Inertial Effect on the Time-Averaged Lift of Flapping Wings

Lung-Jieh Yang[1,*], Balasubramanian Esakki[2], and Reshmi Waikhom[1]

[1] *Department of Mechanical and Electromechanical Engineering, Tamkang University, 251301, Tamsui, Taiwan, R.O.C.*
[2] *Department of Mechanical Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Avadi, Chennai, 600062, Tamil Nadu, India*
[*] *Corresponding author. E-mail: LJYANG@mail.tku.edu.tw*

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This note presents the time-averaged inertial force which relates to the velocity difference between the final and initial states of a flapping wing motion. For the periodic flapping motion with identical final and initial velocities, there are no inertial force contribution to the time-averaged lift. Therefore, the wake capture mechanism proposed by Dickinson justifies more convincing than Sunada's added mass or Sun's rapid acceleration at the stroke onset of hovering. The vanishing inertial force to the time-averaged lift is also beneficial to the concise signal processing of lift data from the wind tunnel test.

Keywords: Flapping Wing; Inertial Force; Hovering; Wake Capture

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1. Objective Description

Dickinson et al. proposed the famous three flapping lift mechanisms including delayed stall, rotation lift and wake capture in 1999 [1]. The unsteady aerodynamics of insects and vertebrates were surveyed [2, 3]. The interpretation of wake capture force generation has been questioned based on the claim that the rotation-dependent lift peak at the beginning of a horizontal figure-8 flapping stroke is due to a reaction caused by accelerating the added mass of fluid [3–5]. Sun and Tang also concluded their unsteady aerodynamic force generation from their computational-fluid-dynamics (CFD) results with three lift mechanisms similar to Dickinson's theory. But they replaced the wake capture mechanism by their rapid acceleration of the wing at the beginning of a stroke [5].

Evaluating the added mass and thus estimating inertial forces are not easy, and it needs the help of CFD, PIV [6] or even the vacuum experiments [7] in the fluid flow domain. Some researchers also found that flapping experiment in vacuum cannot tell us the real phenomena of inertial force compared to the experiment done in presence of air [7]. Another experimental investigation on the aerodynamic performances of flexible membrane wings in flapping flight observed that the inertial force is about 5% of the total lift [8].

However, we can alternatively investigate the reaction force of the added mass acceleration from the wing trajectory domain as well. That is, we could use the stereo high-speed photography to estimate the inertial force directly from the detailed 3D time-varying flapping wing trajectory [9], and to affirm whether or not this inertial effect is the origin of the rotation-dependent lift peak of a stroke onset. The authors took the example of the Tamkang University's "Golden Snitch" in Fig. 1 to demonstrate the aerodynamics analysis [10].

Based on the well knowing about the time-varying wing flapping trajectory with respect to the fixed coordinate on the ground (similar to the flapping wing installed in the wind tunnel), the inertial force estimation around the whole flapping wing is shown as below.

$$\vec{F}_{inertial}(t) = \int_{wing} dm \quad \vec{a}(t) \tag{1}$$

or

$$\vec{F}_{inertial}(t) = \sum_{i=1}^{N} m_i \vec{a}_i(t) \tag{2}$$

where $\vec{a}_i(t)$ is the instantaneous acceleration vector of the infinitesimal flapping wing mass dm. Eq. 1 is for the discrete system with a flapping wing of N parts. For further reference, the flapping wing partition of "Golden-Snitch"

Fig. 1. “Golden Snitch” ornithopter [10].

is shown in Fig. 2. The red cross mark in the figure is the LED diode for determining the 3D trajectory (x_i, y_i, z_i) which help us to find out the values of velocity $\vec{V}$ and acceleration $\vec{a}$. In Fig. 3, we can see the experimental setup of the 3D trajectory capture of the wing beating with two high-speed CCDs from different view directions.

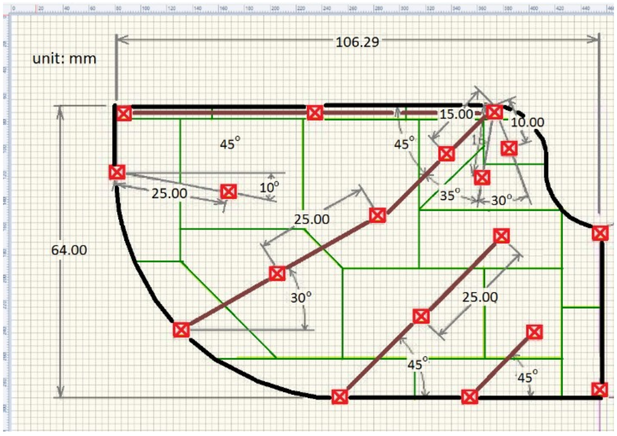

Fig. 2. Flapping wing partition of “Golden-Snitch”.

The time-averaged value of the inertial force $\vec{F}_{ave}$ of the flapping wing over a flapping cycle with period T is the following time-integral form:

$$\vec{F}_{ave} = \frac{1}{T}\int_{t=0}^{t=T} dt \quad \vec{F}_{inertial}(t) \tag{3}$$

Substitute Eq. 1 or 2 into Eq. 3, becomes

$$\vec{F}_{ave}(t) = \int_{t=0}^{t=T} dt \int_{wing} dm \quad \vec{a}(t) \tag{4}$$

$$= \frac{1}{T}\int_{wing} dm \int_{t=0}^{t=T} \vec{a}(t)dt \tag{5}$$

$$= \frac{1}{T}\int_{wing} dm[\vec{V}(t=T) - \vec{V}(t=0)] \tag{6}$$

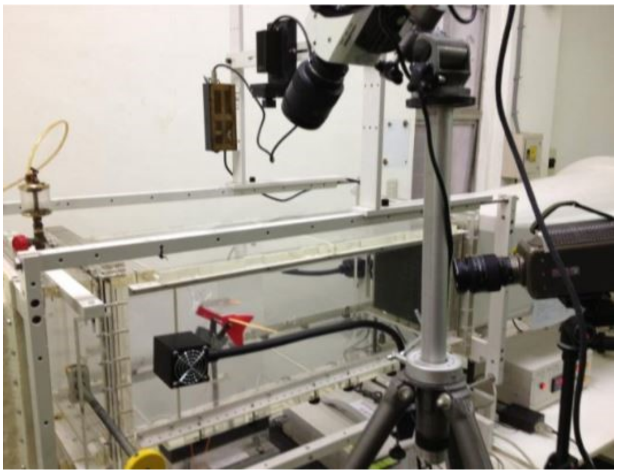

Fig. 3. The 3D trajectory experiment set up with 2 high-speed cameras.

or

$$\vec{F}_{ave} = \frac{1}{T}\sum_{i=1}^{N} m_i[\vec{V}(t=T) - \vec{V}(t=0)]_i \tag{7}$$

where $\vec{V}(t)$ is the instantaneous velocity vector of the infinitesimal flapping wing mass dm. $\vec{a}(t)$ and $\vec{V}(t)$ are time-varying data both from the stereo high speed photography done on an ornithopter or a flapping wing [9]. Eq. 7 is for the discrete system with a flapping wing of N parts. The authors have ever used the 3D unsteady wing trajectory data [9] to calculate the time-averaged inertial force by Eqs. 2 and 3 but found it almost vanished.

2. New Finding and Conclusions

From Eqs. (1-4), several observations are found:

(1) For a periodic flapping wing motion subject to level cruising [9, 10] or hovering [1], the initial velocity $\vec{V}(t=0)$ is identical to the final velocity $\vec{V}(t=T)$. Therefore, the time-averaging of the inertial force $\vec{F}_{ave}$ is zero herein. It means that the inertial force $\vec{F}_{ave}(t)$ of the periodic flapping wing in the wind tunnel [9, 10] or oil tank [1] influences the lift and thrust waveforms locally, but the time-averaged inertial force $\vec{F}_{ave}$ contributes zero net value to the lift and thrust in a global manner.

(2) As the lift contribution from the time-averaged inertial force derived as above is vanished, the non-vanishing first lift peak at the beginning of flapping stroke during hovering [1] is consequently irrelevant to the kinematic inertial acceleration. Dickinson’s wake capture mechanism due to the wing-wake interaction seems to interpret more concise than Sunada’s added mass [4] or Sun’s rapid acceleration [5] about the explanation of flapping lift for hovering flight.

(3) For the flights other than the cruising and hovering,

the initial velocity $\vec{V}(t = 0)$ is not necessarily equal to the final velocity $\vec{V}(t = T)$ of one flapping cycle. Therefore, the time-averaged inertial force $\vec{F}_{ave}$ in Eq. 4 is nonzero generally, and it may influence the flapping motion substantially. Especially for the natural flyers like butterflies, bats or vultures, their wing-to-body ratio is high [3]. The time-averaged inertial force could dominate the motion if the final velocity is on purpose controlled to be greatly different from the initial velocity about one flapping period T.

(4) The wind tunnel test is for the level cruising flight in general. The periodic flapping wing motion in the wind tunnel therefore gives an important conclusion that the time-averaged flapping lift is almost nothing to do with the inertial force accordingly. It is beneficial to the lift signal processing from the force gauge in the wind tunnel. We only adopt the low pass filter to deal with the high-frequency noise and need not get rid of the inertial force component from the wave form of lift. Restated, it is because the time-averaged inertial force vanishes automatically for the cruising flight in the wind tunnel test.

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