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Research paper



Lift of Cambered Flapping Wing Inspired by Bats

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Abstract

In this paper, a bio-mimic approach was used to help characterise a flapping wing for the design of a Micro Air Vehicle (MAV). The main objective of this study is to characterise the lift performance of a flapping wing inspired by bat wings at different angle of attack (AoA), advance ratio (J) and wing camber. A series of flapping bat wings with different wing camber (flat, 6% camber, 9% camber, 12% camber, and 15% camber) was tested for its time averaged lift (C_{Lavg}) at AoA of 0^0 to 50^0 and at three different advance ratios which are; 0.88 (unsteady state regime), 1.76 (steady state regime), 3.09 (steady state regime). The result shows that as the advance ratio increases, the generated C_{Lavg} begins to decay but the enhancement of C_{Lavg} between increasing camber increases. This shows that wing camber begins to have a bigger role at higher advance ratio and hold the key to overcoming the adverse effect of high steady state flight regime on a flapping wing.

Keywords: *Flapping Wing, Micro Air Vehicles, Bio-Inspiration, Wing Camber.*

1. Introduction

Bio-mimicry or Bio-inspiration is a tool for finding solutions using observations found in biology to solve non-biological (or in this case, engineering) problems. This is an old tool in a scientist's tool box that goes back to the days of Isaac Newton and even long be-fore that [1]. Bio-mimicry have also seen a recent attention from aerospace engineers as they try to solve the problem of flapping wing. One of the reasons why, is because flapping wing is not prevalent in artificial flyers but very common in nature.

One of the ways where flapping wing can be used is in the problem of designing a Micro Air Vehicle (MAV). MAVs is defined as an unmanned aircraft that have a wing span smaller than 15cm and have a take-off weight of less than 80g [2]. One of the challenges of MAVs lies in its small size where weight and scale becomes a problem. A fixed wing faces a lot of challenges in MAVs because it is difficult to have a wing area big enough to generate enough lift and increasing the chord length will result in an aspect ratio that is too big where drag becomes a problem. Rotary wings also pose a challenge when being applied to MAVs because rotary wings are generally noisy and inefficient. This means that it requires a lot of power which MAVs cannot afford since additional power supply adds a lot of weight [3].

One type of flapping wing that can be found in nature are bat wings. Bats are a unique animal type because they are the only mammals that can achieve sustainable flight. What makes bat flight so special is that bat flight has both good efficiency and good manoeuvrability. They are known to fly long distances to find their food while at the same time they are agile enough to navigate tight and close areas [4]. What allows bats to have this flight profile is the bat wings itself. Bat wings have appendages that branch to both the span wise and the chord wise of the wing. Compare this to a bird's wing which skeletal structure only stretch only along the wing span, bat wings have a high degree of active morphing [5]. One of the ways the active morphing of a bat's wing is used is during flight, a bat will change the wing's camber to adapt to changing flight conditions and to achieve different manoeuvres. It is this act of changing the wing's camber during flight is the focus of this study. Taking inspiration from the work, this study aims to study the effect of different wing camber on the lift of a bat-inspired flap-ping wing at different Angle of Attack (AoA) and different Advance Ratio (J).

2. Similar Works

There are several previous works that are relevant to this study. Some of which are works previously done by this author, where it was shown that lift can be increased with increasing wing flexibility and increase the stall angle [6] [7]. Similar results have been observed by in works done by Song et al. [8], Rosos et al. [9] Cleaver et al. [10], and Wu et al. [11]. However, a contradicting study that have done by Wenqing et al. [12] and Cheng et al. [13] that observed a degradation in lift generation that occurs with increasing flexibility and it is rigid wings that has better lift generation. It is not until a work done by Heathcore et al. [14] that gives a reason for the contradicting observations. In the work, it is observed that a range of flexibility exists that is optimal for lift generation, where too much lift and too much rigidity can have an adverse effect on lift generation. It is observed that this is due to weak vorticity generation.

However, the magnitude of flexibility is not enough to characterise the flapping conditions of a bat, the direction of the wing flexure is also important. This is because according to Swartz [15], the wing skin of a real-life bat is anisotropic and flexible along the wingspan while stiffer along the chordwise of the wing. The effect of wing anisotropy has been studied by Tay et al. [16] where it was observed that spanwise flexibility helps with increasing thrust genera-tion while a chord-wise flexibility has an adverse effect on

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the thrust generation. A similar study was done by Jeanmonod et al. [17] where a leading-edge flexibility was found to be suitable for pressure-driven situation while a trailing edge flexibility was found to be better in an inertia driven situation. The same observation has been made by Oliver et al. [18] where it was observed that pressure deformations increases the thrust efficiency as the flexibility in-creases.

Further exploration of the effects of wing flexibility can also be found in other studies that focused on other type of wings. While these studies do not focus on bat wings, they are applicable to bat wings and provide a needed observation that the works that have been done on bat wings missed. According to Akkala et al. [19] propulsive efficiency depends on the wing flexibility and the reduced frequency of the wing, showing a relation between wing flexibility and the wing flapping mechanism. Hoke et al. [20] have observed that it is the interaction between the fluid and the leading edge of the wing that causes an increase in efficiency. Sun et al. [21] have also shown that lift generation is increased at low angles of attack due to the leading-edge vortex and as the angle of attack increases, a secondary vortex forms and push the leading-edge vortex away from the wing surface and causes the lift to decrease. This observation is supported by Bleischwitz et al. [22] that observed the airflow lags at stall angles and ends the fluid structure interactions.

In terms of the design of wing flexibility Tay [23] proposed a system where the wing flexibility itself can be change during flight and the flexibility can change the lift, thrust, and efficiency during flight. Also, Huera-Huarte at al. [24] optimized the wing tip deflection that can produce a favourable wake structures that is suitable in different flight conditions. Finally, Lee et al. [25] have observed the optimal a favourable phase angle for flight.

Observing flexibility on its own however, is still not enough since flexibility on its own does not have a direct effect on the aerodynamic performance of a wing. It is the wing shape itself that is directly affects the aerodynamic effect. In terms of wing flexibility, the wing shape is determined by the wing deflection during flight. In this area wing deflection was studied by Waldman et al. [26] and Tian et al. [27] where it was observed that the wing will deform during the downstroke and the upstroke motion of the wing where during the downstroke motion, the wing area will increase by 100%. According to Bleischwitz et al., [28] wing membrane fluctuations increases with increasing angle of attack and at high angles of attack, fluctuations at trailing edge causes high lift and low drag. In terms of the observations of wing deflections of other wings.

However, the knowledge of the effect of wing shape and flexibility is still limited and there are works that needed to be done that focus-es on the effect of specific shape or specific attributes of a wing. This limitation is the main motivation of this study. Therefore, the objective of this study is to study the effect of lift camber in the lift performance of a flapping wing inspired by bat wings at different angle of attack (AoA), advance ratio (J).

3. Methodology

2.1. Test Bat Wing

In this study, an experimental investigation was done on a model of a bat wing using an open loop wind chamber. The wing used for this study is a bat wing model made from aluminium metal structure frame and latex rubber skin previously described by this author [7]. The wing area was made to be at $0.013m^2$ and a thickness of 0.35mm. This is kept for all wing camber. The test wing shape is shown in Fig. 1.

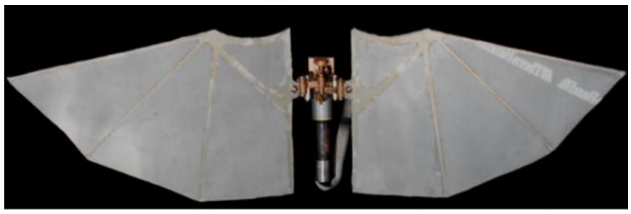


Fig. 1: Tested flapping bat wing

The wing's flapping motion was achieved using a DC mini motor controlled by an Electronic Control System (ECS) where, the ECS consists of a set of micro-controllers, a motor diver, an encoder for the DC motor, a variable resistor, and a power supply. This control system allows the flapping frequency to be measured and the flapping frequency can reduce the flapping error from 25%-35% to 0.4%-1.8%. The up and down motion of the wing is achieved by a system of gears, rockers, and sliders that have been done in a previous study from this author [8]. The flapping mechanism assembly is seen in Fig. 2.

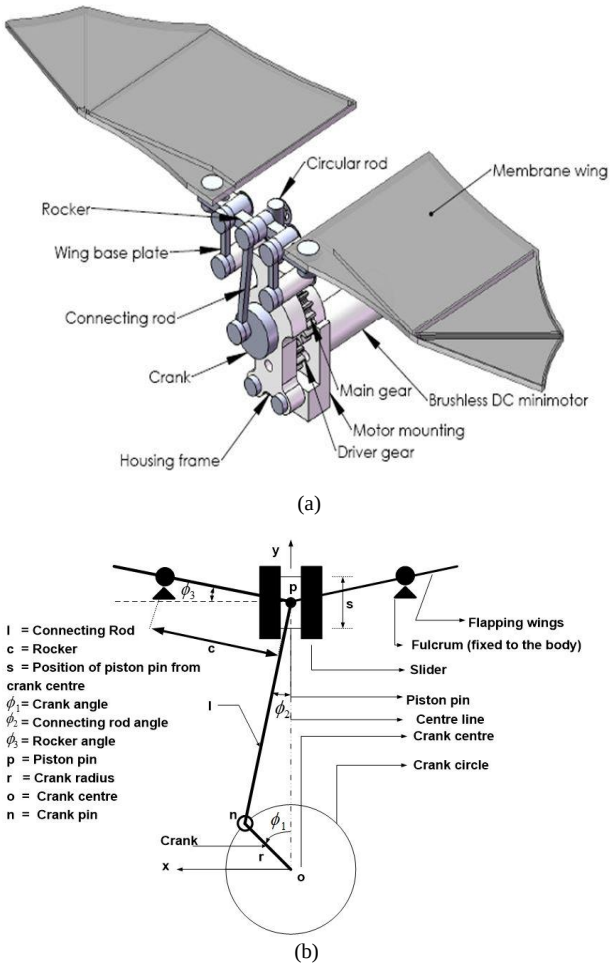


Fig. 2: Flapping wing mechanisms assembly; where (a) is the CAD drawing of the flapping mechanism and (b) is the schematic diagram of the flapping mechanism.

2.2. Testing Conditions

The first variable manipulated for this study is the wing camber of the test wing. As mentioned before, the shape, wing area, and the wing thickness is kept constant along the different wing camber. The cambers that was used for this study was; flat, 6, 9, 12, and 15% camber wings and, as can be seen in Fig. 3, was located at the 0.25 chord length of the wings. The dimensions of the wings at different wing camber is as shown in Table 1.

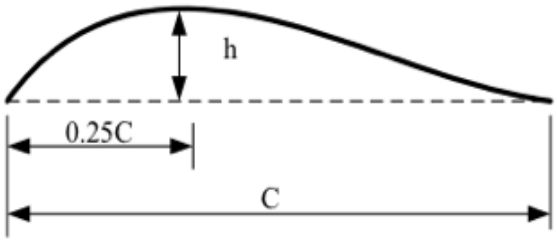


Fig. 3: Wing camber location

Table 1: Test wing dimensions

Camber (%)	6	9	12	15	Flat
Wing area, A (m^2)	0.013	0.013	0.013	0.013	0.013
Chord length, c (mm)	0.08	0.08	0.08	0.08	0.08
Camber height, h (mm)	4.8	7.2	9.6	9.6	-
Thickness, t (mm)	0.35	0.35	0.35	0.35	0.35

The second parameter used in this study is the advance ratio (J). Advance ratio is a non-dimensional parameter that is used to describe the ratio of the flight forward speed and the velocity of the flapping wingtip. Advance ratio is used to describe the flight regime of a flapping wing flight, where, if the advance ratio is less than 1, then the flight regime is unsteady flight regime, and if the advance ratio is more than 1, then the flight regime is quasi-steady flight regime. The advance ratio used in this study was; 0.88, 1.76, 3.09. The advance ratio can be calculated by;

$$J = \frac{U_\infty}{2fb\theta} \quad (1)$$

Where;
f is the flapping frequency,
θ is the total flapping angle,
b is the wing span,
U_∞ is the freestream velocity.

To achieve the different advance ratio, the flapping frequency was kept at 9Hz, and the freestream velocity was changed to 2.0ms^{-1}, 4.0ms^{-1}, 7.0ms^{-1}. The freestream velocity was created using an open channel wind test chamber controlled electronically to reach the different wind speed. The freestream wind was flowed out of a 0.3m X 0.3m open nozzle and the wind chamber consists of an air reservoir to ensure that the output wind is laminar. To ensure that the test output wind was laminar for the study, it was first tested using Laser Doppler Anemometry test which test the free stream turbulence rating to be of 0.3%.

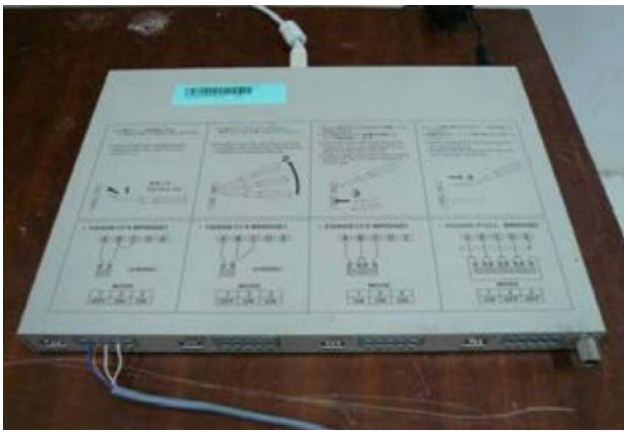
2.3. Time Averaged Lift

The data that was collected for this study is the time averaged lift coefficient. The lift was measured using a series of high precision (0.3% precision) stain gauge sensor attached to the surface of a beam surfaces as shown in Fig. 4(a). The strain gauges measured the lift generated by measuring the displacement of a rigid parallelogram composed of beams that was subjected to bending and torsional loads. The measurement data will the processed through a data acquisition system, in this case a Kyowa PCD 300A DAQ, seen in Fig. 4(b)) and then processed by a LABVIEW software for processing. The diagram of the test system can be seen in Fig. 4(c). The PCD 300A DAQ is capable pf sampling up to 5,000 samples per seconds for each channel input and 40,000 data points was collected.
The collected data was then processed to filter out the mechanical noise of the flapping mechanism using a low pass Butterworth filter with cut off frequency of 5Hz and a second order iterative process in the LABVEW software. The smooth raw data values were then time averaged is a spreadsheet and the time averaged

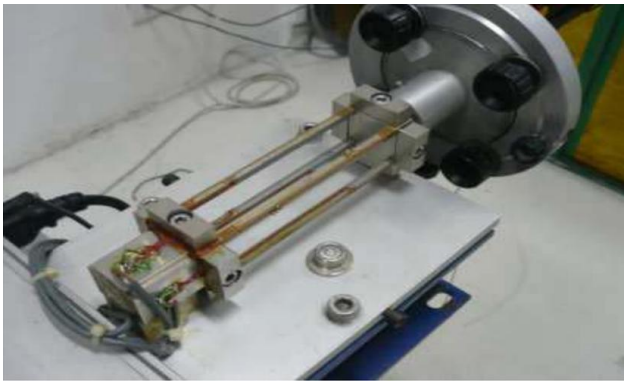
$$C_{L\,avg} = \frac{L_{avg}}{0.5\rho {V_\infty}^2 S} \quad (2)$$

lift values was the used to calculate the average lift coefficient, C_{Lavg}. C_{Lavg} can be calculated in the equation below;

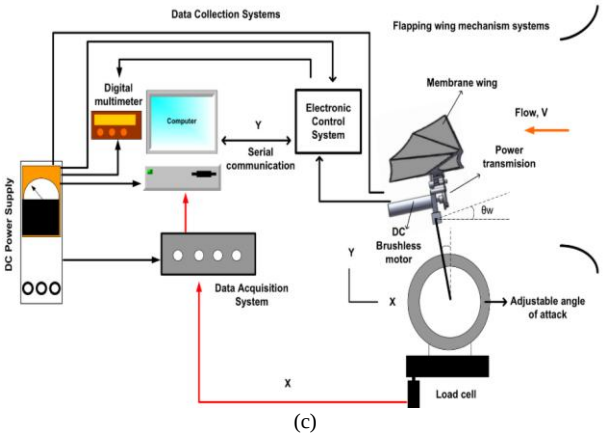
Where,
L_{avg} is the time averaged lift value,
S is the wing platform area,
V_∞ is the freestream velocity.



(a)



(b)



(c)

Fig. 4: Experimental set up where; (a) is the PCD 300-A Data Acquisition System, (b) is the strain attached to the series of beam, and (c) is the diagram of the experimental set up

4. Results

Fig. 4, 5, and, 6 shows different advanced ratio that generated the time averaged lift coefficient with changing angle of attack. Generally, for all the different advance ratio, the change in time averaged lift where, the AoA increases the time averaged lift increases

almost linearly. However, as the AoA increases further, the rate of increasing time averaged lift begins to level out and will drop with increasing AoA, which means that the wing begins to stall. This pattern shows that the tested flapping wing followed the typical lift pattern of most wings.

Another observation that can be made with all the three graphs is that for all AoA, J= 0.88 have the highest generated CL_{avg} followed by J= 1.76, and J= 3.09. This is consistent with a previous study done by this author where the generated CL_{avg} decreases with in-creasing advance ratio.

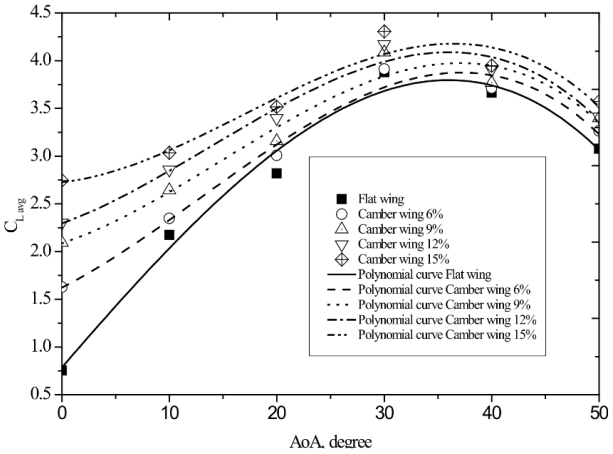


Fig. 4: the C_{Lavg} against AoA for various camber at J=0.88

Fig. 5 shows the change of C_{Lavg} AoA for J= 0.88. In Fig. 4, it is observed that for all AoA, with increasing camber, the generated C_{Lavg} increases. This is especially true for AoA 0^0 and at higher AoA the difference between the wing camber started to become smaller but the curve between the different wing camber never cross, nor did the C_{Lavg} between the camber becomes the same. It is also observed in Fig. 5, the stall angle for all the wing camber is the same which, is around 35^0 .

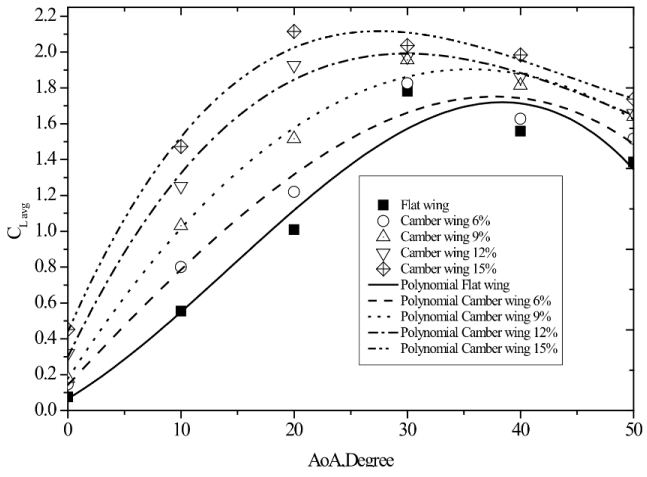


Fig. 5: C_{Lavg} against AoA for various camber at J=1.76

As shown in Fig. 6, at J= 1.76, the effect of the wing camber is like J= 0.88, where, as the wing camber increases, the generated C_{Lavg} also increase. However, at J= 1.76, higher AoA causes the generated C_{Lavg} to converge especially for 9%, 12%, and 15% camber. At AoA 40^0 and above, the difference between C_{Lavg} generated by 9%, 12%, 15% camber seems to become smaller and started to separate away from the generated C_{Lavg} of 6% and flat wing.

Fig. 6 also shows that there is a shift in stall angle for J= 1.76. This is especially true for the higher camber wings. Both 12% and 15% camber wings have a stall angle of around 25^0 while the flat, 6% camber, and 9% camber wings have a stall angle of 40^0 .

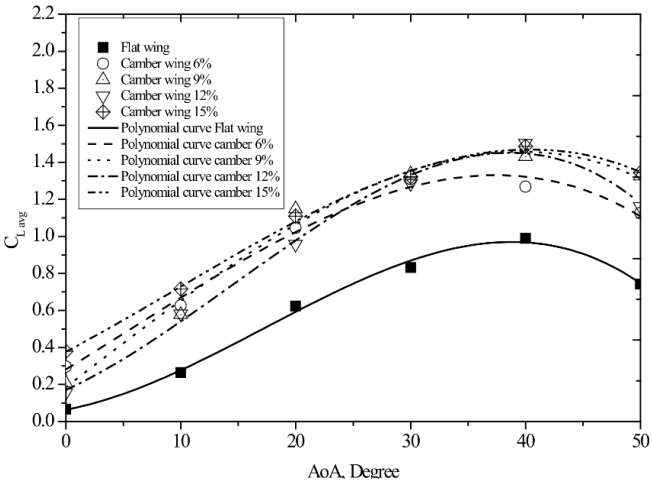


Fig. 6: C_{Lavg} against the AoA at various camber at J = 3.09

At J= 3.09 (as seen in Fig. 6), the difference in generated C_{Lavg} between the camber wings seems to be smaller than that of the previous advance ratio (J= 0.88 and J= 1.76). At all AoA the 6%, 9%, 12%, and 15% camber wings have similar C_{Lavg} but there is a significant difference between the cambered wings and the flat wing. As for the stall angle, Fig. 6, shown that all the different wings have similar stall angle of around 40^0 .

Table 2: C_{Lavg} enhancement at AoA = 10^0 .

Wing configuration	$C_{Lavg\ maximum}$			% of enhancement		
	J=0.88	J=1.76	J=3.09	J=0.88	J=1.76	J=3.09
Flat	3.75	1.7	0.9	-	-	-
Camber 6%	3.8	1.75	1.3	1.33	2.94	44.44
Camber 9%	3.85	1.9	1.45	2.66	11.76	61.11
Camber 12%	4	2	1.45	6.66	17.64	61.11
Camber 15%	4.2	2.1	1.45	12.00	23.52	61.11

Table 2 shows the difference between maximum generated C_{Lavg} between the wing cambers at different advance ratio. Unsurprisingly, with increasing wing camber, the maximum generated C_{Lavg} also increase, with 15% camber generate the most C_{Lavg} among all other wings. It is noted that with increasing advance ratio, there is an increasing percentage of generated maximum generated C_{Lavg} enhancement between the different wing camber. This shows that as the advance ratio increases, the wing camber have more of an effect to the generated C_{Lavg}. However, at J= 3.09, the 9%, 12%, and 15% camber all have the same maximum C_{Lavg} of 61.11%.

The main take away from the result is, as seen previously in a different study done by this author, as the advance ratio increased the generated C_{Lavg} of each wing begins to decrease. However, this study has shown that as the increasing advance ratio also gives a higher lift enhancement on the generated C_{Lavg}. This have shown the role of the increasing camber at different C_{Lavg}, which is to overcome the adverse effect of increasing advance ratio. From a MAV characterisation perspective, this show when different wing camber can be used to manoeuvre the MAV especially when the MAV fly through adverse flight conditions such as gusts or strong wind.

4. Conclusions

From the results, it was observed that generally, the wing camber could enhance the generated C_{Lavg}. At all AoA, increasing the advance ratio will result in decreasing generated C_{Lavg}. However, considering C_{Lavg} enhancement, as the advance ratio increases there seems to have a greater effect of the wing camber when compared to the flat wing. This is seen when comparing the maximum generated C_{Lavg} between different wing camber. This shows that, the flapping bat wing operated better at unsteady state flight regime but if the flight enters a steady state flight regime, the gen-

erated lift begins to decay. However, in steady state flight regime, the wing camber have more of an effect on the generated lift and help overcoming the adverse effect of high advance ratio.

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