Direct-Inverse Transonic Wing-Design Method in Curvilinear Coordinates Including Viscous Interaction

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Abstract

A BRIEF description of some developments in the direct-inverse wing design method is presented. The description includes a discussion of some observed spanwise oscillations and simple remedies, approximate limits on the wing planform, the significance of viscous interaction, and the feasibility of a design that begins aft of the leading edge and terminates prior to the trailing edge.

Contents

Many methods, ranging from optimization procedures to various inverse techniques, have been formulated using potential solvers to design wings in transonic flight. In the direct-inverse scheme,[1] the desired pressure distribution, C_p, is numerically specified over all or part of the wing aft of the stagnation line via the wing's boundary condition. Flow tangency is enforced at the leading edge and in nondesign regions. The input C_p is tailored by an experienced engineer to weaken or eliminate shocks, to reduce excessively large adverse pressure gradients in the aft recovery region, and to provide reasonable pitching moments while maintaining an efficient spanwise loading.

The new geometry, being the streamline adjacent to the pressure boundary, is calculated by periodically integrating the flow tangency equation at constant span computational grid lines laying within the user-specified design region on the wing's surface, or design grid stations (DGS). This integration yields displacements, termed inverse surface changes, δ_{inv}, to the current surface. The δ_{inv} are added normally to the current geometry, a grid is regenerated, and the convergence of the flowfield is continued. At flowfield convergence, a geometry will be calculated which will produce the specified C_p. Often, though, the new geometry may be undesirable; it may have an exceedingly large trailing-edge thickness or may even be "fish-tailed." This situation is remedied with a procedure called relofting, where the new airfoil surface is sheared about the leading edge such that a specified trailing-edge thickness or ordinate is maintained.

To properly include viscous interaction, the current boundary-layer displacement thicknesses are added to the airfoil ordinates at each analysis (direct) station to provide the correct displacement surface. Likewise, since at the design (inverse) stations the displacement surface is the surface computed, the displacement thicknesses are subtracted to yield the ordinates of the actual airfoil in the design regions of the wing.

The direct-inverse method was implemented using TAWFIVE[2] as the basic flow solver, resulting in a wing design program named TAW5D. TAWFIVE uses the conservative finite-volume full potential flow solver, FLO-30,[3] for the inviscid calculations, and a three-dimensional integral boundary-layer scheme to provide the necessary viscous effects in the form of boundary-layer displacement thickness, wake curvature, and wake thickness.

In the first stages of development, it was discovered that inverse designs of wings with significant sweep and low aspect ratio were subject to divergent "odd-even" spanwise oscillations in sectional thickness. Numerical experiments indicated that small spanwise variations in the potential function were amplified by the higher-order spanwise derivatives of the potential present in the residual expression. This amplification caused the residual to oscillate across adjacent spanwise grid stations. Since the residual is used in the calculation of the δ_{inv}, the δ_{inv} also oscillated. Relofting the new surfaces worsened the situation by producing sections that were too thin or too thick. A larger correction to the potential was then necessary to yield the correct surface C_p, causing the potential field at each design grid station to deviate further away from the adjacent fields. This deviation forced an even further undershoot or overshoot of the residual and, hence, the section shapes.

After exploring various alternatives to counter this situation, four simple methods were found that damped or eliminated the spanwise oscillations. In method 1, the inverse boundary condition was specified at a minimum of every other or "odd" DGS, and the δ_{inv} calculated at the odd DGS were linearly interpolated to the "even" DGS in between. With this method, flow tangency was imposed at the even DGS. With method 2, the δ_{inv} were calculated in the same manner as method 1, but the inverse boundary condition is specified at all DGS. In effect, linearly interpolating the δ_{inv} from odd DGS to even DGS eliminated the troublesome "second" solution. In method 3, all spanwise derivatives of the potential function present in the residual expression were based upon a potential function smoothed in the spanwise direction when the residual was used in the calculation of the new section shapes. With method 4, the calculated slopes used in the integration of the new sectional shapes were smoothed in the spanwise direction.

The first two methods successfully suppressed the divergent spanwise oscillation for full- and partial-wing designs utilizing Lockheed Wing-A and Lockheed Wing-B with leading-edge sweeps of 25 and 35 deg and aspect ratios of 8 and 3.8, respectively. Methods 3 and 4 worked well in the middle of the wing but not at the wing root or the tip where smoothing led to large errors. None of these methods were effective in suppressing these oscillations for redesigns of Lockheed Wing-C (leading-edge sweep of 45 deg and an aspect ratio of 2.6) if the new sections were continuously relofted.

In transonic flight, viscous effects can dramatically influence the flowfield and, hence, should have profound effects on designed section shapes. To study these effects, a target C_p was obtained by analyzing Lockheed Wing-A using all of the available viscous effects. The study used $M = .8$, $\alpha = 2$ deg, $Re = 25 \times 10^6$ as the flight conditions. All computations were performed on a fine ($160 \times 24 \times 32$) grid.

This C_p was then used in three cases. In the first case, the wing was designed inviscidly. In the second case, the wing was designed without the wake options but included the boundary

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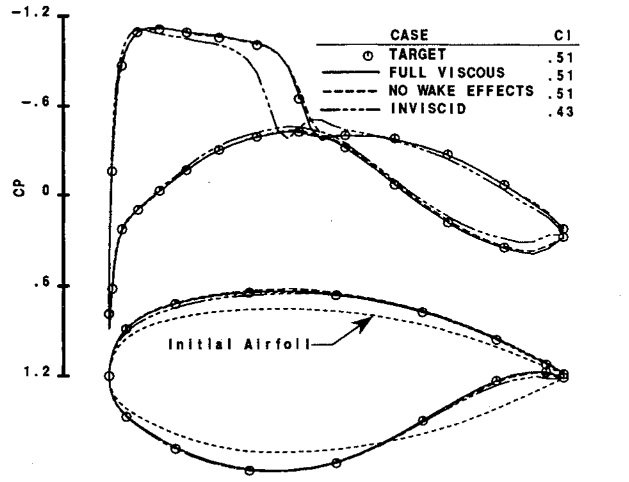

Fig. 1 Comparison of section shapes and their resulting C_p at 50% semispan for designs utilizing different viscous assumptions. The target C_p was obtained from a full viscous analysis of Lockheed Wing-A.

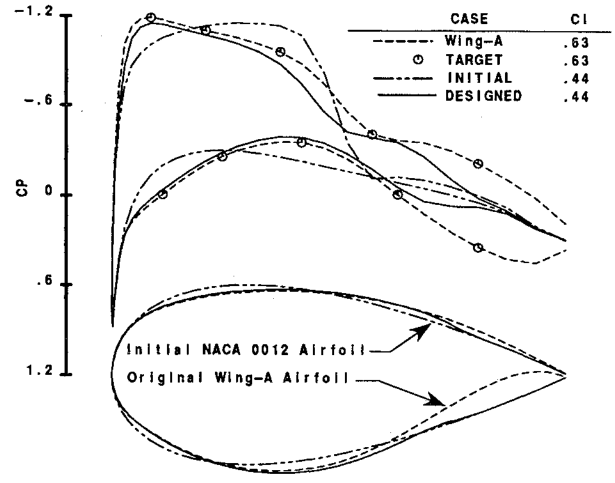

Fig. 2 Comparison of designed section shape and C_p at 50% semispan for a fixed trailing-edge region design case with original and target section shapes and C_p.

displacement thickness effects. In the third case, all available viscous effects were used in the design of the wing. The design region for all three cases extended from 30 to 70% semispan, and began 10% aft of the leading edge of the airfoil. Method 1 was used for this case. The sections were relofted to maintain the original trailing-edge ordinates. The initial airfoil section at 50% semispan was formed by thinning the 12% thick supercritical target section to 6% thick and removing the cove region. The initial sections at the edges of the design region were the same as the target sections, whereas the remaining initial design sections were obtained through linear interpolation. Neglecting wake effects had a small effect on the resulting airfoils in that the sections were only a little thicker than the sections designed with full viscous effects.

The wing sections designed inviscidly were quite decambered at 30 and 70% semispan as compared to the target sections, but subtly decambered at 50% semispan as shown in Fig. 1. Large differences at the inboard and outboard design stations were due to the influence of the inviscid pressure field outside of the design region. Better agreement in the middle of the design region, except in the cove region where the boundary layer was thick and in the "roof-top" region of the upper surface, was due to the influence of the viscous boundary condition at the edges of the design region. The level agreement at 50% would be typical of the shapes at all stations if a full wing design was accomplished. After the wings were designed, all three were analyzed with all available viscous effects to assess the significance of the changes made to the wing on the resulting C_p and to see how well these pressures matched the target C_p. The wings designed with boundary-layer displacement thickness effects included came quite close to matching the targets, while the inviscidly designed wing performed quite unsatisfactorly. For the inviscid case, the shock moved significantly upstream and the sectional lift coefficient produced was as much as 20% smaller than that the target C_l. The reexpansion after the shock is caused by the bump designed into the surface due to the built-in jump in the displacement surface present at the shock location of the target C_p. Representative C_p appear in Fig. 1.

It was foreseen that the capability of fixing the geometry in the aft region of the wing may be needed when there are contour and thickness constraints imposed in the aft region due to flaps or structural considerations. Therefore, this capability was investigated to verify that a fixed trailing-edge design could be accomplished with the present version of the code.

The case chosen utilized Lockheed Wing-A at $M = .8$ and $\alpha = 2$ deg. A NACA 0012 section was used as the initial geometry from 30 to 70% semispan, whereas the remaining part of the wing used the original supercritical sections. The inverse boundary condition was enforced from 5 to 80% chord. The airfoil aft of 80% chord was fixed so that it maintained the NACA 0012 trailing-edge shape. The input C_p were obtained through a medium grid inviscid analysis of the wing with the original supercritical sections used throughout. Furthermore, to provide for a smooth transition at the aft direct-inverse junction, the δ_{inv} were smoothed in the chordwise direction.

Even given the severe constraints to this problem, the designed sections were similar in shape to the the original Wing-A profiles at the 30 and 50% semispan locations. However, at the 70% semispan location, the designed section was more cambered than the original Wing-A section. This cambering was due to the interaction of the geometric constraints and the imposed design C_p. Upon comparison of the C_p obtained from an inviscid analysis of the designed wing those produced by the original Lockheed Wing-A sections and the initial geometry, it was found that the designed C_p matched the target C_p well at the inboard DGS and moderately well as the outboard DGS were approached. More disagreement in the outboard design C_p would be expected due to the influence of any errors in the inboard C_p propagating outboard. A representative section C_p is shown in Fig. 2. This impractical and difficult case, of course, was only meant to demonstrate that it was feasible to fix the aft region of the wing. If a more realistic trailing edge were used, better results would follow.

Further information on this material and discussions on initial airfoil profile, grid, and Mach number compatibility effects can be found in the backup paper for this synoptic.

Acknowledgment

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References

[1]Gally, T. A., and Carlson, L. A., "Transonic Wing Design Using Inverse Methods in Curvilinear Coordinates," *Journal of Aircraft*, Vol. 25, No. 11, 1988, pp. 1009-1017.

[2]Streett, C. L., "Viscous-Inviscid Interaction For Transonic Wing-Body Configurations Including Wake Effects," *AIAA Journal*, Vol. 20, No. 7, 1982, pp. 915-923.

[3]Jameson, A., "Transonic Potential Flow Calculations Using Conservative Form," *Proceedings of the AIAA 2nd Computational Fluid Dynamics Conference*, Hartford, CT, June 1975, pp. 148-161.