ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 9, Issue 6, December 2019

Estimation of maximum velocity during forward flight for hummingbird hawkmoth with computational fluid dynamics

Yao Jie, Yeo Khoon Seng

Abstract: ***Typical insect flight is based on the flapping-wing mechanism. It is interesting to find out how fast an insect can fly. In this paper, computation fluid dynamics (CFD) is employed to solve the flow field involved in the flapping-wing flight and to calculate the aerodynamic force. A model of hummingbird hawkmoth with Reynolds number around 3000 is used in the numerical simulation to find out the maximum forward speed this insect can achieve. Simulation with prescribed motion is studied to reveal the characteristics of the aerodynamic force at different speeds and wing plane angles. With the simulation data, the maximum speed is estimated with the linear interpolation, together with the corresponding wing plane angle. The present study offers an accurate and straightforward way to estimate the forward maximum speed of flying insect.***

Keywords: **Computation fluid dynamics (CFD), flapping-wing aerodynamics, forward flight, hummingbird hawk moth.**

I. INTRODUCTION

In recent decades, better understandings of the mechanisms of flapping wing flight have been revealed by researchers. In early years, quasi-steady theory was used to study the lift generation of flapping wing motion [1-4]. After that, experimental biomechanics and computational fluid dynamics (CFD) become more popular and efficient to study the flapping wing flight as the technology advances. Experimental technologies such as smoke visualization, high-speed camera capturing, particle image velocimetry (PIV) and the development of micro actuators and controllers have enabled researchers to obtain much finer flow details [5-8].Computational fluid dynamics (CFD) can provide better accurate prediction of force coefficients compared to the quasi-steady theory, and much easier visualization of the flow field at different time steps, which yields insight to the physics of the unsteady aerodynamics of flapping flight. Numerous computational techniques have been used to resolve the flapping wing flight problems and valuable results are obtained [9-13].Hovering is the basic flying ability for most insects. Such hovering flight has been well studied by researchers with various insects. Numerical simulation shows that the model insect can perform stable hovering with proper wing kinematics control [14,15]. In addition to hovering, the insect also need to travel and maneuver. Due to the complexity of aerodynamic force generated by different wing kinematics, free maneuvering flight is usually difficult to control.

To perform a certain type of flight, we first need to know the aerodynamic force involved so we can maintain the flight stability with a properly designed controller. Hence, prescribed motion is studied in this paper to find out the aerodynamic force generated at different flight conditions. Based on that, the maximum speed during forward flight is estimated.

II. METHODOLOGY

The model insect we used is the hummingbird hawkmoth (*Macroglossumstellatarum*), which is a relatively large flying insect with Reynolds number around 3000. The insect model and mesh are generated with commercial software. Details of the insect morphological data is shown in Table 1 according to literature [16].

Table 1. Morphological data of hummingbird hawkmoth

Parameters	Value
Wing Mean Chord Length	9 mm
Wing Beating Frequency	65 Hz
Wing Length	20.2 mm
Insect Mass	0.2071 g

The governing equation of fluid flow in insect flapping flight problems is the three-dimensional incompressible Navier-Stokes equations, in the non-dimensional Arbitrary Lagrangian-Eulerian (ALE) form. Above equations are solved on a hybrid background Cartesian grid nodes and clouds of mesh free grids around the insect body and wings. The standard 7-point central finite difference scheme is applied at Cartesian nodes that do not have meshfree nodes nearby, while the SVD-GFD scheme is applied at the meshfree nodes and Cartesian nodes with meshfree nodes nearby. A second-order implicit projection method, based on a fractional-step Crank-Nicolson scheme is applied to solve the ALE form NS equations. More details of the flow computation and coordinate system can be found in [14] and [15].

We focus on the simplest case, i.e., flying forward at a fixed wing beating frequency. The wing beating frequency for maintaining a stable hovering flight is around 65Hz, higher frequency should be adopted to fly forward to maintain the lift and to counter the drag. Hence, the study will be focusing on the flight at frequency of 75Hz.

The theoretical maximum speed of the insect for a specific pitching angle can be approximated as follows. The following study tries to find out the speed limitation for pitching angle at −40 degree, with respect to the normal hovering orientation, Figure 1.

Manuscript received: 26 November 2019
Manuscript received in revised form: 20 December 2019
Manuscript accepted: 07 January 2020
Manuscript Available online: 10 January 2020

DOI: 10.17605/OSF.IO/G9SYJ

During the forward flight, the insect needs to adjust the wing plane angle accurately so that the total thrust is distributed properly to overcome the weight and drag. The wing plane angle is denoted as β in Figure 1. if it is measured with respect to the body, we denoted it as β_r. When the insect is switching from hovering to forward accelerating, it tilts the wing sweeping plane forward to distribute part of the total thrust in the forward direction. In this way, the insect starts to move forward, while the wing plane angle should be adjusted carefully to avoid excessive or insufficient lift. In addition, as the speed varies, the total thrust is also changing, which requires the readjustment of the wing plane angle until the insect reaches a certain speed where the net force on the insect is zero. Hence, prescribed motion is simulated for non-dimensional speed varies from 1 to 3, and wing plane angle (with respect to the body) varies from -30 degree to -10 degree, to specify the region of the speed and wing plane angle to achieve the desired flight status.

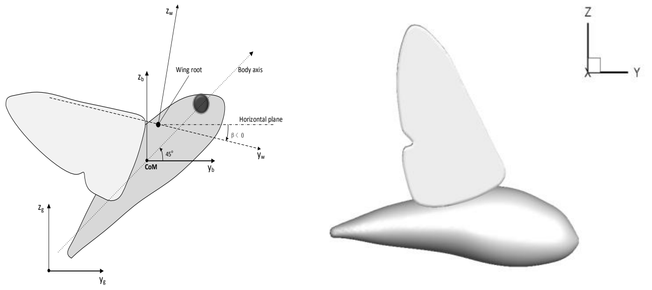

Fig 1. Orientation of the insect for current study, viewed from global frame. The figure on the left shows the orientation at normal hovering. The figure on the right shows the orientation during forward flight.

III. RESULTS OF THE PRESCRIBED SIMULATION

The results of the prescribed motion are summarized in Table 2 and Table 3.

Table 2. Non-dimensional longitudinal net force (F_y)

β_r / Speed	-10	-20	-30
1	1.05		
1.5	0.60		
2	0.11	0.49	0.78
2.5		0.012	0.32
3		-0.50	-0.19

Table 3. Non-dimensional vertical net force (F_z)

β_r / Speed	-10	-20	-30
1	-0.11		
1.5	0.22		
2	0.54	-0.050	-0.73
2.5		0.18	-0.56
3		0.40	-0.40

To get a clearer observation on how the aerodynamic forces vary with the speed and wing plane angle, we plot the above results in Figure 2 and 3. In both figures, the longitudinal force is plotted with solid lines and the vertical force is plotted with dashed lines. Fig 2 shows how the forces change with speed; different curves are marked by varying wing plane angle. Fig 3 shows how the forces change with wing plane angle; different curves are marked by varying forward speed.

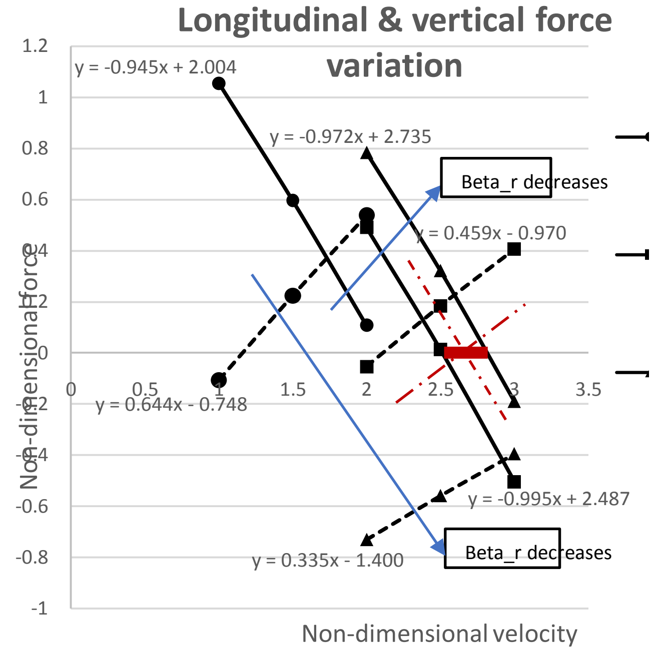

Fig 2. Aerodynamic force VS velocity

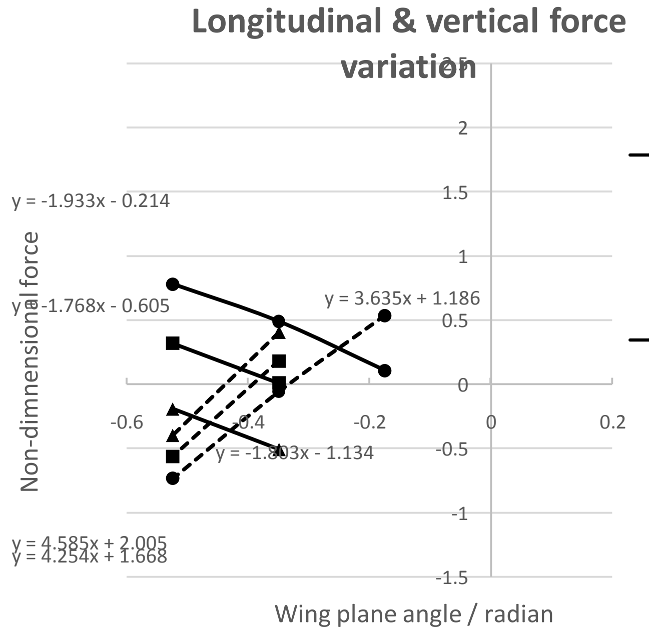

Fig 3. Aerodynamic force VS wing plane angle

From Figure 2, we can see that good linear relationship exists between the force and speed at different wing plane angles. As the wing plane angle gets smaller, the curves shift from left to right, for both the vertical and longitudinal forces. In addition, the force also varies almost linearly with respect to the wing plane angle, which is shown by Figure 3. Only when the wing plane angle is between -30 degrees and -20 degree that both the vertical and longitudinal forces can be zero under the same flight condition, where the speed limitation is reached. Therefore, the maximum speed is within the thick red interval on the x-axis in Figure 2 and can be interpolated with the data from the figures.

IV. ESTIMATION OF THE MAXIMUM SPEED

Assume the longitudinal and vertical forces are functions of flight speed and wing plane angle, i.e.,

$$F_y = f\left(v, \beta_r\right)$$

$$F_z = g\left(v, \beta_r\right)$$

With first order Taylor expansion, we have

$$F_y = f\left(v, \beta_r\right) \approx f\left(v_0, \beta_{r,0}\right) + \frac{\partial f}{\partial v}\left(v - v_0\right) + \frac{\partial f}{\partial \beta_r}\left(\beta_r - \beta_{r,0}\right)$$

$$F_z = g\left(v, \beta_r\right) \approx g\left(v_0, \beta_{r,0}\right) + \frac{\partial g}{\partial v}\left(v - v_0\right) + \frac{\partial g}{\partial \beta_r}\left(\beta_r - \beta_{r,0}\right)$$

From above figures, we can find that

$$\frac{\partial f}{\partial v} \approx -0.98 \quad \frac{\partial f}{\partial \beta_r} \approx -1.8 \quad \frac{\partial g}{\partial v} \approx 0.40 \quad \frac{\partial g}{\partial \beta_r} \approx 4.2$$

Let $v_0 = 2,\ \beta_{r,0} = -20^o = -0.35$, we have

$$F_y = f\left(v, \beta_r\right) \approx 0.49 - 0.98\left(v - 2\right) - 1.8\left(\beta_r + 0.35\right) = 1.8 - 0.98v - 1.8\beta_r$$

$$F_z = g\left(v, \beta_r\right) \approx -0.05 + 0.40\left(v - 2\right) + 4.2\left(\beta_r + 0.35\right) = 0.62 + 0.40v + 4.2\beta_r$$

To calculate the highest speed, we simply need to let

$$F_y = F_z = 0 \cdot$$

Calculation shows that $\begin{cases} v_m = 2.6 \\ \beta_{r,m} = -0.39 = -22^o \end{cases}$

The linear interpolation shows that the maximum speed for the insect is about 2.6 under the restricted flight condition. The wing plane angle is around -22 degree with respect to the body and about -62 degree measured from the horizontal plane.

V. VERIFICATION

To verify the quality of the above estimation for the maximum speed, we simply need to run the prescribed simulation with wing plane angle of -22 degree and forward speed 2.6. The simulation shows that the non-dimensional longitudinal net force is -0.0076 and the non-dimensional vertical net force is 0.090. Comparing to the insect weight, 2.59, the longitudinal force and the vertical force are 0.3% and 3.5% respectively. Hence, the fight with the estimated speed and wing plane angle is very close to the ideal flight status with maximum forward speed under the restricted flight condition. In addition, the linear interpolation is verified to be a good approach to estimate the maximum forward speed.

VI. CONCLUSION

This paper conducted a numerical study on the maximum forward speed of the hummingbird hawkmoth with the wing beating frequency and body pitching angle fixed. The aerodynamic force involved in the flight is calculated with computational fluid dynamics. Region of the ideal flight status is specified with the prescribed motion simulation. Linear interpolation from the simulation data is applied to estimate the maximum speed and the corresponding wing plane angle. At last, the linear interpolation is verified to be an accurate approach to estimate the maximum forward speed.

REFERENCES

[1] Osborne, M., Aerodynamics of flapping flight with application to insects. Journal of Experimental Biology, 1951. **28**(2): p. 221-245.

[2] Weis-Fogh, T., Quick estimates of flight fitness in hovering animals, including novel mechanisms for lift production. Journal of Experimental Biology, 1973. **59**(1): p. 169-230.

[3] Lighthill, M., On the Weis-Fogh mechanism of lift generation. Journal of Fluid Mechanics, 1973. **60**(01): p. 1-17.

[4] Ellington, C., The aerodynamics of hovering insect flight. Philosophical Transactions of the Royal Society B: Biological Sciences, 1984. **305**(1122): p. 1-181.

[5] Brodsky, A., Vortex formation in the tethered flight of the peacock butterfly Inachis io L.(Lepidoptera, Nymphalidae) and some aspects of insect flight evolution. Journal of experimental biology, 1991. **161**(1): p. 77-95.

[6] Shyy, W., et al., Recent progress in flapping wing aerodynamics and aeroelasticity. Progress in Aerospace Sciences, 2010. **46**(7): p. 284-327.

[7] Dickinson, M., The effects of wing rotation on unsteady aerodynamic performance at low Reynolds numbers. The Journal of Experimental Biology, 1994. **192**(1): p. 179-206.

[8] Lua, K., et al., On the aerodynamic characteristics of hovering rigid and flexible hawkmoth-like wings. Experiments in fluids, 2010. **49**(6): p. 1263-1291.

[9] Sun, M. and J. Tang, Unsteady aerodynamic force generation by a model fruit fly wing in flapping motion. Journal of Experimental Biology, 2002. **205**(1): p. 55-70.

[10] Liu, H. and K. Kawachi, A numerical study of insect flight. Journal of Computational Physics, 1998. **146**(1): p. 124-156.

[11] Ramamurti, R. and W.C. Sandberg, A three-dimensional computational study of the aerodynamic mechanisms of insect flight. Journal of Experimental Biology, 2002. **205**(10): p. 1507-1518.

[12] Yamamoto, M. and K. Isogai, Measurement of unsteady fluid dynamic forces for a mechanical dragonfly model. AIAA journal, 2005. **43**(12): p. 2475-2480.

[13] Miller, L.A. and C.S. Peskin, A computational fluid dynamics ofclap and fling'in the smallest insects. Journal of Experimental Biology, 2005. **208**(2): p. 195-212.

DOI: 10.17605/OSF.IO/G9SYJ

[14] Wu, D., K. Yeo, and T. Lim, A numerical study on the free hovering flight of a model insect at low Reynolds number. Computers & Fluids, 2014. **103**: p. 234-261.

[15] Yao, J. and K.S. Yeo, Numerical Study of Flapping-Wing Flight of Hummingbird Hawkmoth during Hovering: Longitudinal Dynamics. World Academy of Science, Engineering and Technology, International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering, 2016. **10**(12): p. 1872-1879.

[16] Wu, G. and L. Zeng, Measuring the kinematics of a free-flying hawk-moth (Macroglossum stellatarum) by a comb-fringe projection method. Acta Mechanica Sinica, 2010. **26**(1): p. 67-71.