Numerical Optimization Design of Advanced Transonic Wing Configurations

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A reliable and fast transonic wing flowfield analysis program, TWING, has been coupled with a modified quasi-Newton unconstrained optimization algorithm, QNMDIF, to create a new design tool. Because of the high computational efficiency of the design code, in particular, the efficiency of TWING on the Cray X-MP vector computer, the computer time required for a typical wing design is significantly reduced over previous methods. The lift-to-drag ratio, previously thought to be too unreliable for numerical optimization, was used as the objective function to be minimized. This, coupled with a new cubic-spline wing parameterization, produced great success, yielding wing designs with nearly shock-free (zero-wave-drag) pressure distributions and reasonable wing section shapes.

Introduction

THE problem of aerodynamic design for optimal cruise performance is a most demanding task. A survey of this subject is given by Lynch.[1] While aerodynamic performance improvements are small, even a 5% reduction in cruise drag on a DC-10-type aircraft may save $500,000 per airplane per year in fuel costs.[1] For this reason, the use of new design techniques is becoming increasingly attractive.

There are three different types of numerical techniques available in aerodynamic design: 1) inverse, 2) indirect, and 3) direct methods. Each offers a different way of finding efficient aerodynamic shapes in the transonic (or other) flight regime, without resorting to expensive cut-and-try wind tunnel testing. The present study will be concerned only with direct methods; discussion of other methods will not be given. The reader is referred to Holst et al.[2] where design methods in general are reviewed.

Direct methods generally consist of those procedures involving design by numerical optimization. A CFD (computational fluid dynamics) analysis program is coupled with a numerical optimization algorithm in such a way as to create a design tool. Aerodynamic quantities such as lift, drag, and pitching moment are computed using the CFD algorithm for a certain configuration and are used in defining an objective function to be minimized by the optimizer. This objective function must relate changes in geometry to improvements in the aerodynamic quality of the design. Minimization of this objective function, through proper choice of the pertinent geometric design variables, should then correspond to a configuration that is "optimal" in some sense. While this is true only for a given flight condition, it is possible to find a design that will most nearly satisfy these optimal requirements for a range of flight regimes by the use of multiple design points. In addition to the merits of multiple point designs, numerical optimization design (NOD) procedures also allow a great deal of control over both the aerodynamic qualities and physical shape of the final configuration.

By far the most persistent criticism of NOD procedures is the large amount of computer time required for the optimization algorithm to "sort out" and decide which configuration is best. This is largely time spent by the CFD algorithm. With current rapid improvements in computer and algorithm speed, this shortcoming may soon be eliminated. An excellent survey of past work in this field is given by Hicks,[3] who points out some of its successes and failures. A case study on the Lockheed C-141B military transport is given by Lores and Hinson,[4] and an application to Learjet-type airfoil design is presented by Hinson.[5]

Drag would appear a natural choice for the objective function. However, little success with this approach has been reported in the literature. Nonuniqueness effects may be present in the problem, and the pressure distribution about a configuration designed by a drag minimization can be physically unreasonable.[2] Another criticism is that numerically generated "noise" inherent in the computed drag value relays incorrect gradient information to the optimization routine. A study of this phenomenon revealed that with the present design program, sufficient accuracy did exist in the computed drag to warrant its use as the design objective. This represents the first time that useful three-dimensional aerodynamic designs have been obtained by drag minimization.

Transonic Wing Flowfield Solution

The transonic wing analysis code used herein is the fast and reliable TWING program developed by Holst and Thomas.[6] It solves the transonic full potential equation using the fully implicit approximate factorization (AF2) algorithm.[7] This algorithm displays rapid convergence and robustness for a wide range of flowfield cases. This is not the case with classical successive line overrelaxation (SLOR) schemes, which slow down dramatically as the residual drops. Thus, implementing a NOD technique where tight convergence is required with an AF2 iteration scheme is a big advantage. In addition, AF2 permits the computer code to be written in a form that allows vector processing, thus greatly increasing the speed of execution.[8] On the Cray X-MP, TWING provides well-converged solutions (maximum residual at termination less than 5×10^{-7}) in 10-20 s for typical cases.

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The assumptions inherent in this equation are that the flow is steady, isentropic, irrotational, and, hence, inviscid. These are quite reasonable assumptions for an aircraft in transonic cruise where only weak shock waves exist and the boundary layer remains attached. Although shock waves represent a source of energy dissipation, and, therefore, entropy production, this effect is negligible if the shocks are acceptably weak (local normal-shock Mach number less than 1.3). This is generally the case on a well-designed wing. If shocks exist that do not satisfy this condition, they are always captured in a pessimistic fashion. That is, they are stronger than they should be. Having this situation built into the conservation potential formulation allows intermediate designs involving strong shocks to be easily discarded by the optimizer. The final design is valid only as long as it consists of (at most) a weak shock.

From the converged potential field, TWING computes the pressure distribution about the wing configuration. These pressures are then integrated to yield the overall wing forces. These forces and the pressure distribution are the primary quantities used in constructing an objective function for a NOD program. By specifying the required accuracy of the computed potential solution (i.e., level of maximum residual before termination), the numerical "noise" inherent in these output quantities can be controlled. Because of the speed of TWING relative to other analysis programs, it is possible to specify much tighter convergence without incurring severe computational penalties. Thus, greater levels of precision in the computed aerodynamic quantities may be achieved. This is vital to an optimization program operating in the highly nonlinear realm of transonic flow and is the key to success in obtaining useful wing designs by using the inherently low precision computed drag in the objective function.

Numerical Optimization

The term numerical optimization is used to describe a procedure by which the extrema of a function of N variables are located using a digital computer. For the present application, namely, transonic wing design, the objective function can be expected to be highly nonlinear and, perhaps, occasionally discontinuous. This characteristic demands an optimization algorithm capable of handling at least occasional functional discontinuities.

Most of the work done in the area of NOD for aerodynamic configurations has utilized the constrained-function minimization (CONMIN) algorithm of Vanderplaats.[9] In the present study, an alternative method known as the quasi-Newton method of unconstrained optimization is used. In a recent comparative study by Kennelly,[10] the optimization code QNMDIF (quasi-Newton method with difference approximation to the derivatives) of Gill et al.[11] and Gill and Murray[12] was shown to be more efficient than CONMIN.

QNMDIF is not a new technique, but its applications have not included transonic aerodynamic design until quite recently, when it was successfully integrated with an airfoil analysis program by Kennelly.[10] In that study, its performance was compared with the CONMIN algorithm,[9] which has been used almost exclusively in transonic applications in the past.

The Quasi-Newton Method Optimization Iteration

The quasi-Newton method attempts to locate the minimum of the objective by taking steps at each iteration k in a direction specified by the curvature information previously acquired. Specifically, the search direction $p(k)$, is computed by solving the linear system given by

$$B(k)p(k) = -g(k)$$

where $g(k)$ is the gradient vector and $B(k)$ represents one of a sequence of matrices which forms an approximation to the true Hessian matrix, or matrix of mixed second partial derivatives. When dealing with objective functions that are inherently imprecise and expensive to evaluate, the true Hessian matrix may be difficult to obtain. The approximate Hessian matrix $B(k)$ may be thought of as the Hessian of a quadratic model of the objective function.

With the search direction $p(k)$ computed, the next step, known as the linear (or one-dimensional) search, is performed. This is essentially an attempt to step to the minimum of the quadratic model of the objective function, based on the accuracy of the current gradient and curvature information. This is denoted by setting [where $\alpha(k)$ is the linear search step size]

$$x_i(k+1) = x_i(k) + \alpha(k)p(k) \qquad i = 1,2,\ldots,N$$

and

$$g_i(k+1) = g_i[x(k+1)] \qquad i = 1,2,\ldots N$$

Here $x_i(k+1)$ is the new approximate solution vector. Now, the gradient estimations are evaluated again in the new region of the design space to which the solution has progressed. Either forward- or central-difference formulas may be used depending on the perceived accuracy of the gradients, and whether a sufficient decrease in function value has been obtained during the last linear search procedure.

The final step in this simplified quasi-Newton process is an update to the approximate Hessian matrix B to reflect changes

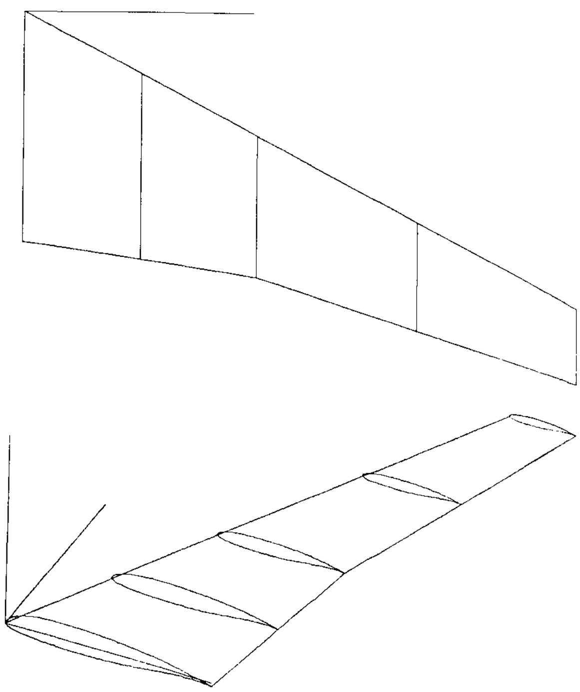


Fig. 1 Lockheed C-141B wing geometry with aspect ratio 7.89 and leading-edge sweep of 27.7 deg.

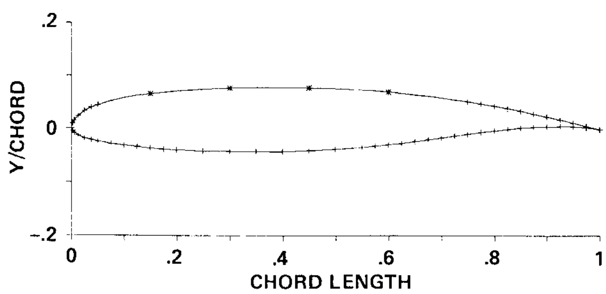


Fig. 2 Location of the fixed (+) and movable (*) spline-support points on the GA(W)-2MOD airfoil.

(and presumably increased information) about the nature of the objective function. This update procedure is given by

$$B(k+1)=B(k)+U(k)$$

where U is the update matrix designed such that the new approximate Hessian $B(k+1)$ satisfies the important quasi-Newton condition that

$$[g(k+1)-g(k)]=B(k+1)[x(k+1)-x(k)]$$

On the first optimization iteration of a new problem, $B(0)$ can be set to the identity matrix until the first update is formulated.

Termination Criteria

For the special case of a quadratic objective in N dimensions, the quasi-Newton algorithm should, in theory, converge to the minimum in N iterations. However, when dealing with an imprecise objective function that displays somewhat discontinuous behavior, the marginal accuracy of the calculated gradients will generally preclude such rapid convergence. Still, a great deal of progress may have been made toward significantly decreasing the function value in these N iterations, as well as reducing its sensitivity to further changes in the solution vector (small gradient norm). Thus, user supervision may be necessary to determine the most valid termination criteria based on the current solution status.

Aerodynamic Design Program Development

The major part of this research effort was coupling the transonic flow-analysis program with the numerical optimization algorithm. The essential function of the main driving routine is operation sequencing and design management. The steps in a typical design iteration are illustrated as follows:

1) Wing geometry generation (G80)
2) Grid generation (GRGEN3)
3) Transonic flow solution (TWING)
4) Evaluation of objective function
5) Compute new geometrical perturbation (QNMDIF)
6) Check convergence and solution; return to step 1.

The names in parentheses refer to the computer programs that handle the particular steps. The first program, G80, is a wing-alone geometry-generation program based on a wing-body geometry generator developed by Sobieczky,[13] and GRGEN3 is the grid-generation subroutine within TWING. Each of these programs is modified somewhat from its original form.

Wing Geometry Generation

A special feature of the G80 routine is the manner in which the airfoil sections that make up the wing are defined. From relatively few (or, alternatively, many) coordinate points, a cubic spline interpolation is used to create a well-defined airfoil. This is done on an expanded scale which reduces the curvature sufficiently so that oscillations in the spline curve may generally be avoided. This produces a smooth leading edge.

The G80 program accepts three input airfoils used as defining stations for the wing. The location of the stations is fixed at the root and tip, with the third main or break station located at some intermediate point specified by the user. The spline-support points defining these three input airfoils are then used to spline-fit many more points to aid in defining the section shapes. In addition, the wing planform and the wing twist and dihedral distributions must also be specified by the user. Because of the flexibility of G80 it is theoretically possible to optimize the wing planform as well as its surface shape. This area of design is largely unexplored.

Evaluation of Objective Function

The objective function must relate improvements in the aerodynamic quality of the design to the optimizer by a decrease in function value. The aerodynamic drag computed by the flow solver is an obvious choice; however, its use has been limited because of inaccuracies associated with its calculation. In theory, the drag calculated by this type of flow solver should be composed of two parts: induced drag and wave drag. For efficient operation in the transonic regime, the wave drag must be minimized (the induced drag is generally a function of lift and spanwise lift distribution, and is determined by the planform).

An approach more sophisticated than simple drag minimization might be maximization of the so-called transonic efficiency parameter, i.e., the product of the freestream Mach number and the lift-to-drag ratio. This quantity is directly related to the cruise range of a turbojet-powered aircraft operating in the transonic regime. This objective will prevent the optimizer from reducing the drag by drastically reducing lift and/or thickness. The best that may be hoped for is a design in which a wing shape is found that produces shock-free flow at the specified Mach number, while preserving as much of the original lift as possible. Since a specified flight Mach number is usually given, it will be removed from the objective function and held constant. Thus, it will be the optimizer's task to maximize the lift-to-drag ratio of the configuration (or, operationally, to minimize its reciprocal).

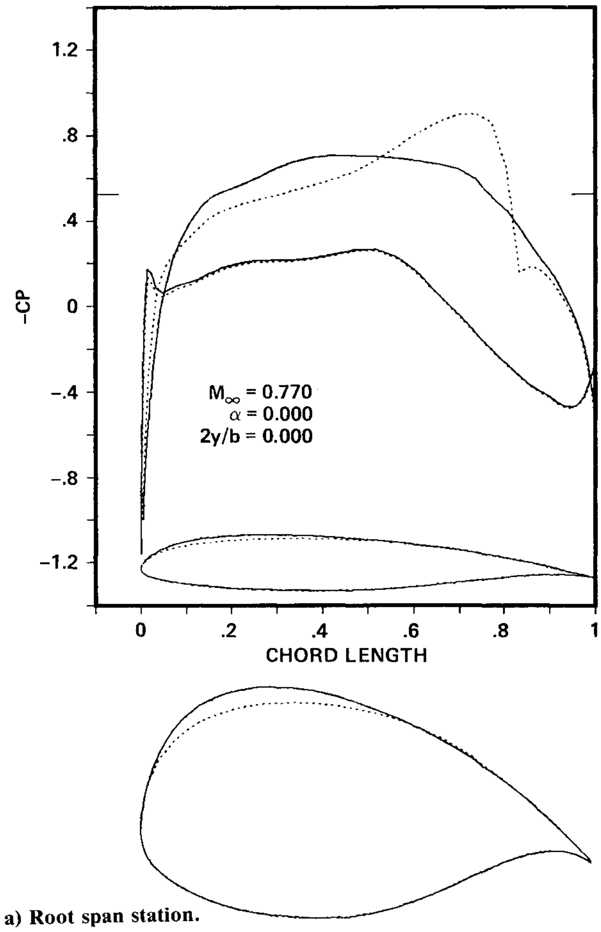
Minimization of the lift-to-drag ratio is effectively the same objective as that of shock-free design methods. However, there is one important difference: Shock-free methods fail to produce an answer if a shock-free solution cannot be found. Also, a shock-free solution may not maximize transonic efficiency. In general, for a given freestream Mach number and wing-loading condition (lift coefficient), there may be no shock-free flow solution. Nevertheless, it may be possible to redesign the surface shape such that the shockwave strength is appreciably weakened while the lift is reduced only slightly (or even increased). Also, these changes may be shown to require minimal changes in wing-section thickness and/or surface shape. Thus, no severe penalties in structural design or fuel capacity need be incurred. For these reasons, the lift-to-drag ratio minimization of an initial wing configuration at a fixed Mach number is defined to be the objective of the present study.

Geometrical Perturbation Technique

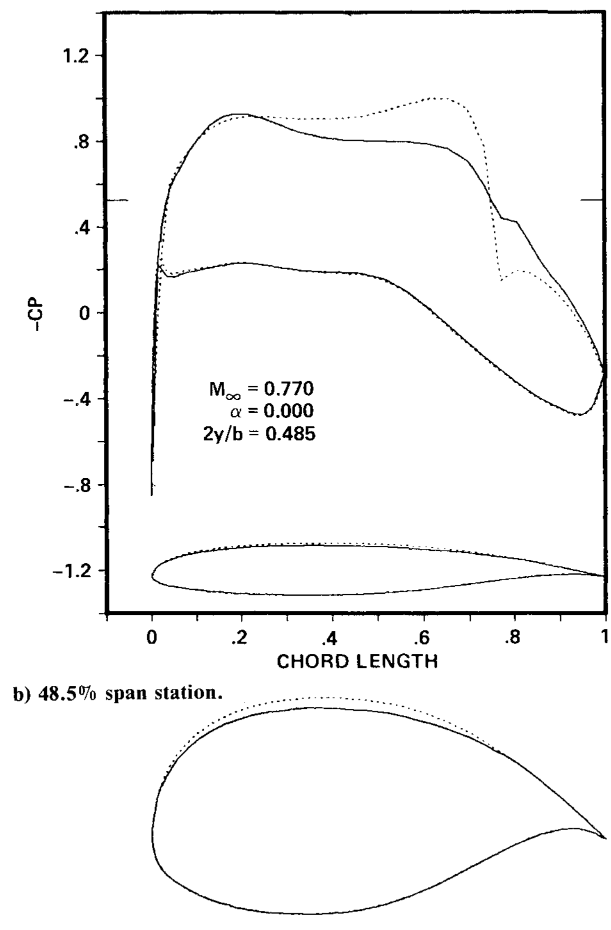
The computer time required for a given design is directly proportional to the number of design variables that must be used. Thus, the minimum number of variables that will allow the design objective to be met with a sufficiently broad definition of the design should be used. In a design study on the Lockheed C-141B aircraft, the shape-function-series technique of Ref. 4 and a total of 120 design variables. In the present study, the new spline-support point movement (SSPM) technique yielded an excellent design at similar conditions using only 12 geometrical design variables.

The SSPM technique is so named because the three defining airfoil sections used in the wing geometry program are derived from a spline fit of several spline-support points. Over the region where surface reshaping is desired, a few support points can be located, and control of their vertical position is given by the optimizer. Thus, subregions of an entire wing may be easily redesigned by modifying only a certain part of the defining airfoil. Over the remainder of the airfoil section, many fixed points are used to control the spline accurately. With care in the initial selection of fixed and movable points, a smooth new airfoil shape will be defined for each new location of the movable support points.

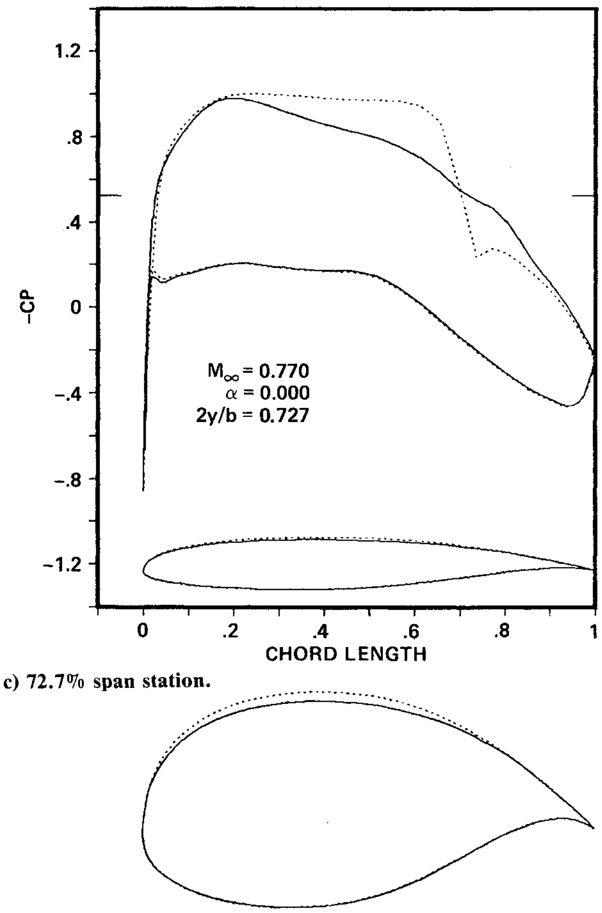
Although constraints may be imposed on the solution with certain types of optimization algorithms, it is generally preferable to formulate the problem such that constraints become unnecessary. The SSPM technique, in a sense, imposes implicit constraints on the design by restricting the class of airfoil that may be defined. Because much of the airfoil



a) Root span station.



b) 48.5% span station.



c) 72.7% span station.

___ AIRFOIL SHAPE AND PRESSURES AFTER OPTIMIZATION RUN

..... ORIGINAL GA(W)-2MOD AIRFOIL SECTION AND PRESSURES

Fig. 3 TWING/QNM light-to-drag ratio minimization results—Lockheed C-141B wing design.

shape is held fixed by the immovable points, the portion where reshaping is permitted must still conform to the rest of the surface in a reasonable way. Thus, large deformations and discontinuous curvature should be avoided by the optimizer, provided they are correctly detected as increases in drag by the flow solver. Hence, the need for the imposition of formal constraints should be reduced with the SSPM method.

Wing-Design Case Results

The new transonic wing-design program, combining TWING with the numerical optimization routine QNMDIF, has been described and will now be applied to practical wing-design problems. The design program as a unit will be referred to as TWING/QNM. Two interesting wing geometries have been selected among aircraft in operation today: the Lockheed C-141B military transport and the Cessna Citation III business jet. The flight conditions at which new improved designs are sought are chosen to be typical of the actual operating conditions for these aircraft. For the Cessna Citation wing, a design was sought at a slightly higher Mach number and lift coefficient than normal.

Lockheed C-141B Design

The Lockheed C-141B military transport is a four-engine aircraft with a high-mounted wing. The simplified isolated-wing geometry treated in this design is shown in Fig. 1. A linear twist distribution is imposed such that the incidence angle varies from + 1.0 deg at the root to − 0.5 deg at the tip. No dihedral is specified. The next step in formulating the design is the selection of three baseline airfoil sections to be used as defining stations. All three sections are selected to be the same GA(W)-2MOD airfoils. This airfoil is based on the low-speed GA(W)-2 airfoil used on general-aviation aircraft, but with a slightly modified upper surface for better highspeed performance. It was selected for its excellent low-speed, high-$C_{L\max}$ characteristics.[14] It is a fairly thick airfoil at 13%, with moderate aft camber. The modified GA(W)-2MOD airfoil used in this work has been thinned to be 11.8% thick.

The next step in setting up a design run is choosing the location of the fixed and movable spline-support points. As improvements in the supercritical performances of the wing are the primary objective, only modifications to the upper surface of the airfoil will be permitted. Further, the region of the shape modification will be restricted to essentially that region wetted by supersonic flow, as it has been shown in a two-dimensional shock-free airfoil design problem by Cosentino[15] that small changes in shape here may have a great effect on the entire flow. Therefore, four spline-support points are positioned somewhat arbitrarily over the region of the upper surface where supersonic flow may be expected. These four points are designated to be movable, and the remainder of the airfoil is defined by a large number of fixed points. This arrangement is illustrated in Fig. 2. Note that the important leading-edge shape and radius, as well as the trailing-edge angle, are preserved by the clustering of fixed points. With this geometrical parameterizaiton, modifications permitting improved transonic performance are facilitated, yet reasonable constraints on airfoil variation are imposed because of the location and number of fixed coordinate points.

The final step before the actual numerical design can begin is the selection of the flight conditions; i.e., the freestream Mach number and lift coefficient. For the first case, a flight Mach number of 0.77 and an initial lift coefficient of 0.60 were chosen.

A complete design problem has now been specified. Note that there are four movable points on each of the three defining wing stations, for a total of 12 design variables. Because the use of the computed drag coefficient is relatively unexplored, the design termination critieria should not be determined from the objective function and gradients alone. Inspection of the wing-surface shapes and resulting pressure distribution is imperative and should be done periodically throughout the design process. The improvement in lift-to-drag ratio combined with smooth pressure distributions with weakened shocks and physically reasonable airfoil shapes, when considered together, are sufficient evidence to declare a design successful.

The Lockheed C-141B wing-design case was terminated after 12 optimization iterations. The optimized airfoil shapes and pressures were reasonable. The C-141B planform with these final optimized airfoils was then analyzed in a separate TWING solution. The results of this solution, superimposed on the original airfoils and pressure distributions, are shown at three span stations in Fig. 3. Note that the airfoil shapes at the bottom of each figure are shown on an expanded scale. These results indicate that a design attempt using the computed lift-to-drag ratio as the objective function has been quite successful. An almost shock-free solution has been found, corresponding to essentially a minimization of the wave-drag component in the total computed drag. This has been accomplished using only 12 geometrical variables, and required just 1.43 h of Cray X-MP time (see Table 1).

Figure 4 displays the convergence characteristics of this design by plotting the objective function (drag/lift × 100) vs the number of flow analysis solutions (function evaluations). The relatively wild behavior over the first third of the curve is actually the result of preliminary gradient estimations. The accumulated information is then passed to QNMDIF, and the first linear search step results in an immediate decrease in the objective. As the design progresses, the amount of improvement (or decrease of objective) at each line search is reduced, and the function levels to some constant value. This may be interpreted physically as the best possible elimination of the wave-drag component, leaving a constant level of induced drag. Note that the iteration was continued to verify that the object function had reached a minimum. As can be seen, most of the actual improvement was made in less than 30 min of CPU time. This represents a significant reduction in CPU time requirements for the transonic configuration design using numerical optimization procedures.

Cessna Model 650 Wing Design

The final design case presented is for the Cessna Model 650 wing used on the new Citation III aircraft, as shown in Fig. 5. This wing is defined by different airfoil sections at the root, break, and tip stations, and the twist distribution is incorporated into the airfoil coordinates. These three airfoils, along with the locations of the fixed and the three movable spline-support points, are shown in Fig. 6. As can be seen, three movable points were chosen at each defining station for this case in contrast to four points for the previous case.

In a private communication,[16] the authors were told that the high-speed cruise conditions for the Citation III are Mach 0.81 and $C_L = 0.21$. For the purposes of this study, a design was sought at Mach = 0.81 and $C_L = 0.57$ (for the initial configuration) rather arbitrarily to provide a more challenging example for TWING/QNM. The objective function to be used is again the wing lift-to-drag ratio.

The results of this design case are presented in Fig. 7 at three span stations. Again, reasonable smooth pressure distributions and airfoil shapes are observed, with reduced shock strengths at every station (the 48.5% span station is nearly shock free). The slight pressure peak at the root station at about 6% of chord might be eliminated by redistributing spline-support point and reinterpolating. The remaining stations are quire well behaved. Note that actually very little modification to the shape or thickness of any section was required to achieve the desired result. This is an indication that the wing was very well designed before any optimization redesign, and yet significant improvements in cruise performance have been obtained (see Table 2).

This design required only six optimization iterations and was completed in just under 1 h of Cray X-MP CPU time (about 90% of the improvement required about 20 min of CPU time). Figure 8 displays the drag-rise characteristics of the original and optimized wings at a fixed lift coefficient. The drag coefficient is plotted at several Mach numbers for both

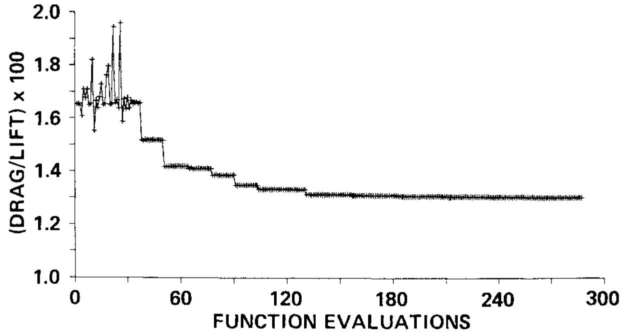


Fig. 4 Objective function ($C_D/C_L \times 100$) vs the number of TWING flow solutions: C-141B wing.

Table 1 Lockheed C-141B wing design summary

	Original wing	New wing	Percent change
C_L	0.585	0.558	−4.62
C_D	0.00967	0.00723	−25.23
L/D	60.535	77.264	+27.64

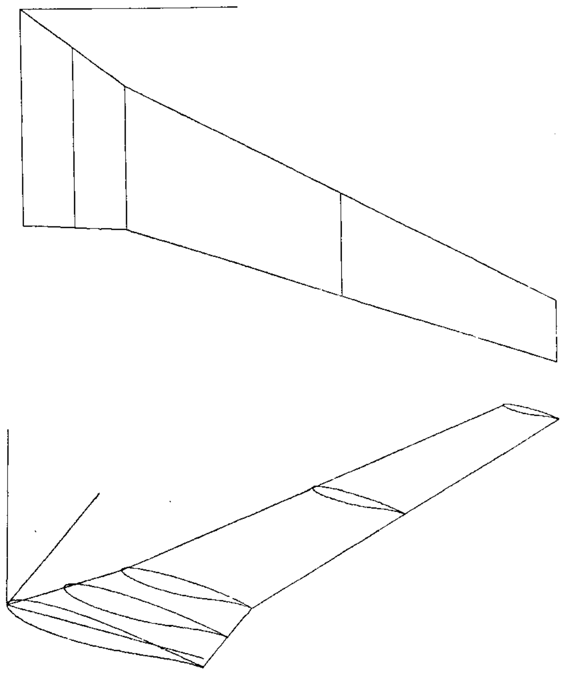


Fig. 5 Cessna Citation III Model 650 wing geometry with aspect ratio 9.0 and leading-edge sweep of 27.2 deg.

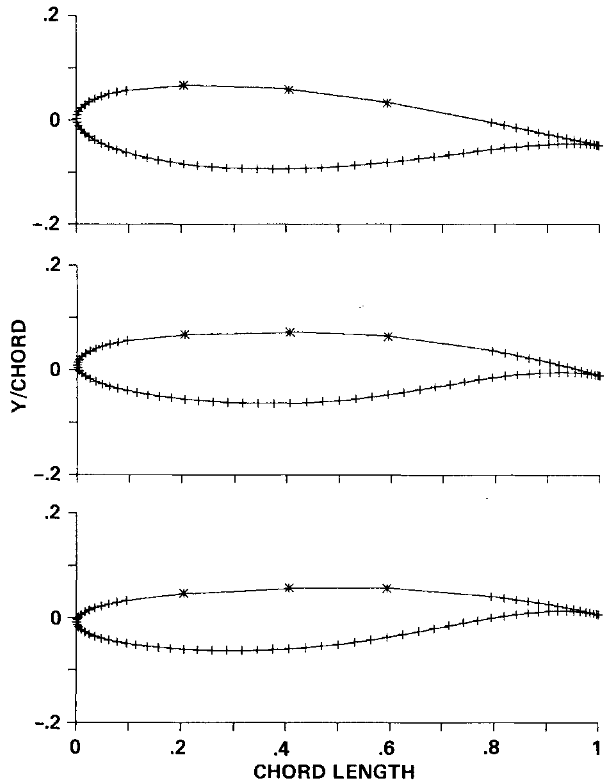


Fig. 6 Location of the fixed (+) and movable (*) spline-support points on the three Cessna airfoils.

wings. As can be seen, the optimized wing displays superior drag-rise characteristics as the Mach number is increased, yet does not suffer any undesirable off-design behavior at the lower Mach numbers. Note that the drag divergence Mach number has been increased by approximately 0.03. Increases of as much as 0.06 in drag divergence Mach number have been observed (see Ref. 17).

Discussion and Conclusions

A new tool has been developed to aid the aircraft designer concerned with efficient aircraft operation at transonic flight speeds. This was done by combing a sophisticated computational analysis program with an optimization algorithm using new techniques to provide the necessary interprogram communication. The availability of a supercomputer such as the Cray X-MP and the high speed of the TWING analysis program have reduced the time required for a single transonic wing flowfield solution by almost an order of magnitude. Numerical optimization design procedures using such an analysis program should no longer be considered prohibitive because of cost. Indeed, exceptional designs have been shown to be achievable in less than 1 h of computer time.

The feasibility of utilizing the computed drag in the objective function for a numerical optimization design scheme has usually been discounted because of problems with computed drag reliability and precision. In a preliminary study, the relative precision inherent in the computed drag (or, more specifically, the lift-to-drag ratio) was found to be of nearly the same order as that of the more widely trusted C_p objective quantity. The problem of objective function reliability is due to lack of convergence of the flowfield solution. If tighter convergence levels are specified, the consistency, or repeatability, of the computation of the objective function is increased. Because of the speed of TWING, the potential solution may be converged to much more stringent levels than what must be accepted with a much slower program, and, consequently, the precision of the drag computation is correspondingly increased. This may well be the major reason for the success of the design presented here.

It should be stressed that the success of a particular design using drag as the objective function should not be judged in terms of the reduction of the objective value alone. As the design progresses, examination of the wing-surface shape and the resulting pressure field is necessary to be sure that physically reasonable modificiations to the design are actually being performed. If this is not the case, redistribution of the movable and fixed spline-support points will remedy the situation. This was necessary for the C-141B case, but not for the Cessna case. The feasibility of using the lift-to-drag ratio as the design objective has been verified by the nearly shock-free design of the C-141B wing.

Table 2 Cessna Model 650 wing design summary

	Original wing	New wing	Percent change
C_L	0.565	0.506	−10.44
C_D	0.00909	0.00438	−51.82
L/D	62.151	115.428	+85.72

In summary, important conclusions drawn from this research effort are as follows:

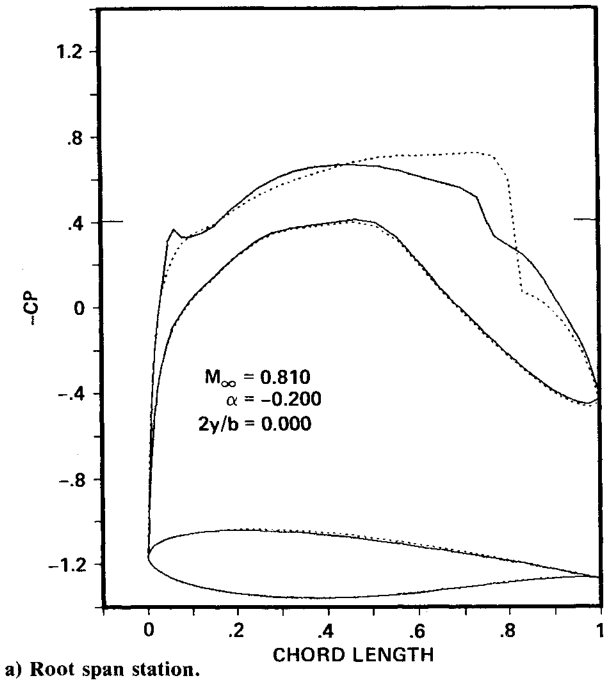
1) Aerodynamic design by numerical optimization procedures need not be prohibitively expensive. The computational time required can be reduced greatly by employing advanced technology and supercomputer power.

2) By specifying tight convergence levels for the potential flow solution, the numerical precision of the computed aerodynamic forces is sufficient to make possible their use as design objective functions.

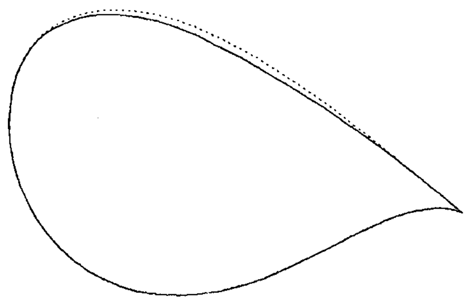
3) Transonic wing designs obtained by lift-to-drag minimization are quite practical, and yield physically reasonable pressure distributions.

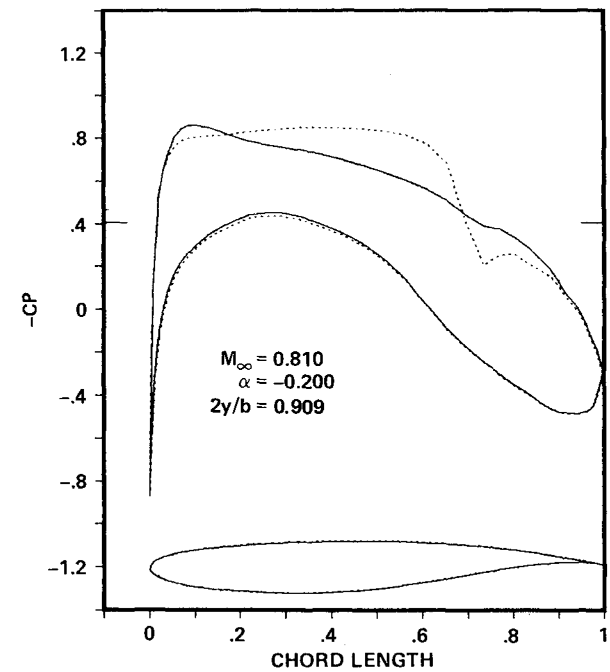
4) Some user expertise and intervention are required and will aid greatly in the production of useful designs.

5) Numerical optimization design procedures are reliable and versatile; the extension to more complex wing-fuselage designs is possible and depends only on the availability of the flow-solution algorithm.

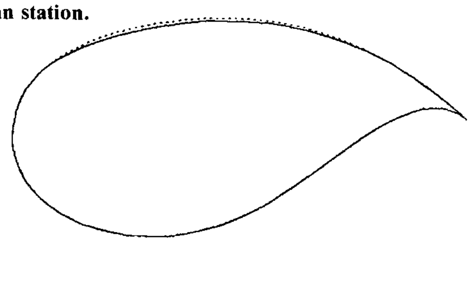


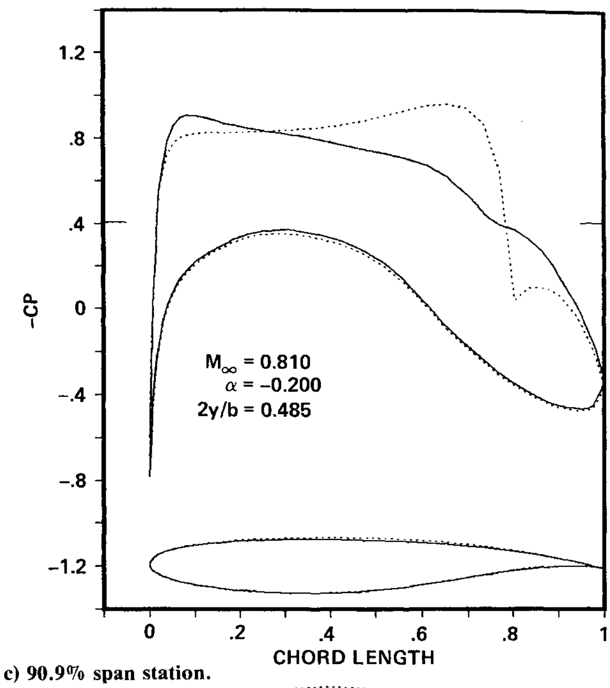
a) Root span station.





b) 48.5% span station.





c) 90.9% span station.

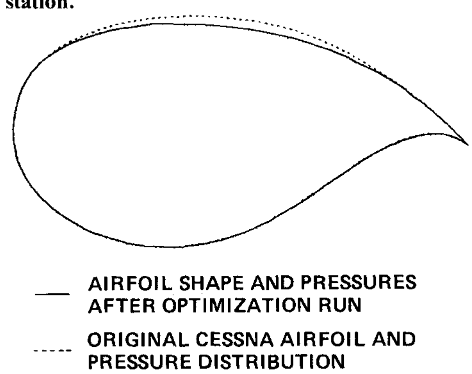


Fig. 7 TWING/QNM lift-to-drag ratio minimization result—Cessna Model 650 wing design.

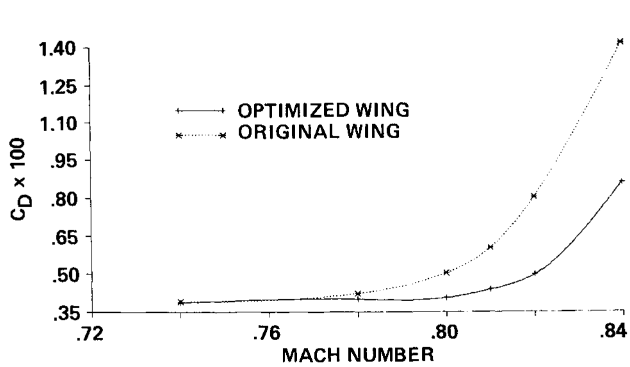


Fig. 8 Coefficient of drag (×100) vs Mach number for the original and optimized wings—Cessna Model 650 case, $C_L = 0.506$.

The greatly enhanced efficiency of this numerical optimization design technique should broaden the range of its practical applications. This design method, in combination with more advanced flow simulations using the Euler or the full Navier-Stokes equations and more powerful computers, should allow the computation of truly realistic aircraft designs in the near future.

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