TRANSONIC WING DESIGN BY INVERSE OPTIMIZATION USING MOGA

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ABSTRACT

An inverse optimization method coupled with a multiobjective Genetic Algorithm has been applied to design a transonic wing for mid-size regional aircraft. Optimization of target pressure distributions was formulated to give minimum induced drag as well as minimum profile drag. The straight isobar pattern of pressure contours was specified on the upper surface of the wing. To design a realistic wing, constraints of wing volume and smoothness of wing twist were considered. The resulting design shows good performance over a wide range of Mach numbers.

INTRODUCTION

Development of an aerodynamic shape optimization method is important to improve design efficiency in today's competitive environment for the commercial aircraft industry. With the aid of Computational Fluid Dynamics (CFD), various aerodynamic design techniques have been proposed. In [1], these aerodynamic optimization methods were categorized into two classes: direct and inverse numerical optimization methods.

The direct numerical optimization methods are formed by coupling CFD codes with numerical optimization algorithms. They minimize (or maximize) a given aerodynamic object function by iterating directly on the geometry. Such procedures, however, become extremely expensive as the number of geometry parameters or flow constraints is increased. Unfortunately, flow fields are often very sensitive to geometry, and the number of parameters increases with a more precise geometry definition. Thus those procedures do not seem practical even with the aid of current supercomputers.

Inverse numerical optimization methods deal with pressure distributions rather than geometry, to minimize, for example, drag for a given lift and pitching moment. Since pressure is the primary force acting on aerodynamic objects, one can design for desired aerodynamic characteristics by specifying pressure distributions. Once the target pressure distribution is optimized, a corresponding geometry can then be determined by the inverse methods. This approach avoids most of the limitations of the inverse methods while requiring considerably less computational effort than the direct numerical optimization approach. Therefore, this paper considers the inverse optimization of wing shapes.

The design of a wing usually proceeds in two steps. First, the airfoil section is designed. In [2], a Genetic Algorithm (GA) was applied to optimize target pressure distributions around airfoils for inverse design methods. Pressure distributions were parameterized by B-spline polygons and the airfoil drag was minimized under constraints on lift, airfoil thickness and other design principles. Since the pressure distribution was constrained to avoid a shock wave or flow separation, the drag minimization became the viscous drag minimization. Viscous drag was then estimated by the Squire-Young relation, without solving expensive CFD codes. Once the target pressure distribution was obtained, the corresponding airfoil geometry was computed by an inverse design code by Takanashi [3] coupled with a Navier-Stokes solver. Successful design results were obtained for transonic cases with and without a shock wave.

As an extension of [2], optimization of target pressure distributions for the three-dimensional wing design was considered in [4] using mulitobjective GAs (MOGAs). When the airfoil shape is designed, the next step of the wing design is to determine the variation of the designed airfoil in the spanwise direction. The design principles for this step are essentially twofold: (1) to preserve the two-dimensional performance as much as possible, and (2) to minimize the induced drag. A straight isobar pattern on the wing upper surface yields the first design principle and can be easily implemented in the inverse design. The second design principle is achieved by requiring an elliptical lift distribution. The pressure distributions are to be optimized for each airfoil section so as to reduce the section profile drag, as well as to minimize the induced drag of the entire wing (*i.e.* by achieving the elliptical lift distribution). This leads to a multiobjective optimization. To solve it, a MOGA based on the Pareto-based ranking method by Fonseca and Fleming [5] was used.

In this paper, this inverse optimization method has been applied to design a transonic wing for mid-size regional aircraft with realistic constraints. The performance of a wing designed using this method will be compared with that of a baseline wing configuration.

OPTIMIZATION OF TARGET PRESSURES

Pressure Distribution for Airfoil Section

In GA, design candidates are considered as individuals in the population. An individual is characterized by genes represented as a string of parameters. In this work, a B-spline curve is used to represent the chordwise pressure distribution. The chordwise pressure distribution is split into two curves, corresponding to the upper and lower surfaces of an airfoil. Eight and seven points are used to define B-spline polygons for upper and lower surfaces, respectively, as shown in Fig. 1. Except for the leading- and trailing-edge points, a total of 13 points are considered as genes representing design candidates. Real number coding is used with a randomized weighted average as a crossover operator [2].

The two-dimensional optimization problem is then defined as

Minimize: Drag coefficient C_d

Subject to:
1. Lift coefficient C_l = specified
2. Airfoil thickness t/c = specified
3. Additional constraints for chordwise pressure distribution

where C_d , C_l and t/c are evaluated from the pressure distribution as described in [2]. For example, the viscous drag coefficient is obtained by applying the Squire-Young relation after a two-dimensional integral boundary layer calculation. The specification of airfoil thickness can be done approximately in two dimensions, but not in three dimensions. Thus it was dropped in the following three-dimensional optimization. Additional constraints as illustrated in Fig. 2 are required to guarantee a reasonable solution of the aerodynamic inverse problem (see [2] for the exact objective function which combines all the constraints).

Pressure Distribution for Wing

One of the main objectives of wing design is to minimize the induced drag. This is achieved by enforcing an elliptical lift distribution in the spanwise direction of the wing. The constraint in the total lift will specify an elliptical lift distribution uniquely. The objective function can be given by differences of the sectional lifts to the elliptic distribution at several spanwise sections. Therefore, the three-dimensional target pressure optimization problem is now defined as

Minimize:

1. Difference between the spanwise lift distribution and an elliptic distribution for a specified total lift
2. Two-dimensional drag coefficient C_d at each spanwise section

Subject to: Additional constraints for chordwise pressure distributions at each spanwise section

We can further redefine the constrained problem to the unconstrained multiobjective optimization problem by introducing a penalty function and minimizing it for the chordwise pressure distribution at each spanwise section (see [2]).

Straight Isobar Pattern

The straight isobar pattern was imprinted to the initial population for MOGA as follows. At first, the two-dimensional GA was used to evolve a population of feasible solutions since random creation of an initial population produced infeasible solutions due to severe constraints as mentioned in [2]. Then, the sectional pressure distributions were distributed along the span at six spanwise sections from the 12% to 90% span, so as to give the elliptical lift distribution approximately. This was done by changing the pressure distribution only on the lower surface of the airfoil. In this way, the first design principle for the wing mentioned in the Introduction was implicitly satisfied, *i.e.* to maintain two-dimensional performance on the wing upper surface. The straight isobar pattern of pressures on the upper surface of the wing is expected to produce a near constant drag-divergence Mach number along the entire wing span, and thus the resulting drag-divergence Mach number of the wing will be similar to that of the airfoil section. Two hundred individuals were used as the initial population of the present MOGA. The upper surface pressures remain unchanged through the MOGA.

INVERSE DESIGN

Once the present MOGA finds an optimum target pressure distribution, a corresponding wing geometry can be obtained by an inverse design method. Here the inverse design code, WinDes [3], is used. WinDes uses the following iterative procedure (Fig. 3). Suppose the initial geometry and surface pressure distribution obtained from any CFD code are given. First, pressure differences are calculated from the given initial and target pressure distributions. From these pressure differences, corresponding geometry corrections can be computed from the integral equations discretized at the panels on the initial geometry. An improved geometry is then obtained from the initial geometry and the computed geometry corrections. Finally, the CFD code is used again to check how close the resulting pressure distribution is to the target distribution. If the differences are still large, the process is iterated. In practice, 15 design cycles are sufficient to obtain the final geometry. The inverse design code, Navier-Stokes code, and algebraic grid generator form a nearly automated loop for the inverse design with reasonable computational requirements [2].

Inverse design methods have difficulty in enforcing geometric constraints. For example, as mentioned previously, the wing thickness cannot be easily specified. When a shock-free wing is designed, the resulting wing tends to be too thin. This leads to penalties for the complete aircraft design, such as increased structural weight and reduced fuel volume. Therefore, an attempt at constraining the wing volume is made in the following design.

In general, a thicker body produces lower pressures on its surface. Thus, the optimization of target pressures was modified with the additional constraints as follows. The upper surface pressure distribution should have the lowest and longest plateau that is possible without causing a shock wave or flow separation. The lower surface pressure should also be low, but its amount is limited due to the total lift and the elliptic lift distribution. These requirements are balanced by changing the chordwise extent of the negative *Cp* region in order to increase the wing volume, and the chordwise extent of the positive *Cp* (rear loading) region in order to increase the lift coefficient.

The volume constraint introduced here can be regarded as a structural constraint. Since the parabolic lift distribution is known to give the minimum induced drag under structural constraint, all of the terms related to the elliptic loading above are changed to the parabolic loading.

In addition, the designed wing can have a wavy (non-monotonic) spanwise wing twist distribution. This might cause manufacturing problems. Therefore, after a few inverse design cycles, the trailing-edge line is smoothed and thereafter fixed. In subsequent design cycles, the geometry correction calculated at each spanwise section is rotated back so that the modified airfoil section has the specified trailing-edge location. This slows down the convergence of the inverse design, but the final result has a much smoother spanwise wing twist distribution.

RESULTS

The aircraft considered here is mid-size regional aircraft with a wing area of 525 ft^2. A cruise Mach number of 0.75 and Reynolds number based on the root chord of 1.5×10^7 was assumed. The wing planform has a quarter-chord sweep angle of 10 degrees and a taper ratio of 0.25 (see Fig. 4). The baseline design consisted of a wing root airfoil section of approximately 14% thickness-to-chord ratio and a tip airfoil section of about 11% *t/c*. Both sections had been previously optimized in 2-D. The baseline wing was given approximately 3 degrees of washout at the tip relative to the root.

The parabolic lift distribution is monitored at seven locations from the 12% to the 90% spanwise locations as indicated in Fig. 4. The inverse solver is used at these same spanwise locations for the geometry correction. For the Navier-Stokes analysis, modification of wing geometry is linearly interpolated spanwise between those sections, and twist angles of the designed wing at those sections are smoothed for simplicity of manufacturing, as mentioned previously. At the tip and root region, the airfoil sections are extrapolated from the interior sections, while the wing twist is linearly extrapolated. At the root section the fuselage is ignored and the symmetry plane is assumed. It should be pointed out that the tip and root sections are usually designed by other means since the present inverse method is based on the small disturbance theory. The computational mesh for Navier-Stokes analysis used for the inverse design has a C-O topology and contains 169×49×37 grid points in the chordwise, normal (to the surface) direction and spanwise directions, respectively.

Figure 4 shows the wing planform and the computed pressure contours on the upper surface of the wing designed by the inverse method based on the target pressure distributions optimized by MOGA. The resulting straight isobar pattern satisfies the first design principle of the wing well and thus indicates good performance at higher Mach numbers. Figure 5 shows the target chordwise pressures obtained from MOGA, the resulting airfoil shapes of the wing obtained from WINDES, and the corresponding pressures computed by the Navier-Stokes solver. It confirms that the inverse problem is solved satisfactorily. Figure 6 shows the computed lift distribution of the designed wing in comparison to the parabolic distribution. The result is found to satisfy the second design principle of the wing.

Figure 7 summarizes the performance of the baseline and designed wings. The designed wing produces less drag over a wide range of Mach numbers for a constant lift coefficient. Although the baseline wing appears to produce slightly less drag at subsonic Mach numbers, the designed wing is considerably less sensitive to drag creep. What is particularly impressive is that the designed wing has a drag-critical Mach number about 0.02 higher than the baseline wing. For the sake of brevity, a comparison of spanwise loading is not shown. The spanwise loads, however, have been observed to be nearly identical for the baseline and designed wings. This indicates that the induced drag for both wings is similar. This is further confirmed by the very similar values of drag computed at Mach 0.60.

Figure 8 shows a comparison of wing twist between the two wings. Although the shapes of the curves are quite different, it is seen that the inverse design method has converged to a magnitude of wing twist similar to that of the baseline wing. Figure 8 also confirms the inverse design method is capable of producing wings which possess smooth and monotonic spanwise twist distributions.

Figure 9 shows the variation of maximum thickness-to-chord ratio across the wing span, for both the baseline and designed wings. It is seen that the inverse design method has some difficulty in maintaining a smooth and monotonically reducing spanwise wing thickness distribution. Figure 9 also indicates that the chief reason for the designed wing's improved high Mach number performance is the reduced *t/c*'s over a large portion of the wing. Additionally, from the resulting wing volume, the designed wing possesses about 10% less fuel volume than the baseline wing.

CONCLUSION

Aerodynamic design of a transonic wing by the inverse optimization method has been performed. The optimization problem was formulated to minimize both the induced drag as well as the profile drag. The present design procedure also enforced the straight isobar pattern on the upper surface of the wing at the same time. MOGA, based on the Fonseca-Fleming's Pareto ranking method, was applied to optimize the three-dimensional target pressures.

The resulting procedure was successfully applied to transonic wing design. The standard design procedure for transonic wings previously focused on creating a straight isobar pattern over the wing. Reduction of the induced drag relied only on the use of proper taper ratio and twist. The present design procedure allows the minimization of the induced drag for arbitrary wing planforms with any taper ratio. This provides greater design flexibility which leads to increased aerodynamic performance.

The inverse optimization method has been shown to produce wings possessing superior aerodynamic performance. The current method will be extended to provide greater control of spanwise thickness distributions to ensure that the wing is both manufacturable and large enough to carry the required fuel load.

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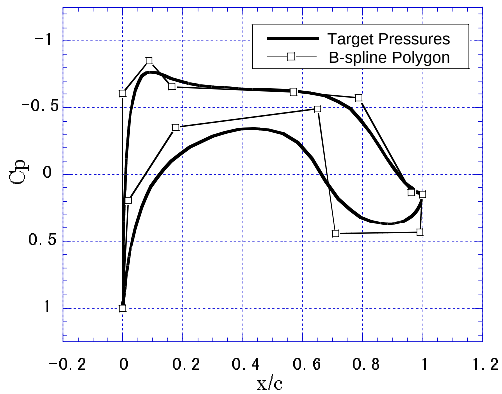

Fig. 1 B-spline polygon and corresponding pressure distribution.

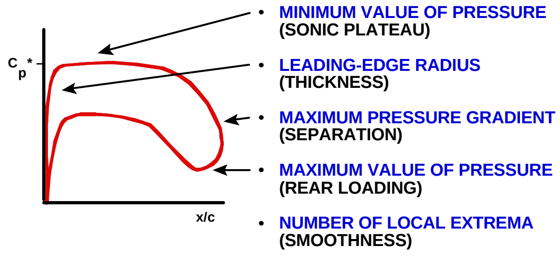

Fig. 2 Additional constraints for chordwise pressure optimization.

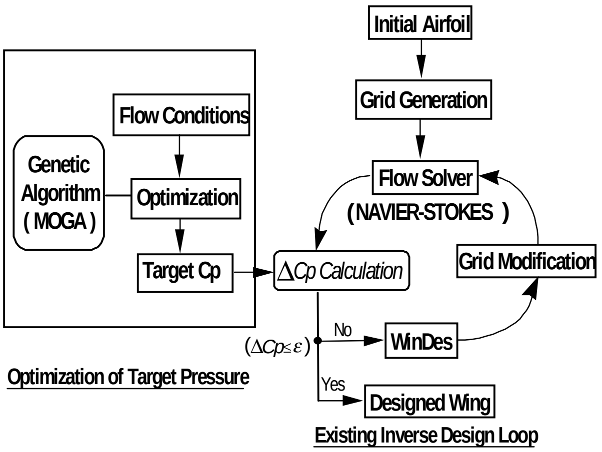

Fig. 3 Flowchart of the design procedure.

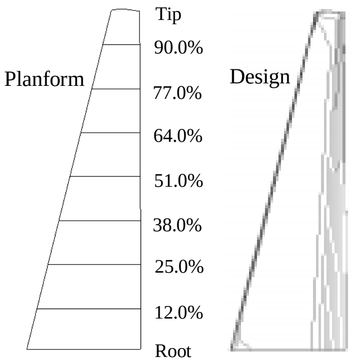

Fig. 4 Wing planform and computed pressure distribution on the designed wing.

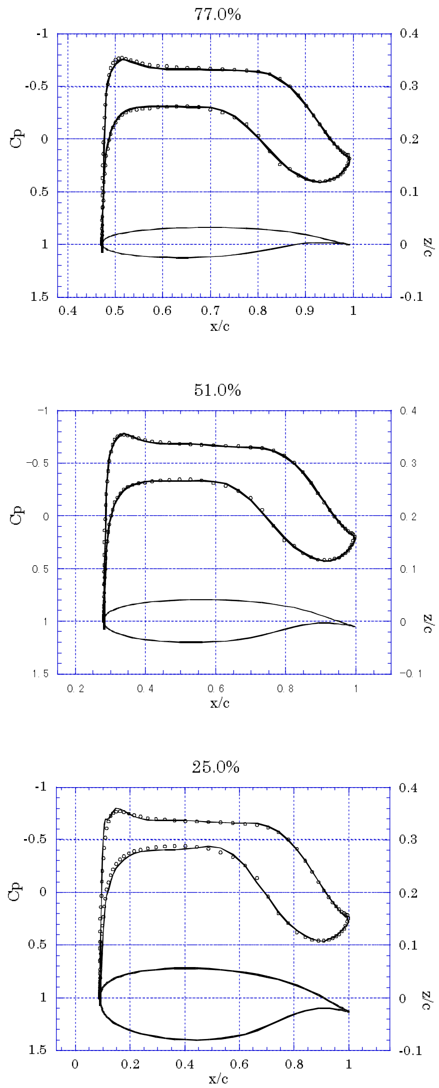

Fig. 5 Designed airfoil sections and corresponding chordwise pressure distributions.

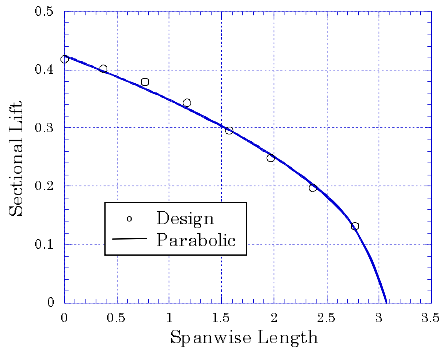

Fig. 6 Sectional lift distribution in the spanwise direction.

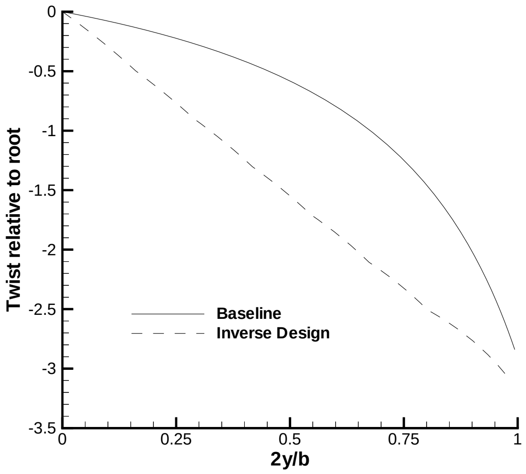

Fig. 8 Comparison of twist angle distributions.

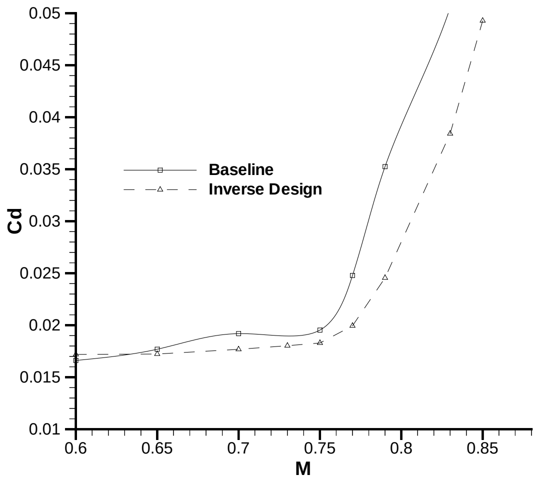

Fig. 7 Comparison of drag rise behavior with Mach number.

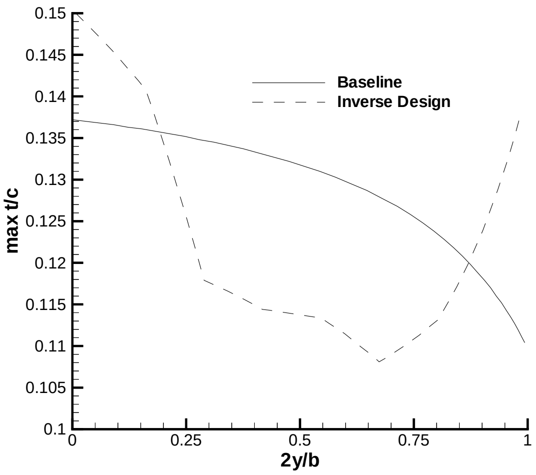

Fig. 9 Comparison of maximum airfoil thickness distributions.