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Is clicking mechanism good for flapping wing micro aerial vehicle?

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ABSTRACT

In this paper, we examine the effect of non-sinusoidal flapping motion caused by click mechanism and compared it to a sinusoidal flapping motion. Many had observed and described the click mechanism through insect's anatomy. Through theoretical models and numerical studies, some dismissed its effect on flapping efficiency, while others predicted better thrust generation with it. Without concrete experimental proof, the argument is hypothetical. This work showed the benefits of the click mechanism by experiment, with its simple compliant thorax designed using carbon fiber and polyimide film. The click mechanism system is designed like a thin elastic plate which was compressed until bent, with its center point stable at either the top most extreme or the bottom most extreme positions. 'Clicking' occurs when the plate center is moved forcibly from one extreme to the other. Before it passes the midpoint, the plate center moves slowly as it tends to return to the original extreme and resist the displacement. When moved passed the midpoint, it now tends to move to the other extreme, together with the external force, resulting in a fast, snapping 'click' to the other extreme. Hence, the clicking prototype showed a sudden high increase in wing flap speed when it is moved beyond midpoint towards the other end. It also showed quick wing reversal and is able to produce consistent large wing stroke ($\sim 115^\circ$). The clicking prototype, which weighs 3.78g, produces a higher thrust of 2.9g at a flapping frequency of 19Hz. In comparison, a 3.26g prototype of sinusoidal flapping motion with similar design configuration produces only 2.2g of thrust at 19Hz.

Keywords: Flapping wing micro aerial vehicle, click mechanism, compliant mechanism, bio-inspired, biomimetics.

1. INTRODUCTION

Flapping flight is the flying insect's means of producing thrust and lift in order move around. The wing kinematics is important to thrust generation. Yet, the effect of wing kinematics is not fully understood. Several insects' wing kinematics are well observed and documented. Theses natural flyers provide inspiration to design flapping-wing micro-air-vehicles. A better thrust performance would mean longer flight endurance and better power efficiency, which is critical for flapping wing MAV because of their limited on-board power density.

Currently, most of the flapping wing micro aerial vehicles are designed to flap in a simple harmonic flapping motion, which is of sinusoidal profile, for example the DelFly and Harvard's Microrobotic Fly. [1] [2] [3] [4] Their wings accelerate from rest at the beginning of the stroke towards the mid stroke, and then decelerate towards the end, after the mid stroke. This means that the wing velocity increases gradually from the start of the stroke and reach a maximum at the mid stroke and then decreases gradually to stop at the end of the stroke.

However, it is very uncommon that the insects flap in a smooth sinusoidal way, as reported by many biologists who investigated insect flight. [5] [6] In fact, *Dipteran* insects flap in a way such that the wing angular velocity remains relatively uniform throughout the stroke, except that the wing slows down rather quickly at the end of the down stroke and then reverse to start the upstroke in a slower speed. [6] This is observed from the fact that the angular position of the wings has a slope that is almost linear when it moves from the beginning of the stroke to the end stroke, while the wing reversal is quick at the end of the stroke.

The profile of the wing flap motion is determined by the mechanism which drives it. Biologists had proposed different mechanism in order to achieve the same flap profile, based on insect morphological examination. The most widely accepted model is the click mechanism, which is first proposed by Boettiger and Furshpan (1952) through observation of

wing movement of *Dipteran* flies under the influence of CCL₄ anesthetic. [7] In click mechanism, the wings stop in either top or down position when at rest. When the flight muscles actuate the wing from rest, the wings is first depressed slowly, but upon reaching a critical point at mid stroke, it snaps to the opposite end and is stopped abruptly to rest there. This bistable mechanism occurred due to the complex interaction of the indirect muscles and movement of the mesopleural processes as described in [7].

However, biologists disagreed on the details of how the click mechanism worked in biological bodies. [8] Miyan and Ewing (1985) argued that it is the anesthetic which caused the click mechanism, and they instead proposed that in actual flight the wings are stopped at the end stroke by a radial stop. [9] Ennos (1986) also presented an alternative mechanism which involved the distortion of the scutum of the insect's thorax and the radial stop, as he believed that there is no evidence of the click mechanism found in the kinematic record of dipteran flight. [10] On the other hand, Pfau (1987) defended the click mechanism observed by Boettiger with additional elaboration. [11] The differences in opinion created confusion over the effect of click mechanism, where some argued that it does not really bring about any benefits, while the other believed that it is aerodynamically more efficient than harmonic sinusoidal motion (Pringle, 1981) [12].

Despite the clear evidence of the non-sinusoidal flapping motion in most insects, the aerodynamic advantage was not well established. While most mechanical design tends to engage the resonant driving of the flapping wing, there are not many who had engaged the click mechanism for flapping wing nor presented any experimental study on it. However, there are some analytical models and numerical studies which attempt to predict the aerodynamic result of the click mechanism. Thomson and Thompson (1977) [13] proposed a mathematical model to describe the click mechanism, which was then used for a numerical analysis by Brennan (2003) [14]. It was initially theorized to have no advantages over the linear resonant system where the flapping is in simple harmonic motion. However, the first study was based on simple model of air damping, which is deemed inaccurate to the actual aerodynamic model. [15] Subsequently, another numerical study was carried out by Tang (2011) using the more accurate quadratic air damping factor for the aerodynamic load model. This time, the click mechanism was predicted to produce more kinetic energy in flapping given same mechanical work input, compared against resonant system. [15]

Therefore, in this paper we would like to clarify the mist around the click mechanism by presenting further analysis of click mechanism prototype which we had developed previously. [16] It is our aim try to understand how the wing kinematics results in better thrust performance, by identifying the key features of the click mechanism and relating it to the established understanding in the aerodynamics of flapping wing [17] Furthermore, we would like examine the effect of the wing motion on the thrust production given the same work input of the click mechanism compared to a sinusoidal flapping motion.

2. METHODOLOGY

2.1 Design of Click Mechanism

In order to produce the non-sinusoidal flapping motion observed in insects, we have to first examine and understand the principle of operation of the click mechanism. The mechanisms that presented in the literature brought up two distinct highlights of insect flight (Figure 1). The classical 'click' mechanism shows a sudden quick flap stroke (click) upon crossing a critical point at mid stroke. It also demonstrated an abrupt stop at the end of the stroke due to position locking and followed by wing reversal. This is somewhat logic defying in the physical sense that this sudden stop would cause large impulsive force, which could cause high stresses in the wing-joints and may cause fracture. Whereas the radial-stop proposal gives a better solution on the quick wing reversal through elastic energy recovery, where the wing is stopped elastically and bounced back by the elastic radial stop at the end of the stroke. In our prototype, we would like to combine both of these features in our mechanism, to obtain a wing flap which clicks and have a quick wing reversal.

It is important to note that the tergum is bent or moved inwards for both models in the literature. This motion allows for the flapping wing motion in regards of the geometric constraint, because if it is rigid and fixed, it is impossible for the wings to move. However, it also serves other purpose in the flapping mechanism. In the classical click model, the tergum is acting as spring, where it stores up elastic strain energy as it is bent inwards as the wing moves towards mid stroke (Position 2). This stored elastic strain energy is later released to assist the wing flap after the wing passes the mid stroke. Whereas in the radial-stop model, the stop itself is acting as an elastic spring, but it is acting only at the end of

the stroke to slow down the wing by its bending deformation. The elastic radial stop then bounces the wing back to the opposite direction with its stored energy. In this case, the tergum is just a rigid element that translates the actuation force from the muscle to the wing, and is not storing energy.

Figure 1 Wing mechanisms as illustrated by Bennet-Clark [8], reused with permission. 1a) The illustration for the classical click mechanism as observed by Boettiger. During upstroke, the tergum is bent in upon the contraction of the dorsoventral muscle (d-vm). The pleurosternal muscle (psm) provides the spring force to stress the elastic skeleton of the thorax for toggling the click at the metastable position 2. At position 2, the tergum which was bent now releases its elastic energy to assist the wing motion to move down. These interactions result in a flapping motion along time as illustrated at the bottom. 1b) The new radial-stop model as described by Miyan & Ewing. The wings are moved by the muscle contraction from position 1 to position 2, where the stop engages near the bottom of the stroke. The downward movement is slowed down by the stop, and the elastic stop is deformed as result. The wing is then bounced off to the opposite direction by the stop, resulting in a rapid reversal of movement.

Our click mechanism is designed differently from the insect's thorax that is illustrated in most literature (see Figure 2). Our tergum center is on the same rigid link of which the wing base is attached to, and it is directly actuated by a crank slider mechanism. Instead of having the tergum bending inwards, we incorporated flexural hinges to the wing process in the thorax such that the wing process bends out when the tergum is pull down towards the mid stroke. Such bending has the same energy storage effect as the tergum bending inward.

As such, the design has two flexural hinges with the wing process between them at each pleural wall. They are made of polyimide film. The joints are designed to have stiffness which gives comparable resistive force to the motor input force. This is such that the elastic strain energy stored by bending is able to produce significant force when released to assist the motor in moving the wing against the air. The motor used has a rated torque output of 0.2mNm at 3V at rated speed. With the range of stiffness of the joint roughly identified, the bistable state of thorax is then created by simply assembling the tergum with the width between the pleural walls being smaller than the tergum width, so that geometry of the stable position is such like position 1 and position 3.

Figure 2 Illustration of the mechanism in our prototypes during down stroke. Left - The click mechanism. Instead of having an inward bending tergum, the wing process at the pleural wall is bent outward to facilitate the 'click'. Right - A simple rigid body mechanism with slots and revolute joints for sinusoidal flapping motion, to be compared with the click mechanism.

We now illustrate how our click mechanism worked with reference to Figure 2. Initially, the wing rest in the 'up' position (1) where the joints are in equilibrium position with no force required to maintain the position. As the down stroke begins, the tergum is pushed up in a slower speed towards the mid stroke, because it is acting to bend the joints and to move the wings through the air. However, upon reaching the mid stroke which is a metastable position (2), the joint resistance is now acting horizontally towards the tergum and a slight nudge pass it activates the 'click' to 3.

To appreciate how the joint resistive force and its direction participated in the click mechanism, the tergum is tested using tensile load tester to examine the force required to move the tergum vertically.

Figure 3 The vertical component of the joint resistive force measured along the tergum displacement using tensile tester

The intersections of the curve at zero force represent the stable point and the metastable point. The metastable position is the point where an upward displacement of the tergum from it will have the resistive force pushing the tergum up, or a downward displacement will have the resistive force pushing the tergum down. Whereas the stable is characterized by the resistive force acting against the displacement, i.e. an upward displacement from the point will experience a resistive force pushing it down.

Ideally, the force variation along displacement should be the same for down stroke and up stroke, but due to free play between the tergum joint and the slider link as well as the bending of the link, the curves become different. For the downward displacement of the tergum, it is moving from right to left in the graph, while the upward displacement moves from left to right. The joint resistive force is negative when it is directed in the upward direction and positive in the downward direction. Note that the wing stroke moves in the opposite direction of the tergum, hence an upward motion of the tergum causes a wing downstroke.

As the tergum moves upwards from stable position 1, it encounters a positive resistive force, which is acting downwards to resist the movement. Hence, initially the downstroke is relatively slow as there is an addition of resistive force from the joints to work against. At the metastable position 2, the resistive force is reduced to zero in the vertical direction, but the joints are still bent to a stressed state due the horizontal outward bending of the wing process, being ever ready to release its elastic strain energy. A slight tilt above 2, the resistive force is now negative, acting in the upward direction, aligned to the movement of the tergum. The stressed joints are now relieved by unbending, and the resulting joint force is assisting the downstroke motion. With this additional force assistance, the tergum is accelerated even more quickly towards stable point 2, compared to when it moves from point 1 to metastable point. This results in the 'click' phenomena where the wing is suddenly moved much faster after passing the mid-stroke.

From position 2 to position 3, the joint resistive force now acts in the same direction as the tergum movement and thus assists the tergum to click down quickly until it reach the stable position 3. However, due to the high momentum, the wings do not stop exactly at the stable position, but exceeds the stable position and deforms the thorax further and bend the wing process further inwards. The thorax is designed to act like the radial stop at this point, where the joint resistance increases much more rapidly when the tergum moves further than the stable point. This will result in a strong bounce off at the end of the stroke, which is the characteristic of quick wing reversal.

2.2 Comparative Study of Click Mechanism Prototype and Sinusoidal Flapping Prototype

Figure 4 The prototypes fabricated for comparison. Left - The click mechanism. Right - Rigid body mechanism

With the main idea of thorax mechanism laid out, we proceed to fabricate the thorax. The main thorax body frame is made of carbon fiber reinforced polymer (CFRP) (Hex Ply M10.1) and polyimide film (DuPont Kapton HN). The CFRP is used as a rigid reinforcement to maintain the thorax shape. Acrylic is used to house the motor and a crank slider mechanism is used to move the tergum of the thorax. The crank is also made of acrylic, while the slider link is made using stainless steel pin. A vertical guide is also incorporated in the acrylic housing to ensure the slider moves vertically and not distort sideways. The acrylic housings are joined to the CFRP frame through basswood strips which also act as spacer. When the motor is operated, the crank slider will move the tergum up and down in an oscillatory motion. The downward movement of the tergum will cause the wings to flap up and vice versa. The wings are made of Mylar Films of 25 micron thickness, and have an aspect ratio of 2 with a quarter-ellipse shape. The leading edge and the root chord of the wings are reinforced by CFRP strip.

In order to compare to the click mechanism, a rigid body mechanism (RBM) prototype which flaps in sinusoidal motion is also designed and fabricated using acrylic. The RBM prototype has similar wing design and also width of tergum. It is operated using similar crank slider mechanism with the same crank length. However, as its wings are pivoted at a fixed rotation point, resulting in a slightly lower total wing stroke compared to the click mechanism.

Table 1 Comparison between the click mechanism and the rigid body mechanism prototypes

Components	Click Mechanism	Rigid Body Mechanism
Wing Design	Quarter Ellipse Wing with Aspect Ratio 2, wing span wise length of 6cm	
Crank length	Crank length of 6mm	
Tergum width	12mm	
Total Wing Stroke	~115°	~100°
Driving mechanism and wing-body joints	Crank-slider-driven compliant mechanism, wings rotate about flexural joints	Crank-slider with guiding slots, wings rotate about revolute joints
Weight	3.78g	3.26g

3. RESULTS

3.1 Wing flap profile

The prototypes are first operated at 3V for the observation of its wing motion. The wing motion of the prototype is recorded using high speed camera. The wing motions are then tracked to obtain the flap angle over time plot. However, as the prototype has to be clamped on a fixed platform so that the high speed camera can be focused, the performance is somewhat different from the tethered flight using the pendulum. The clamping caused stresses on the thorax and indirectly on the motor casing. This would affect the motor performance because the pressure on the gear motor casing will cause the precision planetary gears in it to experience high friction. At 3V when clamped, the click mechanism is taken when it is flapping at 9.4Hz, while the rigid body mechanism is flapping at 12.5Hz. It is quite difficult to match the flapping frequency for both prototypes because of inconsistent performance caused by the clamping.

Figure 5 The wing flap angle tracked along time for the click mechanism (left) and the rigid body mechanism (right). An ideal sinusoidal curve is inserted for comparison.

The click mechanism has unique non-sinusoidal flapping profile. Its flapping cycle is biased to having a fast down stroke, followed by a quick reversal and then a long up stroke with a gradual reversal. The sharp turn at the end of the down stroke suggest a quick wing reversal. This has similar features compared to the illustration of the wing position

over time from the literature. We can associate the down stroke with an almost linear profile to that of the classical click mechanism, whereas the wing reversal is similar to that of the radial-stop mechanism. The rigid body mechanism on the other hand has wing flap motion similar to a sinusoidal profile.

Figure 6 Sequential frames of the click mechanism at 9.4 Hz for a flap cycle. Each frame is 8ms apart.

3.2 Wing angular velocity

The wing angular velocity is derived from the time differentiation of the wing flap angle and is plotted against flap cycle to give an overview of the stroke variation. An ideal sinusoidal curve is also inserted as the benchmark for comparison, as the software tracking and experimental environment may introduce error.

The down stroke angular velocity is of higher magnitude for the click mechanism in a consistent behavior. As the aerodynamic thrust generation is proportional to the square of the angular velocity in general, a faster down stroke is associated with larger lift generation given the same lift coefficient. The angular velocities at the end of each stroke are also changing quickly to the opposite, which is representative of a quick wing reversal.

Figure 7 Sequential frames of the rigid body mechanism running at 12.5 hz for a flap cycle. Each frame is 6.5ms apart.

Figure 8 The wing angular velocity variation in the flap cycle obtained from the high speed video tracking.

3.3 Passive wing pitching about leading edge

The quick wing reversal also brings about another effect which enhances lift generation. As the wing is flexible in the chord wise direction, the abrupt change in direction brings about a large passive wing pitch about the leading edge. It is observed that the wing pitching is larger in the down stroke of the click mechanism and lasted longer than that of the sinusoidal motion, even though the rigid body mechanism is actually flapping at higher frequency at 12.5Hz compared to the click mechanism at 9.4Hz. This wing pitching represents the angle of attack of the wing relative to the air, so a larger wing pitch magnitude suggests that it is working to push more air backwards. Hence, it is expected that even at lower frequency, the click mechanism may actually produce higher thrust compared to the sinusoidal flapping motion.

Figure 9 Wing pitch variation over time for both prototypes estimated from the high speed video footage.

3.4 Thrust measurement

We are interested in how the thrust produced differed for each type of wing kinematic. To estimate the aerodynamic thrust generated, a simple pendulum setup is used for obtaining an average thrust estimate. This setup is comprised of a pendulum arm, made using CFRP strip, rotating freely around the center of a protractor, which indicates the angle of swing of the pendulum arm. The prototype will be attached to the free end of the pendulum arm. By static equilibrium, the moment caused by the thrust will displace the prototype to a certain swing angle. Hence, the swing angle would give an indication of the thrust. However, the maximum thrust measurable is limited to the swing angle of 90°, in which we consider the prototype has achieved tethered hovering. Beyond 90°, the prototype will no longer be in static equilibrium.

The thrust is measured across a range of frequency, where the flapping frequency is increased by adjusting the voltage. The voltage and current are also recorded simultaneously during the thrust measurement. However, to obtain the flapping frequency, the current variation over time is analyzed as it varies accordingly to the flap cycle due to the cyclic loading, instead of using imaging devices to track the wing motion.

The click mechanism has slightly lower frequency at the same voltage compared to the rigid body mechanism. Furthermore, the click mechanism could only operate at 2.2V and above. This is because it requires a minimum torque to overcome the joint resistive force, whereas the rigid body mechanism does not. At the same voltage, the click mechanism will run slightly slower due to this extra resistance. However, the thrust generated by the click mechanism is much higher than the rigid body mechanism at the same flapping frequency.

Figure 10 The frequency variation over voltage and the thrust variation over frequency for both prototypes

3.5 Work Input

Other than just the thrust generation, we are also interested in the work input required for generating the thrust. The electrical power is recorded simultaneously along the thrust measurement, so we can do estimate the thrust-to-power ratio for both the prototypes to examine the overall propulsive efficiency. It is observed that the click mechanism actually consumes slightly more power at each frequency compared to the rigid body mechanism, but its thrust-to-power ratio is much higher.

Figure 11 The electrical power and the thrust-to-electrical power ratio variation over frequency for both prototypes

However, we realized that the electrical power may exactly represent the mechanical work input into the system, due to the motor's efficiency variation along torque load. In our case, the motor runs only at 15-18% efficiency in most of the frequency range (Figure 12), which means much of the electrical power input has been lost in the motor itself. This also implies that the electrical power-to-thrust ratio is motor specific, so if we use different motor, we will have different trends.

Hence, we would like to have more accurate comparison with the actual work input into the system by using the motor shaft power output. The average shaft power that was produced by the motor is obtained by multiplying the average torque output and the average angular velocity. The average torque output is obtained by multiplying the average current with the motor torque constant that is given by the manufacturer.

Figure 12 Variation of motor efficiency over frequency for both prototypes

Figure 13 The mechanical power input into the flapping system from the shaft power of the motor along frequency and the thrust-to-shaft input power ratio for both prototypes

Again, the click mechanism shows higher thrust-to-shaft power ratio compared to the rigid body mechanism. However, it is also quite interesting to see that the actual thrust-to-shaft power is actually decreasing over frequency for both prototypes. This suggests that flapping at high frequency may not power efficient for our case, if the motor efficiency is disregarded, so it is better to design the MAV to flap at lower frequency, provided that it could produce sufficient thrust.

4. DISCUSSION

In order to see the benefit of click mechanism in the MAV application, we need to consider the system as a whole. The fact that MAV has much many constraints than the natural flying insects is undeniable. First of all, the power density of a battery is much limited compared to insect. Considering also that the power density on-board is limited to certain effective output voltage, usually in the range of 3-10V, the MAV and its actuator have to operate within the voltage limit. Usually the voltage increases as the frequency goes higher. While resonant systems could perform well only at high frequencies near its natural frequency [15], the click mechanism could do well even at low frequency. Thus, the click mechanism could be a better choice because it allows for higher thrust output at low frequency and voltage, compared to the common sinusoidal flapping system. There are other ways to overcome the voltage requirement, for example to incorporate a transform on board to increase the output voltage, but this definitely leads to additional components with weights. This has to be weighted into consideration to see if it brings more benefits than disadvantages to entire system.

Secondly, it is currently difficult to find efficient actuators working at the small scale that could produce sufficient torque and speed. We could see that in our case even the dc motor has only a peak efficiency of about 16% to convert the electrical power input into useful mechanical shaft output. This inefficiency has already wasted much of the electrical power stored in the battery. So it is important to make full use of whatever is left. It may be thought that common means of energy storage could increase power efficiency, for example, by adding spring elements to the sinusoidal flapping motion, as it is in a linear resonant system. But the thrust production would not be increased as it produces the same sinusoidal wing kinematics. The click mechanism, however, differs from the resonant system in the way that the energy is stored and released, resulting in the difference in the wing kinematic. The dynamics of the 'click' flapping motion is able induce stronger unsteady aerodynamic effects that enhances lift generation. Thus, even at the same frequency, the thrust production of the click mechanism is much higher compared to the sinusoidal flapping motion.

5. CONCLUSION

In conclusion, our results showed that the click mechanism produces higher thrust given the same work input compared to a rigid body mechanism with sinusoidal flapping motion. The click mechanism is effective in producing much higher thrust at the same flapping frequency, with only slightly more power consumed. This is suitable especially for low flapping frequency flapping wing MAVs.

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