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Impact of Butterfly Wing-Pitch Interaction on Flight Performance

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1 Introduction

In the study of flapping flight, the significance of wing rotation and body oscillation in butterfly flight is acknowledged [1–3]. These behaviours affect the angle of attack, a vital aspect of aerodynamic production. Through wing rotation, the orientation of the wings relative to the oncoming airflow can be adjusted, contributing to the dynamic and harmonious flight of butterflies. Additionally, body pitching indirectly influences the flight through its effect on the position of the butterfly's centre of gravity and the orientation of the wings. As a result of this coordination, butterflies can constantly adjust the angle of attack and make rapid changes in direction or altitude as the situation demands. Due to difficulties in data collection, the effect of the coupling of two crucial factors on the flight has not been the subject of in-depth investigation.

In this study, we utilised a state-of-the-art artificial neural network (ANN) model to investigate the coupling of these two. The model underwent training using combinations of angles of different amplitudes and implemented the model to simulate the dynamic relationship between these behaviours and their impact on the aerodynamic forces. This offers new perspectives on the complexities of butterfly flight and enhances our comprehension of the significance of the wing-pitch interaction in determining flight dynamics.

2 Data Collection and Simulation

To obtain the flight dynamics of the butterfly as a reference, we utilised two high-speed cameras (Phantom v7.3 and v310, Vision Research, New Jersey, USA) to record the forward flight of the blue tiger butterfly (*Tirumala septentrionis*). The synchronised photographic films were further analysed to obtain the kinematics equation of various body parts. Both recordings were made at 1000 frames per second with a resolution of 1024×1024. The experiments have shown that the flapping frequency was about 11.02 ± 1.08 Hz ($N = 15$). The measured body pitching angle θ and wing rotation angle α can be found in Figure 1 with 95% confidence intervals (shaded areas), where T is the normalised time in a flapping cycle.

Since measuring aerodynamics from biological experiments was challenging, we utilised computational fluid dynamics (CFD) simulation to collect these data. Considering

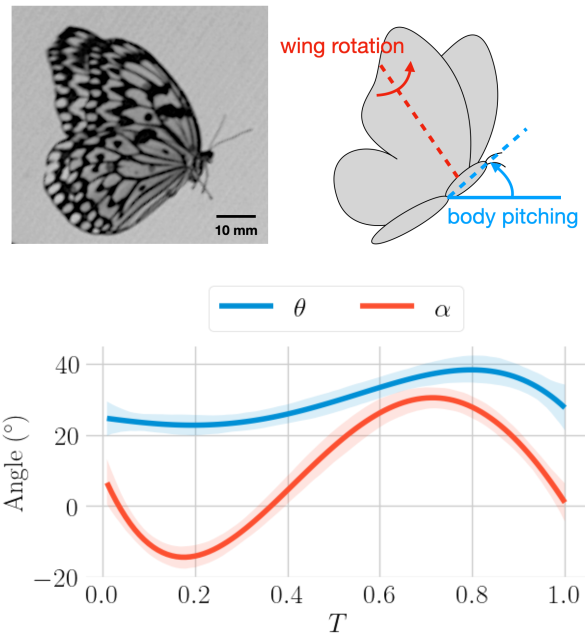

Figure 1: Flight dynamics of a flying butterfly ($N = 15$).

that the flying Reynolds number of butterflies in nature is between 10^3 and 10^4 [4], we deemed the medium an incompressible Newtonian laminar flow. Therefore, we employed the unsteady incompressible viscous Navier-Stokes equations for computation [5].

To efficiently enlarge the database to explore the interaction between body oscillation and wing rotation, we introduced a neural network framework to obtain the transient aerodynamic forces under various parameter combinations. The model's structure was based on [6], which was proven to provide highly accurate transient results. Consequently, an extensive database of aerodynamic properties could be obtained. The aerodynamic parameters were nondimensionalised to facilitate comparison with other outcomes. This standardisation allows for a more meaningful evaluation of the results that can be employed for further analysis to gain deeper insights.

3 Results

The four most representative results were selected for comparison from 1461 sets of simulated data. Figure 2 illustrates the optimal coefficient of horizontal force F_h and

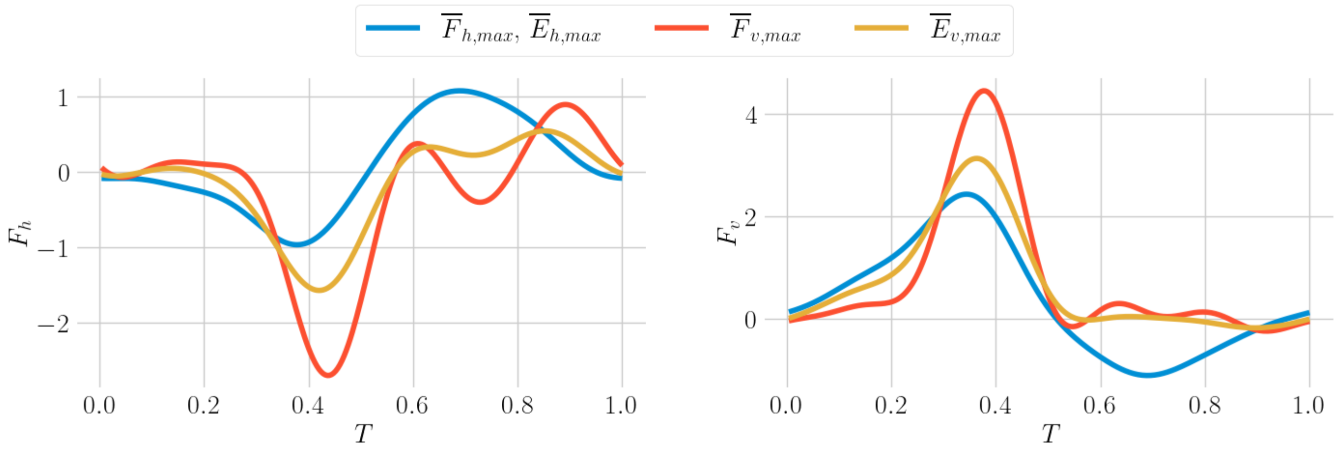

Figure 2: Optimal coefficient of horizontal force F_h and vertical force F_v.

vertical force F_v. Regarding the vertical force, it was observed that the highest mean value $\overline{F}_{v,max} = 0.76$ was obtained when both amplitudes were doubled (red line). In contrast, the standard kinematics (Figure 1) only gave a value of 0.55. Compared to other cases, there was a massive increase in the peak value of F_v. Moreover, the negative lift generated by the wings during the upstroke phase ($T \geq 0.6$) was visibly reduced, as the overall $\overline{F}_v$ was substantially enhanced. However, with this combination of parameters, our simulation results showed that the model flew backwards since the mean thrust was negative.

When the amplitudes of body pitching and wing rotation were set to 0 and 0.75 times, a butterfly could produce the highest thrust $\overline{F}_{h,max}$ in a single flapping cycle (blue line). Although the value underwent an increase of 286% compared to the original flight dynamics, the overall value remained low, with a measure of 0.06 only. Under this condition, the total $\overline{F}_v$ was 0.35, more than fourfold grander than the thrust.

In terms of power consumption, the kinematics of the best thrust efficiency $\overline{E}_{h,max} = 0.08$ was the same as $\overline{F}_{h,max}$. Nevertheless, to achieve the highest lift efficiency $\overline{E}_{v,max} = 1.02$ (amber line), the amplitude multipliers of body pitching and wing rotation should be adjusted to 2 and 1.25, respectively. Although the value F_v dropped slightly to 0.67 (12% reduction), the lift efficiency $\overline{E}_{v,max}$ rose from 0.80 to 1.02 (27% increase).

4 Conclusion

In this study, a detailed simulation study was performed utilising the advanced techniques of CFD and ANN to thoroughly examine the impact of the wing-pitch interaction on butterfly flight dynamics. The results indicate that while increasing both body pitching and wing rotation can be beneficial in terms of lift generation, excessive wing rotation has a detrimental impact on lift efficiency. Although the impact on thrust is minor, it can still be improved through the adjustment of the wing-pitch motion. These results offer valuable insight into the diverse flight strategies that a butterfly can adopt to enhance lift or thrust, depending on the circumstances.

The outcome of this study could have important implications for the design and development of flapping wing micro aerial vehicles, as it indicates that it is possible to achieve improved performance by reducing the complexity of the mechanisms involved. By incorporating the critical insights from this study, researchers can strive to create flapping wing micro aerial vehicles that are more efficient and effective in the future.

Acknowledgement

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