MULTIOBJECTIVE DESIGN EXPLORATION AND ITS APPLICATION TO AN AERODYNAMIC FLAPPING AIRFOIL DESIGN

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Abstract - Aerodynamic knowledge for flapping airfoil is obtained by application of the multi-objective design exploration framework to a multiobjective aerodynamic flapping airfoil design optimization problem, where the airfoil oscillates in plunging and pitching modes. Pareto-optimal solutions are obtained by a multiobjective evolutionary optimization and analyzed with the self-organizing map. Aerodynamic performance of each flapping airfoil is evaluated by a two-dimensional Navier-Stokes solver. Analysis of the flow over the extreme Pareto-optimal flapping airfoils provides insights into flow mechanism for thrust maximization, lift maximization, and required power minimization. Analysis of the design objectives and design parameters with the self-organizing map leads to useful guidelines for practical flapping-wing micro air vehicles.

Nomenclatures

c	= airfoil chord
$C_L(t)$	= lift coefficient
$C_{PR}(t)$	= required power coefficient
$C_T(t)$	= thrust coefficient
h	= plunge amplitude nondimensionalized with c
k	= reduced frequency, $2\pi fc/U_\infty$
t	= time nondimensionalized with U_∞ and c
U_∞	= freestream velocity
$x(t)$	= horizontal position nondimensionalized with c
$y(t)$	= vertical position nondimensionalized with c
$\alpha(t)$	= pitch angle
α_0	= pitch angle offset
α_1	= pitch angle amplitude
ϕ	= phase shift

Subscript

ave	= time-averaged value over one flapping cycle

Introduction

Research interest in flapping wings in aerospace engineering recently increases as flapping wing system may be more suitable for micro air vehicles (MAVs) than fixed wing system at low Reynolds number. For the development of MAV with flapping wing system, understanding of aerodynamic mechanism of a flapping wing for higher aerodynamic performance in terms of lift, thrust, and efficiency is important.

Recently, idea of 'multi-objective design exploration (MODE)' was proposed as a tool to extract essential knowledge from multiobjective optimization problem such as tradeoff information between contradicting objectives and effect of each design parameter on the objectives. In the framework of MODE, Pareto-optimal solutions are obtained by multiobjective optimization using such as multiobjective evolutionary algorithm and then important design knowledge is extracted by analyzing the obtained Pareto-optimal solutions using so-called data mining approaches such as self-organizing map (SOM) and analysis of variance. Obayashi et al. applied the idea of MODE to understand fly-back booster of reusable launch vehicle design and regional-jet wing design and got some practically import design knowledge[1].

The objective of the present study is to extract aerodynamic knowledge on the flapping motion such as 1) tradeoff information between lift, thrust, and required power, 2) effect of flapping motion parameters such as plunge amplitude and frequency. To obtain such knowledge, the MODE framework is applied to a multiobjective aerodynamic design optimization problem of a flapping airfoil for a MAV for Mars exploration where lift and thrust are maximized and required power is minimized.

Design optimization problem

Entomopter, which is a MAV discussed in the United States for future Mars exploration [2], is considered. Entomopter has flapping wing system intending higher lift in extremely low atmospheric density at Mars surface (1/70 that at Earth surface) and take off, landing, and hovering capabilities. This MAV has a span length of 1 [m] and chord length of 0.1 [m]. The wing airfoil is thin with moderate camber and a sharp leading edge to enhance vortex generation. Its cruising speed is more than 10 [km/hour] and flight time of typical mission is 12 minutes. The cruising Reynolds number based on Mars air properties and reference length of the chord is assumed to be 10^3. Note that the results are applicable to MAV on the earth because the Reynolds number is only the non-dimensional parameter that represents Mars atmosphere in this study.

As a first step of understanding flapping wing mechanism, flapping airfoil is considered in this study. The objectives of the present design optimization problem are maximization of the time-averaged lift and thrust coefficients and minimization of the time-averaged required power coefficient at its cruising condition. Constraints are applied on averaged lift and thrust coefficients so that they are positive. The airfoil is assumed to be NACA 0002 airfoil. The flapping motion of the airfoilis expressed by plunging and pitching motions as:

$$x(t) = t \tag{1}$$

$$y(t) = h \cdot \sin(kt) \tag{2}$$

$$\alpha(t) = \alpha_1 \sin(kt + \phi) + \alpha_0 \tag{3}$$

where design parameters are h, k, α_0, α_1, and ϕ.

Approach

Values of the present objective and constraint functions C_L, C_T, and C_{PR} of each design candidate are evaluated by using a two-dimensional Navier-Stokes solver. The Pareto-optimal solutions are obtained by using a multiobjective evolutionary algortihm where fitness of each design candidate is computed according to Pareto-ranking, fitness sharing, and Pareto-based constraint handling. Evaluation process at each generation is parallelized using the master-slave concept; where the grid generations and the flow calculations associated to the individuals of a generation are distributed into 32 processing elements of the JAXA ISAS NEC SX-6 computing system.

A software package called Viscovery SOMine plus 4.0 produced by Eudaptics GmbH is used for data mining. Here, the Pareto-optimal solutions distributed in the present three-dimensional objective function space (C_L maximization, C_T maximization, and C_{PR} minimization) are mapped into nodes on a two-dimensional grid according to the similarity in terms of the objective function values. Then the two-dimensional map colored according to each objective function, each design parameter, propulsion efficiency, and Strouhal number are compared for the knowledge acquisition from the present problem. For more detail of the present approach, see Reference [3].

Results and discussion

In this section, first, flowfield of each extreme Pareto-optimal solution is investigated. Then, objective function values and parameter values of all Pareto-optimal solutions are analised by using SOM.

Analyses of the extreme Pareto-optimal solutions

Flapping motion for maximum thrust

Pressure coefficient distribution around the flapping airfoil for maximum thrust is shown in Fig. 1. This figure indicates that the upstroke produces a strong vortex separated from the leading edge on the lower surface to generate large thrust and the downstroke produces another strong vortex separated from the leading edge on the upper surface for large thrust. While this flapping motion produces thrust in both upstroke and downstroke, averaged lift is small because the vortex generated in upstroke produces negative lift.

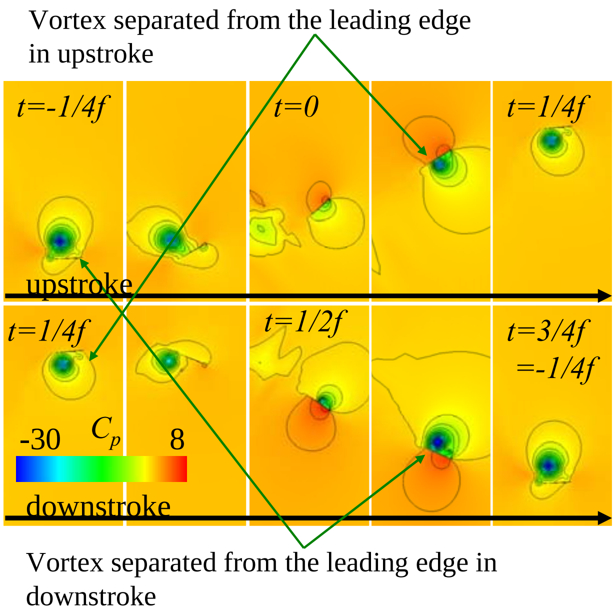

Figure 1 Pressure coefficient distribution around the thrust maximum flapping motion.

Flapping motion for maximum lift

Pressure coefficient distribution around the flapping airfoil for maximum lift is presented in Fig. 2. During the upstroke motion, the airfoil does not generate any large vortex as it would produce negative lift. On the other hand, during the downstroke, the airfoil generates two vortices; one separated from the leading edge and one separated from the trailing edge. It is estimated that as the vortex separated from the trailing edge does not contribute to thrust, the flapping motion for maximum thrust did not generate it.

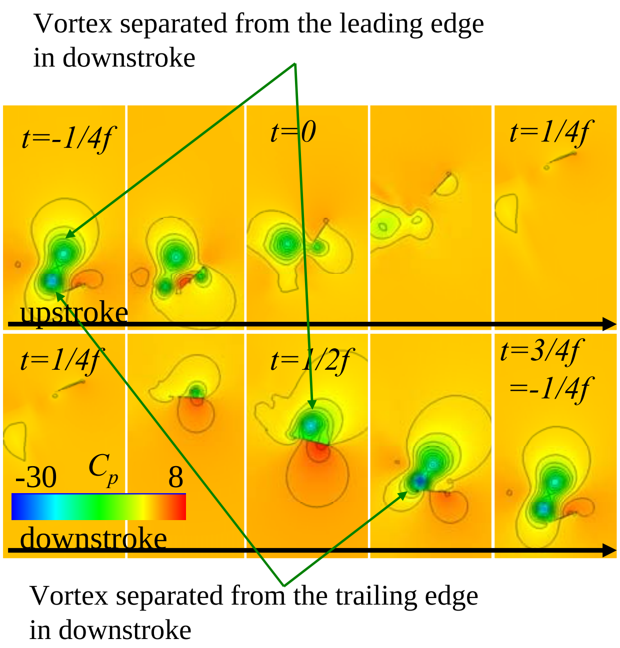

Figure 2 Pressure coefficient distribution around the lift maximum flapping motion.

Flapping motion for minimum required power

Pressure coefficient distribution around the flapping airfoil for minimum required power is presented in Fig. 3. In contrast to the previous extreme flapping motions, this flapping motion does not create any strong vortex in both downstroke and upstroke to minimize the required power.

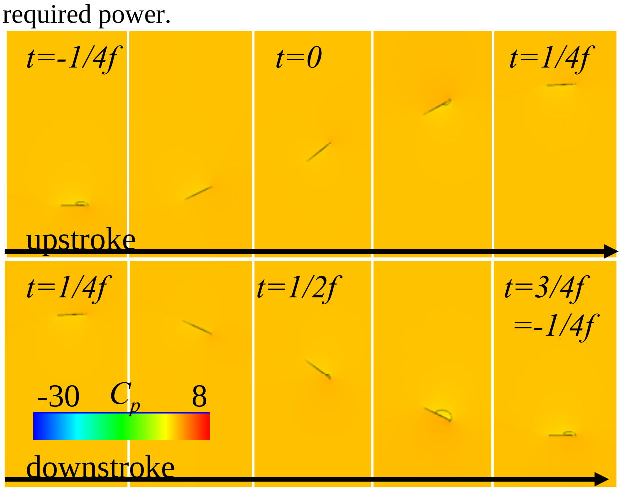

Figure 3 Pressure coefficient distribution around the required power minimum flapping motion.

Data mining using SOM

Figure 4 is the obtained SOM where each node is colored according to each objective function value. Flapping motions for smaller required power are mapped on the right side of the SOM. Flapping motions for large lift are mapped on the lower left and right corners where flapping motions mapped on the lower left corner require large power while those mapped on the lower right corner require smaller power. The flapping motions for large thrust are mapped on the left hand side. These results indicate the tradeoff between the three objectives exists and thus there is no solution that optimizes all three objectives simultaneously. This figure also indicates that maximizing thrust requires more power than maximizing lift.

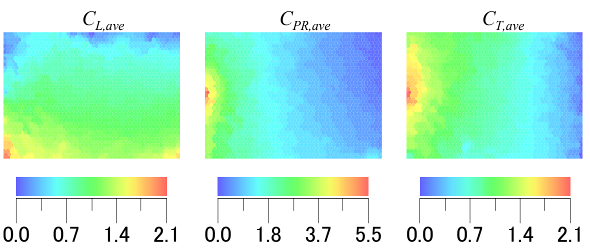

Figure 4 SOM colored according to each objective function.

The same SOM colored according to each design parameter value is presented in Fig. 5. Color range of the map corresponds to the present design range. Comparison between Figs. 4 and 5 gives additional knowledge on the present design optimization problem;

1) Phase shift between plunging and pitch angle cycles of the obtained Pareto-optimal solutions is almost ninety degrees.
2) Pitch angle offset of most Pareto-optimal flapping motions is almost zero except for the flapping motions for high lift. This is understandable as the thrust maximum and required power minimum flapping motion is symmetric while lift maximum flapping motion generates lift only in downstroke.
3) Reduced frequency seems to be a tradeoff parameter between minimization of required power and maximization of lift or thrust where smaller frequency leads to smaller required power.
4) Plunge amplitude of most Pareto-optimal flapping motions reached the upper limit of the present design space. This fact indicates that larger plunge amplitude is preferable when two-dimensional flow is assumed. However, in real flapping wing design, the plunge amplitude is restricted by span length and angle of the flapping wing along the flap arc.
5) Pitch angle amplitude of the most Pareto-optimal solutions distributes between 35 and 45 degrees, which indicates that certain level of pitch angle amplitude is optimum for high performance flapping motion. This figure also indicates that better solutions may have been found if the search space was wider since 45 degrees is upper limit of the present search space of α_1.

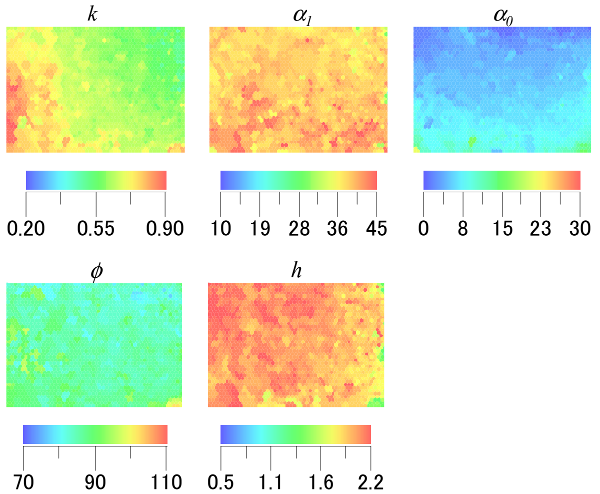

Figure 5 SOM colored according to each design parameter.

Conclusions

The MODE framework has been applied to a multiobjective aerodynamic design optimization problem of a flapping airfoil to obtain aerodynamic knowledge for practical flapping-wing MAV design. To explore the design problem, the Pareto-optimal solutions obtained by a multiobjective evolutionary algorithm were analyzed with the self-organizing map and the time histories of lift, thrust, and required power coefficients and corresponding pressure coefficient distribution of the extreme Pareto-optimal solutions were discussed.

Discussion on the aerodynamics of the extreme Pareto-optimal solutions gave us insight into flow mechanism for thrust maximization, lift maximization, and required power minimization. Analysis of the objective function values of the Pareto-optimal solutions using SOM showed tradeoff between thrust maximization, lift maximization and required power minimization. Analysis of the design variables of the Pareto-optimal solutions using SOM leaded to some knowledge on aerodynamic flapping mechanism.

The present result ensured that the MODE framework coupled with CFD is useful approach for real world design optimization problems. Though the present demonstration was MAV design for Mars exploration, the aerodynamic knowledge extracted from the present study should be useful for designers of flapping-wing MAV for Earth air as long as Reynolds number and cruising speed is almost same.

References

[1] S. Obayashi, S. Jeong, and K. Chiba; Multi-Objective Design Exploration for Aerodynamic Configurations, AIAA Paper 2005-4666, 2005.

[2] A. Colozza, G. Landis, and V. Lyons; Overview of Innovative Aircraft Power and Propulsion Systems and Their Applications for Planetary Exploration, NASA TM-212459, 2003.

[3] A. Oyama, Y. Okabe, K. Fujii, and K. Shimoyama; A Study on Flapping Motion for MAV Design Using Design Exploration, AIAA-2007-2878, 2007.