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Numerical simulation of a flapping four-wing micro-aerial vehicle

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ABSTRACT

A three-dimensional numerical simulation of a four-wing (two wings on each side, one on top of another) flapping micro-aerial vehicle (FMAV), known as the Delfly micro, is performed using an immersed boundary method Navier–Stokes finite volume solver at Reynolds numbers of 5500 (forward flight condition). The objective of the present investigation is to gain an insight to the aerodynamics of flapping wing biplane configuration, by making an analysis on a geometry that is simplified, yet captures the major aspects of the wing behavior. The fractional step method is used to solve the Navier–Stokes equations. Results show that in comparison to the Delfly II flapping kinematics (a similar FMAV configuration but smaller flapping stroke angles), the Delfly-Micro flapping kinematics provides more thrust while maintaining the same efficiency. The Delfly-Micro biplane configuration generates more lift than expected when the inclination angle increases, due to the formation of a uniform leading edge vortex. Estimates of the lift produced in the forward flight conditions confirm that in the current design, the MAV is able to sustain forward flight. The potential effect of wing flexibility on the aerodynamic performance in the biplane configuration context is investigated through prescribed flexibility in the simulations. Increasing the wing' spanwise flexibility increases thrust but increasing chordwise flexibility causes thrust to first increase and then decrease. Moreover, combining both spanwise and chordwise flexibility outperforms cases with only either spanwise or chordwise flexibility.

1. Introduction

The Delfly-Micro (DFM) is a flapping wing micro-aerial vehicle (FMAV) developed at the Delft University of Technology (De Croon et al., 2009). It is the latest addition to the Delfly family of ornithopters, which so far consists of the Delfly I and II, with a wingspan of 50 and 28 cm respectively, as shown in Fig. 1.[1] The DFM, the smallest of the three, weighs only 3 g and has a wingspan of 10 cm, making it the smallest flying ornithopter carrying a camera.

The unique feature of the Delfly MAVs, which differentiate them from other FMAVs (see e.g. Keennon et al., 2012; Pornsin-sirirak et al., 2000) is that they have two pairs of wings, one on top of the other, instead of one (biplane flapping configuration). It therefore generates more thrust compared to a single pair of wings, and gives minimal rocking amplitude (vertical oscillation, perpendicular to the FMAVs flight path), which is a beneficial property for FMAVs to be used as a camera

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[1] More information can be obtained from http://www.delfly.nl.

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0889-9746/

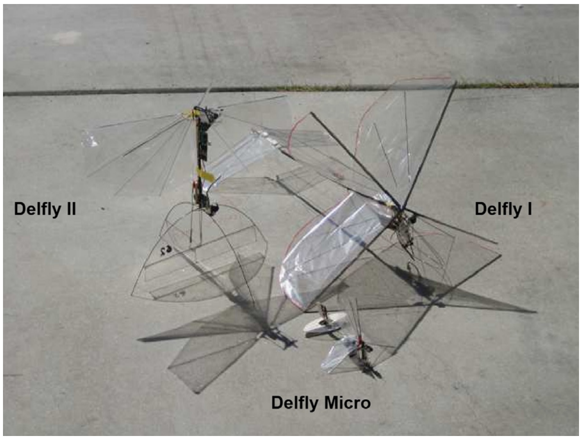

Fig. 1. Different versions of Delfly: I (right), II (left), Micro (middle).

Table 1
Parameters of the DF2 and DFM under typical forward flight conditions.

	Wingspan (cm)	Wing root chord (cm)	Forward speed (m/s)	Re	Stroke angle (deg)	Flapping frequency (Hz)
DF2	28.0	8.1	7.0	36,000	22.0	11.0
DFM	10.0	2.89	3.0	5500	25.5	37.5

platform. Due to the close distance between the upper and lower wings during the instroke, an important lift enhancing mechanism known as the clap-and-peel motion (Ellington, 1984) is active. This motion, which is actually a variant of the clap-and-fling motion (Weis-Fogh, 1973) known from insect flight, further helps to improve the thrust generation.

Of the three Delfly models, the Delfly II (DF2) is the most established and well-documented platform as a substantial number of experiments and simulations has been performed upon this configuration. Tay et al. (2014) used the immersed boundary method (IBM) (Mittal and Iaccarino, 2005) to perform numerical simulations on a simplified DF2 model in forward-flight configuration with either rigid wings or with a prescribed spanwise deformation at Reynolds number (Re) of 1000 and 5000. It was shown that the biplane wing configuration produces more than twice the average thrust of only the equivalent upper wing of DF2, confirming the thrust enhancing effect of the wing interaction. However, DF2's average thrust is only 40% of that of the upper wing when it is made to flap at twice the stroke angle amplitude (θ_0), which indicates the potential for thrust enhancement by increasing the stroke angle. Although the latter result indicates that larger thrust can be generated by using, instead of the two pair of wings, only a single pair of wings flapping over the full stroke angle, the increased stability due to the DF2's smaller lift and moment variation makes it more suited as a camera platform. For that reason, the DFM retains the biplane configuration, but with an increased stroke angle for increasing the lift. The study further revealed that increasing the body inclination angle generates a spanwise uniform LEV instead of a conical one along the wingspan, which is accompanied by higher lift. Lastly, increasing the spanwise flexibility of the wings increases the thrust slightly but decreases the efficiency.

In comparison to the extensive analysis (numerical and experimental) of the DF2 configuration, to the best of the authors' knowledge, there are only two studies specific to a flapping wing MAV of a configuration comparable to the DFM. A hummingbird-inspired, flexible wing FMAV developed by Nakata et al. (2011), which is very similar to the DFM, formed the subject of a combined numerical and experimental study. In the numerical flow simulation, an overset solver was applied for simulating the FMAV under hovering conditions. A strong negative pressure region associated to a leading edge vortex (LEV) was found on the upper and lower wings during both of the half strokes. In the experimental investigation, Nakata et al. performed wind tunnel experiments on their FMAV under forward flight conditions. It was found that the biplane wing configuration may or may not be better compared to the single wing pair configuration. The former generated twice as much lift compared to the latter configuration at body inclination angles larger than 40°. But if softer Mylar wings were used in the single wing pair configuration, it generated more lift at body inclination angles larger than 30° compared to the biplane wing configuration. Deng et al. (2013) performed experimental investigation on the DFM by measuring the force generated and studying the effect of wing flexibility. Results show that while a relatively rigid wing can produce more force, but at a lower efficiency. Sustained flight at 2–3 m/s is possible at a flapping frequency 28–34 Hz and angle of attack between 25° and 36°.

As mentioned earlier, despite similarities in terms of appearance between DF2 and DFM, there are several differences between the two FMAVs, as documented in Table 1. Being much smaller, DFM's Re is only 5500 (based on forward speed and chord length), indicating that its flow field is mostly laminar, whereas for DF2, Re is about 36 000 and the flow is likely to be transitional. Due to the larger flapping stroke amplitude, the wings of the DFM touch one another not only during the