WINGTIP TRAJECTORY OF A FLAPPING MICRO-AIR-VEHICLE IN ITS FORWARD FLIGHT

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Summary A point-mass vibration model is conducted to describe the wingtip motion of a flapping micro-air-vehicle (MAV). The unsteady lift and net thrust are synchronously simulated from the real measurement of a flapping MAV in the wind tunnel. The figure-of-8 wingtip motion pattern confirmed by this model agrees with the real gesture of this 20 cm-span MAV during its forward flight in a qualitative manner. The corresponding fluid structure interaction and the important dimensionless parameter are also addressed.

INTRODUCTION TO FLAPPING MAVS

In ICTAM 2012, the author reported the figure-of-8 flapping gesture of "Golden Snitch" in Fig. 1 [1]. "Golden Snitch" is a 20 cm-span flapping MAV developed at Tamkang University since 2008 [2]. The total body mass of it ranges from 5.9 to 11 gram and the maximum flight endurance is 8 min. With the flexible wing frame structure and its intrinsic nature of aero-elastic behaviour, "Golden Snitch" exhibits the oblique figure-of-8 flapping pattern shown in Fig. 2.

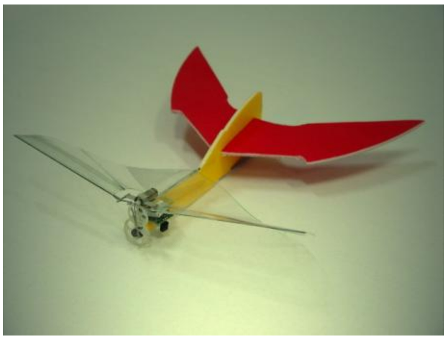


Fig. 1. The 20 cm-span flapping MAV "Golden Snitch"[2].

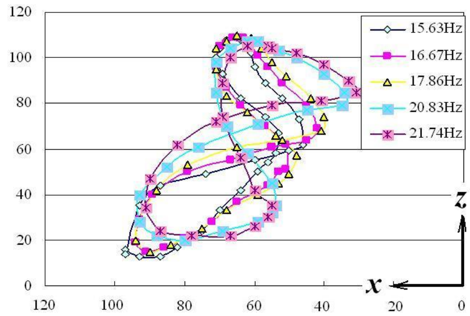
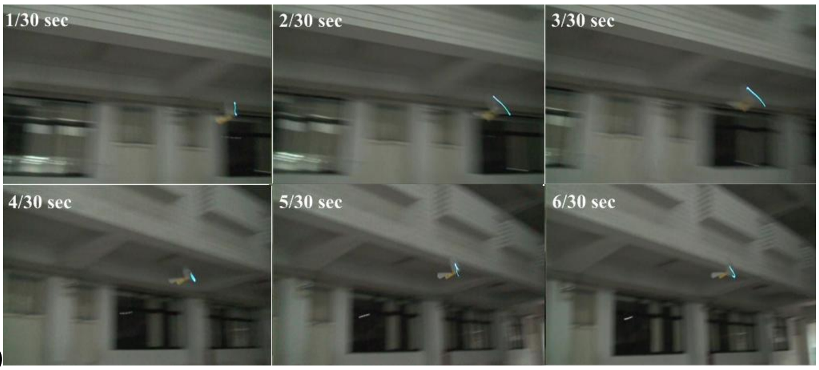


Fig. 2. Figure-of-8 wingtip trace of "Golden Snitch"[1,3].

Figure-of-8 flapping images enhanced by wingtip LEDs

The first generation of figure-of-8 is captured from a stationary MAV on the ground by a high-speed camera [1]. Again, the author installed a LED die at the wingtip of the flapping MAV as the illuminating marker. And he used a simple DV to take the dynamic image of the wingtip trajectory during the real forward flight of the MAV in Fig. 3. By subtracting the contribution from the forward flight speed, the dynamic trace pattern in Fig. 3 is supposed to being qualitatively similar to the ground-based experiment result of Fig. 2. The figure-of-8 is no doubt confirmed by experiments [1-3].

(a)


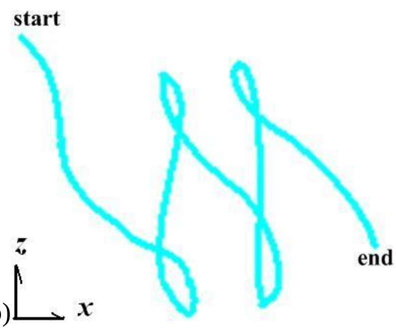
(b)


Fig. 3. The flying "Golden Snitch" illuminated by LEDs: (a) Successive pictures; (b) Wingtip trace.

THE POINT-MASS VIBRATION MODEL

The point-mass vibration model with 2 degrees of freedom

Herein, the author tried to conduct a concise point-mass model with two degrees of freedom (DOF) for describing the dynamic motion of the MAV wingtip as Eq. (1).

$$\begin{aligned} \ddot{z} + \omega_z^{\,2} z &= [W - L(t)]/M = [W - f_z(\omega t + \phi_z)]/M \\ \ddot{x} + \omega_x^{\,2} x &= -T(t)/M = -f_x(2\omega t + \phi_x)/M \end{aligned} \quad (1)$$

where the time-varying coordinate ($x(t)$, $z(t)$) of the wingtip coincides the direction defined in Figs. 2 and 3. Symbols L, W, T, and M denote the lift, total weight, net thrust, and the wing mass of the MAV. If the driving frequency ω is much lower than the natural frequencies ω_z and ω_x, the acceleration terms in Eq. (1) can be neglected.

$$\omega << \omega_z = \sqrt{K_z / M_z} \quad and \quad \omega_x = \sqrt{K_x / M_x} \tag{2}$$

Therefore we have the approximate time-varying solutions of wingtip coordinates ($x(t)$, $z(t)$) shown as follows.

$$\begin{aligned} z(t) &\approx \left[W - f_z(\omega t + \phi_z)\right]/2K_z \\ x(t) &\approx -f_x(2\omega t + \phi_x)/K_x \end{aligned} \quad ; \quad \begin{aligned} K_z &= 24EI_z/b^3 \\ K_x &= 24EI_x/b^3 \end{aligned} \tag{3}$$

where E, I, b, ϕ, and K denote the Young's modulus, moment of inertia, wingspan, phase lag, and stiffness of flap wing.

Unsteady lift and net thrust measurement

The periodic forms of the unsteady lift $L(t)$ and net thrust $T(t)$ in Eq. (1) are actually modelled by the synchronized aerodynamic force measured data from the MAV wind tunnel testing at Tamkang University. Fig. 4 shows a classical signal set of lift and net thrust subject to a high-frequency wingbeating [4]. In a flapping cycle of a MAV, positive lift is mainly generated during the downstroke, whereas positive net thrust are gained both in downstroke and upstroke. That is the reason why the thrust function f_x has a double frequency 2ω compared to the lift case f_z in Eqs. (1) and (3).

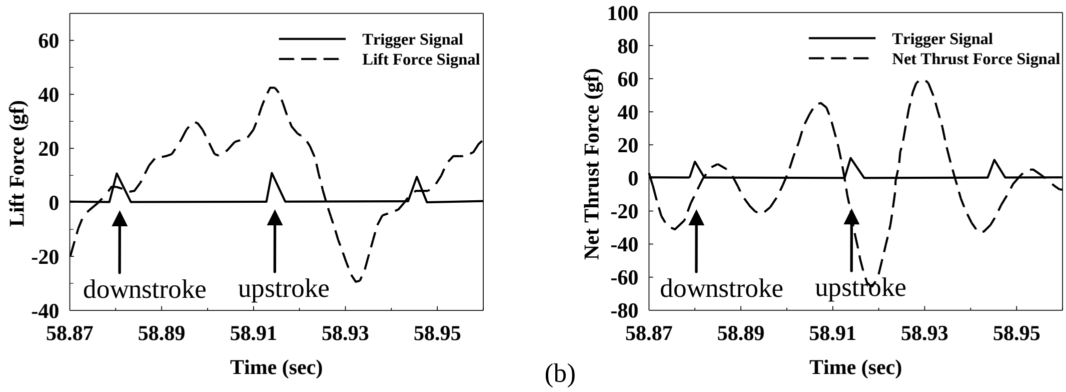


Fig. 4. The classical signals of unsteady (a) lift force $L(t)$ and (b) net thrust force $T(t)$ subject to ω=15.4 Hz [4].

Qualitative behaviour of theoretical prediction

The author substituted the measured values in Fig. 4 into Eq. (3) and plotted the wingtip trajectory ($x(t)$, $z(t)$) in Fig. 5 theoretically. The measured trajectory pattern in Fig. 2 (ω=15.63 Hz) and the theoretically predicted pattern in Fig. 5 (ω=15.4 Hz) both have the characteristic of figure-of-8. Hence the wingtip motion pattern confirmed by the model of this paper agrees with the real gesture of the MAV during its forward flight in a qualitative manner.

Dimensionless fluid-structure interaction parameter

In order to evaluate the fluid-structure interaction of a flapping flight more quantitatively, a dimensionless flexibility Λ revealed from Eq. (3) is defined as follows:

$$\Lambda(\approx z/0.5b) = W/bK_z(= Wb^2/24EI) \tag{4}$$

Herein, the empirical value of Λ is 0.228 for a successful MAV design with wingbeat frequency ω=15.4 Hz. In other words, a high-frequency flapping wing with the bending deflection at the wingtip is recommended as close as 22.8% of half span to ensure the sufficient lift generation from the author's experience.

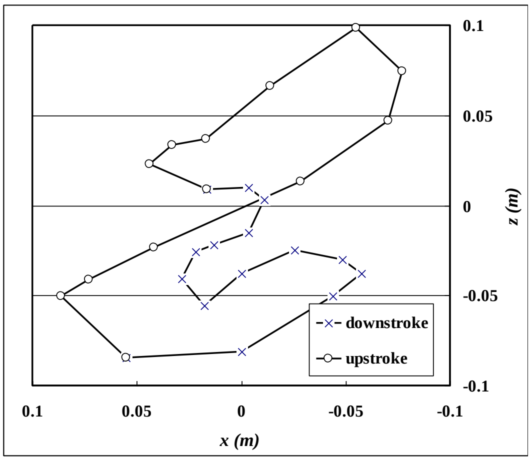


Fig. 5. Theoretical wingtip trajectory with the flapping frequency ω=15.4 Hz; K_z=1.89 N/m [4, 5]; K_x=7.56 N/m; W=8.8 gf.

CONCLUSIONS

The author analyzed the complicated flapping motion by a concise point mass model with 2 DOF in this work. The input of instantaneous lift and thrust histories are important to validating this theoretical model. More MAV designs are looked forward to beefing up this model and the dimensionless flexibility information.

References

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