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Transonic Airfoil Design by Constrained Optimization

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Abstract

AN aerodynamic design method is developed which couples flow analysis and numerical optimization to find an airfoil shape with improved aerodynamic performance. The flow analysis code is based on the coupled Euler and boundary-layer equations in order to include the rotational, viscous physics of transonic flows. The numerical optimization process searches for the best feasible design for the specified design objective and design constraints. The method is demonstrated with several examples at transonic flow conditions.

Contents

Introduction

The motivation for using numerical optimization is to employ a rational, directed design procedure. It is used to generate an optimum shape at a specified flight condition having certain characteristics, while satisfying some design constraints. Constraints are imposed so that the improvement in the desired aspect does not degrade other aspects. Unlike inverse design, constrained design optimization does not require the prescription of the target pressure, and guarantees an improved design.

Design Tool

The reliability of a design result depends on the ability to accurately simulate the flowfield. The flow model used in design, therefore, should be able to represent all the significant flow physics involved. The present flow analysis is based on the coupled Euler and boundary-layer equations in order to include the nonlinear, rotational, viscous physics of transonic flows. The flow code solves the unsteady Euler equations and the unsteady integral boundary-layer equations simultaneously, by marching in time, and therefore eliminates the periodic coupling between the two regions. The simultaneous coupling has been shown to be an efficient means of inviscid-viscous coupling for a wide range of transonic analyses, as demonstrated in applications with inverse design optimization.[1]

In the present design, an initial airfoil geometry is modified by adding a smooth perturbation. The geometry perturbation is defined as a linear combination of base functions. The coefficients of the linear combination are the design variables to be determined through the optimization procedure. The base functions used in the present design are the sinusoidal functions developed by Hicks and Henne.[2] A total of 16 base functions are used: 8 on the upper and 8 on the lower sides of the airfoil. Figure 1 shows examples of the base functions. The optimization process is performed with a commercially available constrained optimization tool.[3] The sensitivity of the flow to the perturbation is calculated by finite differences.

The effectiveness and efficiency of the design process are influenced by many factors: the number and the shape of the base functions, the number and the tolerance of the constraints, the flow model and the grid used for flow analyses, and the flight condition at the design point.

Design Demonstration

The objective of the present design is to produce minimum drag at a specified transonic flight condition. Inequality constraints are imposed on lift, pitching moment, and cross-sectional area of the optimized airfoil. The lift and the area of the optimized airfoil should not be smaller than those of the original airfoil, and the pitching moment should not increase in absolute value. Also imposed are side constraints which limit the magnitude of the design variables. Side constraints are important because a large geometry change can cause boundary-layer separation leading to a termination of the flow solver.

The performance of the present design method was tested with three different airfoils: 1) RAE 2822, 2) NACA 0012,

Table 1 Drag minimization with three constraints: Jones airfoil at $M_\infty = 0.75$, $Re = 9 \times 10^6$, $\alpha = 2$ deg

Aerodynamic parameters	Original airfoil	Optimized airfoil	Percent change
C_l	0.5912	0.5920	0.13
C_d	0.0188	0.0098	−47.87
C_m	−0.0622	−0.0620	0.32
Area	0.0775	0.0779	0.52

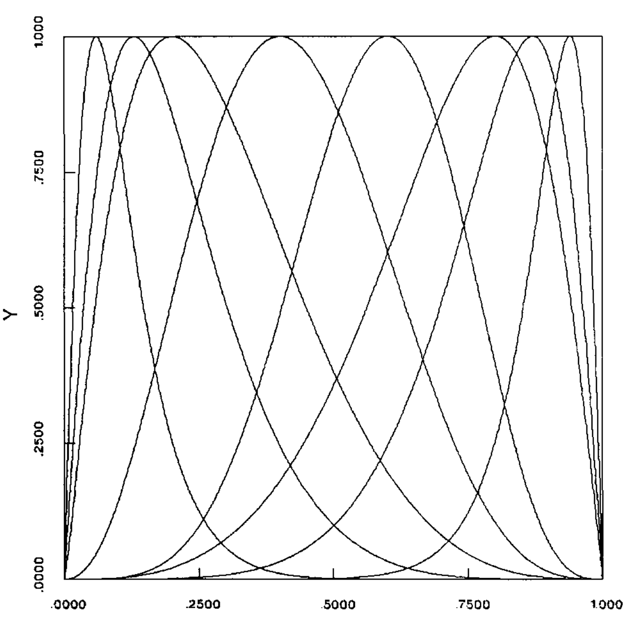

Fig. 1 Examples of base functions.

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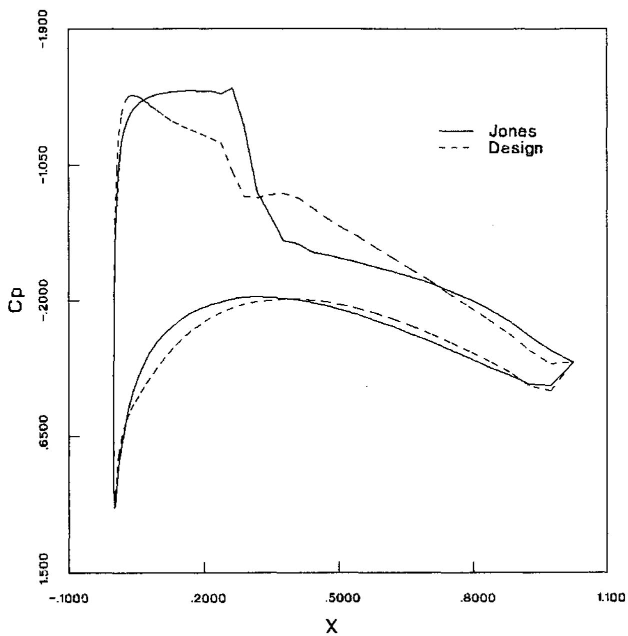
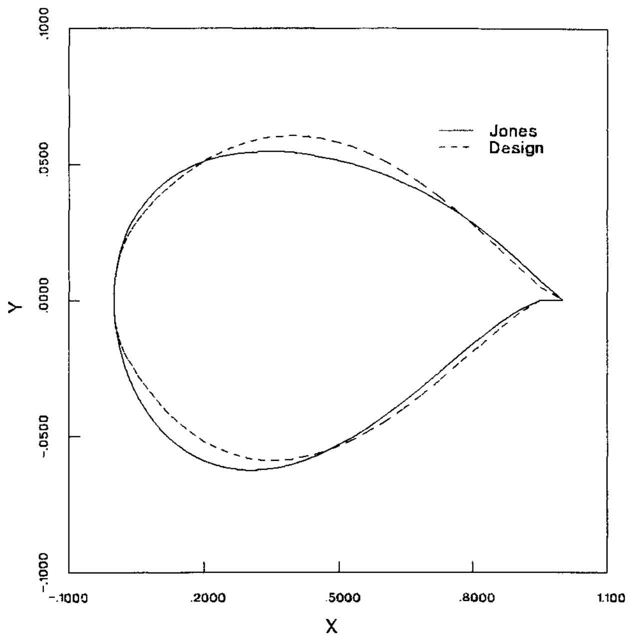


a) Surface pressure comparison



b) Airfoil geometry comparison

Fig. 2 Drag minimization with three constraints: Jones airfoil at $M_\infty = 0.75$, $Re = 9 \times 10^6$, $\alpha = 2$ deg.

and 3) Jones airfoils. All the design practices used a C-type grid of 129 × 33 with 81 points on the airfoil surface. Flow calculations were terminated when the maximum residual was reduced to a specified tolerance.

The design practices were first performed with only two constraints on lift and airfoil area. In all test cases, the optimization was able to reduce the total drag significantly, ranging from 22 to 48%. A major drag reduction was achieved by weakening the shock strength of transonic flows. That is, the optimization reduced transonic drag by increasing the drag divergence Mach number without significantly affecting the subsonic characteristics. In some cases, however, the absolute value of pitching moment was increased. This unfavorable change in pitching moment was prevented by adding a constraint on the pitching moment. Table 1 and Fig. 2 show an example of the three-constraint design case with the Jones airfoil. Compared to the two-constraint design, however, the added constraint produces a large difference in the airfoil geometry and increases the design cost significantly.

A typical optimization with two constraints requires about 60–70 function calls. Each function call represents one analysis mode. However, because the geometry perturbations are small and the flowfield is initialized with the original airfoil solutions, the cost of a transonic design optimization with two constraints is equivalent to about 15–20 new-geometry analyses. Optimization with three constraints increases the number of function calls, and therefore the design cost; sometimes more than twice. However, the design method is efficient considering the design quality that results from the large number of design variables, multiple constraints, and high-level physics. Future advances in flow code accuracy and further reductions in computing cost will make the method even more attractive.

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