AIRFOIL DESIGN OPTIMIZATION
FOR AIRPLANE FOR MARS EXPLORATION

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Abstract

Aerodynamic design optimization of an airfoil for the Mars exploration airplane has been demonstrated by using an evolutionary algorithm. The adaptive range genetic algorithm is used for efficient and robust design optimization. Two-dimensional Navier-Stokes solver is used for accurate aerodynamic performance evaluation. The present computation is parallelized on the SX-6 vector computers in Institute of Space and Aeronautical Science (ISAS) / Japan Aerospace Exploration Agency (JAXA).

The optimized airfoil achieved very high aerodynamic performance. The optimum airfoil for Mars exploration airfoil has extremely thin airfoil thickness and strong camber while an optimum airfoil for typical airplane fly on Earth has substantial airfoil thickness in the front. However, a thin airfoil has disadvantages such as structural weight and fuel tank space (if an engine is used for propulsion). The present optimization indicates necessity of multiobjective design optimization for practical airfoil design for Mars exploration airplane.

Keywords: Aerodynamic Optimization, Evolutionary Computation, Airplane, Mars exploration

1. Introduction

Historical discoveries about Mars have been made in rapid succession in 2004. In January, Mars Express by ESA proved that water ice is present at the south Mars pole. In March, a Mars rover developed by NASA named Opportunity found evidences that a salty sea was once covering the Mars. As a result, Mars has been receiving a large amount of public attention.

Current and previous missions to Mars are based on ground-based rovers and orbiters. Rovers provide high-resolution data but their reach is limited to a very small area. On the other hand, orbiting sensors provide large spatial coverage but can not provide the resolution of lower altitude systems. Therefore, it has recently been suggested to fly a aircraft in the Mars atmosphere [1,2]. Atmospheric exploration of Mars extends the reach of robotic sensors by an order of magnitude over any other surface exploration technique while decreasing resolution only slightly.

The airplane for Mars exploration should be very different from the conventional airplanes on Earth. First, the air is very thin compared with the air at the altitude where most of airplanes fly on Earth. As a result, Reynolds number is smaller (100,000) than flow condition of typical airplanes on Earth (10,000,000). Second, gravity on Mars is about one-third of that on Earth. In addition, there are severe limitations on weight and size of the airplane.

Therefore, objective of the present study is to obtain an optimum airfoil shape by an evolutionary algorithm and to obtain design guideline for airplane for future Mars explorations. Adaptive range genetic algorithm (ARGA) is used for robust airfoil design optimization. Two-dimensional Navier-Stokes solver is used for aerodynamic performance estimation of airfoil design candidates because the viscosity effect is not negligible at the very low Reynolds number flight condition of the airplane.

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2. Formulation of the design problem

The present Mars exploration mission bases on the reference [1]. The objective of the present airfoil design problem is maximization of the lift-to-drag ratio *L/D* at the cruising condition. The cruising Mach number is 0.4735 assuming that the Mars exploration airplane flies 2,000 kilometers in five hours considering the daylight hour on Mars is about 10 hours. The cruising angle of attack of the airfoil is set to two degrees. The Reynolds number is 100,000 based on the Mars air properties and reference length of chord of one meter. Turbulent flow is assumed. No thickness constraint is posed to see pure aerodynamic characteristics.

3. Approach

3.1 Airfoil shape parameterization

Selection of a parameterization technique is an important step for airfoil shape design optimization [3]. Here, the B-Spline curves are used for the airfoil shape parameterization. The parameterization based on the B-Spline has advantages such as 1) second-order derivative is continuous, 2) various airfoil shapes can be expressed with small number of design parameters, and 3) definition of initial design space is intuitive. In this study, nine control points are used to control the B-Spline curves (Fig.1). Because the control points at the leading and trailing edges are fixed, number of the control points to be optimized is six. The design parameters are the x and z coordinates of the six control points. Total number of design parameters is twelve. The airfoil shape represented by the B-Spline curves are modified so that the airfoil shape passes (0,0) and (1,0).

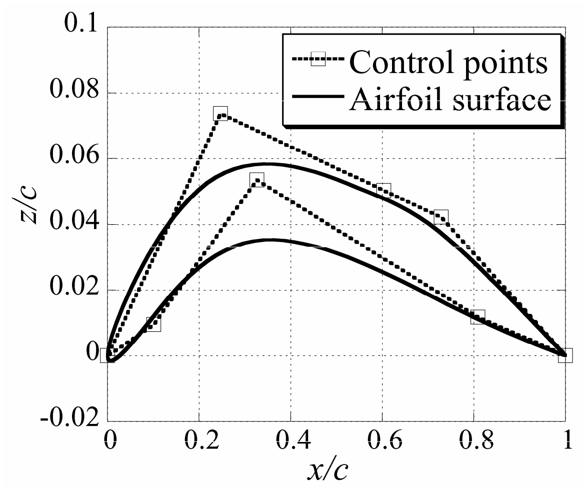

Fig. 1 Airfoil shape parameterization based on the B-Spline curves.

3.2 Evolutionary algorithm

Evolutionary algorithms (EAs) [4] are emergent optimization algorithms mimicking mechanism of the natural evolution, where a biological population evolves over generations to adapt to an environment by selection, recombination and mutation. When EAs are applied to optimization problems, fitness, individual and genes usually correspond to an objective function value, a design candidate, and design variables, respectively. One of the key features of EAs is that they search from multiple points in the design space, instead of moving from a single point like gradient-based methods do. Furthermore, these methods work on function evaluations alone and do not require derivatives or gradients of the objective function. These features lead to the following advantages:

1）Robustness: EAs have capability of finding a global optimum, because they don't use function gradients that direct the search toward an exact local optimum. In addition, EAs have capability to handle any design problems that may involve non-differentiable objective function and/or a mix of continuous, discrete, and integer design parameters.

2）Suitability to parallel computing: Since EAs are population-based search algorithms, all design candidates in each generation can be evaluated in parallel by using the simple master-slave concept. Parallel efficiency is also very high, if objective function evaluations consume most of CPU time. Aerodynamic optimization using Computational Fluid Dynamics (CFD) is a typical case.

３） Simplicity in coupling CFD codes: As these methods use only objective function values of design candidates, EAs do not need substantial modification or sophisticated interface to the CFD code. If an all-out re-coding were required to every optimization problem, like the adjoint methods, extensive validation of the new code would be necessary every time. EAs can save such troubles.

Owing to the above advantages over the analytical methods, EAs have become increasingly popular in a broad class of design problems [5].

In this paper, real-coded Adaptive Range Genetic Algorithm (ARGA) [6] was used. The real-coded ARGA is a robust and efficient EA that is developed by incorporating the idea of the dynamic coding and floating-point representation. The read-coded ARGA solves large-scale design optimization problems very efficiently by promoting the population toward promising design regions during the optimization process (Fig. 2). For detail, see [6].

The present ARGA adopts the elitist strategy [7] where the best and the second best individuals in each generation are transferred into the next generation without any recombination or mutation. The parental selection consists of the stochastic universal sampling [8] and the ranking method using Michalewicz's nonlinear function [9]. Blended crossover (BLX-0.5) [10] is used for recombination. Mutation takes place at a probability of 10% and then adds a random disturbance to the corresponding gene up to 10% of the given range of each design parameter. The population size is kept at 64 and the maximum number of generations is set to 100. The initial population is generated randomly over the entire design space. Evaluation process at each generation was parallelized using the master-slave concept; the grid generations and the flow calculations associated to the individuals of a generation were distributed into 32 processing elements of the ISAS/JAXA SX-6. This made the corresponding turnaround time almost 1/32 because the CPU time used for EA operators are negligible.

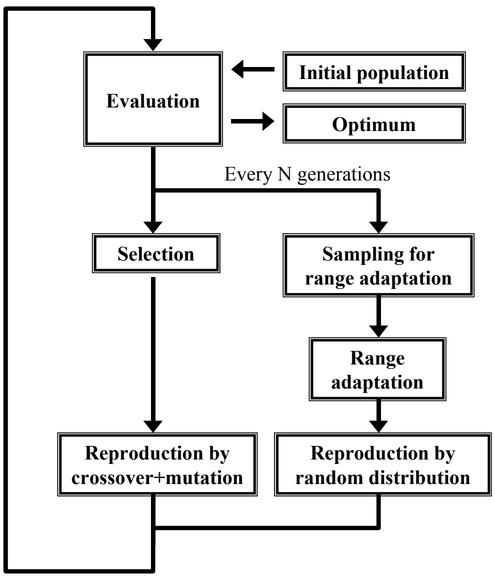

Fig. 2 Flow chart of the real-coded adaptive range genetic algorithm.

3.3 Aerodynamic evaluation

The flow physics can be represented by a wide range of approximations. Although a Reynolds-averaged Navier-Stokes calculation is computationally expensive, the two-dimensional Navier-Stokes equations must be solved for the present aerodynamic airfoil shape design optimization because flows around an airfoil at the present flow condition involve significant viscous effects such as potential boundary-layer separations. In this paper, a two-dimensional thin-layer Reynolds-averaged Navier-Stokes solver is used to guarantee an accurate model of the flow field.

The present grid generator algebraically creates a C-type grid (201 grid points in chordwise direction, 49 grid points in normal direction) for each design candidate. The present Navier-Stokes code employs total variation diminishing type upwind differencing [11], the lower-upper symmetric Gauss-Seidel scheme [12], and Boldwin-Lomax turbulent model. The multigrid method [13] and space variable time step is employed for convergence acceleration.

4. Results

Table 1 present lift-to-drag ratio and lift and drag coefficients of the optimized airfoil at the present design condition (Reynolds number of 10^5). The optimized airfoil achieved very high lift-to-drag ratio of 40.2.

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Table 1 Lift-to-drag ratio and lift and drag coefficients of the optimized airfoil at Reynolds number of 10^5.

Lift-to-drag ratio	***Lift coefficient***	***Drag coefficient***
40.2	***0.977***	***0.0243***

Figure 3 present Mach number and pressure contours of the optimized airfoil. The optimized airfoil shape has very thin airfoil thickness and strong camber. As a result, the optimized airfoil has relatively low pressure on the upper surface and relatively high pressure to produce larger lift while avoiding large flow separation to reduce its drag.

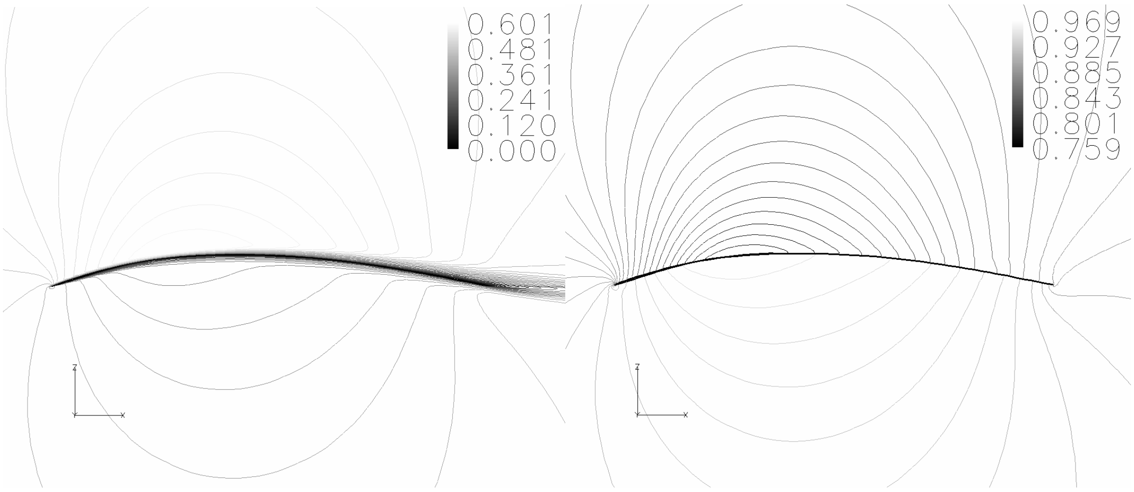

Fig. 3 Mach number (left) and pressure (right) contours of the optimized airfoil shape.

Figure 4 compares the optimized airfoil at Reynolds number of 10^5 (Mars airplane flight condition) and the optimized airfoil at Reynolds number of 10^7 (flight condition of typical airplanes on Earth). While the optimized airfoil for Mars airplane has extremely thin airfoil thickness, the optimized airfoil for typical airplanes on Earth has substantial thickness in the front of the airfoil because a sharp leading edge leads to flow separation near the leading edge in the Earth air. In addition, camber of the airfoil for airplanes for Earth is smaller than that for Mars.

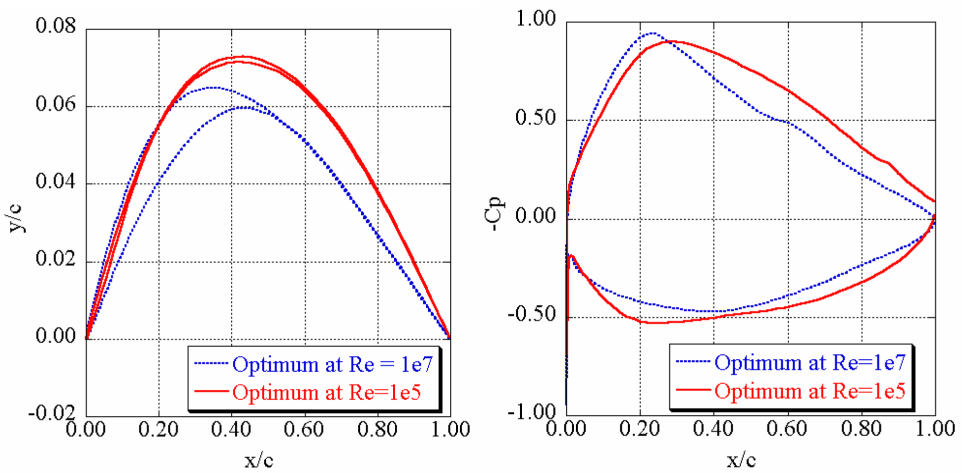

Fig. 4 Comparison of the optimum airfoil shapes and corresponding surface pressure distributions.

Lift-to-drag ratio and lift and drag coefficients of the optimized airfoils are compared in Table 2. The optimized airfoil design at Reynolds number of 10^5 (flight condition of the Mars exploration airplane) has larger drag coefficient and thus smaller lift-to-drag ratio because of the larger viscous drag.

Table 2 Comparison of lift-to-drag ratio and lift and drag coefficients of the optimized airfoils.

	Lift-to-drag ratio	***Lift coefficient***	***Drag coefficient***
Optimum at Re=1e5	***40.2***	***0.977***	***0.0243***
Optimum at Re=1e7	***77.9***	***0.844***	***0.0108***

The above results demonstrated that the optimum airfoil for Mars in terms of aerodynamic performance is different from that for Earth at the present design condition. However, the airplane for Mars exploration will fly at various angles of attack (for example, the angle of attack is different for ascent, cruise and descend) while the angle of attack of the present optimization is fixed at two degrees). To maintain good aerodynamic performance over wide range of angle of attack, larger leading edge radius is required for the Mars exploration airplane. In addition, a practical airfoil for Mars airplane needs sufficient thickness in terms of structural weight, which is a contradicting requirement to aerodynamic optimality. Therefore, a multiobjective design optimization method is required for airfoil design optimization for Mars exploration airplane. The most promising multiobjective design optimization method is probably multiobjective evolutionary algorithms because they can efficiently capture many Pareto-optimal designs enough to reveal the tradeoff information.

4. Summary

In the present study, aerodynamic design optimization of an airfoil for the Mars exploration airplane has been demonstrated by using an evolutionary algorithm. The adaptive range genetic algorithm is used for efficient and robust design optimization. Two-dimensional Navier-Stokes solver is used for accurate aerodynamic performance evaluation. The present computation is parallelized on the SX-6 vector computers in ISAS/JAXA.

The optimized airfoil achieved very high aerodynamic performance. The optimum airfoil for Mars exploration airfoil has extremely thin airfoil thickness and strong camber while an optimum airfoil for typical airplane fly on Earth has substantial airfoil thickness in the front. However, a thin airfoil has disadvantages such as structural weight. The present optimization indicates necessity of multiobjective design optimization for practical airfoil design for Mars exploration airplane.

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