Three-Dimensional Aerodynamic Optimization with Genetic Algorithm

Shigeru Obayashi [1] and *Akira Oyama* [2]

Abstract. A Genetic Algorithm has been applied to optimize a wing shape for generic subsonic transportation aircraft by using Navier-Stokes computations. To overcome enormous computational time necessary for this optimization, Numerical Wind tunnel at National Aerospace Laboratory, a parallel vector machine with 166 processing elements, was used. Design results indicate feasibility of the present approach for the aerodynamic optimization in advanced computational environments.

1 INTRODUCTION

Aerodynamic shape optimization is a difficult task. For example, in [8], it was reported that distribution of the objective function could be extremely rough even in a simplified problem. Furthermore, evaluation of the design (computation of flow about the geometry) is highly costly. Thus, the optimization procedure is computer-intensive, yet only a local optimum is hoped for. To accomplish this task satisfactory, we need a global optimization algorithm and a powerful computer facility.

Among optimization algorithms, Genetic Algorithm (GA, see [5]) is attractive for aerodynamic optimization since it is capable of finding a more global optimum than a simple hill climbing strategy. GAs simulate evolution by selection. Initial population consists of individuals of strings, for example, finite sets of binary numbers, representing design variables. Selection takes place based on their fitness as design candidates. A new population is then generated from the selected parents by mutation and recombination of their strings. The combination of mutation and recombination allows in principle for leaving a smaller hill and therefore prevents evolution from getting stuck on local extreme. Several GA applications were reported recently in the field of aeronautics, such as [4], [6], [7], [10] and [12].

In this paper, GA is applied to aerodynamic shape optimization of a wing for subsonic transport aircraft. The aim of wing design in high subsonic speeds is to delay the drag divergence to higher Mach numbers as explained in [11]. The design policy is usually based on the straight isobar pattern that is obtained from the same chordwise sectional pressure distributions at any spanwize station. If this is achieved, the flow will be approximately two-dimensional and the drag divergence will occur at the same Mach number everywhere along the span. To achieve this design policy, spanwise thickness and twist angle distributions are known to play an important role and thus they are selected for design variables in this study.

Direct application of GA to the aerodynamic shape optimization, however, requires an enormous amount of computational time, because GA requires a large number of function evaluations. The previous investigations were therefore limited to the two-dimensional problems, unless the flow physics was greatly simplified. In contrast, the three-dimensional Navier-Stokes equations will be used to guarantee an accurate model of the flow field and to assess the feasibility of the methodology.

To overcome the expected difficulty in computational time, the present work consists of three key elements. First, as mentioned above, only thickness and twist angle distributions were selected as design variables to model the essence of the wing shape. Second, the multigrid technique was applied to the Navier-Stokes solver to accelerate the convergence [13]. Finally, the computations were performed on Numerical Wind Tunnel (NWT, winner of IEEE's 1995 Gordon Bell Prize for performance), a parallel vector machine at peak performance of 279 GFLOPS with 166 processing elements, located at National Aerospace Laboratory in Japan.

2 APPROACH

2.1 Coding of Design Variables

To model the essence of the design of a three-dimensional wing, spanwise distributions of maximum thickness and twist angle of airfoil section are considered. By using the second-order Spline interpolation, those distributions can

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[1] Department of Aeronautics and Space Engineering, Tohoku University, Sendai 908-77, JAPAN. E-mail: obayashi@ad.mech.tohoku.ac.jp
[2] Graduate School, Tohoku University, Sendai 980-77, JAPAN

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further be described by polygons (control points) of (y,t) and (y, α) where y, t and α are the spanwise location, thickness and twist angle, respectively. Five vertices are used to determine each distribution, including the fixed wing root and tip locations. In contrast to the standard GA characterized by the use of binary coding, the set of real numbers are used as genes.

In this research, the airfoil shape is given by NACA230xx where xx is originally a two-digit number indicating the maximum airfoil thickness to the chord in percent. This parameter is given by a real number between 5 and 20 here. The twist angle is given in degree between -5 and 10. To avoid wavy surface definition, the thickness and twist angle parameters are always rearranged into numerical order from tip to root.

For the given planform of the wing, an airfoil shape and its twist angle specified at each spanwise section will determine the wing shape. Each airfoil shape can be specified by a camber line and thickness distribution. With the aid of NACA airfoil series, the specification of the airfoil is further reduced to specification of the maximum thickness of the airfoil.

2.2 GA Operators

A simple GA is composed of three operators: 1. Reproduction (selection), 2. Crossover, and 3. Mutation[5]. Reproduction is a process in which individual strings are copied according to their fitness values. This implies that a string with a higher value has a higher probability of contributing one or more offsprings in the next generation. Instead of the typical roulette-wheel method described in [5], the stochastic universal sampling due to [1] is employed here.

Crossover operator combines parameters form the selected parents into a gene at random. Mutation takes place at a probability of 10% and then adds a random disturbance to the parameter in the amount up to ±1.

The initial population is created randomly. During the evolution, the elite strategy [3] is employed, that is, the best and the second best individuals in each generation are transferred into new generation automatically.

2.3 Evaluation

In this paper, we maximize the lift-to-drag ratio L/D of the wing. To evaluate L/D, a Navier-Stokes solver is used for each member (design candidate) of the population at every generation. The flow solver uses TVD type upwind differencing (see [9]), the LU-SGS scheme and the multigrid method (see [13]).

Structural constraint is introduced to avoid an apparent solution of zero thickness wing for low drag in high speeds. For the brevity, the wing is approximated by a cantilever and the lift distribution is replaced by spanwise concentrated loads. From the loads, the bending moment distribution is calculated, which gives the structural stress of the wing. The constraint is then given by the local stress to be less than the ultimate shear stress of Aluminum alloy 2024-T351 (see, for example, [2]).

In the present GA, the population consists of 64 members and evaluation of each member is distributed to one processing element of NWT. It takes about 50 minutes of the run time to advance a generation.

3 RESULTS

In the present test case, flow condition was set to the freestream Mach number of 0.6 and an angle of attack of zero. Figure 1 shows the planform of the wing and the optimized airfoil sections at selected spanwise sections.

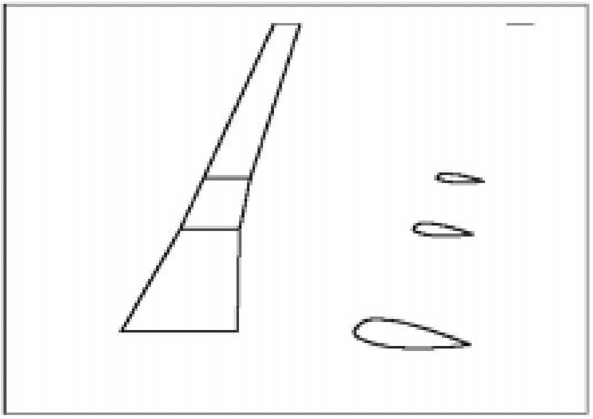

Figure 1. Optimum wing design

Figure 2 shows the optimization history of the present GA. Since only a reduced set of design variables are used in this study, the optimum is found within 50 generations.

The thickness distribution of the optimum wing design is shown in Fig. 3. The structural constraint is also plotted by the broken line. The maximum thickness is found necessary at the kink. The optimized wing design satisfies this constraint.

The twist angle distribution of the designed wing is shown in Fig. 4. To increase the lift, positive distribution is obtained. In addition, an aerodynamic washout (twist) is seen. By experience [11], a twist of more than five degrees is known to result in unacceptably large induced drag increments. The present design satisfies this criterion.

Figure 5 shows the spanwise load distribution. The solid line indicates the parabolic loading distribution that is known to give the minimum induced drag when the structural constraint is considered. The design result follows the parabola closely.

The pressure contours on the upper surface of the designed wing are plotted in Fig. 6. They appear nearly two-dimensional in the spanwise direction, despite of the large variation of thickness and twist angle distributions. The resulting isobar pattern is consistent with the existing design policy.

The present design is examined for the thickness, twist angle and load distributions, as well as the isobar pattern of pressure contours. The results indicate that the optimum solution obtained here is consistent with the design principles obtained form existing theory and experience. For practical designs, the airfoil shape is also needed to be optimized in future.

4 CONCLUSION

GA has been applied to optimize a wing shape for generic subsonic transport aircraft by using Navier-Stokes computations. To overcome enormous computational time necessary for GA, 1. Maximum thickness and twist angle distributions were selected as design variables. 2. The multigrid technique was applied. 3. NWT was used. The structural constraint was also considered.

In the optimum design obtained form the present GA, the design principles for the wing developed by existing theory and experience are found to be materialized. This indicates the feasibility of the present approach for the aerodynamic optimization in advanced computational environments.

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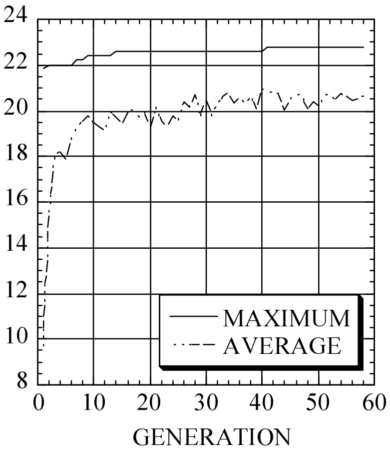

Figure 2. Optimization history

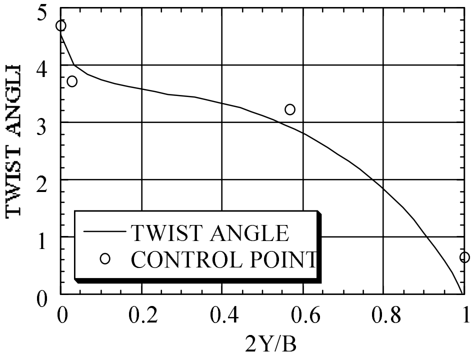

Figure 4. Spanwise twist angle distribution

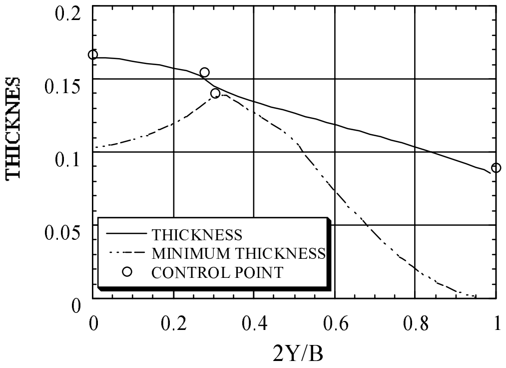

Figure 3. Spanwise thickness distribution

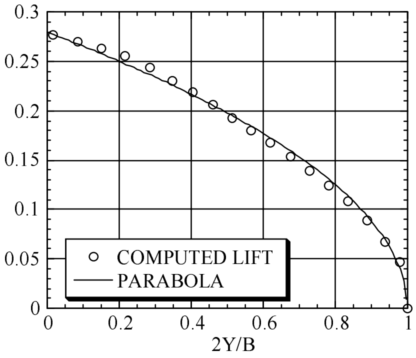

Figure 5. Spanwise load distribution

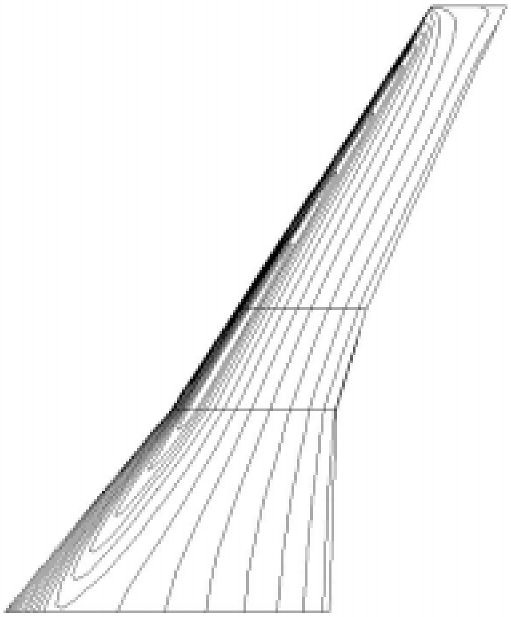

Figure 6. Pressure contours on the upper surface of the designed wing