

## **7.0 Summary and Recommendations**

The first two steps toward the development of an integrated multidisciplinary design optimization procedure which is capable of analyzing the nonlinear fluid flow about geometrically complex aeroelastic configurations has been reported. In order to address the various aspects and specialized needs of such a procedure, a divide-and-conquer strategy, which is schematically illustrated in Figs. 1.2 and 1.3, was adopted. The underlying focus of the present work was the development of techniques capable of accurately modeling geometrically complex aerodynamic configurations of practical interest within the limits of modern computational resources.

The first step was to overcome a shortcoming of previously developed aerodynamic shape optimization procedures by acquiring the ability to model extremely complex configurations. In the current work this deficiency was eliminated by performing the aerodynamic analysis, and the corresponding shape sensitivity analysis, on unstructured grids. Discretization of the fluid domain with this technique permitted the investigation of practical two- and three-dimensional configurations. Furthermore, this work constituted the first successful attempt at fully consistent, second-order spatially accurate, discrete sensitivity analysis on unstructured grids.

Accomplishing the task of computing discrete sensitivity derivatives for the system of Euler equations required the use of novel computational methods for large-scale three-dimensional configurations. To this end, a relatively new technique in CFD analysis which allows efficient construction of Jacobian matrix-vector products was incorporated into the shape sensitivity analysis. The incorporation of this technique is only possible when the

sensitivity equation is recast into the well known incremental iterative form. With this procedure first- and higher-order spatially accurate sensitivity analysis may be performed with about the same memory as that required to perform the CFD analysis.

To demonstrate this aerodynamic shape optimization procedure, several two- and three-dimensional configurations were optimized. The accuracy of the current shape sensitivity analysis code was verified by comparison with finite-difference calculations for each configuration examined. Also a series of solution strategies which varied the spatial accuracy of the nonlinear aerodynamic analysis and shape sensitivity analysis were investigated, and the potential hazards of using inconsistent sensitivity derivatives was discussed. The ability of the present shape optimization procedure to analyze and design geometrically complex configurations was illustrated through the study of a two-dimensional high-lift multielement airfoil and a complete Boeing 747-200 aircraft.

Finally, it should be noted that once the aerodynamic shape optimization code has been developed and verified, only the design surface parameterization routines change from application to application. As discussed, an extremely important and vital aspect in any design optimization procedure, which uses discrete sensitivity analysis, is the accurate evaluation of the grid sensitivity terms. These grid sensitivities are dependent upon the surface parameterization techniques employed. To reduce the *set-up* time incurred to differentiate and verify these derivatives, the automatic differentiation software tool ADIFOR was used. Direct application of ADIFOR on the surface parameterization and interior volume grid adaptation subroutines was shown to produce an extremely accurate evaluation of the grid sensitivity.

The second step, illustrated in Fig. 1.3, was to develop the capability to accurately account for the multidisciplinary interactions. To accomplish this, the aforementioned aerodynamic analysis code was coupled with a structural finite-element method. This enabled the ability to perform static aeroelastic analysis. Since unstructured tetrahedral grids

are used to discretize the fluid domain, this method can resolve geometrically complex configurations of practical interest. Because a domain-decomposition approach has been adopted, the disciplines were coupled at the boundary interfaces. For this coupling, a load-lumping procedure was developed to transfer the aerodynamic forces to the surface structural nodes, and a polynomial regression technique was introduced to parameterize the corresponding structural deformations. This parameterization was used subsequently to update the wing-surface aerodynamic mesh, with the interior volume grid adapted to reflect these changes using the developed grid adaptation procedure.

To enable the eventual multidisciplinary sensitivity analysis and optimization, in which numerous aeroelastic analyses will be required, a high efficiency of the multidisciplinary analysis procedure is paramount. In the current study, extremely efficient static aeroelastic analysis was accomplished via interaction analysis control parameters. It was shown that for both subcritical and supercritical wing flows this analysis incurred less than a 10-percent penalty in terms of the central processing unit time over the time required for the rigid-wing CFD analysis. However, the interaction analysis control parameter values that yielded the most robust solution procedure were those for interaction at every iteration, incurring less than a 20-percent penalty for all flow cases considered. Therefore these values were used for the present computations. The static aeroelastic response was found for low subsonic, high subsonic (subcritical), transonic (supercritical), and supersonic wing flows. The supercritical wing flow case illustrated the dramatic loss of lift and the large deflections that are common to this flow regime. In addition, trimmed aeroelastic solutions were computed by using a feedback loop; however, a somewhat greater computational cost was incurred.

The first recommendation for future work is to complete the last step in Fig. 1.1; that is to couple the structural and aerodynamic sensitivity equations to perform the multidisciplinary

sensitivity analysis and optimization. This next step in itself will enable numerous trade-off studies between single- and multidisciplinary optimization. Through these studies, the importance of multidisciplinary design optimization in the design of engineering systems may be accessed.

To analyze the flow fields about geometries of practical interest, or to attempt meaningful multipoint optimization studies, design procedures will require the inclusion of the higher-fidelity fluid equations, e.g., the Navier-Stokes equations with turbulence modeling. The degree of resolution required to model the viscous, turbulent flow about a configuration makes these analyses extremely expensive. Thus, future work should include the study of alternative numerical optimization procedures which reduce the total number of analyses needed during the design process. Several of these alternative methods have been previously discussed in the introduction. In addition, the design optimization of realistic configurations will require sophisticated surface parameterization techniques that are consistent with the CAD definition of the geometry. These parameterization techniques must also be differentiated to provide the grid sensitivity for the discrete sensitivity analysis.

For pure three-dimensional aerodynamic shape optimization, the discrete-adjoint approach should be incorporated into the aerodynamic design loop of Fig. 1.2. It has been shown that the transpose of the Jacobian matrix-vector product may also be constructed using the technique presented herein. Hence, the memory efficiency shown for the current direct-differentiation approach to sensitivity analysis is attainable for the adjoint approach.