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Aerodynamic characterization of 'DelFly Micro' in forward flight configuration by force measurements and flow field visualization

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Abstract

This study explores the flow structures and unsteady force generation mechanisms of a flapping-wing micro air vehicle 'DelFly Micro' in forward flight configuration. Stereoscopic Particle Image Velocimetry (Stereo-PIV) measurements were performed to acquire three dimensional flow fields in the wake. Six components of forces and moments were captured simultaneously by use of a miniature force sensor.

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Keywords: flapping-wing MAV; DelFly Micro; aerodynamic force; wake flow topolygy

1. Introduction

Micro Air Vehicles (MAVs) have become one of the most intriguing subjects for researchers from different disciplines particularly in the last decades due to their potential use in military and civil applications such as reconnaissance, surveillance and exploration in hazardous and inaccessible areas for human[1]. Flapping-wing MAVs, which take inspiration from natural flyers like birds and insects, offer intriguing configurations with promising features to be exploited for the aforementioned tasks. Flapping-wing MAV is considered to be aerodynamically efficient in terms of force generation through unconventional unsteady aerodynamic mechanisms, such as delayed stall [2], wake capture [3] and clap-and-fling [4].

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The Delft University of Technology has started to develop a new generation of flapping-wing MAVs in 2005[5], this project combined different disciplines, such as mechanics, materials, aerodynamics, electronics, stability and control in order to achieve a successful ornithopter. As a result, a series of flapping-wing MAVs, namly DelFly [5], has been successively developed following a top-down approach. In each of the DelFly designs, there are two pairs of wings, mounted on each side of the fuselage and each wing pair flaps in counter-phase. The DelFly Micro [6], see Fig. 1, is the smallest member in the DelFly family, which weighs only 3 g and has a flat wing span of 10 cm. These features make it the smallest ornithopter in the world with a camera on board. The DelFly Micro is an ideal platform for investigating both the aerodynamics and autonomy of small flying robots. Although being relatively small in size, the flow field around and in the wake of flapping wings is quite complex in terms of behavior of vortical structures and better understanding of the aerodynamic phenomena can contribute to further improvement and optimization of the MAV designs.

Previous studies [7, 8] have defined the flight envelop of DelFly Micro. The effects of wing flexibility, aspect ratio and flapping frequency on aerodynamic force production have been revealed. Moreover, the wake of DelFly Micro flapping wings in hover was experimentally visualized by PIV measurements. This study investigated the aerodynamic characteristics of the DelFly Micro in the forward flight configuration by use of simultaneous wake flow field and force measurements.

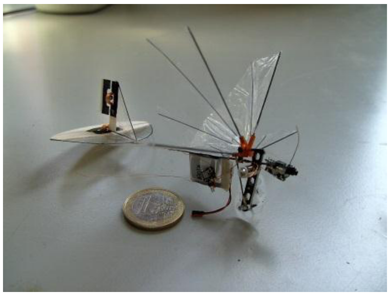

Fig. 1 DelFly Micro.

2. Experimental Set-up

2.1. Experimental model and wind tunnel

A DelFly Model without tail was used in the measurement as the experimental model. The flapping motion was driven by a 0.6 g brushless DC motor and controlled by an in-house built micro-controller system that also synchronized the flapping motion with the PIV and force measurement. The flapping frequency was varied between 20Hz and 30Hz with an increment of 5 Hz. The wings were built from 5 μm Mylar foil and stiffened by thin carbon rods to achieve the desirable flexibility distribution. The experiments were conducted in a low speed wind tunnel at the Aerodynamic Laboratory of DUT. The wind tunnel has an open test section with cross-section of 600 mm × 600 mm, which is large enough to prevent any interaction between the free shear layer from the nozzle exit and the tested model. The free-stream velocity was set at 2 m/s, which is a typical value in the forward flight of DelFly Micro [7]. The DelFly model was mounted on a miniature six-component force sensor (ATI Nano-17 Titanium) to record the instantaneous forces and moments with a date acquisition frequency of 10 kHz. Simultaneously, also the current and voltage fed to the driving motor were also logged to evaluate the power consumption of the motor.

2.2. Stereoscopic-PIV

A field of view of 160 mm × 160 mm was captured with two CMOS-cameras (Photron Fastcam SA 1.1) with a resolution of 1,024 × 1,024 pixels. The cameras were equipped with 60 mm focal length lenses and mounted with Scheimpflug adapters. For each test, 300 double-frame images were captured with an image recording rate of 300

Hz, which allowed acquisition of sufficient number of flapping cycles for ensemble averaging. The laser light sheet was aligned in the span-wise direction, which is normal to the free stream. The measurement planes was positioned at 20 mm downstream from the trailing edge of the wings. Two cameras were positioned on both sides of the DelFly model (see Fig. 2) to capture the entire area in the wake. An independent camera was positioned in front of the test model for monitoring the flapping stroke. The field of view was illuminated by a double pulse Quantronix Darwin (Nd: YLF) laser. A SAFEX fog generator was used to produce water-glycol based fog of droplets with a mean diameter of 1 μm, which are used as the tracer particles in the measurements. The PIV data are captured and analyzed by LaVision DaVis (8.2.0) software. For the image interrogation, a multi-pass stereo cross-correlation was used (96 × 96 and 64 × 64 with 50% and 75% overlap respectively).

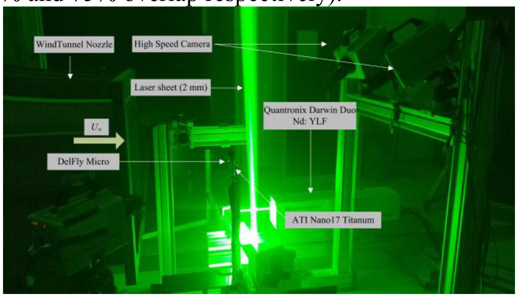

Fig. 2. Experimental setup.

3. Results

3.1. Aerodynamic forces

The measured forces were filtered using a Chebyshev II type low pass filter to keep the first five harmonics as suggested by previous studies [7]. Fig. 3(a) depicts the thrust generation for different flapping frequencies, alongside with the temporal variation of the upper wing phase angle (black line) in one flapping cycle, with the free stream set at 2 m/s. Note that due to the construction of the driving mechanism, the flapping cycle is not exactly symmetrical. The instroke phase occupies around 45% of the entire flapping cycle, which results from a faster velocity and higher acceleration of the wing motion during the instroke with respect to the outstroke. This asymmetry is also reflected in the force generation. Two thrust peaks different in magnitude are present in each flapping cycle. The lower peak occurs at approximately the middle of the instroke, while the higher one peaks after the onset of the outstroke. Increasing the flapping frequency is seen to significantly increase the thrust force production. The force generation curves for each case are nearly in phase with each other, except for a small shift which might be caused by the flexibility effects due to different levels of flapping acceleration. As is expected, the power consumption increases with flapping frequency and thus follows the same trend as the thrust force, as shown in Fig. 3 (b).

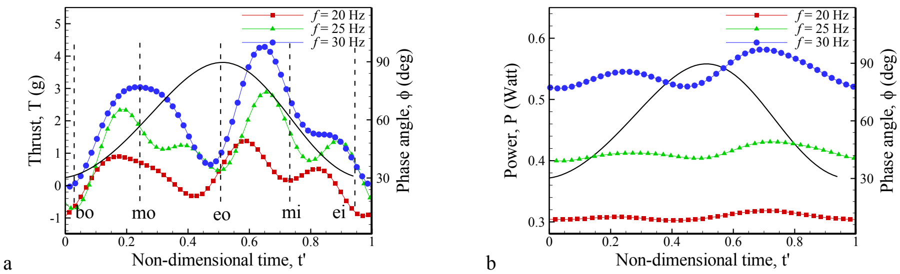

Fig. 3 Thrust generation and power consumption of DelFly Micro; the thrust is defined as the force component in the opposite direction of the free stream; the time-marks: bo (beginning of outstroke), mo (mi of outstroke), eo (end of outstroke), mi (mid of instroke), ei (end of introke).

3.2. Wake topology

The behavior of the flow structures associated to a certain event during the flapping motion, such as clap-and-fling, introke and outstroke, can be visualized by making use of a convection model (Taylor's hypothesis[9]) and performing a spatial-temporal wake reconstruction. This implied that the data of the measurement plane is translated with the free-stream velocity($\Delta x = U\infty \cdot \Delta t$ where Δt is the time difference between the image pairs) to reconstruct three-dimensional wake of the flapping wings.

Fig. 4 shows the wake topology of the DelFly Micro flapping at 20 Hz in a free-stream flow of 2 m/s. Three-dimensional vortical structures were visualized by isosurfaces of Q-criterion, which are colored by the stream-wise vorticity component. The wake reconstruction was performed for two flapping cycles. It is clear that there are two major structures involved in each flapping cycle: (1) an arc shaped vortex formation (region 1 in Fig.4b)) generated during the outstroke phase and sheds at the end of the fling motion; (2) a U-shaped flow structure formed in the instroke phase and sheds at the end of clap motion (region 2 Fig.4b)). These two structures are linked to each other at the end of instroke. A small gap without any vortex activity is observed after the end of instroke, which is caused by the wings being momentarily stationary and parallel to each other. At the beginning of outstroke, mainly drag is generated, which is a result of small rotational velocity of the wings and thus diminished strength of the flow structures. Moreover, the wings do not display large deformations at this moment, therefore, vortical projection of the wing surface, which works as the suction area in the generation of thrust, is relatively small. Moving to the middle of the outstroke, the wings are half way open, the arc shape structure is formed as a result of formation and interaction of tip vortices emanating from upper and lower wings. In addition to this, increasing wing deformation brings in an increased effective angle of attack and a peak in thrust generation, as shown in Fig. 3. Again, there is no thrust generated at the end of the instroke, which changes in increasing manner after the stroke reversal. The thrust reaches its maximum when the wings clap are approximately in the middle of the instroke. This indicates that the deformation caused by a fast moving wing motion provides a higher effective angle of attack and large vertical suction area those boost the force generation.

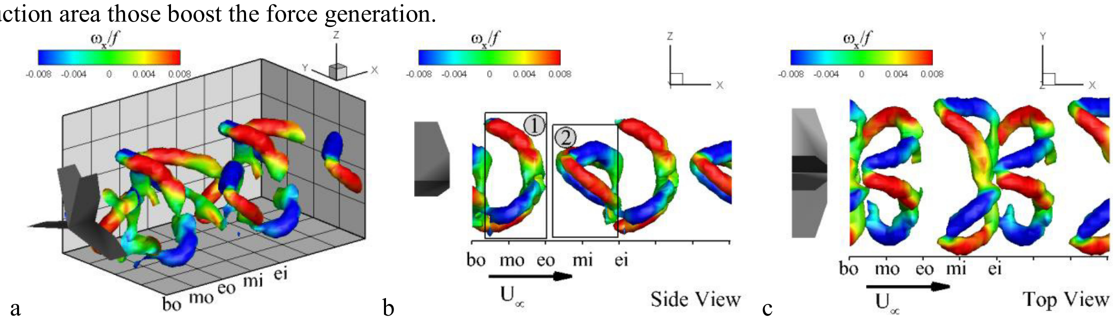

Fig. 4. Vortex wake of DelFly Micro for two flapping cycles, reconstructed from a series of PIV images captured at 2 cm downstream from the trailing edge with flapping frequency at 20 Hz and free stream velocity at 2 m/s; Ensemble averaging was performed over 5 flapping cycles. Isosurface of Q = 0.006 are coloured by the normalized stream-wise vorticity, i.e.w_x/f.

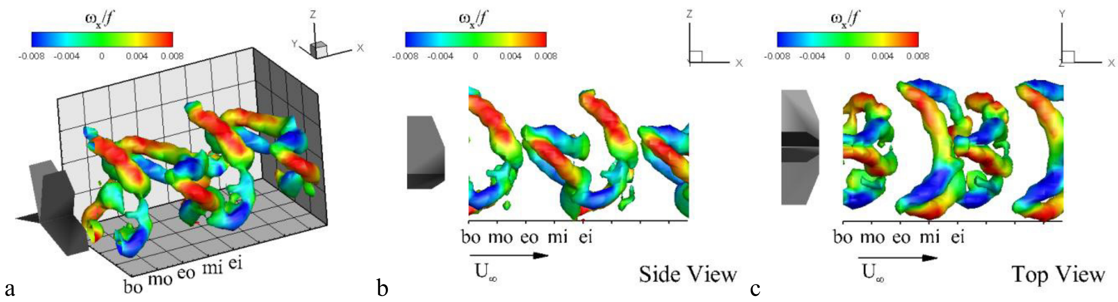

Fig. 5 Wake structure of DelFly Micro. Isosurface of Q = 0.006 colored with w_x/f for flapping at 25 Hz with 2 m/s free stream.

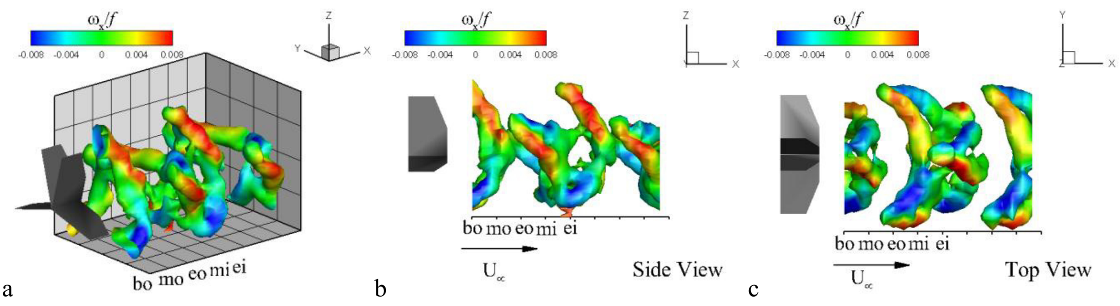

Fig. 6. Wake structure of DelFly Micro. Isosurface of Q = 0.006 rendered with w_x/f for flapping at 30 Hz with 2 m/s free stream.

In order to examine the effect of flapping frequency, the reconstructed wake for flapping frequency of 25 Hz and 30 Hz are plotted in Fig. 5 and Fig. 6, respectively. Note that the wake reconstruction was performed for two flapping periods for high flapping frequency cases. When compared to the wake structures of 20 Hz case, the higher frequency cases display nearly the same flow topology, except that the wake structure is compressed in stream-wise direction that is a natural results of increasing reduced frequency. The gap between the flow structures of the instoke and the outstroke becomes smaller with the frequency.

4. Conclusions

In the present paper, aerodynamic characteristics of a flapping wing MAV 'DelFly Micro' was investigated experimentally in forward flight configuration by means of force and Stereo-PIV measurement. The effect of flapping frequency on force generation, power consumption and flow topology is examined. The results revealed that thrust generation and power consumption increase with the increasing frequency. Three-dimensional wake of the flapping wings are reconstructed by use of a convection model based on Taylor's hypothesis on the data of the measurement plane. The formation of the vortical structures throughout the flapping cycle were visualized and associated with the temporal variation of forces.

Acknowledgements

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