A click mechanism moderates drone's flapping wing kinematics for enhanced thrust generation

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ABSTRACT

In the motorized drive of a flapping-wing drone, the transmission loss well exceeds the inertial and aerodynamics power. Such transmission loss is however minor in the natural flight apparatus of Dipteran insects by using thoracic compliant mechanisms. In particular, Dipteran insects such as fruit flies make good use of a bi-stable click mechanism to enhance thrust generation and efficiency. It is not clear if an enlarged click mechanism remains beneficial to a larger flapping-wing drone. Here, we designed a bioinspired drone prototype, with a 40 times larger wingspan and a 300 times heavier mass than a fruit fly of 7.3mm span and 0.1gram mass. Interestingly, given the same wing pairs, the enlarged click mechanism enhanced the thrust generation (up to 30 grams) by 50% than the non-click mechanism. This click mechanism modulated the wing stroke speed profile to have a high plateau at which the wing rotation peaks. This insight on the click effect on wing kinematics and aerodynamics will help better future bioinspired drones.

1 INTRODUCTION

Natural flyers like birds and insects have been the source of inspiration for the development of bioinspired micro air vehicles (MAV), or flapping-wing drones in other words. Bird-inspired drones were named ornithopters, while insect-inspired drones were named entomopter. Artificial flapping-wing drones had exploited the bio-inspired aerodynamics, such as clap-and-fling wing-wing interaction employed by wasps and even pigeons during the laters' vertical takeoff. However, the drive mechanism for flapping-wing drone is still motorized transmission, for example, a crank-rocker mechanism, which converts the motor rotation into wing reciprocation. A recent study shows the transmission loss can overweigh the inertial and aerodynamics power expenditure during flapping-wing drive. This challenge motivates us to relook into the insect drive mechanism for a simpler and better design of the flapping wing mechanism [1].

Click mechanism are first found on Diptera flies while anesthetized [2][3]. The flight thorax on dipterans is more than just a box-like structure; it can store elastic energy when deformed and release when elastically recoiled. Such means of elastic energy storage were reported to help decelerate and accelerate wings at reduced inertial power expenditure. It was thought to be beneficial to increase the power output more than what flight muscles alone can be delivered. In addition, the click mechanism found at the wing base of Dipteran insects was thought as useful as deformable flight thorax for elastic storage.

Brennan (2003) simplified the click mechanism as several link-spring models as shown in figure 1 [4][5]. When the tip-point is pushed upward, the spring is compressed and generates a vertical force against the moving direction. After the tip-point

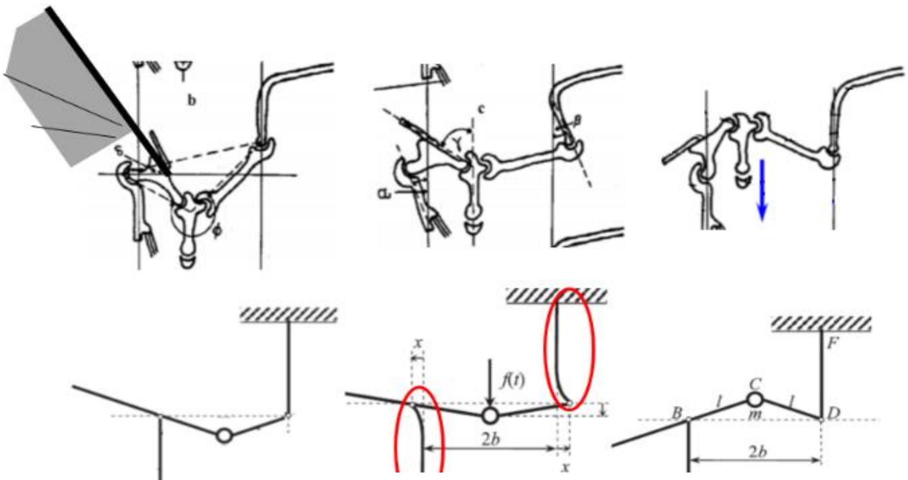

Figure 1: Click mechanism and link-spring model [4].

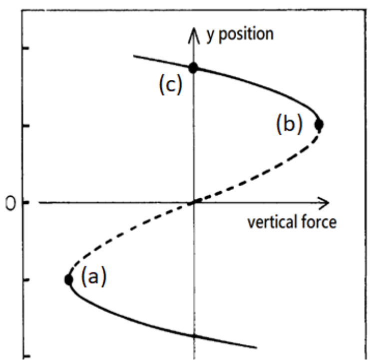

Figure 2: Vertical force versus position of click mechanism [5].

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passes the mid-line, the vertical force from the spring turns to the same direction as motion, triggers the "click," and accelerates the tip-point to jump to the other side.

Chin (2013) designed a 3.78g weighted ornithopter prototype of a click mechanism for flapping a pair of 130mm-span wings, as shown in figure 4. Chin's works show that the click mechanism effectively produces higher thrust than a non-click prototype at both the same flapping frequency and power consumed [6][7]. However, the wing kinematics delivered by the motorized click transmission (a combination of click mechanism at the wing base and the driving crank-slider mechanism) appeared as a distorted sine wave rather than the bi-stable snaps demonstrated by the click mechanism alone. Further, it is noted the elastic storage in the click mechanism is maximum at the mid-stroke of flapping wings; it is in contrary to the maximum elastic energy storage expected at the end of wing stroke. His later research showed partial elastic energy storage in the elastic hinged wings is better than full elastic energy storage for not impeding motorized flapping-wing transmission.

It was not clear if the click mechanism found in Dipteran insect is applicable to a larger flapping-wing drone in the same manner as to how the clap-and-flying wing-wing interaction scales from small wasp to larger pigeons. In this paper, we first enlarged a click mechanism for a 27.6-gram flapping-wing drone of 300 mm wingspan. In addition, we find the effect of click mechanism moderating the wing kinematics distinctly at relatively low frequency (4Hz) and high frequency (10Hz).

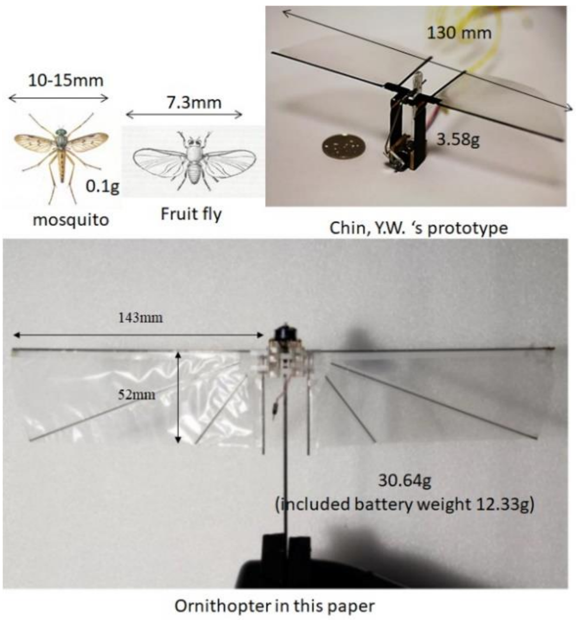

Figure 3: Size of Dipteran, Chin's prototype and ornithopter in this paper.

2 MECHANISM MODEL

2.1 *Mechanism model design*

We designed a large click ornithopter with two 14.3mm-long wings at a stroke of 106 °. This click mechanism is similar to that presented by Tang and Brennan but differs from the latter by the drive mechanism. Here, a crank-rocker mechanism was to pull down and push up the vertex of the click mechanism. A powerful small brushless motor AP05 and a set of speed-reduction gear sets were used to drive the crank-rocker mechanism. As in figure 4, the driving force is transmitted through reduction gear sets, a crank-rocker system (red linkages) and a double rocker system (black linkages) from the motor to wings. While in the "click" case, a cantilever spring replaces one of the rockers in the double rocker system.

As such, the wing kinematics follow the reciprocation primarily by the crank-rocker mechanism. Meanwhile, the click mechanism moderated the harmonic wing stroke profile by providing extra elastic resistance towards the mid-stroke position and extra elastic recoil away from the mid-stroke position.

2.2 *Pull test*

The spring of the click structure is a POM cantilever beam, as shown in figure 5. While the black links moved toward the mid-point, the cantilever spring was pressed toward the left and exerted force (red arrow) to the wing base. Thus we do the pull test to plot the vertical reaction force.

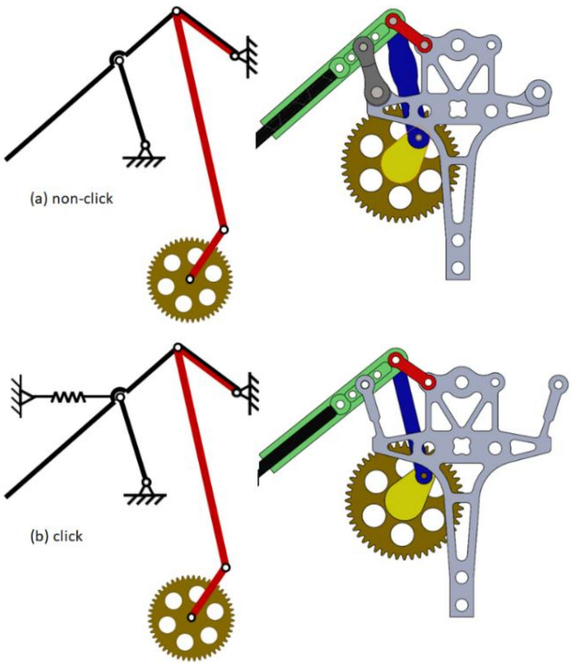

Figure 4: Transmission mechanisms.
Crank (yellow): 4mm, link (blue): 15.1mm, rocker (red): 5mm, wing base (green): 5mm, rocker of non-click (gray): 6mm.

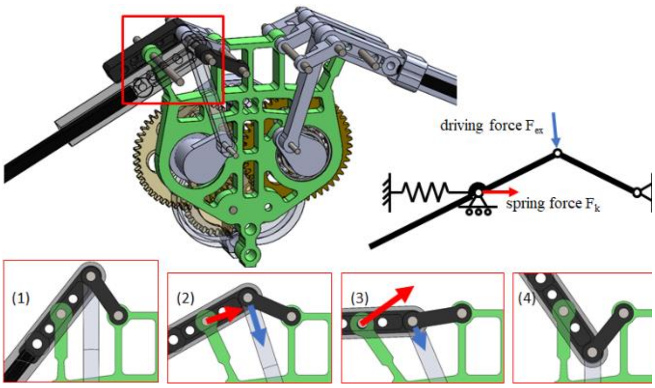

Figure 5: Click mechanism in this paper. The left green beam is the cantilever spring.

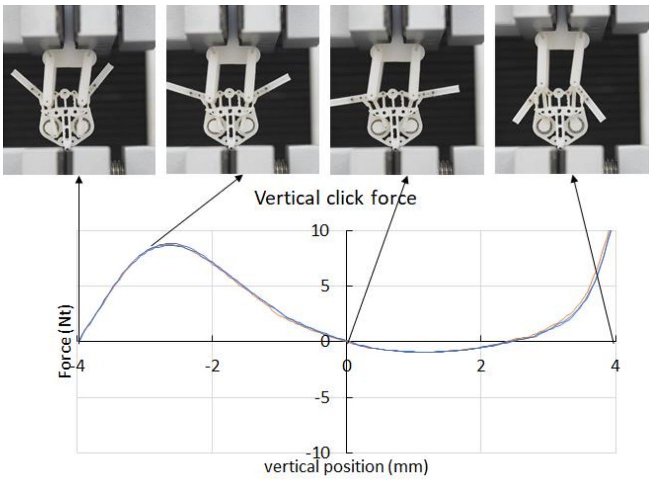

Figure 6: Vertical force tested with tensile test machine.

As shown in Figure 6, the bi-stable elastic behavior of a prototype of click mechanism was measured from a pull test using a tensile tester (Cometech QC-508M1F). Prior to the pull-test, the vertex of the click mechanism was set to the bottom stable position. During the test, the vertex was pulled upwards from the bottom stable position -4mm to the top stable position +4m while the pulling force was measured continuously. The pulling force required at the bottom stable position was zero; it increased towards a peak pull force of 8.7N at -2.6mm. When pulled up beyond the peak force position, the force requirement diminishes towards and becomes zero at the mid-stroke position.

Snap happens beyond the mid-stroke position with the pull force turning negative until the 2.5mm position. There was increasing positive pull force required to reach the top stable position because of misalignment in the pulling rod. Backlashes and skewed jigs are the reason for the asymmetry of the curve.

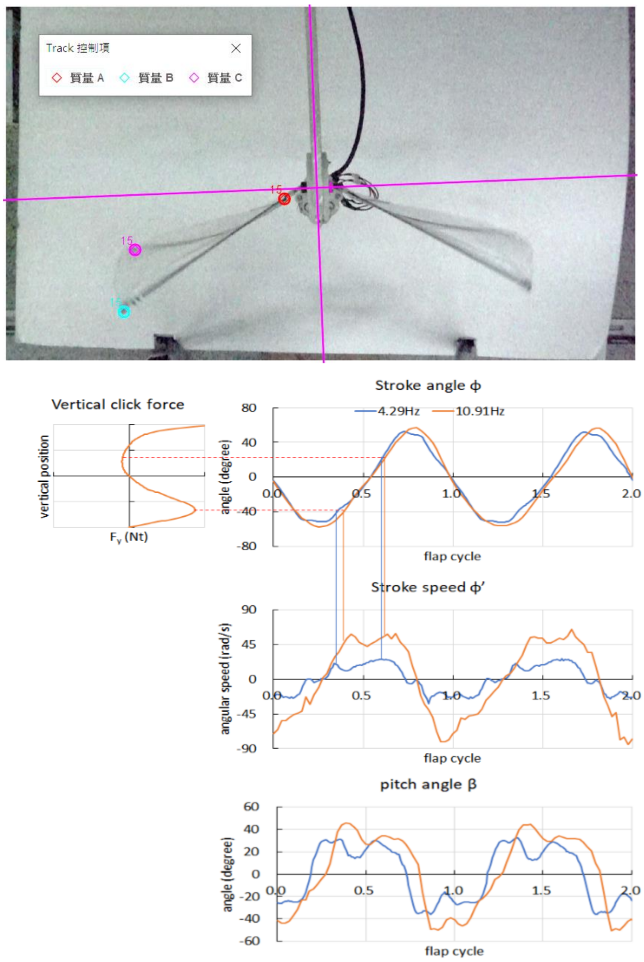

Figure 7: Stroke angle, Stroke speed, and pitch angle versus time.

3 WING KINEMATICS

Next, we investigated the dynamics effect of the click mechanism on flapping-wing kinematics at low and high frequencies. First, the brushless motor was run at 40% throttle to beat a pair of wings hinged on a clicking mechanism at a low frequency of 4.29Hz. Second, the motor was driven to full throttle and flap the wing pair faster at a wingbeat frequency of 10.91Hz. During the test, a high-speed camera was used to record the wing motions. Subsequently, Tracker software was used to extract the stroke angle and pitch angle over cycles of wingbeat.

Figure 7 shows that the wing kinematics over two wingbeat cycles. It noted that the time profile of wing stroke angle appeared like a sinusoidal function, following the drive of the crank-rocker mechanism. However, the stroke amplitude varies with the wingbeat frequency. For example, the stroke amplitude was 57.1 ° at 10.91Hz wingbeat frequency; it is higher than 52.8° at 4.29Hz. The stroke amplitude at full throttle was amplified more than static stroke because of the elasticity provided by the click mechanism to the wing base.

Stroke speed can be calculated as the time derivates of stroke position. As shown in Figure 7, the time profile of stroke speed measured deviates from a simple harmonic function. Noted was a speed moderation, i.e., a mild dip, at the mid-stroke position, where a peak stroke speed was expected. The speed dip and the maximum spring resistance happened in the same phase. In other words, the resistive spring force of click slowed down the wingbeat and depressed the stroke speed curve at the mid-stroke position. After the wings pass the middle stroke, the recoiled spring force helped accelerate the wingbeat and keep the 'plateaus' of relatively high speed for a longer duration. The matching of high stroke speed with a high pitch angle enhances the thrust generation. As such, the stroke speed moderation is believed helpful to enhance thrust generation at this moderate wingbeat frequency of 10Hz.

4 FLIGHT TEST

Next, we conducted a fixed flapping test to measure the maximum thrust of this click-ornithopter prototype with a pair of wings each of 143mm wing length and 52mm chord width. As shown in Figure 8, a 6-axis force/torque sensor was used to measure the thrust generated by the flapping-wing prototype mounted below it. It is shown that ornithopter with click generates 30.83g thrust while non-click ornithopter only generates 22.20g. The click mechanism increased the maximum throttle by 35.7% and remained the same power consumption.

Last but not least, this click-ornithopter was tested for a free vertical takeoff. During the launch test, the click-ornithopter's fuselage, i.e., a carbon fiber rod body, was guided in a PVC tube. A tail stabilizer was stripped off the prototype but replaced with an extra weight of 3gram to enable free takeoff from the guiding tube. Figure 10 shows the initial state and the launched state of the click-ornithopter. The tethered flight test showed that this prototype was capable of 30.06-gram average thrust generation when driven at full throttle.

5 CONCLUSION

In conclusion, the click mechanism, which alone was bi-stable at the end stroke position, did not snap the wings pass mid-stroke position when it was under the drive by a motorized crank-rocker mechanism. However, it presented extra resistive elastic load to alter the stroke speed of flapping wings. Its elastic resistance and recoil help widen and smoothen the plateau of relatively high speed nearly the mid-stroke position where the pitch angle was high. As such, the click mechanism enabled a relatively large ornithopter of 27.64-gram self-weight with extra 3-gram load to launch a vertical takeoff.

Figure 8: Equipment in force sensor thrust test.

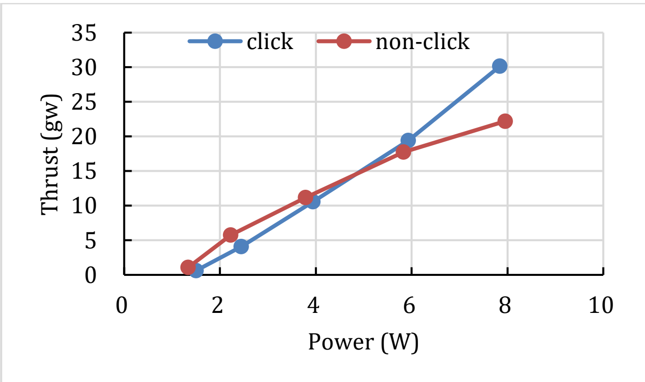

Figure 9: Thrust generated by click/non-click prototype with the corresponding size.

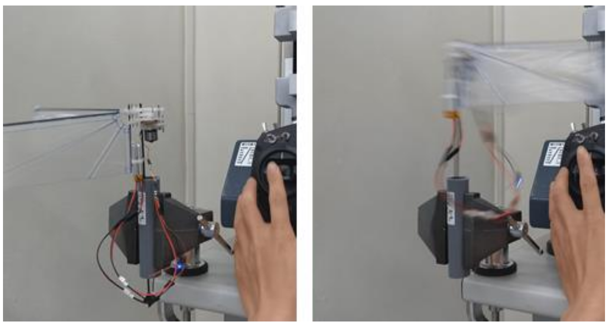

Figure 10: Vertical takeoff in constraint of a PVC tube.

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