Wing Design with Attainable Leading-Edge Thrust Considerations

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This paper presents a brief description of a means of introducing consideration of attainable leading-edge thrust estimated by empirical methods into the design of wings capable of high aerodynamic efficiency at subsonic or supersonic speeds. The relatively mild camber surfaces called for when leading-edge thrust forces are appreciable offer advantages in structural simplicity and in aerodynamic performance at off-design flight conditions. Inclusion of attainable thrust considerations in the linearized theory design process necessitates the use of optimization techniques based on candidate surfaces rather than the more usual candidate wing loading distributions. This causes some computational complexities, but also introduces compensating advantages. One of these is the ability to restrict the extent of candidate surfaces on the wing planform for special problems such as the design of mission adaptive surfaces or selection of flap systems. The validity of the design method is illustrated in comparisons of the results given by the present method for zero thrust cases with results given by other design methods. The new design capabilities offered by the computer program are discussed, and examples of program application to representative problems are given.

Nomenclature

A_{le} = weighting factor for leading-edge modification surface
AR = wing aspect ratio, b^2/s
b = wing span
C_D = drag coefficient
$C_{D,0}$ = drag coefficient at zero lift for a flat wing
ΔC_D = drag coefficient due to lift, $C_D - C_{D,0}$
C_L = lift coefficient
$C_{L,\text{cru}}$ = cruise lift coefficient
$C_{L,\text{des}}$ = design lift coefficient
$C_{L,\alpha}$ = lift curve slope
ΔC_p = loading coefficient, difference in pressure coefficient across the lifting surface
c = local wing chord
c_r = wing root chord
M = Mach number
R = Reynolds number
r = wing section leading-edge radius
S = wing reference area
S_s = suction parameter, $\dfrac{C_L \tan(C_L/C_{L,\alpha}) - \Delta C_D}{C_L \tan(C_L/C_{L,\alpha}) - C_L^2/\pi AR}$
t = wing-section maximum thickness
x, y, z = Cartesian coordinates
x' = distance in the x direction measured from the wing leading edge
z_{le} = wing leading-edge z coordinate
z_{te} = wing trailing-edge z coordinate
α = angle of attack
α_{des} = design angle of attack, angle of attack corresponding to the design lift coefficient
$\Delta\alpha_{ft}$ = range of wing angle of attack for full theoretical leading-edge thrust for a specified wing spanwise station
α_{zt} = wing angle of attack giving a local theoretical leading-edge thrust of zero for a specified wing spanwise station

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Introduction

WINGS that achieve leading-edge thrust approaching linearized theory theoretical values can produce high levels of aerodynamic efficiency without resort to twist or camber. Conversely, wings that employ well-designed distributions of twist and camber can produce comparable performance levels without the need for leading-edge thrust. In effect, a distributed thrust-producing force over much of the forward portion of the wing airfoil is substituted for a concentrated force in the immediate vicinity of the leading edge. Because full theoretical leading-edge thrust is seldom achieved and the amount actually attainable is difficult to predict, it has become common practice to design wings with twist and camber distributions that do not require any leading-edge thrust. In this approach, the twist and camber are tailored to a specific design point and, of course, at off-design points will give less than optimum performance. Performance gains resulting from appreciable levels of actual leading-edge thrust, on the other hand, are not nearly as sensitive to flight conditions. Thus, it would be desirable to include attainable leading-edge thrust considerations in the design process so as to strike a balance between performance gains associated with twist and camber and those attributable to attainable thrust, and in the process obtain a wing with a more moderate camber surface.

In Ref. 1, a study of the factors that place limits on the theoretical leading-edge thrust was made, and an empirical method for estimation of attainable leading-edge thrust was developed. This established the groundwork for development of the linearized theory wing design computer program including attainable thrust considerations which is presented in Ref. 2. The program provides an analysis as well as a design capability and is applicable to both subsonic and supersonic speeds. It is, however, subject to the usual limitations on the applicability of linearized theory methods. For instance, it is not a transonic code, and it may have deficiencies at high lift coefficients and for severe camber surfaces.

Consideration of attainable thrust necessitated a design approach based on an optimum combination of candidate surfaces rather than an optimum combination of candidate loadings, which had been used in the past. Because a large number of candidate surfaces are required, the process is more expensive than candidate loading design methods. There are, however, some additional advantages that result from the use of surfaces. One of these is the ability to restrict the areas over which candidate surfaces apply to permit the design of mission adaptive surfaces at conditions differing from those of the design point camber surface. The same approach also provides information that aids in the selection of flap systems for further analysis by use of the computer program described in Ref. 3.

This paper presents a brief description of the design process, with particular emphasis on the effect of attainable thrust. The validity of the design method is illustrated in comparisons of results given by the present method for zero thrust cases with results given by other design methods. The new design capabilities afforded by the computer program are discussed and an example of a special design application for mission adaptive surfaces is given.

Discussion

The discussion will begin with a brief description of numerical methods used in the evaluation of the aerodynamic characteristics of candidate surfaces. This will be followed by a description of the steps used in the selection of an optimum combination of candidate surfaces, and the way in which attainable thrust affects the design. Finally, examples of the application of the program to the design of wing surfaces for subsonic and supersonic cruise and the redesign of a mission adaptive surface for a subsonic maneuver condition will be given.

Outline of Evaluation Methods

The aerodynamic evaluation techniques employed in the wing design computer program of Ref. 2 are basically the subsonic method described in Ref. 4 and the supersonic method described in Ref. 5. The grid and wing element systems used for both subsonic and supersonic analysis of candidate surfaces are shown in Fig. 1. Both solutions employ a rectangular grid system. The primary difference is that the wing is represented by a relatively small number of swept elements for the subsonic analysis and by a large number of unswept elements for supersonic analysis. The regularity of the supersonic element pattern stems from the need to avoid the coincidence of Mach line singularities and element control points. Because of the poorer representation of the wing planform, particularly at the leading edge, a larger number of elements must be used.

Some of the key features of the evaluation methods are listed in Fig. 2. In the subsonic solution an iterative process is used to define element pressure loadings which, within a specified accuracy, produce flow tangency conditions at each of the element control points. For the supersonic solution, the Mach line limit to disturbance propagation and the chosen grid element system make an iterative solution unnecessary. In both cases, the marching process goes from inboard to outboard wing positions and from front to rear as indicated by the arrows. Another significant feature is a strategy which allows chordwise loading distributions to be separated into components with and without a leading-edge singularity. This allows for more accurate evaluation of wing forces by matching numerical integration techniques to the special character of each component. The separation process, which is described in some detail in Ref. 4, is dependent on the angle of attack for zero thrust (to be discussed later). The estimation of attainable thrust is based on methods introduced in Ref. 1 and further developed in Ref. 4. For this purpose, a combination of theoretical and empirical analysis is used to calculate at-

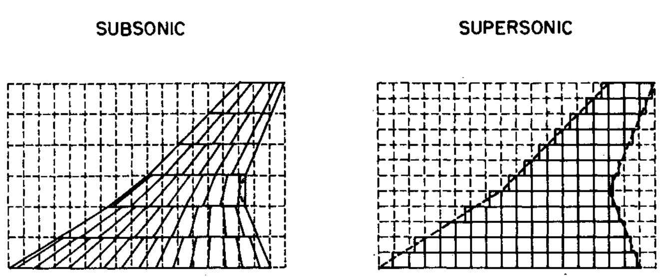

Fig. 1 Grid and element systems used in evaluation methods.

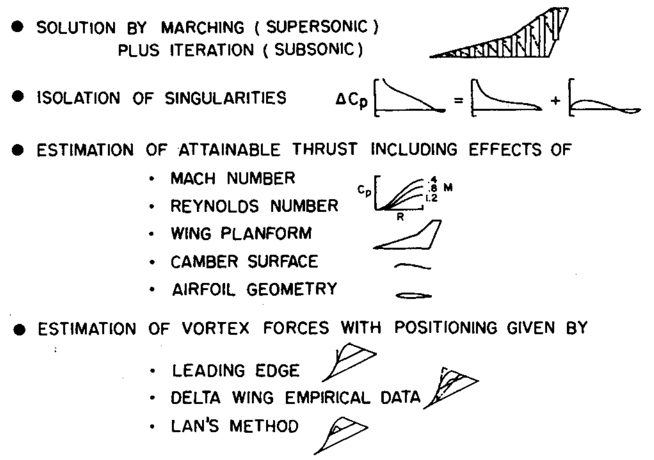

Fig. 2 Features of wing evaluation method.

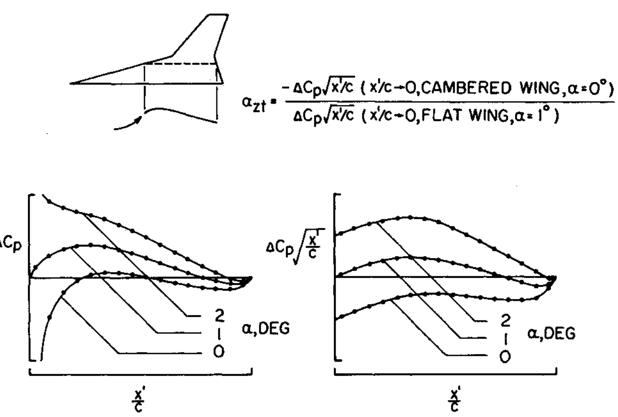

Fig. 3 Definition of angle of attack for zero thrust.

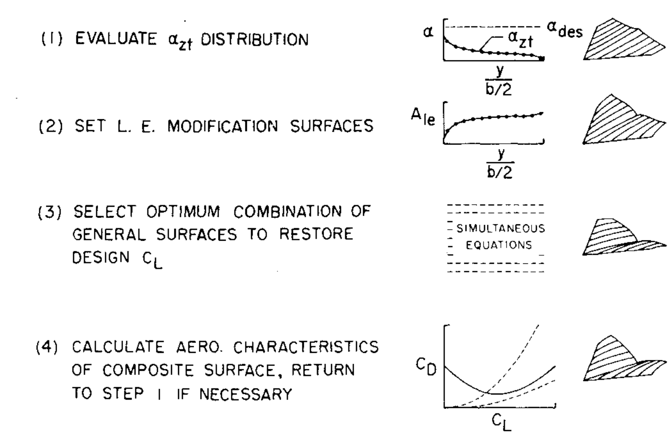

Fig. 4 Steps in wing design process. Sharp leading-edge wing example.

tainable leading-edge thrust with each of the listed factors being taken into account. The program user is offered a choice of three options for estimation of the forces induced by a separated leading-edge vortex that forms when full thrust cannot be achieved. These options differ primarily in the means used to locate the induced vortex pressure field.

A means of defining the previously mentioned angle of attack for zero thrust may be described with the aid of Fig. 3. This parameter is valuable for its use in integration routines and, as will be seen later, is an essential feature of the design process. Shown at the left side of the figure are loading distributions of the mid-semispan of a twisted and cambered wing for three angles of attack. At the right side of the figure, these same loading distributions are given in terms of the leading-edge singularity parameter. The limiting value of the parameter as x'/c approaches zero is a measure of the strength of the leading-edge singularity and of the theoretical leading-edge thrust. For this example, ΔC_p and the singularity parameter at the leading edge are zero at $\alpha = 1$ deg. Thus, for this wing, the angle of attack for zero thrust at the semispan station shown is 1 deg. A general expression that defines the angle of attack for zero thrust is given at the top of the figure. The disappearance of the leading-edge singularity when the wing angle of attack equals the local angle of attack for zero thrust indicates a local leading-edge condition in which the flow just ahead of the leading edge is tangent to the wing surface just behind the leading edge.

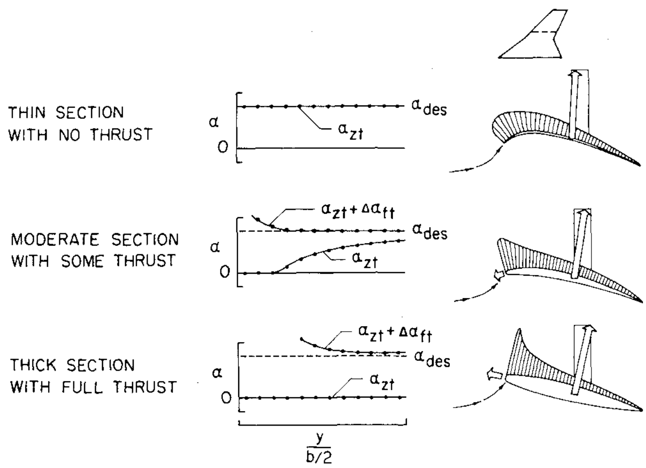

Fig. 5 Effect of attainable thrust on design surface.

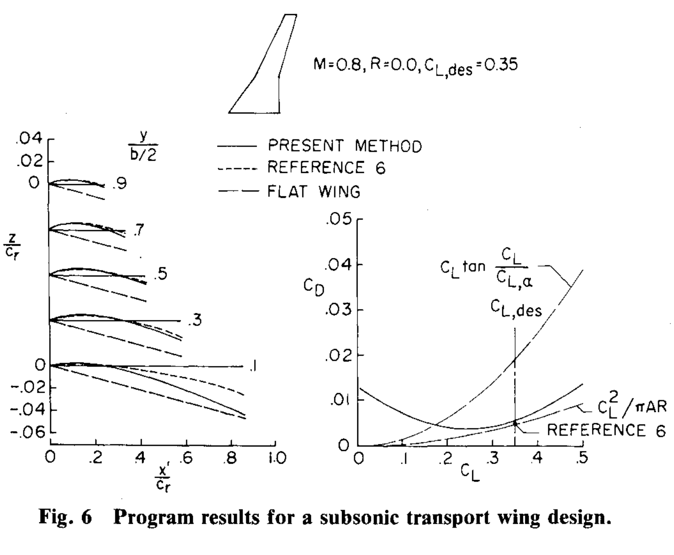

Fig. 6 Program results for a subsonic transport wing design.

Description of Wing Design Process

The steps in the wing design process as implemented in the computer program are outlined in Fig. 4. For simplicity, an example for a sharp leading-edge wing which can not achieve any of the theoretical leading-edge thrust is shown. The effect of attainable thrust on the design will be shown later. The program defines the camber surface by an iterative process which cycles through the four listed steps as often as is necessary to obtain convergence.

In the first step, the spanwise distribution of the angle of attack for zero thrust of the original surface is found. For the first cycle, this original surface is defined by program input data. Except for special-purpose designs, this surface will be that of a flat wing at an angle of attack of zero. For subsequent design cycles, the "original" surface will be the previously optimized surface. One purpose of the design is to create a wing surface that results in an α_{zt} distribution matching the design angle of attack for the original surface. The design angle of attack, α_{des}, is simply the angle required to generate the design lift coefficient.

In the second step, the difference between α_{zt} and α_{des} is used to define a distribution of leading-edge modification surfaces which attempt to modify the wing α_{zt} distribution so as to match the surface slope at the wing leading edge to the local upwash for all span stations. These leading-edge modification surfaces (one for each semispan station represented in the program grid system) have a finite slope at the leading edge and progressively decreasing slopes aft of the leading edge. They are intended to exert a significant influence on α_{zt} and at the same time introduce only moderate changes in the wing lift coefficient which may be compensated for in the following step.

The third step brings into play an additional set of candidate surfaces. The purpose of these surfaces is to restore the design lift coefficient with as little change as possible in the α_{zt} distribution and to do so with a minimum increase in drag. Surfaces used in this step, with one exception, have slopes of zero at the leading edge and thus have a relatively small effect on the angle of attack for zero thrust. The exception is a flat surface which changes α_{zt} uniformly across the entire semispan. The Lagrange method of undetermined multipliers is used to find the combination of these general surfaces that produces the necessary changes in lift coefficient with a minimum drag increase. If desired, the optimization may be performed with an appropriate constraint so as to produce a desired design moment coefficient.

In the fourth step, the aerodynamic characteristics of the composite surface (the original surface, plus the leading-edge modification surfaces, and the general surfaces) are found by consideration of all of the mutual interference terms involving pairs of surfaces and loadings created by the surfaces. Generally, the new surface will have a different design angle of attack than the original surface and will have a distribution of α_{zt} that more closely approaches the design goal. At this point, if design convergence criteria are not met, the program will return to step 1 and the process will be repeated. Convergence criteria are met when α_{des} changes between successive iterations are less than 0.01 deg (or some other value specified by the user) and when the program moment coefficient differs from the design goal by less than ± 0.001 (or some other value specified by the user).

Effect of Attainable Thrust on Design Process

The way in which attainable leading-edge thrust alters the design may be illustrated with the aid of Fig. 5. At the top of the figure are shown a spanwise distribution of α_{zt} and a typical mid-semispan wing section for a converged program solution for a thin wing with a leading-edge radius of zero. Such a design will display a considerable amount of camber so as to generate an appreciable portion of the total lift on forward portions of the wing where distributed thrust can be generated. For a thick wing section with a relatively large leading-edge radius, such as that shown at the bottom of the figure, an appreciable amount of thrust can be generated without resort to twist or camber. When the range of angle of attack for fully attainable theoretical thrust is taken into account, the spanwise distribution of the desired α_{zt} can be quite different from that shown at the top of the figure. In fact, if the α range for full thrust is sufficiently large, a flat wing will produce aerodynamic performance comparable to that of a cambered wing and, as shown here, the present design procedure could call for α_{zt} values of zero across the entire wing span. For intermediate section thicknesses and radii, as shown at the middle of the figure, a design with considerable variation of the severity of camber across the wing semispan could result. For inboard stations of a swept wing, little or no camber would be required, but for stations near the wing tip, the camber could approach that required for the thin wing with no leading-edge thrust. These examples show how the present design method may be used to define a wing with the mildest twist and camber capable of achieving performance levels comparable to those attainable with full theoretical thrust.

New Program Comparisons with Other Methods

One way to help demonstrate the validity of the design method is to compare results with those of established methods. This can be done for examples in which the present method is limited to consideration of wings with sharp leading edges. Figure 6 permits a comparison of camber surfaces generated by the present design method with those given by the method of Ref. 6 for a typical subsonic transport wing. The design conditions are a Mach number of 0.8 and a lift coefficient of 0.35. The camber surfaces given by the two methods are seen to be very similar in spite of large differences in the design approach and in the numerical methods used in the solution. Note especially the close correspondence of the curves in the critical leading-edge region. As shown at the right of the figure, the drag coefficient at the design condition given by the present method is slightly higher than the value given by Ref. 6. This is due in part to the assumption used in the present method which relates pressure coefficients to the sine of the angle of attack rather than the angle itself.

A comparison of camber surfaces given by the present method and by the method of Ref. 5 for a supersonic Mach number is given in Fig. 7. Again, there is good agreement between the surfaces generated by the two methods. As shown in the lift-drag polar plot, the drag given by the program in the design mode is less than the value given by the program when the completed design surface is subject to evaluation. This occurs because the design is performed by consideration of many different candidate surfaces (in this case 35) and because the optimization process will take advantage of any errors in the numerical solution to favor surfaces which lead to low drag values, even though the values are unrealistic. The program evaluation data are determined by consideration of only two surfaces, the final combined camber surface and a flat surface and thus must be considered to be the more accurate. Reference 2 gives a more complete discussion of these discrepancies and provides a means of compensation to prevent detrimental effects on the design.

New Program Attainable Thrust Design

Alternate means of employing the new wing design program to permit consideration of the effect of attainable leading-edge thrust are illustrated in Fig. 8. The figure depicts three solutions to the problem of defining an efficient camber surface for the wing planform shown in the sketch at the top of the figure. The flight conditions are a Mach number of 1.6, a Reynolds number of 50×10^6, and a cruise lift coefficient of 0.16. The wing is assumed to employ a NACA 65A004 wing section.

At the left of the figure, data are shown for a conventional design approach in which attainable thrust considerations play no part. For this case, the program is set to provide a sharp leading-edge solution (effected by setting $r/c=0.0$) for a design lift coefficient equal to the cruise lift coefficient. Because the wing-section profiles are relatively smooth and of similar shape, the quantity $(z_{te}-z_{le})/c_r$, shown as a function of wing spanwise position in the upper part of the figure, pro-

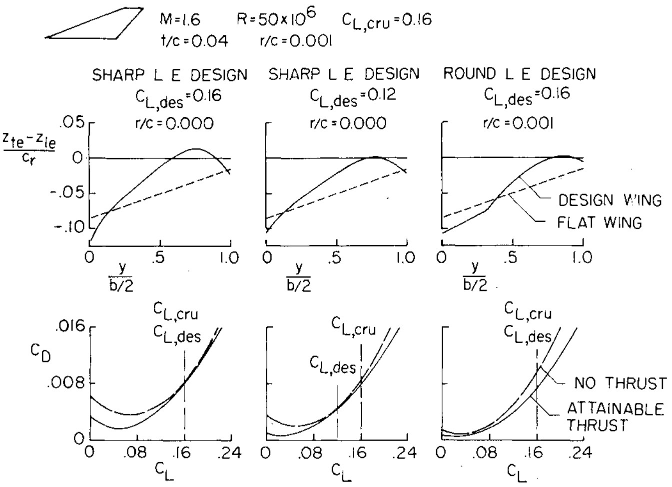

Fig. 8 Illustration of program attainable thrust design application.

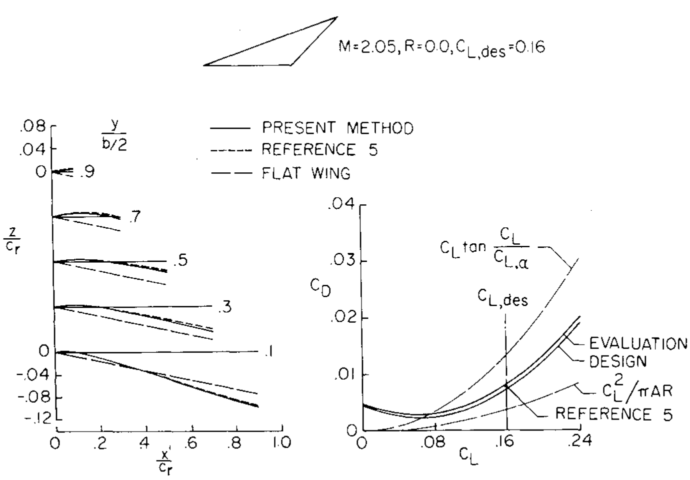

Fig. 7 Program results for a supersonic arrow wing design.

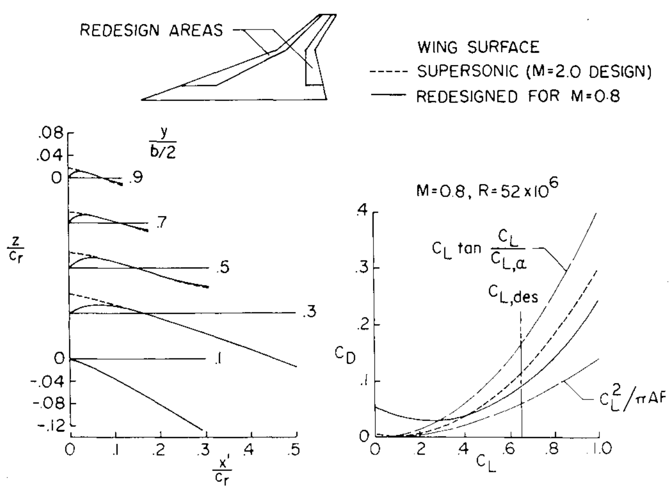

Fig. 9 Illustration of program use for special-purpose design.

vides a good indication of the severity of the design surface. For reference, this quantity for a flat wing developing the same lift is shown as the dashed line. The drag information shown below has been obtained by program evaluation of the design surface with no thrust ($r/c = 0.0$) and with attainable thrust ($r/c = 0.001$). It is seen that for the design lift coefficient, there is no performance benefit due to the attainable thrust but that off-design benefits can be substantial. The high no-thrust drag value at $C_L = 0$ gives evidence of a fairly severe camber surface. Experience has shown that the drag of such a surface may be significantly greater than that given by linearized theory methods, especially at supersonic speeds. It has become common practice for supersonic design to reduce the severity of the wing surface by employing a design lift coefficient less than the cruise lift coefficient by use of rule-of-thumb factors from about 0.5 to about 0.8. Even though this increases the theoretical drag at the cruise condition, the actual drag will generally be less than for the full cruise lift coefficient design.

The present wing program affords the designer an opportunity to introduce attainable thrust considerations and to design more moderate surfaces with comparable theoretical cruise point performance levels. The reduced camber surface severity should lead to improved performance at lift coefficients up to and including the cruise lift coefficient. One of these approaches, illustrated in the center of Fig. 8, uses the program generated range of full thrust information (for $r/c = 0.001$) to allow a smaller design lift coefficient for a sharp leading-edge design. The design lift coefficient of 0.12, in combination with the range of full thrust (a minimum of 1.33 deg for the outboard semispan station, corresponding to a lift coefficient increment of 0.04), permits a theoretical drag level at the cruise condition comparable to that of the sharp leading-edge design for $C_{L,\text{des}} = 0.16$ shown at the left. The reduced design lift coefficient also leads to lower drag coefficients for most of the C_L range shown. For a given family of wing designs, surface ordinates tend to vary directly with the design lift coefficient, and the drag at zero C_L tends to vary as the square of the design lift coefficient.

The wing surface design shown at the right of Fig. 8 maximizes the use of estimated attainable leading-edge thrust to reduce camber surface severity. This is the program standard automated design procedure which has been previously described. The clearest evidence that this surface is indeed milder than the other two is the reduced drag at $C_L = 0$. Note that the surface is similar to that of a flat wing for the inboard 30% of the wing semispan. For thicker wing sections or higher Reynolds numbers, a greater portion of the wing surface would tend to be flat. If the program estimates of attainable thrust are correct, this wing design will have drag values equal to or lower than the other two designs for all lift coefficients equal to or lower than the cruise value.

New Program Special Capability

An additional feature of the new design method is the capability for redesign of a wing camber surface for a new set of flight conditions with camber surface changes restricted to specified areas. This feature permits the program to be used for the design of mission adaptive surfaces and for guidance in selection of flap systems.

An example of a redesign problem is shown in Fig. 9. The original wing surface was designed for a Mach number of 2.0, a lift coefficient of 0.24, and a moment coefficient of 0.0. The design covered the entire wing planform and accounted for attainable thrust at a Reynolds number of 37×10^6 for a 4% thick airfoil with a rounded leading edge. In this figure, the surface for the original $M = 2.0$ design is shown as a dashed line. A redesigned surface for a Mach number of 0.8, a lift coefficient of 0.65, a moment coefficient of 0.0, and a Reynolds number of 52×10^6, in which surface ordinate changes are restricted to the designated areas, is shown as the solid line. A comparison of the surfaces shows a considerable change in the leading-edge region, but only a small change in the trailing-edge region. The leading-edge change is brought about in large part by the increased upwash generated at the higher lift coefficient. Lift-drag polars for the two surfaces from program evaluation data for a Mach number of 0.8 and a Reynolds number of 52×10^6 are shown at the right of the figure. Even though the supersonic camber surface is relatively mild, the program predicts an aerodynamic performance considerably better than that of a flat wing with no thrust, [C_L tan $(C_L / C_{L,\alpha})$]. This occurs primarily because of some achievement of leading-edge thrust on the rounded leading edges and because of vortex lift effects. The redesigned camber surface is seen to offer a substantial improvement over the supersonic surface. This improvement could be larger if restrictions on the leading-edge redesign area were less severe for outboard span positions.

Notes on the use of the design program for the definition of simple hinged flap systems to approach as closely as possible the benefits of well-designed camber surface are given in Ref. 2. The actual performance of candidate flap systems at subsonic speeds may be estimated by use of the computer program described in Ref. 3.

Concluding Remarks

One of the most important features of the new wing design program is the capability for both design and evaluation functions. The program may be operated in an evaluation mode which bypasses all the design routines. In the design mode, evaluation routines are employed to determine the aerodynamic characteristics of candidate surfaces, an optimum combination of candidate surfaces is selected, and, if desired, the completed design may be subjected to an immediate evaluation without the need for manual intervention. Both design and analysis may be conducted at subsonic or supersonic speeds with restrictions on regions of applicability governed by the usual linearized theory limitations. The use of an optimum combination of candidate surfaces (rather than candidate loadings) in the design process has the disadvantage of increased complexity and increased computational costs but does offer compensating advantages. One of these advantages is a reduced tendency for the appearance of surface irregularities and the elimination of singularities (infinite ordinates and surface slopes). Another outgrowth of the candidate surface approach is the ability to include attainable thrust considerations in the design process. This permits the definition of as mild as possible a camber surface which under the design conditions will achieve aerodynamic performance levels comparable to those attainable with full theoretical leading-edge thrust. A final benefit is the capability for special-purpose design, such as definition of mission adaptive surfaces or selection of flap systems.

References

[1]Carlson, H. W., Mack, R. J., and Barger, R. L., "Estimation of Attainable Leading-Edge Thrust for Wings at Subsonic and Supersonic Speeds," NASA TP-1500, 1979.

[2]Carlson, H. W. and Walkley, K. B., "Numerical Methods and a Computer Program for Subsonic and Supersonic Aerodynamic Design and Analysis of Wings with Attainable Thrust Considerations," NASA CR-3808, 1984.

[3]Carlson, H. W. and Walkley, K. B., "An Aerodynamic Analysis Computer Program and Design Notes for Low Speed Wing Flap Systems," NASA CR-3675, 1983.

[4]Carlson, H. W. and Walkley, K. B., "A Computer Program for Wing Subsonic Aerodynamic Performance Estimates Including Attainable Thrust and Vortex Lift Effects," NASA CR-3515, 1982.

[5]Carlson, H. W. and Miller, D. S., "Numerical Methods for the Design and Analysis of Wings at Supersonic Speeds," NASA TN D-7713, 1974.

[6]Kuhlman, J. M. and Shu, Jin-Yea, "Computer Program Documentation for a Subcritical Wing Design Code Using Higher Order Far-Field Drag Minimization," NASA CR-3457, 1981.