Euler and Navier Stokes Inverse Problem Studies of Airfoil by Genetic Algorithm

F. Zhang, S. Chen and M. Khalid
Institute for Aerospace Research (IAR)
National Research Council (NRC)
Ottawa, K1A 0R6, Ontario, Canada
Steve.Zhang@nrc.ca

Abstract

The Genetic Algorithm (GA), coupled with the 2D CFD solver ARC2D, was successfully applied to airfoil inverse problem. Both Euler and Navier Stokes redesigns for airfoil NACA64A410 were carried out by using this technique. The NACA0012 airfoil was selected as the starting profile. Both pressure distribution and geometry of redesigned airfoil agreed well with their target values, demonstrating the powerful ability of this technique to deal with this kind of problem. The results also showed that the airfoil from Navier Stokes redesign by using the Euler target pressure distribution is thinner than that from the Euler redesign, which reflects the influence of the boundary layers.

Introduction

The industry relies on experimental data banks, analytical techniques and CFD (computational fluid dynamics) methods to design efficient airfoils. There is some uncertainty in this approach as the analysts use their experience in affecting modifications and implementing a combination of above strategies to arrive at the final design. The success of the final design depends on the knowledge and intuition of the designer. This is very cost and time consuming. An alternative approach, known as the inverse design method, is one where the performance is specified and the geometry that would accomplish such performance is determined. Most of the traditional inverse methods make use of conformal mapping of the flow domains. However, they can only be used for two-dimensional (2D) potential and Euler flows in which the flow equations can be transformed. On the other hand, the optimization methods, which are based on the non-analytical approaches, aim at minimizing some objective function characteristic of the airfoil/wing performance. The solution of the flow equations is taken as one kind of aerodynamic constraints in the optimization procedure. They do not need any mapping of the flow domain. Therefore, not only can these methods be used for 2D, potential and Euler flows, but also for 3D and Navier Stokes flows. In the last decade, these methods have become more and more popular.

For the inverse problem, the desired pressure distributions (target) on the airfoil (or wing) surfaces are specified. The least squares difference between the actual ($p_i$) and target ($p_{it}$) pressures is used as the objective function $F$ (fitness) which can be described as

$$F = \sum_{i=1}^{N} (p_i - p_{it})^2$$

where N is the number of grid point on the airfoil (or wing) surfaces.
The optimizer modifies the shape of the airfoil (or wing) to minimize the objective function in which the actual pressure is approaching its target pressure. The actual pressure can be obtained by using a CFD solver. This means that not only does the optimization of aerodynamic design depend on the aforementioned techniques, but it also relies on the accuracy of the numerical modeling. At present, CFD has matured to deal accurately and efficiently with a wide range of flow problems such as Euler/NS, subsonic, transonic and supersonic flows. It can be widely used as a key tool for aerodynamic design.

Perhaps the most widely used optimization methods are the gradient-based methods which involve the computation of sensitivity gradients. These are local methods which only search one part of the design space. They are unsuitable for all but some limited problems because of the restrictive requirements of a continuous derivative function across different regions. In contrast to these local methods, the global methods such as Genetic Algorithm (GA) take into consideration the entire design space. They have the advantage of operating on discontinuous design space and of being capable of obtaining the global optimal value.

In recent years, GA has been widely used due to its efficiency and robustness. It is a search algorithm for performing selections based on the principles of the natural selection and natural genetics. It utilizes three operators: reproduction, crossover and mutation. The basis of genetic algorithms can be found in reference [1].

It should be mentioned here that GA is independent of the CFD solver used. This means that GA can be applied to any kind of aerodynamic optimization problems as long as the appropriate CFD solver is used.

At IAR, GA based method, coupled with the CFD codes ARC2D for 2D problem and KTRAN for 3D problem, has successfully been applied to airfoil and wing drag minimizations [2,3]. Based on the work in reference 2, this technique was extended to the Euler and Navier Stokes inverse problem studies for redesigning NACA64A410 airfoil in the current work. The airfoil NACA0012 was adopted as the starting profile. Both Euler and Navier Stokes inverse studies used the same target pressure from the Euler solution for the original NACA64A410 airfoil. As a result, the NACA61A410 airfoil was redesigned by using this technique.

Genetic Algorithm Operations

GA works on a coding of the design variables subject to certain performance constraints. Traditionally, the binary coding of the design variables is used which evenly discretizes a real design space. However, it suffers from some disadvantages when applying it to a real problem involving a large number of design variables [4]. One of them is a huge string length. Another drawback comes from the discrepancy between the binary representation space and the actual problem space. In this study, a B-spline curve with 6th order is used to represent the airfoil geometry. The actual values of the x and y coordinates of the control nodes for the B-spline curves are designated as the design variables. There are 8 control points for each of the lower and upper sides of the airfoil. Generally, we begin the work from a given initial shape, which is precisely defined by the coordinates of the shape points rather than the control points. The first step is then to find the control points based on the initial shape coordinates by using the least square function method.

As suggested in reference [5], using Micro-Genetic Algorithm (µGA) can facilitate fitness convergence and enhance the algorithm’s capability to void local optima. The implication behind
μGA is that with a small population size, the sub-optimal solution can be rapidly achieved in a cycle of GA operation. Then a new cycle of GA operation starts with the new population members generated from the sub-optimal member in the previous cycle of GA operation. In this study, this technique was also used.

A given population contains a certain number of airfoils. An airfoil is a chromosome in the population. In this study, the population size is set to 10. One GA cycle includes 10 generations. The starting population is generated by mutation from the initial airfoil (NACA0012).

Fitness evaluation is the basis for GA search and selection procedure. GA aims to reward individuals with high fitness values and to select them as parents to reproduce offspring. Parents are chosen based on the Roulette wheel method where the probability of a parent being chosen is proportional to its fitness value. Each pair of parents produces one offspring. After a new population is produced, the fitness of each member is compared to that of the parent generation and the best members in the generation are assigned to the new generation without crossover or mutation (elitism) [6]. Use of this technique guarantees that the best member in all the populations will not be filtered out by using the GA operators during the optimization procedures.

A simple one-point crossover scheme is applied. The probability of the crossover is set at 80%, as the use of smaller values was observed to deteriorate the GA performance.

Mutation is carried out by randomly selecting a gene and changing its value by an arbitrary amount within a prescribed range (1% chord). As this change is applied to the selected node, its neighboring nodes are also adjusted so that the change in slope and curvature of the section profile will not be too abrupt. As discussed by Mantel et. al [7], a high mutation rate of 80% is chosen for better GA performance with real number coding.

To obtain a realistic airfoil geometry constraints, such as the minimum allowable maximum thickness (>8% chord) and the maximum allowed trailing edge angle (>5°, <20°), are imposed. The minimum gap between the two control nodes at the trailing edge is also forced to prevent the section upper and lower surfaces cross-over.

Grid Generations and CFD Solver

A hyperbolic, 2D grid generator HYGRID was used to generate the grids. A typical C grid on an airfoil is shown in Figure 1. There are 169 mesh points distributed around the surface of the airfoil and 49 points in the direction normal to the airfoil surface. The computations were carried out using ARC2D for this study. The code makes use of the implicit pentadiagonal form of the approximate factorization scheme due to Beam and Warming [8] for solving the Euler/Navier-Stokes equations. The multi-step Runge-Kutta scheme due to Jameson, et al. [9] based on the cell-vertex control volume, is also available. Second and fourth order artificial dissipations were used in both schemes, and the corresponding dissipation coefficients were set at 0.25 and 0.64 for a fast convergence. The Baldwin-Lomax turbulence model is available in this code to consider the viscous effects. The flow solver calculates the actual pressure and sends it to GA, which then calculates the objective function value.
Results and Discussions

Lighthill and Wood proved that a solution to an inverse problem does not exist unless three integral constraints are satisfied: the airfoil to be closed, the Mach number and angle of attack to be given [10]. In the current work, both Euler and Navier Stokes inverse problem studies were carried out for the NACA64A410 airfoil. The airfoil NACA0012 was taken as a starting profile. The leading edge and trailing edge points are fixed in order to keep the airfoil closed. In our experience, ARC2D is found to give fairly accurate solutions for subsonic and transonic flows. For the present study, the free stream Mach number was set at $M_\infty=0.30$ and the angle of attack $\alpha=4.06$ degrees.

Figure 2 shows the GA fitness versus number of CFD (ARC2D) calls for the Euler inverse problem. These results represent typical GA convergence histories. It should be mentioned here that the maximum fitness in the figure corresponds to the best member in each generation and the averaged fitness of the entire members in the generation. It was noted after about 650 CFD calls, that the fitness value reaches its converged value. After this point, the maximum fitness maintains almost the same value although the averaged fitness changes a lot. This is attributed to the using of elitism skill. The trend of the fitness in this figure strongly shows that the target was being approached from one generation to another, demonstrating the reliability of the Genetic Algorithm.

Figure 3 displays the redesigned NACA64A410 airfoil in comparison with the starting NACA0012 airfoil and its target airfoil for Euler solution. Figure 4 shows the corresponding pressure distributions on the airfoil surfaces. The redesigned airfoil shape and its pressure distribution are in a good agreement with their targets. This furthermore demonstrates the GA’s ability to deal with the inverse problem. However, CFD calculation time of this problem consumed by GA was much larger than that required by traditional inverse methods.

The shape of the redesigned airfoil as computed from a Navier Stokes calculation is shown Figure 5. The corresponding pressure trace is shown in Figure 6. Both the shape and the pressure distribution are slightly different from their counterparts from the Euler solution already shown in Figures 3 and 4. It is well known from the boundary layer theory that the existence of the boundary layer is equivalent to the increase of the airfoil thickness compared with the inviscid flow. The amount of this increase equals the displacement of the boundary layer. If the airfoil geometry is given, the real flow will generate smaller load than that from inviscid flow. If the same load is expected, the real airfoil thickness should be thinner. Considering that the same target pressure distribution, which means the same load, is used for both Euler and Navier Stokes problems here, the thinner airfoil for Navier Stokes problem was obtained (Figure 5). The comparison of the airfoil shapes between Euler and Navier Stokes solutions is shown in Figure 7. With the Euler solution, the redesigned shape and pressure distribution agree well with their target counterparts. Using the Navier Stokes solution, the effect of the boundary layer becomes significant over the rear part of the airfoil, resulting in a thinner, more cambered airfoil. Over the forward part of the airfoil, the boundary layer is very thin and there is hardly any difference between the Euler and Navier Stokes solutions. Furthermore, because the trailing edge point is fixed, the inverse study has not much freedom to adjust the airfoil shape close to this point.

The Mach number contours for redesigned airfoil from Euler solution is displayed in Figure 8. Figure 9 displays its counterpart from Navier Stokes solution. The boundary layer can be clearly seen from this figure.
The problem of boundary layer effect discussed above can be solved by using the Navier Stokes target pressure distribution. The results for this study are displayed in Figures 10 and 11. It is demonstrated from these figures that not only was the pressure distribution reached to its target value, but the airfoil shape was also reached its target profile.

Conclusions

The Euler and Navier Stokes inverse studies using genetic algorithms couple with CFD solver, ARC2D, were carried out for redesigning the airfoil NACA64A410. The results demonstrated the powerful ability of the genetic algorithms to deal with this kind of problem.

Both the redesigned airfoil shape and its pressure distribution from the Euler solution are in a good agreement with their targets. The existence of the boundary layer in the Navier Stokes study by using the same Euler target pressure distribution results in the thinner airfoil, especially after the middle chord of the airfoil. This can be changed by using the target pressure from the Navier Stokes solution.

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References

Figure 1. C grid around an airfoil

Figure 2. Fitness convergence histories, Euler solution

Figure 3. Initial, target and redesigned airfoils, Euler solution

Figure 4. Initial, target and redesigned pressure distributions, Euler solution

Figure 5. Initial, target and redesigned airfoils, Navier Stokes solution

Figure 6. Initial, target and redesigned pressure distributions, Navier Stokes solution
Figure 7. Comparison of the airfoil shapes between Euler and Navier Stokes solutions

Figure 8. Mach number contours around the redesigned airfoil, Euler solution

Figure 9. Mach number contours around the redesigned airfoil, Navier Stokes solution

Figure 10. Initial, target and redesigned airfoils, Navier Stokes solution

Figure 11. Initial, target and redesigned pressure distributions, Navier Stokes solution