Multi-objective Optimization of Airfoil of Mars Exploration Aircraft using Evolutionary Algorithm

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Abstract

The airfoils of Mars exploration aircraft are designed by genetic algorithm and evaluated by computational fluid dynamics. The objectives of optimization are maximization of lift coefficient and minimization of drag coefficient at the angle of attack of 3 degrees. Reynolds number is carefully set to 2.3×10^4, which is the cruising condition of the aircraft. The present computation is utilized supercomputers FX-1 in Institute of Space and Aeronautical Science (ISAS) / Japan Aerospace Exploration Agency (JAXA).

The results show that two types of airfoil excel in aerodynamic performance. One airfoil with two large cambers which generate separation bubbles at upper surface has large lift coefficient. The other one with a strong camber in the front of under surface has small drag coefficient and fairy large lift coefficient. Most airfoils on Pareto front have thin thickness under 10% of cord. The present optimization indicates the first step of multi-objective design optimization for practical airfoil design for Mars exploration aircraft.

Key words: Optimization, Low Reynolds number flow, Airfoil design

Introduction

Mars exploration aircraft is now being researched by a working group of JAXA/ISAS an Aerospace Exploration Agency/Institute of Space and Astronautical Sciences) and university researchers for the near future multi-objective planet exploration mission called MELOS (Mars Exploration with Lander-Orbiter Synergy). The aircraft type explorer has the advantages in current and previous Martian surface survey; wider area exploration than a rover and closer image capturing than an orbiting satellite [1].

The order of Mars flight Reynolds number is about the range from 10^4 to 10^5 due to ultra low Martian atmospheric density which is an about one-hundredth part of that of the earth. Many researchers have reported that the aerodynamic characteristics on the low Reynolds number flow around airfoil are quite different from that of commercial aircrafts in the earth, which caused by laminar separations and unsteady vortices on airfoil upper surface. Because of this, conventional airfoils of earth aircrafts cannot satisfy the required performance to fly on Mars [2][3][4].

Therefore, the purpose of this study is to find the optimal airfoil in low Reynolds number condition as the first step to design the optimal airfoil for Mars exploration aircraft. The airfoil is designed by genetic algorithm and evaluated by computational fluid dynamics (CFD).

Airfoil Shape Parameterization

The first step of airfoil shape design optimization is the parameterization of airfoil shape. In this study, nine control points and B-spline curves are used for the parameterization (Fig.1). In order to express leading and trailing edges of airfoil, three control points are pegged. The movable points have the x and z coordinated values, which are design parameters. Table 1 shows the upper and lower bounds of control points. Designing airfoil with B-spline curves enables various expression of airfoil shape with small number of design parameters.

Table.1 The Range of Control Points

Design parameter	Upper bound	Lower bound
x1	0.999	0.66
x2	0.66	0.33
x3	0.33	0.001
x4	0.33	0.001
x5	0.66	0.33
x6	0.999	0.66
y1	0.2	-0.2
y2	0.2	-0.2
y3	0.2	-0.2
y4	0.4	-0.05
y5	0.4	-0.05
y6	0.4	-0.05

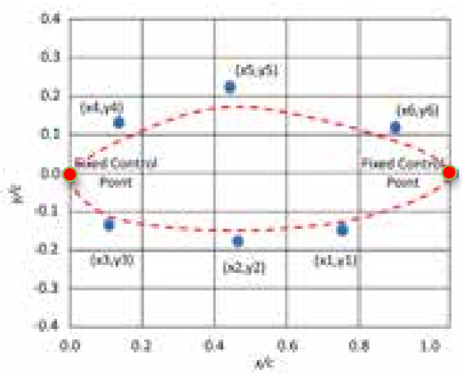


Fig.1 Design Airfoil

Genetic Algorithm

Genetic Algorisms (GA) simulates the mechanism of natural evolution where biological populations which consist of multiple individuals evolves over generations to adapt to an certain environment by genetic operators such as selection and reproduction, and consequently can bear the best individual adapting to the environment (Fig.2) [5].

In recent years, GA has been applied to various design optimization problems because it has some advantages. First, GA can be applied to any design optimization problem. Second, GA can solve optimization problems without any special knowledge of the problems if only the objective and constraint functions are given mathematically. Third, GA can avoid local optimal solutions and find the global optimal solution independently of initial values of solution because GA deals with multiple solutions simultaneously during the optimization process.

In this study, Non-dominated Sorting Genetic Algorithms II (NSGA-II) [6][7] was used. NSGA-II has an outstanding feature that emphasizes population members which are placed a distance from a set of supplied or predefined reference points. That means NSGA-II has advantages for globally search and acquirement Pareto front than any genetic algorithm (Fig.3). Pareto front is some elements that are at least as good on every variable. Blended crossover (BLX-0.7) is used for recombination, and mutation takes place at a probability of 10%. The population size is 20 and the maximum number of generations is set to 20. The initial population is generated randomly over the entire design space. The objective functions of the design optimization problem are maximization of the lift coefficient and minimization of drag coefficient.

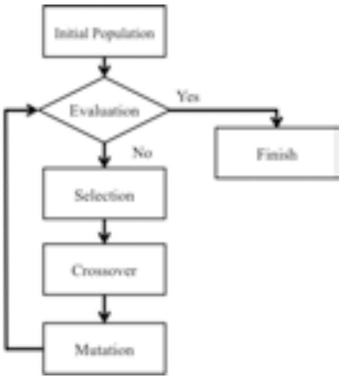


Fig.2 Flow Chart of Genetic Algorithm

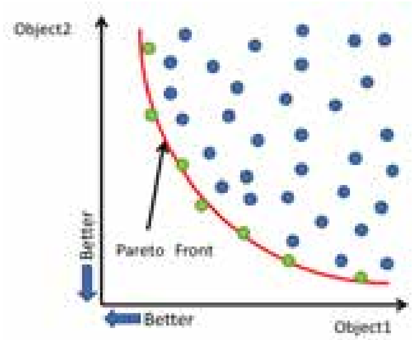


Fig.3 Plato Front

Aerodynamic evaluation

Mach number is 0.2 and Reynolds number is 2.3 × 10^4. The two-dimensional compressible Favre Averaged Navier-Stokes equations are solved for the aerodynamic airfoil shape design optimization. In addition, all flow fields are assumed as laminar flow without turbulence. Angle of attack is 3 degrees.

For each design candidates in the optimal process, the grid generator by algebraic method creates C-typed grid: 497 grid points in chordwise direction, 101 grid points in normal direction.

In addition, in order to judge whether the optimal airfoil has superior aerodynamic performance compared with ready-made airfoil, the Ishii airfoil is also evaluated (Fig.4). Ishii airfoil has a good aerodynamic performance at the low Reynolds number condition from the past experimental studies [2][8][9].

Fig.4 Ishii Airfoil

Results

The plots in figure 5 present non-dominated solutions and dominated solutions with NSGA-II and CFD. The number of non-dominated solutions is 36. In addition, there are 26 airfoils that the lift-drag ratio larger than Ishii airfoil. This figure also indicates that there are two groups with the boundary that lift coefficient is roughly 0.75 in the obtained non-dominated solutions; low drag design region and high lift design region compared with Ishii airfoil (Fig.5).

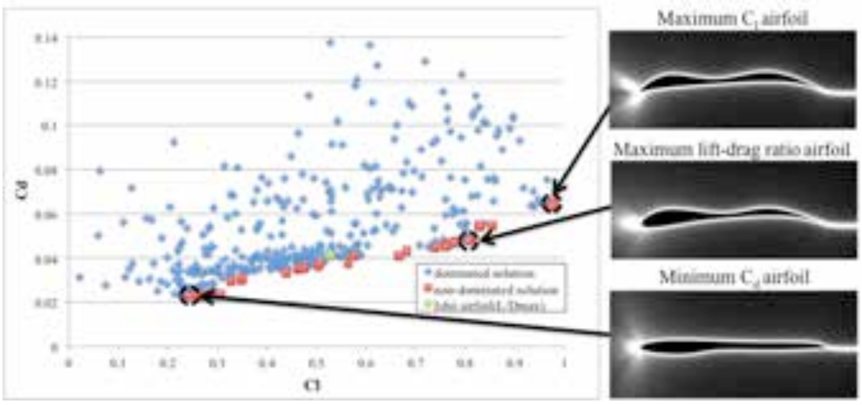
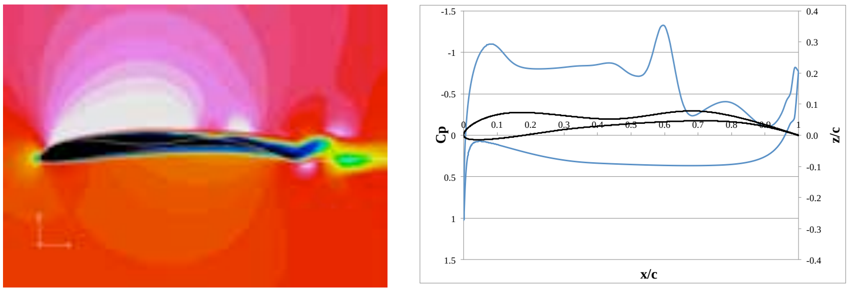
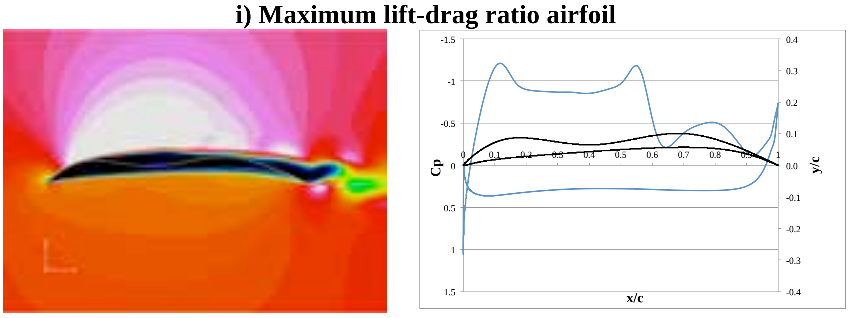


Fig. 5 Distribution of Non-Dominated and Dominated Solutions by NSGA-II

Figure 6 presents the average flow field and surface pressure distributions of typical airfoil in high lift design region. These airfoils have two large convex to generate separation bubbles at upper surface. This is the reason why these airfoils can generate high negative pressure on upper surface. In addition, they have a particular shape like a circular arc airfoil at lower surface and like a flap at trailing edge. The shape produces high positive pressure [10][11]. Table 2 shows aerodynamic characteristics of Ishii airfoil and the some optimized airfoils at the present design condition. The aerodynamic characteristics of Ishii airfoil are calculated by the same computational fluid dynamics as the optimization. The optimized airfoil that has the maximum lift-drag ratio has 30% larger lift-drag ratio than that of Ishii airfoil.



i) Maximum lift-drag ratio airfoil



ii) Maximum lift coefficient airfoil

Fig. 6 Average Flow Field and Surface Pressure Distributions

Table.2

Airfoil	Lift coefficient	Drag coefficient	Lift-drag ratio
Ishii airfoil at maximum lift-drag ratio	0.527	0.042	12.90
Maximum lift coefficient airfoil	0.976	0.065	15.11
Minimum drag coefficient airfoil	0.241	0.023	10.51
Maximum lift-drag ratio airfoil	0.808	0.048	16.88

Almost all of optimum airfoils in small drag design region have characteristic shape like the minimum drag coefficient airfoil (Fig. 7). One of the feature is flat shape on upper surface to moderate laminar separation. This phenomenon brings a good aerodynamic effect in low Reynolds condition [2][9][11].

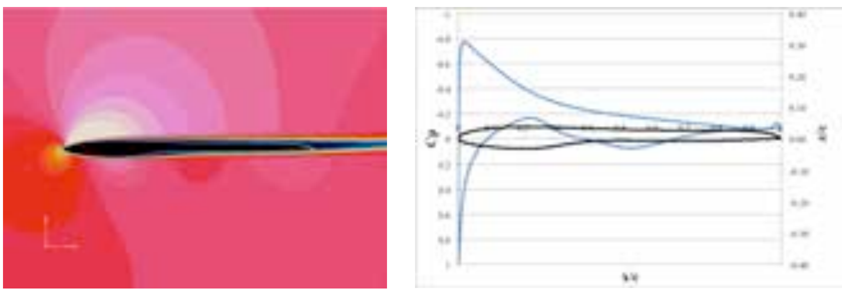


Fig. 7 Average Flow Field and Surface Pressure Distributions of The Minimum Drag Coefficient Airfoil

The other feature is strong camber in the front of under surface. As shown in figure 8, at the point of the strong camber, the pressure of lower surface changes from negative pressure to positive pressure. This phenomenon is also observed the Ishii airfoil [2][8].

Conclusions

This study shows that aerodynamic design optimization of an airfoil in low Reynolds number flow by using a genetic algorithm is effective measure. This is a preliminary research of the optimization of Mars exploration aircraft airfoil so that the optimization was done only the condition of three degrees angle of attack. The population of each generation was only 20; however, some important findings were obtained. 1) There are many airfoils on Pareto front, but some of them can be grouped. 2) Some solutions can be superior to a ready-made airfoil. In the future, the optimization will be conducted for various angles of attack, which will include cruising, ascending, descending and so on.

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