Adaptive pitching motion kinematics for tuning flapping wing aerodynamic performance

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1 Introduction

Recently, vast improvements have been made in the design and manufacturing of fast and manoeuvrable bio-inspired flapping wing micro air vehicles (MAVs). Even the most performant human-engineered vehicles are still far less efficient than their natural counter parts and they suffer from a limited operation time and range. The aerodynamic performance of flapping wing flyers is directly tied to the unsteady vortex dominated flow field generated by their wings. Small changes in the wing kinematics can alter the development and strength of the leading edge vortex, which is a major contributor to the lift generation. Natural flyers automatically adapt their flapping motion kinematics to optimally fit varying flight conditions, which is a highly desirable ability for human-engineered devices.

To find and optimise adapted flapping wing motion kinematics we refer to data driven approaches such as genetic or evolutionary optimisation algorithms which are capable of dealing with a large number of degrees of freedom, interacting parameters, and multiple optimisation criteria. Genetic algorithms repeatedly test individuals of the population in successive generations to identify the fittest according to a predefined objective function. New generations are successively produced through mutation and recombination of the fittest individuals to ensure evolutionary advancement. As each iteration depends solely on the previous one, genetic algorithms are robust in handling experimental optimisations which are inherently prone to measurement uncertainties.

In this study, we present a multi-objective genetic algorithm optimisation to find adaptive kinematics for an experimental flapping wing set-up mimicking hovering flight. The two objectives are maximising the average lift coefficient $\overline{C}_L$ and the hovering efficiency η. The Pareto-optimal solutions are analysed to identify characteristic features that lead to more efficient or more lift producing kinematics. Based on these results, we aim to derive adapted kinematics for arbitrary lift and efficiency requirements.

2 Wing model, kinematics, and optimisation

The flapping wing kinematics of an insect are defined by three Euler angles relative to its body. The sweeping motion of the wing, the stroke, is indicated by the angle ϕ and is the major contributor to the kinetic energy of the wing. The pitch angle α controls the angle of attack of the wing. The impact of the flap or elevation angle θ on the aerodynamic forces in hovering flight is negligible [1]. The elevation angle is kept constant in this study.

The aerodynamics of flapping wing flight are governed by the reduced frequency k and the Reynolds number Re. For a stroke frequency $f = 0.25\,\text{Hz}$, a peak-to-peak stroke amplitude $2\phi = 180°$, and the geometric parameters of the wing outlined in [2], a reduced frequency of $k = 0.37$ and a Reynolds number $Re = 2450$ are obtained. These values are comparable to insects like the honeybee or hawkmoth [3].

The stroke kinematics are represented by a sinusoidal function and remain unchanged in the optimisation. The pitch angle evolution $\alpha(t)$ is characterised by a sum of polynomial functions with 7 parameters and is the subject of the genetic algorithm optimisation. A detailed description of dynamic scaling and the kinematic functions for the optimisation process can be found in [2]. The objectives in the genetic algorithm optimisation are the average lift coefficient $\overline{C}_L$ and the hovering efficiency η:

$$C_L = \frac{L}{\frac{1}{2}\rho Rc\overline{U}^2}, \quad C_P = \frac{P}{\frac{1}{2}\rho Rc\overline{U}^3}, \quad \eta = \frac{\overline{C}_L}{\overline{C}_P} \quad . \tag{1}$$

The lift L and aerodynamic power P are determined from force and torque measurements and normalised using the stroke average velocity $\overline{U}$.

3 Results

The genetic algorithm optimisation on the experimental setup advances towards the final Pareto optimal solution after about 10 generations. From there, the Pareto front fluctuates in a small band and only minor improvements are made. The mean lift production for the solutions along the Pareto front of the 41st and final generation range from $\overline{C}_L$ =4.81 to 8.37. The efficiency ranges from η =0.34 to 0.65. The efficiency of the flapping wing system can be increased by 93% by trading off 43% of the total lift at the extremities of the objective space (Figure 1a).

The resulting pitch kinematics α, lift coefficient C_L, and power coefficient C_P over one stroke cycle for the final generation are presented in Figure 1b-d. Three selected solutions within the Pareto front are highlighted in colour. The shape of the pitching kinematics that yield the highest mean

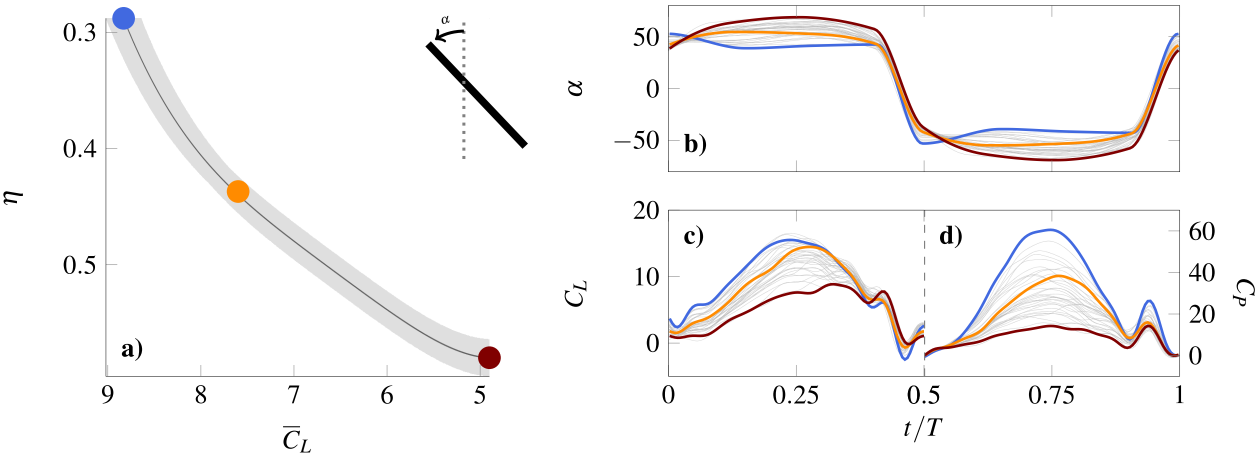

Figure 1: a) Converged Pareto front envelope, b) pitch angle kinematics α, c) lift coefficient C_L and d) power coefficient C_P for one stroke period T. Selected individuals are highlighted in colour.

lift closely resembles a trapezoidal profile with an additional peak right on top of the ascending flank at the start of the stroke cycle ($t/T = 0$). The plateau of the trapezoid lies at $\alpha = 40°$ leading to an effective angle of attack of 50° for most of the stroke period. At stroke reversal, α briefly overshoots to 52°. Moving towards more efficient solutions on the Pareto front, the pitch kinematics become more sinusoidal and the amplitude increases reaching $\alpha = 69°$ for the most efficient individual. High amplitude of α implies a low angle of attack for the flapping wing.

For the highest lift achieving solution (Figure 1c in blue), C_L matches the sinusoidal stroke motion as reported in the past by numerous experimental and numerical studies for hovering flight. Right before stroke reversal, at $t/T = 0.42$, lift peaks due to rotational acceleration and wake-capture for all individuals. For the more efficient solutions depicted in orange and red, the lift amplitude decreases with increasing efficiency and the maximum is reached later in the flapping cycle. The power coefficient C_P in Figure 1d also follows a sinusoidal evolution and peaks before stroke reversal, similar to the C_L history. The power coefficient is more sensitive to changes in the pitch kinematics. For the lift optimised solution, the power coefficient can reach an amplitude 4 times higher than for the efficiency optimised kinematics.

The general effects of these pitch angle variations on the aerodynamic forces have been explained based on velocity flow field measurements for optimal lift and efficiency kinematics separately in [2]. For optimal lift production, the higher angle of attack over large portions of the stroke cycle leads to the development of a large leading edge vortex contributing to the lift production but also imposing a strong drag component which leads to reduced η. For optimal efficiency, the leading edge vortex is reduced in size and strength leading to improved hovering efficiency due to a lower power consumption $\overline{C}_P$.

In addition to the individually optimised solutions from our previous study, we now obtained an ensemble of solutions along the Pareto front which indicates that the most desirable solutions are not at individually optimised ones as the trade-off in lift or efficiency to obtain the optimal efficiency or lift is very high. In the central portion of the front, the lift to efficiency ratio is linear allowing for a smooth transition between different flight states. This is the interesting area for MAV control applications.

4 Conclusions

A Pareto front representing a family of optimal solutions for different flight envelops was experimentally determined for a flapping wing system in hover. The trade-off between $\overline{C}_L$ and η is non-linear and maximising the lift production causes a substantial loss in hovering efficiency. This can be attributed to the increasingly demanding power requirements to further enhance the average lift production along the solutions on the Pareto front. For each set of objective parameters, lift coefficient vs. efficiency, adaptive pitch kinematics can be found directly or by interpolation between two nearby solutions of the motion kinematics on the Pareto front. Future studies will include an optimisation of the full pitching and yawing kinematics to obtain adaptive manoeuvrability and control of the transition between flight states.

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