N92-13838

Experiences with Optimizing Airfoil Shapes for Maximum Lift over Drag

by

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The goal of my work this summer was to find airfoil shapes which maximize the ratio of lift over drag for given flow conditions. For a fixed Mach number, Reynolds number and angle of attack, the lift and drag depend only on the airfoil shape. This then becomes a problem in optimization: find the shape which leads to a maximum value of lift over drag. The optimization was carried out using a package developed by Gregory A. Wrenn called KSOPT [1]. This is a self contained computer code for finding the minimum of a function subject to constraints. To find the lift and drag for each airfoil shape a flow solution has to be obtained. This was done using a two dimensional Navier Stokes code developed by Swanson, Turkel and Jameson.

The airfoil shape is defined analytically as a linear combination of orthonormal basis functions. The amplitudes of each term uniquely define a surface. Four terms are retained for both the upper and lower airfoil surface. Therefore there are a total of eight design parameters which characterize an airfoil shape. For fixed free stream flow conditions the lift and drag depend only on these eight design parameters.

The objective function is the quantity which is to minimized. In the present work the goal is to maximize lift over drag. This suggests two possibilities for the objective function — the negative of the ratio of lift over drag or the inverse, namely, the ratio of drag over lift. More success was obtained with the former.

It was found during the course of the work that several geometric constraints had to be put on the design space. These constraints were necessary to prevent the optimizer from specifying airfoil shapes which were impossible or unrealistic. A total of six geometric constraints were imposed. These included constraints on the airfoil area, the radius of curvature at the leading edge and minimum thickness.

Several problem areas became apparent as various cases were tried. First of all, even though constraints were imposed, the optimizer sometimes generated unrealistic shapes. This is because KSOPT allows constraints to be violated as it carries out its search for an optimum. For these cases a call to the flow code has to be skipped. Secondly, the flow code becomes unsteady or divergent for some shapes, particularly at shapes with high lift. This presents a dilemma for the optimizer because it must generate shapes with high lift but not so high that the flow code cannot handle them. Its like asking the optimizer to go right up to the edge of the cliff and search around but not fall over. There is also a difficulty with resolution in the flow solution. The resolution in lift and drag may be less than the change in lift and drag caused by a change of shape. In this case, the optimizer may not get the correct sign for the gradient of the objective function and start the search in the wrong direction. The objective function has more than one local minimum. Therefore the optimizer may end up at a relative minimum instead of the absolute minimum. For this reason it is important to start with more than one guess for the initial shape. For the runs carried out this summer two initial shapes were used: a symmetric NACA 0012 and a NACA 0012 with five percent camber.

The optimization process was carried out for a number of cases. In all cases the free stream Mach number was kept at 0.3 and the Reynolds number at 5 million. In one case the angle of attack was 6.0 degrees. In all others the flow was kept at zero incidence. Airfoil shapes were obtained with lift over drag ratios as high as 113. Some general guidelines emerged as experience with the optimizer increased. Some of these are as follows

1. The optimization process seems to work better with the objective function equal to the negative of lift over drag.
2. There is more than one local minimum. So start with more than one initial shape, at least one with camber.
3. The final shape obtained depends on the mesh size and number of multigrid cycles used in the flow code.
4. Use the internal scaling option in KSOPT.
5. Additional constraints or modifications in the objective function may be necessary to avoid obtaining shapes which are too highly cambered or have very sharp trailing edges.

From experiences with KSOPT it is clear that airfoil optimization it is not yet at a point where it can be fully automated. Human intervention in the process is still necessary. However, if the user is persistent and provides some intelligent and patient prodding, the optimization process can lead to some good airfoil designs. In future work it would be interesting to investigate the effects of adding additional constraints on the maximum camber, the trailing edge angle, and the pitching moment. Also some additional investigation into other objective functions may prove useful.

Reference

1. Wrenn, Gregory A. , "An Indirect Method for Numerical Optimization Using the Kreisselmeier-Steinhauser Function", NASA Contractor Report 4220, March 1989.