discontinuities and that the radii of curvature be of similar magnitude to the present configurations.. It is expected that further improvements in performance be achieved by the optimization of the Coanda geometry alone, a task for the new analytical codes.

Two areas where benefits of a new design procedure may be accrued are the tip and root sections for stopped rotor application. Thick, non-elliptic sections may be designed specifically to fair over the large blade attachment points while maintaining satisfactory lift and drag characteristics. At the tip, drag rise might be relieved by the use of quasi-supercritical circulation control sections and the balancing of rolling moments to remove the need for collective pitch may be possible by the incorporation of different blade camber distributions. Those distributions made possible by the freedom of the new airfoil design scheme.

A NEW GEOMETRIC DEFINITION

It is desirable to define the airfoil coordinates numerically such that perturbations of the shape may be simply evaluated. A formulation was chosen that maintained the second derivative smooth and continuous at all points on the surface. The basic planform was defined as a function of the leading/trailing edge radius R, the airfoil mid-chord thickness T, and the degree of mid-chord camber S. To provide further flexibility on the definition of the camber line, two eccentricity parameters are defined, one for the upper surface, E_1, one for the lower surface, E_2. These provide the capability for accurate contouring of the local surface curvature such that fine control of the pressure distribution and smoothing of the pressure peaks is available. The requirement for fore and aft symmetry is observed by establishing that the slope be zero at the mid-chord and that the curvature be continuous. The final form of the surface definition is:

$$y_{upper} = R.F(x) + (T/2 + S).G(X) + E_1.H(x) \quad [1]$$

$$y_{lower} = -R.F(x) - (T/2 - S).G(x) - E_2.H(x)$$

where F(x), G(x) and H(x) are functions of the chordwise coordinate.

It must be clearly stated that no attempt is being made to define optimized or improved Coanda profiles by the proposed functions. The fact that these profiles are smooth in the second derivative suggests that they should operate at least as efficiently as other previously tested shapes.

The eccentricities E_1 and E_2 are extremely powerful tools in the development of new airfoil contours. They can be used to control the shape of the camber line and as such can permit higher degrees of mid-chord camber before the onset of severe adverse pressure gradients in the region ahead of the slot. In essence, they may be used to spread the load over more of the airfoil chord and can be used to dissipate highly loaded areas. Some examples of the airfoils shapes that can be defined are shown in figure 4. Note that sections bearing a strong similarity to ellipses may be produced by the new geometric definition. Therefore any advantages of those sections may still be available to the new definitions.

The definition of the internal geometry and the placement of the slot exit is extremely simple with the new airfoil definition. Referring to figure 5, one must simply define the slot location x_s, the slot height h, and the slot lip thickness ℓ, At a second chordwise location x_1, the plenum height p, and the skin thickness δ are also defined to provide a solution for the geometric equations. If the lower surface geometry is maintained then a smooth blend of the internal surfaces occurs at the trailing edge point. The prescribed slot location gives $F(x_s)$,$G(x_s)$ and $H(x_s)$ which will be annotated as F_s, G_s and H_s. Similarly for F_1, G_1 and H_1. Assume that we need perturbations of the thickness, camber and upper surface eccentricities T', S' and E_1', and also note that to maintain the lower surface

$$(T/2 - S) = (T'/2 - S') \quad [2]$$

Let

$$\begin{aligned} \delta S &= S - S' \\ \delta T &= T - T' \\ \delta E_1 &= E_1 - E_1' \end{aligned} \quad [3]$$

The surface equations,[1] may now be solved for the three unknowns to give

$$\delta T = \frac{(A - B.H_1/H_s)}{(G_1 - G_s.H_1/H_s)}$$

$$\delta E_1 = \frac{B - \delta T.G_s}{H_s}$$

$$\delta S = \delta T/2$$

where for the slot lip

$$A = \delta \qquad B = \ell$$

and for the internal Coanda surface

$$A = \delta + p \qquad B = h + \ell$$

Some examples of the possible internal geometry for two different slot locations are shown in figure 6. This could of course be extended to include any number of slots, in any orientation while still preserving smoothness and continuity of the second derivative.

PERFORMANCE EVALUATION OF THE NEW AIRFOILS

At present a small number of airfoils defined by the new technique have been evaluated using an inviscid code (FLO6). A technique of rotating the airfoil about a predetermined point at the trailing edge, with a corresponding rotation of the free stream direction, 'fools' the code into injecting circulation at constant angle of attack. This requires no modification of the code to enable high lift cases to be examined without a wall jet code. This is justified since the match between experimental and inviscid analytical pressure distributions has been well documented. A further step has been to calculate the boundary layer growth on the upper surface of the test airfoils presently using a simple incompressible boundary layer code. Two airfoils have been compared, the first a thick, cambered ellipse., the second an airfoil similar to (b) in figure 4. Both airfoils produced similar lift coefficients at zero angle of attack without added circulation, but the second (new) airfoil has a distinctly different pressure distribution, figure 7. The comparable boundary layer growths are shown in figure 8. From the previous discussion of the performance characteristics, one would anticipate the new airfoil to exhibit a high augmentation over a wider range of operational parameters, α, M_∞, Re.

A simple optimization technique is proposed based on the evaluation of the partial derivatives of five airfoil properties with respect to the five airfoil definition parameters. The airfoil properties are

1. The boundary layer thickness ahead of the slot exit.

2. The maximum shape factor on the upper and lower surfaces.

3. The minimum pressure on the airfoil.

4 The lift increment.

Thus for any airfoil at any condition, the partials may be evaluated and a required ΔC_ℓ used to solve for the perturbations of the airfoil parameters. The choice of the five properties has some inherent characteristics. The maximum shape factors on the surfaces will avoid separation of the flow at any point ahead of the slot. The boundary layer thickness ahead of the slot will preserve a high level of lift augmentation. The maintenance of the minimum pressure on the airfoil should avoid jet stall conditions and the lift increment assures a net positive lift. This technique is yet to be fully implemented for a practical operational case.

Naturally the true test of the characteristics of the proposed airfoils will be evaluation by one or other of the full numerical codes which include wall jet modelling. At present no code is thought to be sufficiently robust or reliable to implement this phase in a more than exploratory manner.

CONCLUSIONS

A new analytical definition has been proposed for the design of circulation control airfoils. The scheme should greatly simplify the fairing in and contouring of the slot location, the Coanda surface and the internal geometry. The five parameter definition allows fine control of the thickness and camber distributions which in turn should be beneficial in maintaining satisfactory boundary layer growth over a wide range of operational conditions. The eccentricities applied to both the upper and lower surfaces should also allow dissipation of any peak loadings, thereby avoiding shocks and separations. The geometry also maintains a smooth and continuous second derivative which has been shown to be important.

The proposed analytical definition is very suitable for inclusion in two-dimensional optimization schemes once a suitable code has been made available. The freedom of the airfoil parameters to be varied and yet still produce acceptable circulation control contours should be a significant advantage. This freedom of design should also be of great importance in the further optimization of the blade geometry for vehicle performance improvement.

REFERENCES

Wood, Norman J.; and Nielsen, Jack N: Circulation Control Airfoils - Past, Present, Future. AIAA paper 85-0204, 1985.

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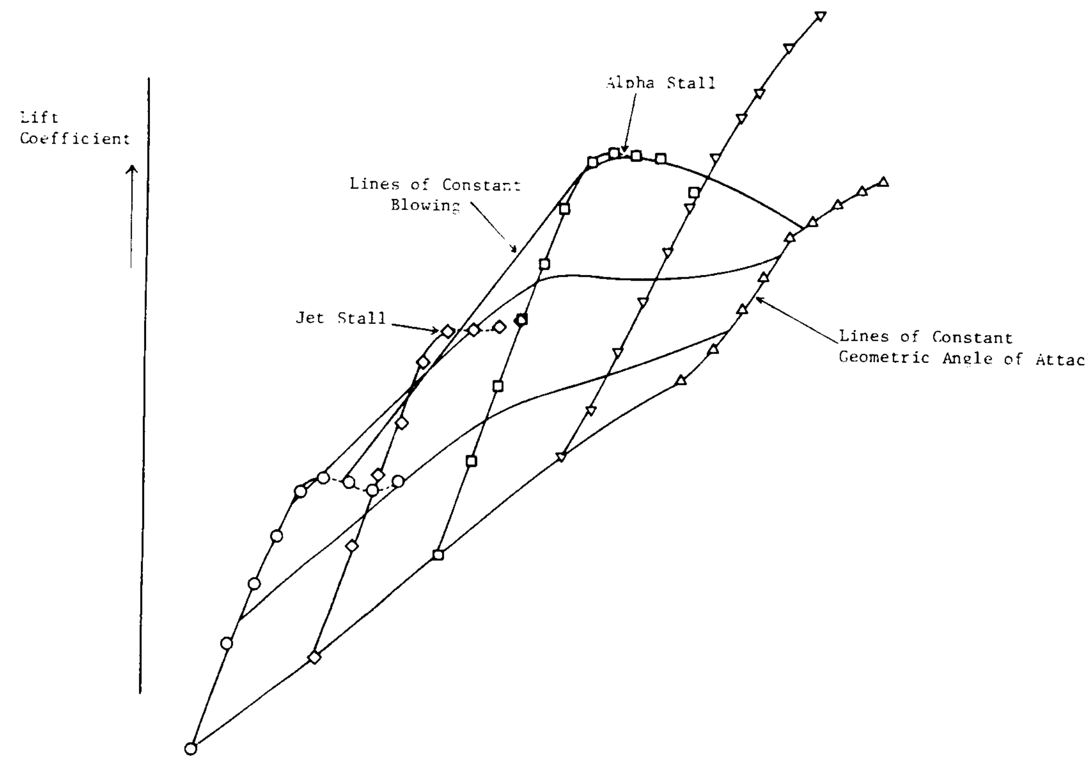


Figure 1.-Typical performance trends of a circulation control airfoil.

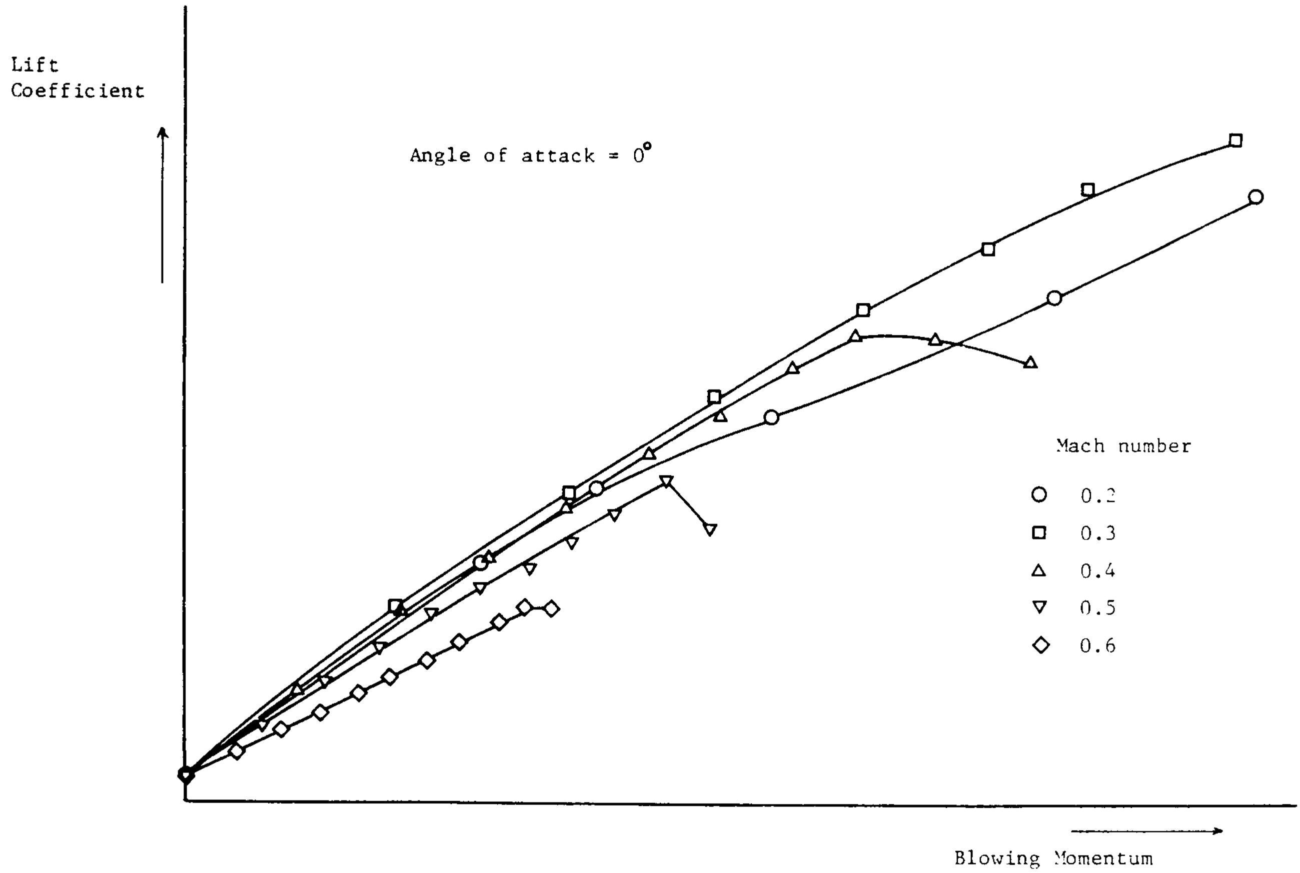
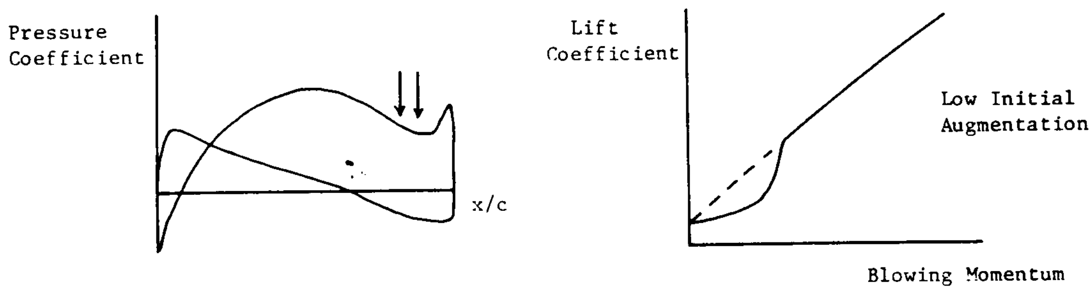
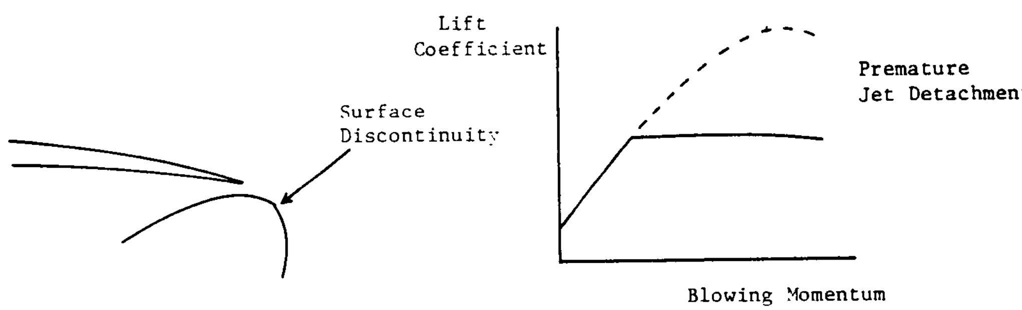


Figure 2.-Effects of Mach number on lifting performance.



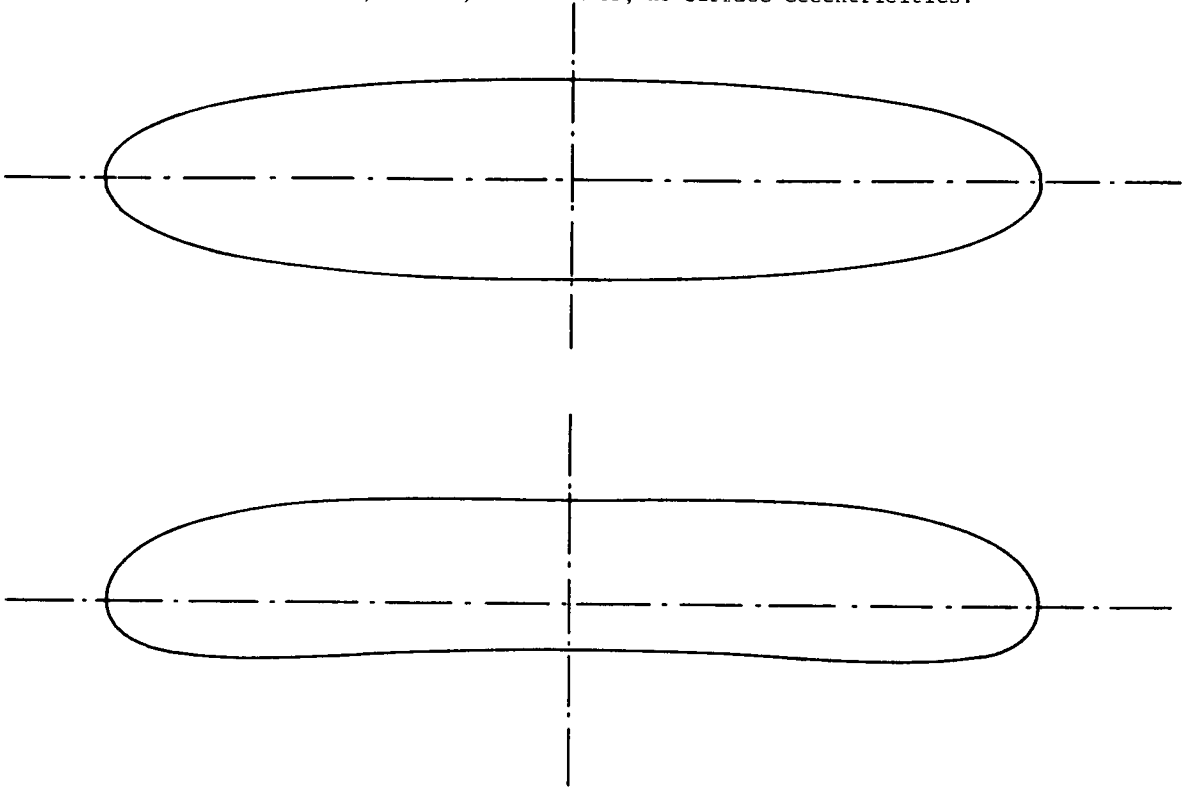
Effects of Aft Adverse Pressure Gradients



Effect of Coanda Surface Discontinuity

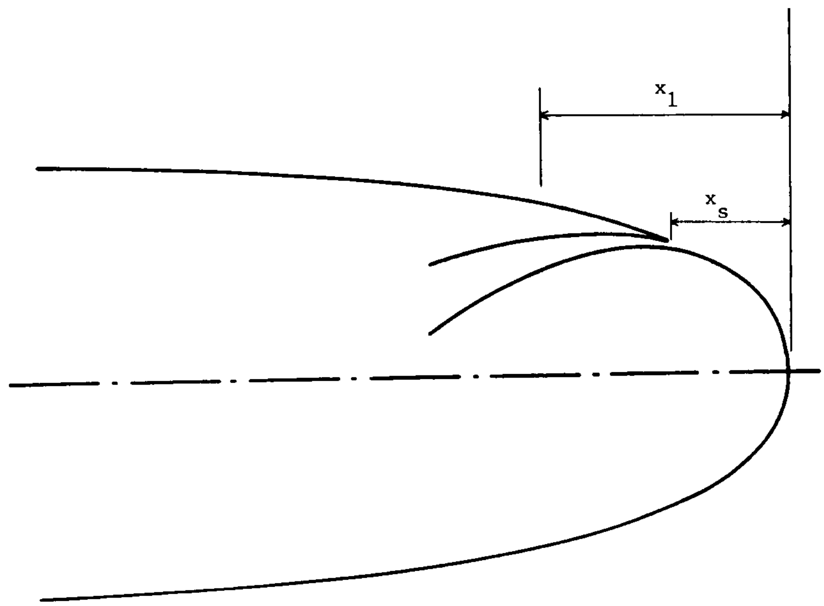
Figure 3.-Effects of surface discontinuities.

(a) T = 20%, R = 4%, zero camber, no surface eccentricities.



(b) T = 15%, R = 3%, 3% camber, 5% upper surface eccentricity

Figure 4.-Examples of new airfoil definitions.



At x_s : h = slot height

ℓ = lip thickness

At x_1 : δ = plenum gap

p = lip thickness

Figure 5.-Notation for internal geometry definition.

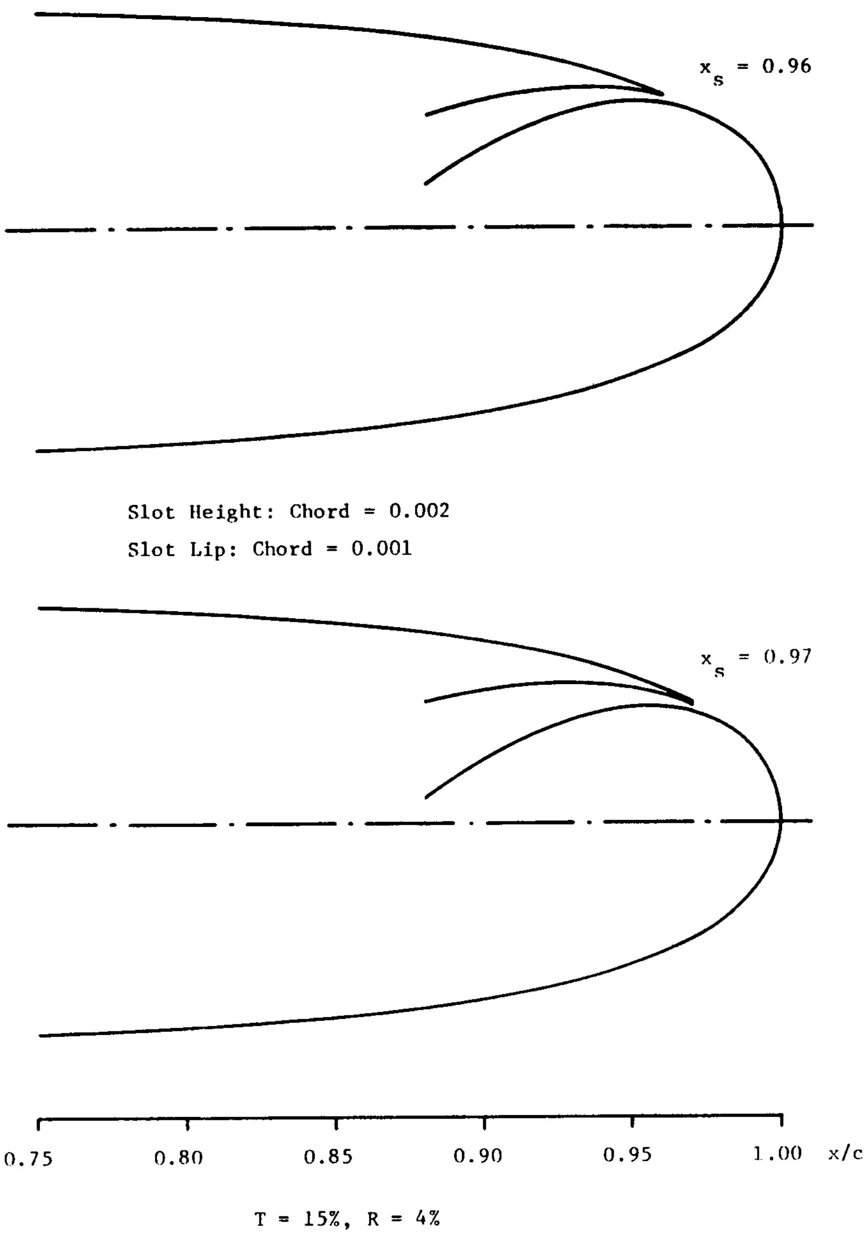


Figure 6.-Examples of internal geometry for different slot locations.

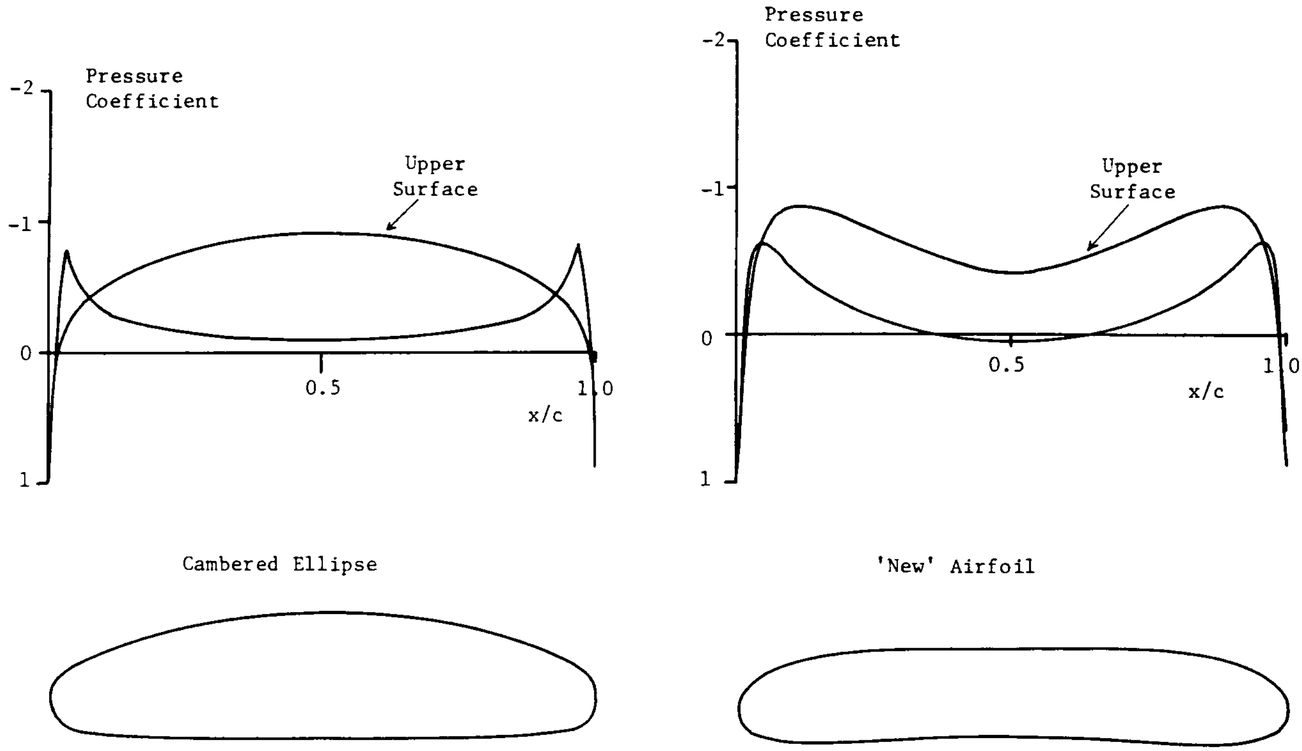


Figure 7.-Two different pressure distributions.

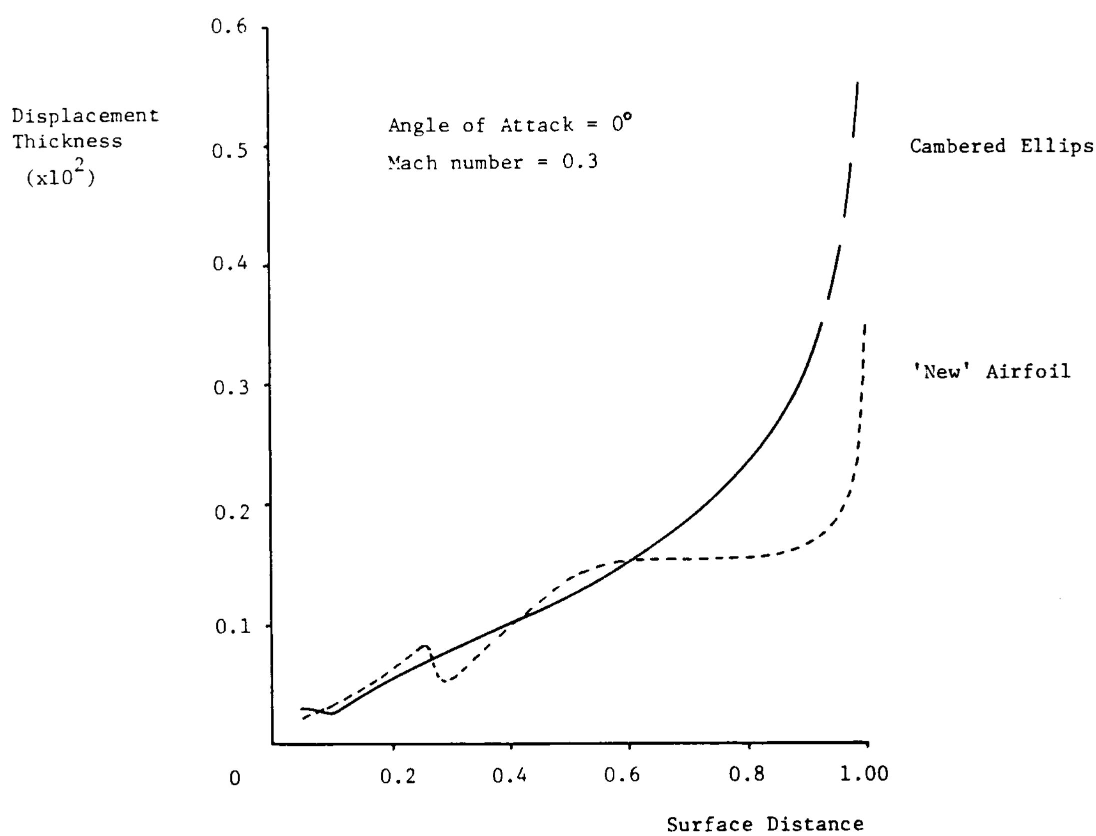


Figure 8.-Effects of pressure distributions upon boundary layer growth.