Aerodynamic Multiobjective Design Exploration of Flapping Wing Using a Navier-Stokes Solver

Yuuki Yamazaki , Akira Oyama, Taku Nonomura, Kozo Fujii, and Makoto Yamamoto

Abstract An aerodynamic design optimization problem of a three-dimensional flapping wing is explored with the multiobjective design exploration framework coupled with a Navier-Stokes solver. The results show that there is a tradeoff among lift maximization, thrust maximization, and required power minimization. The results also show that strong vortex is generated in both down stroke and up stroke motions for thrust maximization while strong vortex is generated only in down stroke motion for lift maximization. This study also reveals effects of the design parameters on the design objectives, for example, pitch offset has positive linear relationship to the lift.

1 Introduction

Research interest in aircraft with flapping wing is now increasing. One reason is that it is more efficient than other type of aircraft at low Reynolds number flight condition. Another reason is that it has hovering, vertical

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·Yuuki Yamazaki
Tokyo University of Science, 1-14-6 Kudankita, Chiyoda, Tokyo, Japan, currently, IHI cooperation, e-mail: yamazaki@flab.isas.jaxa.jp
Akira Oyama
Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo, Sagamihara, Kanagawa, Japan, e-mail: oyama@flab.isas.jaxa.jp
Taku Nonomura
Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo, Sagamihara, Kanagawa, Japan, e-mail: nonomura@flab.isas.jaxa.jp
Kozo Fujii
Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3-1-1 Yoshinodai, Chuo, Sagamihara, Kanagawa, Japan, e-mail: fujii@flab.isas.jaxa.jp
Makoto Yamamoto
Tokyo University of Science, 1-14-6 Kudankita, Chiyoda, Tokyo, Japan, e-mail: yamamoto@rs.kagu.tus.ac.jp

landing, and vertical take-off capabilities. In designing an aircraft with flapping wings, it is important to understand aerodynamics of flapping wings. In reference [1], Oyama et al studied aerodynamic design of a two-dimensional flapping wing using multiobjective design exploration (MODE) framework coupled with a two-dimensional Navier-Stokes solver and obtained some useful information for aerodynamic design of flapping wings. However, it is not clear if the obtained information is applicable to aerodynamic design of three-dimensional flapping wings. Therefore, objective of the present study is to explore an aerodynamic design optimization problem of a three-dimensional flapping wing with MODE framework coupled with a three-dimensional Navier-Stokes solver.

2 Approach

2.1 Design Optimization Problem Formulation

Entomopter, which is an aircraft studied in the United States for future Mars exploration [1], is considered as the reference aircraft. This aircraft has a span length of 1 m and chord length of 0.1 m. Its cruising speed is more than 10 km/h. Based on these specifications, Reynolds number based on the chord length is set to 1,000 and incompressible flow is assumed. Wing aspect ratio is 5 and NACA 0002 airfoil is used as the wing profile. The design objectives are maximization of time-averaged lift and thrust coefficients (C_L and C_T) and minimization of time-averaged required power coefficient (C_{PR}) at the cruising condition. Constraints are applied on the time-averaged lift and thrust coefficients so that they are positive. The flapping motion of the wing is defined by plunging and pitching motions. Plunging angle is expressed by a sine curve as

$$\alpha_{flap} = \theta_f \sin\left(kt - \frac{\pi}{2}\right) \tag{1}$$

where

$$\theta_f = \sin^{-1}\left(\frac{2h}{l_{span}}\right) \tag{2}$$

Pitching angle is also expressed by a sine curve as

$$\alpha_{pitch} = \alpha_1 \sin\left(kt - \frac{\pi}{2} + \phi \right) + \alpha_0 \tag{3}$$

where θ_f, k, h, l_{span}, α_0, α_1, ϕ, t are plunge angle, reduced frequency, plunge amplitude, span length, pitch angle offset, pitch angle amplitude, phase shift and non-dimensionalized time, respectively.

2.2 Computational Method

The present three-dimensional Navier-Stokes solver bases on pseudo-compressible flow simulation approach. The dual-time stepping procedure, which allows an implicit method to be used in real time with the updated solution obtained through sub-iterations in pseudo-time, is employed. The numerical fluxes are evaluated with the Roe scheme where physical properties at the grid interface are evaluated by the MUSCL interpolation based on primitive variables. The viscous terms are evaluated by second-order central differencing scheme. Lower-upper symmetric Gauss-Seidel factorization implicit algorithm is used for the time integration. No turbulence model is used in this simulation. A C-H type computational grid is used where the grid size is 201 (chordwise direction) x 99 (normal direction) x 101(spanwise direction). Computations are impulsively started, and after two cycle of flapping motion, averaged lift, thrust coefficients and required power are obtained in the third cycle of the flapping motion.

A multiobjective evolutionary computation [1] is used to obtain the Pareto-optimal solutions. Population size and number of generations are set to 20 and 13, respectively while size of the initial population is 30. As a result, 290 flapping motions are evaluated.

3 Result

3.1 Data mining of Pareto-Optimal Solutions

Sixty-one Pareto-optimal solutions are obtained in the present computation. Figure 1 is scatter plot matrix of the Pareto-optimal solutions. This figure shows tradeoff relations among maximization of lift and thrust as well as minimization of required power. This figure also indicates some important information for aerodynamic design of a flapping wing such as 1) pitch offset has positive linear relationship to lift, 2) high thrust design should have small pitch offset, 3) pitch amplitude has negative linear relationship to lift, 4) high thrust design should have plunging amplitude of 2.8 (plunge angle of 34 deg.), and 5) phase shift should be greater than 90 degrees to become one of the Pareto-optimal solutions.

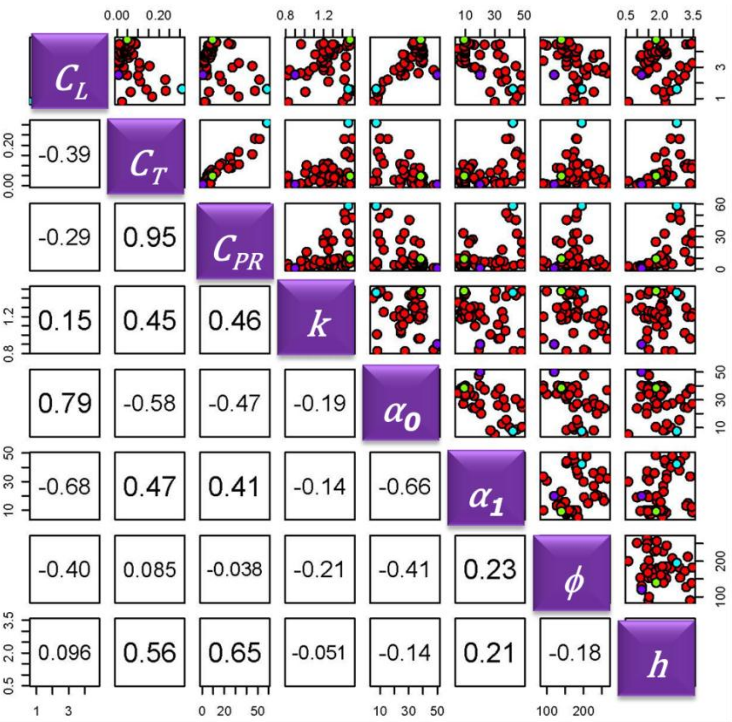

Fig. 1 Scatter plot matrix of the Pareto-optimal solutions

3.2 Analysis of C_L and C_T maximum solutions

The lift maximum and thrust maximum flapping motions are analyzed. Table 1 presents the design parameter values of the solutions. Both solutions maximized the reduced frequency to increase lift or thrust. On the other hand, there is a remarkable difference in pitching motion: while the lift maximum solution has a large pitch offset value and small pitch amplitude value, the thrust maximum solutions has a small pitch offset value and large pitch amplitude value.

Table 1 Design parameter values of the Pareto-optimal solutions

Design parameters	lower limit	C_L max.	C_T max.	upper limit
Reduced frequency	0.8	1.48	1.46	1.5
Pitch offset (deg.)	5	38.4	7.3	50
Pitch amplitude (deg.)	5	9.24	42.3	50
Plunge amplitude	0.5	1.85	2.76	3.5
Phase shift (deg.)	10	140	195	270

Figures 2 and 3 are lift and thrust histories of the lift maximum and thrust maximum solutions. The thrust maximum solution produces significant thrust in both downstroke and upstroke motions though negative lift is generated in the upstoke. On the other hand, the lift maximum solution does not create any significant negative lift in the upstroke motion.

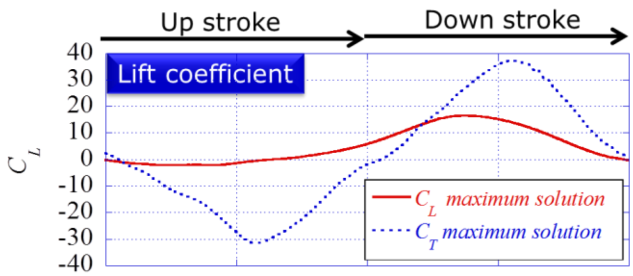

Fig. 2 Lift of the lift maximum and thrust maximum solutions

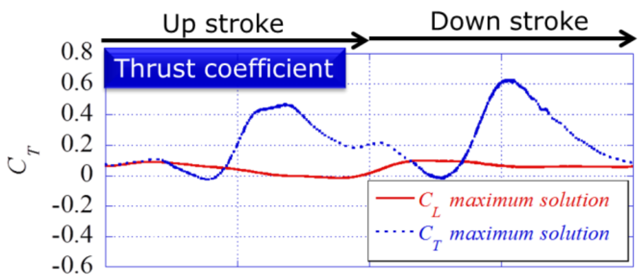

Fig. 3 Thrust of the lift maximum and thrust maximum solutions

Instantaneous flow field and corresponding spanwise lift coefficient distribution of the lift maximum solution in down stroke motion are shown in Fig. 4. The vortex structures are expressed by isosurfaces of the second invariant of the velocity gradient tensor. One of the key features of three-dimensional flapping compared with two-dimensional flapping and is that the wing tip creates strong vortex, which significantly contributes to the lift generation.

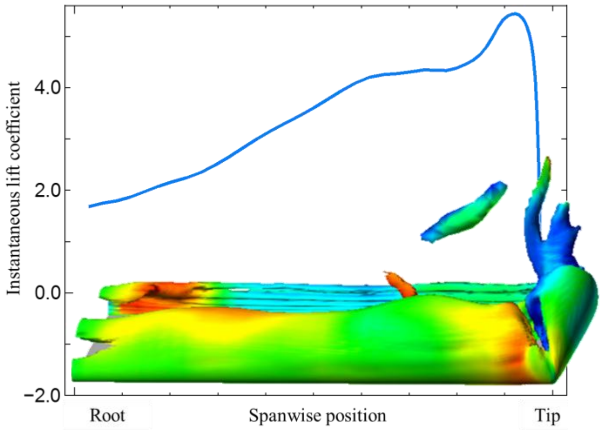

Fig. 4 Instantaneous flow field and corresponding spanwise C_L distribution

4 Summary

An aerodynamic design optimization problem of a three-dimensional flapping wing has been explored with the multiobjective design exploration framework coupled with a Navier-Stokes solver. The results showed that there is a tradeoff among lift maximization, thrust maximization, and required power minimization. The results also showed that strong vortex is generated in both down stroke and up stroke motions for thrust maximization while strong vortex is generated only in down stroke motion for lift maximization. This study also revealed effects of the design parameters.

References

1. Oyama, A., Okabe, Y., Fujii, K., Shimoyama, K. (2009). Aerodynamic multiobjective design Exploration of a flapping airfoil using a Navier-Stokes solver. *Journal of Aerospace Computing, Information, and Communication* doi:10.2514/1.35992.
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