A Novel Flapping Mechanism for 20cm-Wingspan Micro Air Vehicle

L.J. Yang [1], K.C. Hung [2], S. Marimuthu [3] and C.M. Cheng [4]

Abstract**—** This paper presents a progressive iteration of monoplane flapping wing mechanisms in the past few years. The primary objective of the research was to create an efficient, low power, low volume flapping mechanism capable of producing lift force large enough to enable vertical take-off and landing (VTOL), with zero phase lag between the wings, large flapping stroke and minimal transverse vibration. Three iterations of the mechanisms are presented here with problems pertaining to the primary objective progressively solved. The performance characteristics for each mechanism was evaluated based on various parameters and the final mechanism is believed to deliver the best performance for a sub 20 cm wingspan category of micro air vehicles (MAV).

Keywords**—**Flapping mechanism; Micro air vehicle (MAV); Vertical take-off and landing (VTOL); Phase lag; Monoplane

I. INTRODUCTION

THE micro gearbox for a flapping micro air vehicle (MAV) has been a topic of great concentration given its apex role in a flapping wing system. Despite many developments in the design and development of flapping mechanism over the past years [1-4], the number of monoplane mechanisms capable of vertical take-off and landing (VTOL) is relatively rare compared to the biplane counterparts. Biplane flapping mechanisms have demonstrated successful VTOL capabilities and handle larger payloads compared to monoplane configurations owing to their wing area that is double the area for a monoplane wing [5]. While it is evident that biplane flapping MAVs have shown a good performance, they heavily compromise on the biomimetic aspect of the MAV development and completely sacrifice the looks, for a performance incentive.

Development of a monoplane flapping mechanism capable of VTOL needs a higher degree of understanding of the nature's flapping mechanism. Also a greater amount of work goes into refining the mechanism to draw optimized power from the battery and sustain flight for a prolonged endurance. In most of the cases, a four bar linkage (FBL) mechanism of Fig. 1 is selected for this purpose because of its simplicity and versatility [6].

The major problem faced with monoplane flapping mechanism besides lack of sufficient forces for VTOL is the phase lag between the left and right wings during flapping. The phase lag less than 3° results in an intrinsic level-turning behavior for the flapping MAV in trajectory and less asymmetric lifts for both wings [7]. A conventional approach is taken in the design of such mechanisms where the number of linkages is kept to a minimum, to keep the overall weight of the gearbox less and to minimize performance losses due to friction in linkage vertices.

While this has a great benefit in terms of the weight and efficiency, it is not suitable for production of higher wing beat amplitudes or the flapping stroke. In most cases, the beat amplitude is limited to angles far less than 90°. (The case of the authors' previous "Golden Snitch" is only 53° [6].) Another problem that prevents a single 4 bar mechanism to power both the wings is that there is a phase lag between the two wings and it invariably results in a one sided turning making the MAV to execute circles in air with the radius of it depending on the magnitude of phase lag. Using two individual 4 bar linkage mechanism for exclusively for each wing eliminates this issue, but adds to the weight, deterring the performance. Thus, a monoplane mechanism with a 4-bar linkage requires an addition of another mitigating mechanism to eliminate the problem of phase lag. In the forth coming sections, the evolution of a basic 4 bar linkage mechanism with a considerable phase lag into a reliable, VTOL capable mechanism with zero phase lag is summarized along with experimental findings.

The choice of the mitigating mechanism is an elaborate process, as it constrains the amplitude of the wing beat, while helping to reduce the phase lag. While maintaining a zero phase lag, it is essential to maximize the amplitude, in order to obtain maximum lift from a single cycle.

II. FOUR BAR LINKAGE (FBL) MECHANISM

In 2007, the team designed and developed it first propulsive flapping mechanism that was later integrated into a 20cm wingspan MAV called 'Golden Snitch' [6] which had an endurance of 480 seconds in the flight tests. It employed a four bar linkage mechanism driven by a 6mm motor with a gear reduction factor of 26.67. The FBL mechanism of Fig. 1 consists of a base, 3 gears, and 2 linkages. From Fig. 1, there are two FBLs including OPFG and OPHI. Points of F and H cannot coincide with each other together, and they are impossible along a vertical trajectory. Therefore the phase lag between two wings must exist. As the flapping of both the wings depended solely on the crank guided by a single gear, there was a phase difference of 3° (Fig. 2 [8]), inducing a right-ward turning moment that deterred the turning performance on the left side.

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The authors used the free computation code *Flap design 2.2 JAVA* provided by the *Ornithopter* website [9] to design two kinds of bases with **w**=20 and 16 mm. The flapping stroke angle or flap angle amplitude of the cases **w**= 20 and 16 mm herein are designed as 52.8° and 50.8°, respectively. These stroke angles are much smaller than the 120° of natural birds [10]. The small stroke angle of MAVs in this work is constrained by the limited phase difference of two wings.

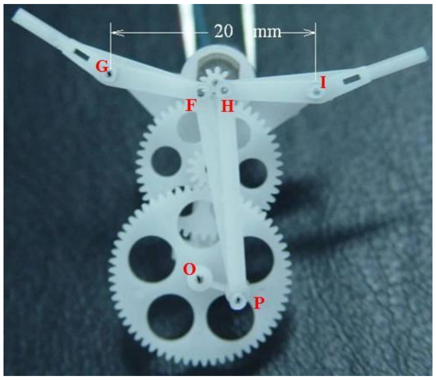


Fig. 1 FBL mechanism used in Golden Snitch [6]

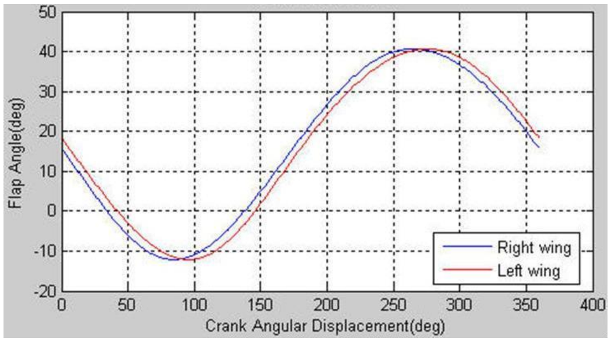


Fig. 2 Phase difference of FBL mechanism [8]

The authors have ever proposed to add an elastic spring to replace the second rigid linkage **b** in the flapping mechanism of Fig. 1 and to reduce the phase lag between two wings [11]. A first trial of modifying the flapping mechanism as Fig. 3 with the flap stroke angle from 53 degrees to 68 degrees and minimizing the phase lag between two wings from 3 degrees to zero. But the real flight test demonstrated that the elastic linkage cannot avoid the asymmetric problem as well as the phase lag actually.

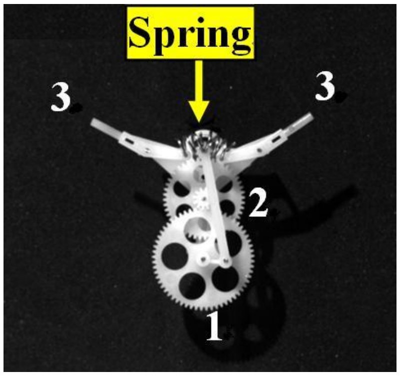
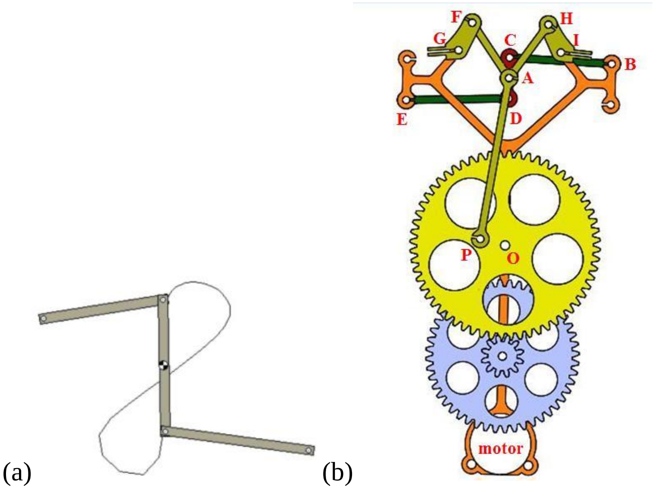


Fig. 3. The modified flapping mechanism using elastic linkage [11].

III. FBL WITH WATT'S MECHANISM

For solving the phase lag problem of conventional FBL mechanism using in flapping MAVs, the authors added several linkages to create symmetry configuration for the flapping mechanism. Inspired by the Watts' mechanism in Fig. 4(a) [12], the central part of the figure-8 trajectory is almost a straight line. Therefore the authors tried to integrate the Watt's mechanism of Fig. 4(a) into the conventional FBL and generated the modified flapping mechanism as Fig. 4(b). The linkage set BCADE is the Watt's mechanism. Point A can only move along a vertical line and created the symmetry for Fig. 4(b). So there is almost no phase lag for two wings in theoretical manner.

Fig. 4(b) is officially called as the 3rd type of Stephenson six-link mechanism [13-14]. It can be decomposed as a Watt's linear mechanism engaged with several 5-bar linkages. (OPAFG and OPAHI are both 5-bar linkages.) Consequently the phase lag between two wings can be apparently reduced from 3° in Fig. 1 down to 0° in Fig. 4(b). The phase difference of Fig. 4(b) is shown in Fig. 5.



(a) (b)

Fig. 4 (a) the figure-8 trajectory of Watt's mechanism [12]; (b)FBL with Watt's mechanism.

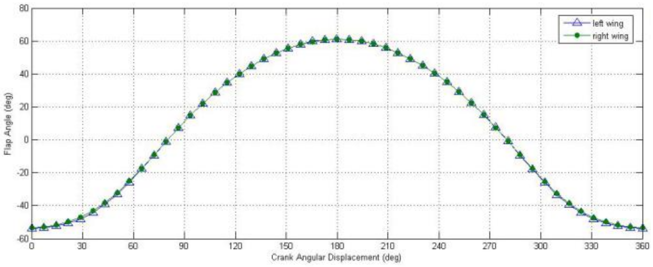


Fig. 5 Phase difference of FBL with Watt's mechanism in Fig. 4.

Fig. 5 shows that not only the phase lag is reduced, but also the flapping stroke angle effectively increased from 53° to 60° as well. The drawback of the flapping mechanism in Fig. 4(b) is its complexity with many bars and its longer shape for coupling more vibration during flapping. Moreover the motor is put at the bottom of the whole mechanism and may cause a bad position for mass stability of the whole MAV. The authors have a preliminary flight test as Fig. 6, and the instantaneous angle of attack (AOA) is about 66°.

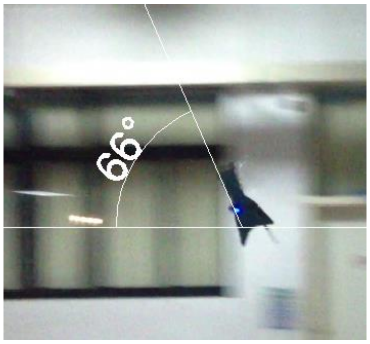


Fig. 6 Flight test of the flapping mechanism in Fig. 4.

IV. FBL WITH EVAN'S MECHANISM

As shown in the previous section, Watt's linear mechanism effectively decreases the phase lag, but it also occupied too much space and induced too much vibration torque during flapping. For ensuring a good hovering motion in the future, the authors moreover applied the Evan's straight line mechanism to replacing the Watt's mechanism.

The modified version is shown in Fig. 7. Even with an asymmetric geometry, the Evans' mechanism ACB has a simpler and smaller dimension than BCDE in Fig. 4(b) so as designing a more compact layout for the whole flapping mechanism. Point A in Fig. 7 is also guided to move along a vertical straight line. Therefore this modified flapping mechanism can be comparable to the conventional small size of FBL in Fig. 1 but provide the similar function (almost zero phase lag) of Watt's mechanism. Fig. 8 is used to show the different center of mass for the two sets of flapping mechanisms. The mechanism design of Fig. 7 is supposed to generate less vibration and good for hovering control.

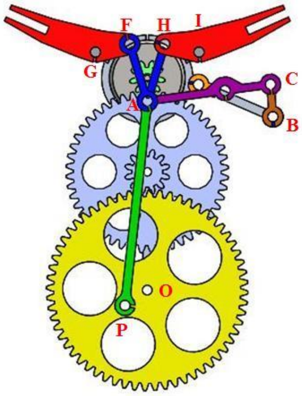


Fig. 7 FBL with Evan's straight line mechanism

The authors tried several times to design the proper linkage lengths of Fig. 7 and finally obtained the flap angle of more than 60° in Fig. 4(b). Fig. 9 shows the phase difference of FBL with Evan's mechanism in Fig. 7. The preliminary flight test in Fig. 10 moreover confirm the better instantaneous AOA of 86° than the 66° case in Fig. 6.

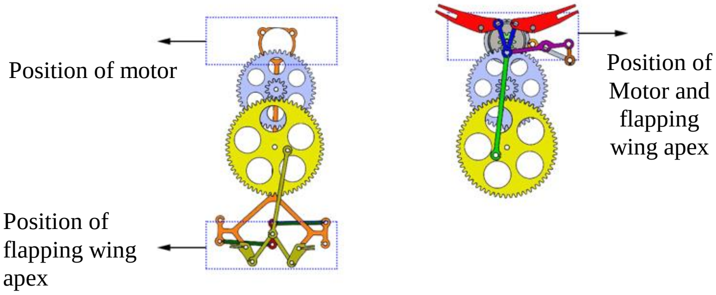


Fig. 8 Physical comparison of Watt's and Evan's mechanisms.

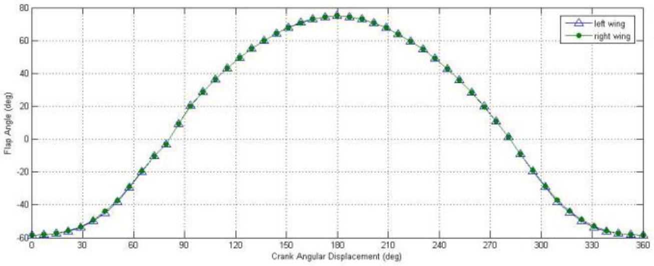


Fig. 9 Phase difference of FBL with Evan's mechanism in Fig. 7. The stroke angle or flap angle herein is up to 80° and larger than 60° in Fig. 4(b).

Fig. 10 Flight test of the flapping mechanism in Fig. 7.

V. WIND TUNNEL STUDIES

The detailed performance testing of the Evan's mechanism (Fig. 7) coupled with wing of Fig. 11 is still under investigation. The following of Figs. 12-13 and Table I show only the aerodynamic forces, torques and the flapping frequency subject to different driving voltage of the Watt's mechanism in Fig. 4(b). Both Watt's and Evan's mechanisms have the advantages of almost zero phase lag and larger flapping stroke, and the authors believe their aerodynamic performance are similar but only different in flight stability.

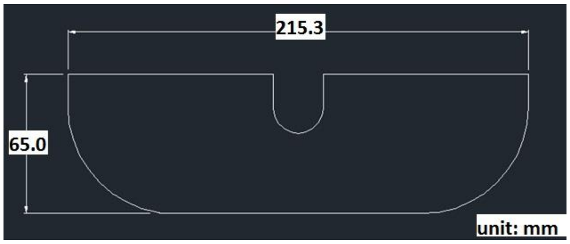


Fig. 11 The flapping wing configuration of 20cm-wingspan "Golden Snitch"; its apsect ratio is 3.78.

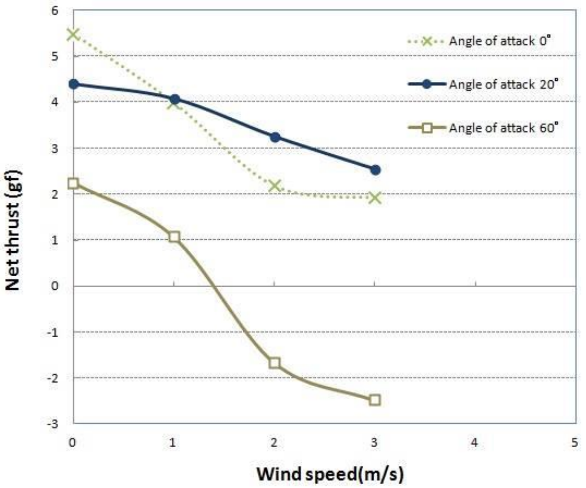


Fig. 12 Thrust force vs. wind speed w.r.t. different AOA using the mechanism Fig. 4(b). Driving voltage is 3.7V; the gear reduction ratio is 26.7; wing aspect-ratio is 3.78.

The net thrust in Fig. 12 denotes the thrust force minus the drag force in the wind tunnel. The larger the upwind speed and the air drag, the smaller the net thrust. If AOA is increased up to 60°, the decomposed horizontal component or the thrust force is decreased dramatically as well.

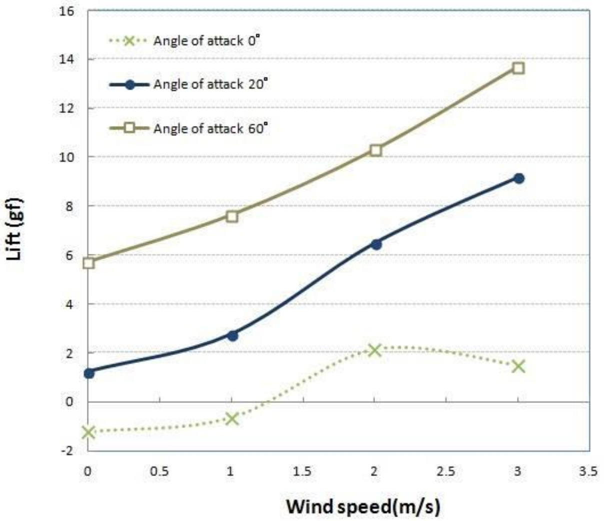


Fig. 13 Lift force vs. wind speed w.r.t. different AOA using the mechanism Fig. 4(b). Driving voltage is 3.7V; the gear reduction ratio is 26.7; wing aspect-ratio is 3.78.

Higher AOA is beneficial to the lift of flapping MAVs. Even for the case of 60°, there's almost no separation or stall happened. The lift data at high AOA from wind tunnel can explain the flight situation in Figs. 6 and 10.

Table I Forces, torques and frequency data using the Watt's mechanism in Fig. 4(b); the wing foil is shown in Fig. 11; the gear reduction ratio is 26.67; wing aspect-ratio is 3.78.

Driving voltage V (V)	Output torque without wing T_0 (N · m)	Flapping frequency without wing f_0 (Hz)	Output torque with wing T_{all} (N · m)	Flapping frequency with wing f_{all} (Hz)	Net thrust force (gf)
1	0.000344	6.71	0.002037	6.76	0.1
1.2	0.000333	9.17	0.00276	8.2	0.2
1.4	0.000397	10.1	0.003367	9	0.2
1.6	0.000423	12.05	0.004147	10.1	0.4
1.8	0.00045	13.7	0.00505	10.75	0.6
2	0.000458	15.63	0.005529	12.35	0.7
2.2	0.000508	17.24	0.006252	13.33	0.9
2.4	0.000567	18.18	0.006452	14.8	1.1
2.6	0.000579	20	0.007539	15.15	1.4
2.8	0.000592	22.22	0.008357	16.13	1.7
3	0.000647	23.26	0.009495	16.67	2.1
3.2	0.000693	25	0.010152	17.86	2.4
3.4	0.000741	27.03	0.011132	18.52	2.7
3.6	0.000835	27.78	0.011848	19.61	3.1
3.7	0.000855	28.57	0.012396	20	3.2

The actual condition for the hovering motion for flapping MAVs in the future are AOA=90° and zero upwind velocity. So the thrust force necessary to be against the gravitation of whole MAV is more crucial than lift defined in Figs. 12-13. Therefore the authors only mentioned the net thrust force in Table I. For the first glance about the thrust force, the maximum value of 3.2 gram seems not enough to support the weight about 10 gram of the MAV. The corresponding flapping frequency engaged with flapping wing for generating the maximum thrust is only 20 Hz, comparable to the FBL case in Fig. 1. It means that even the modified FBL with Watt's mechanism ideally solve the problem of zero phase lag, but the friction issue for retarding the flapping frequency up to 30 Hz is still pending. Looking at the flapping frequency engaged with no flapping wing is only 28.57 Hz reveals that the Watt's mechanism in Fig. 4(b) has intrinsic problem of big friction loss. The authors are right now testing the new mechanism of Fig. 7 and look forward to a better performance about the higher flapping frequency and the larger thrust force.

VI. CONCLUDING REMARKS

The authors herein novelly used two kinds of straight line mechanisms including Watt's mechanism and Evan's mechanism to provide almost zero phase lags and large flapping stoke angles for 20cm-wingspan flapping MAVs. The final goal of this flapping MAV is to hover like hummingbirds with low cost and light weight. The mass production of the mechanism using plastic injection molding is also suspected to be realized in the next stage of the MAV development.

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