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Lift and Drag Performance Based on Varying Flapping Wing Camber at Low Reynolds Number of Micro Air Vehicles (MAVs)

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Abstract – *Flapping-Wing Micro Air Vehicles (FW-MAVs) are small hand-held flying vehicles that can maneuver in constrained space owing to their lightweight, low aspect ratio and the ability to fly in a low Reynolds number environment. In this study, the aerodynamic characteristics such as time-averaged lift (CL avg) and time-averaged drag (CD avg) of camber wings with different five wind tunnel test models with 6, 9, 12, and 15 per cent camber were developed and the results were compared with a flat wing to assess the effects of camber wing on the aerodynamic performance for flapping flight applications. The experiments were performed in an open chamber with non-return airflow with a test section of (0.3 x 0.3) m and capable of speeds from 0.5 to 30 m/s. The (CL avg) and (CD avg) as functions of the angle of attack at 10º, associated with flapping frequency at 9 Hz and low Re = 3600 of the flapping motions concerning the incoming flows are measured by using a strain gauge balance and KYOWA PCD-300A sensor interface data acquisition system. It is found that camber would bring significant aerodynamic benefits in a higher lift in comparison to the flat wing and increase with increasing camber instead of drag shows contrary a decreasing of performance with increase drag when the camber raised.*

Keywords: Flapping wing, camber wing, aerodynamics

1.0 INTRODUCTION

Micro Air Vehicles (MAVs) is defined as unmanned aircraft that has a size limited to 15 mm and are capable of operating at a speed lower than 15 m/s (Null & Shkarayev, 2005). MAVs have a wide of applications in both the military sector and the civilian sector. Applications such as reconnaissance, crowd control, traffic management, survivor reach, and high risk indoors inspections. Plus, the potential applications of MAVs are high due to their recent revolutionary developments of MAVs. Generally, MAVs can be categorized into several categories; fixed-wing, rotary-wing and flapping wings. Fixed-wing is used for long-endurance outdoors missions while the rotary-wing is used for shorter endurance outdoors missions with hover flight (Galinski & Zbikowski, 2007). While these wing types are designed for difficult circumstances, these wings still have their limitations when it comes to Reynolds number conditions (flights at speeds lower than 10m/s) (Hu et al., 2010) (Pornsin-Sirirak et al., 2001). Another limitation of the fixed-wing is the inherited wingspan and surface area of the wing. This means that the MAV will have lower agility in avoiding indoor obstacles while rotary wings are relatively noisy and have poor efficiency at low Reynolds number (Galinski & Zbikowski, 2007; Hu et al., 2010). Another type of wing is that can potentially overcome the shortcomings of these wings is the flapping wing MAV. Quasi-steady state aerodynamic theory shows that it is difficult to generate enough lift during hover while slowly flying forward (Muijires, et al., 2008).

Nevertheless, it is different when it comes to bats and other flying mammals. This is due to the thin and compliant wings that have the capability of expanding and contracting the wing area, which allows for the wing chamber to form into a shape that is well suited for undesirable flow situations such as a gusty wind (Galyao et al., 2006). The incredible performance observed from some of nature's best flyers has inspired FW-MAV designers to employ membrane wings that have a variable chamber or an adaptive wing surface to achieve improved agility and efficiency during manoeuvring while flying at low speed. While a flexible membrane wing seems to be promising, but there is still a detailed analysis of an adaptive wing shape of a flexible wing membrane. There have been, several successful efforts made over the years to adopt camber wing shape in the design of several functioning MAVs (Lin et al., 2009). Previous works have shown that a cambered wing can provide additional enhancement of aerodynamic performance compared to a flat wing of the same design. Another previous work has shown that adaptive camber wings can also enhance aerodynamic performance (Yusoff et al., 2011).

Many studies have been done in studying the characteristics of chamber wings, but these studies only deal with fixed-wing MAVs. The effects of camber wings on flapping wings have not been studied except for the past few years (Kim & Han, 2006; Kim et al., 2009; Kim et al., 2008). Even still, the effect of cambers in a flapping flight is still a relatively unexplored subject. Only recent works done by (Shkarayev et al., 2010) shows camber plays a crucial influence on the aerodynamic performance in flapping flights when compared with a conventional rigid flat wing. This study aims to explore the benefits of varying camber wings on an unsteady condition. This study will focus on camber flapping wings for MAV application by evaluating the aerodynamic benefits of the camber wing compared to the flat wing. The aerodynamic benefits were evaluated by testing the time average lift generated by the wings with a function of flapping frequency, free stream velocity. The test uses a fixed angle of attack of 10^{o} and uses a flapping mechanism integrated with a novel electronic control system developed in a previous study done by the author.

2.0 METHODOLOGY

2.1 Experimental Setup

This study utilizes an open chamber with a nuzzle as can be seen in Figure 1(a). The turbine of the air chamber was located at the rear of the chamber is used to generate the required wind velocities. The air intake is first stored in a reservoir before it is channeled out to reduce possible turbulence. Airflow speed can be digitally controlled via the control unit as the air velocity increases with turbine rotational frequency. The Chamber is the open test section, non-return airflow with a test section of 1 x 1 ft (0.3 x 0.3 m) and is capable of speeds from 0.5 to 30 m/s. The turbulence level of axial flow direction is rated at 0.3% was a test using Laser Doppler Anemometry (LDA) to verify the uniformity of the free stream velocities used in the present study.

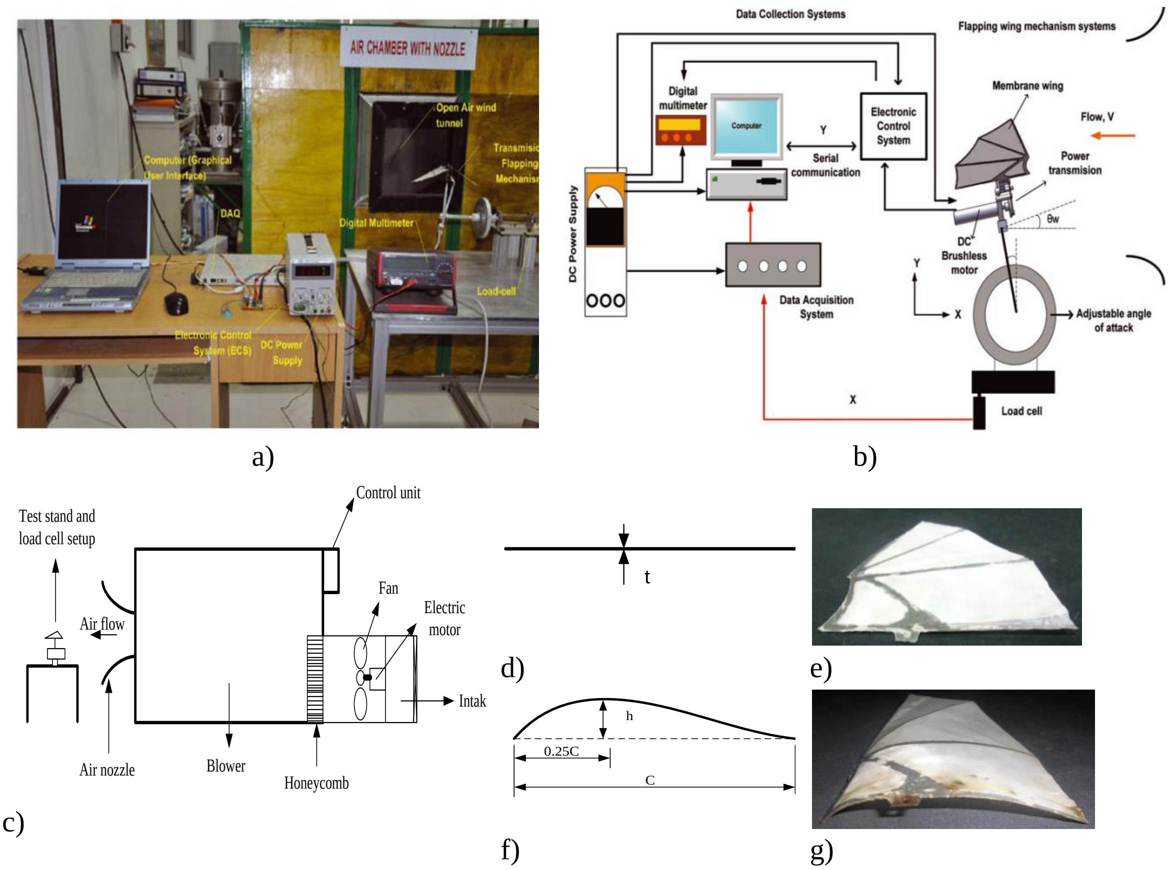

Figure 1: a) The apparatus of experimental; b) schematic of the experimental setup (Yusoff et al., 2010); c) schematic of air chamber design study; d) & e) schematic of flat and photo wing; and f) & g) schematic of camber and photo wing

Deltalab strain gauge sensor was used to measure lift and drag with high precision by attaching the flapper system to an intermediate mount. The initial manufacturer's system has been wired and configured to provide measurements for lift, drag and moment. However, for purpose of this study only lift and drag forces. Measurements are based on the displacement of a rigid parallelogram, composed of four beams subjected to bending or torsional loads. A strain gauge is fixed to the beam surfaces. The displacements are very small and the model under test, attached to the balance remains in the same plane and perpendicular to the flow direction. The precision of the force sensor for measurement in a maximum error of 0.3% of the full-scale

5N. The Kyowa data acquisition system (DAQ-type of PCD 300A model) is capable of sampling rates up to 5000 samples per second for each channel input. The calibration of the PCD 300 A model was done at default channel condition settings with a range of 10000 µm/m which a calibration factor of 1.67 and zero offset value. The instrument LabView 6.0 software providers the user interfaces and is formed for the sampling data from the DAQ devices and send the sampled raw data into a Microsoft Excel spreadsheet for aerodynamic analysis. The resolution of the DAQ is 8 bits. We collected 40,000 points of data in every single point test condition and integrate them into time-averaged values of lift and drag. Low pass Butterworth filter with cut off frequency 5Hz and 2nd iteration process was used to smooth the raw data. To determine the flapping frequency, we built in the house of an Electronic Control System (ECS) established by the system consists of a microcontroller, motor driver, DC mini motor with encoder, variable resistor power supply and a personal computer with GUI (Graphical User Interface) software. Based on a single measurement of the frequency selected in the previous report mentioned by (Yusoff et al., 2011), showed the precision error of frequency measurement in the range of 0.4 to 1.8 %. Five wind tunnel models were built with 6,9,12, and 15% camber according to the design by (Shkarayev et al., 2010), and all wings design same with according to the flat wing as mentioned earlier in previous work done by the author (Yusoff et al., 2011).

Table 1: The series of wings model geometry

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

All wings had the same chord length c, wing area A, and thickness t. The percentage of camber calculate based on the maximum height of camber relative to the chord length at the wing root that its camber 6,9,12, and 15% were defined in this study. The rest of the wings can be found in Table 1. Lastly, the testing was conducted at low Re = 3600 corresponding to 1 m/s, and the flapping frequency was set at 9 Hz. The AoA was set 10^o flapping axis respectively to the free stream velocity by adjusting the test stand of the flapper system as referred to in Table 2.

Table 2: The parameters and variables of test conditions

Parameters	**Values**
Flapping frequencies, Hz	9.0
Re	3600
The angle of attack, degree	10
Flapping angle, degree	60

3.0 RESULTS AND DISCUSSION

Effects of the camber on the aerodynamic performance of the flapping flight were investigated in the present study. During the experiments, the flapping frequency, AoA, and Re of the tested wings were kept constant, (i.e., f = 9 Hz, AoA = 10^o, Re = 3,600). Figures 2 and 3 present the aerodynamic parameters C_{Lavg} and C_{Davg} for varying camber wings from 6 – 15% when compared to the flat wing. The lift force and drag coefficient presented in Tables 3 and 4 are useful in the overall understanding of the aerodynamic performance of camber wing effectiveness on the flapping wing. Worth noting is that at low Re = 3600, the coefficient of the lift due to camber wing was found to be as high as 5.19, 5.76, 6.51, and 9.21 for the tested camber wings 6%, 9%, 12%, and 15%, respectively. Based on the trend, the lift coefficient appears to increase significantly as the camber increases. The cambered wings likewise indicate a similar trend observed in fixed wings (Null & Shkarayev, 2005), with the increase in the amount of camber, lift curves plotted move upward and the lift increase is higher for higher cambers.

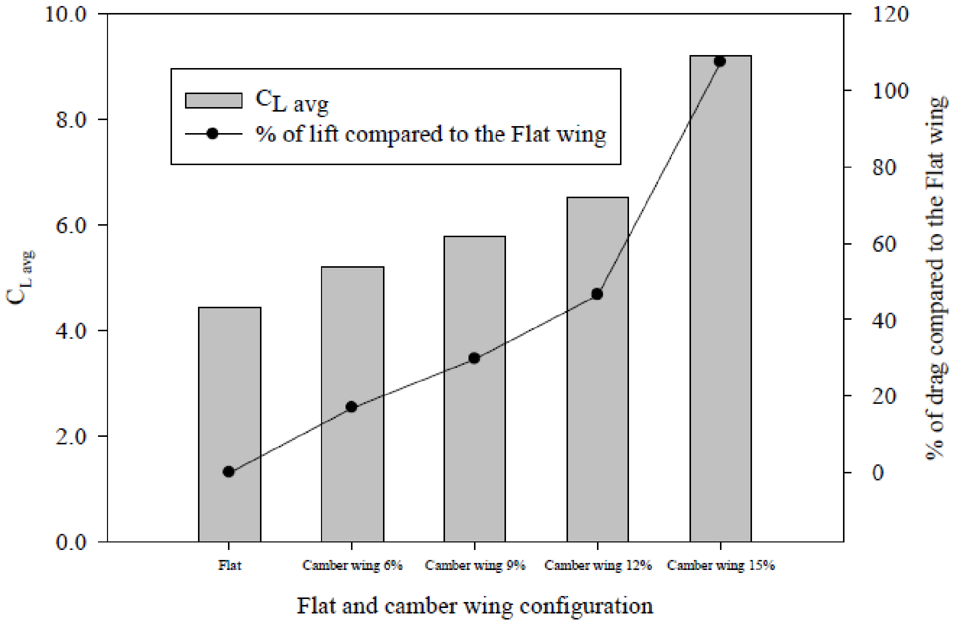

Figure 2: Time-averaged of lift coefficient from different configurations of camber at low Re = 3,600 for at flapping frequency 9Hz. (AoA 10º)

Table 3: Enhancement of C_{Lavg} based on camber condition at Re = 3600 (F = 9 Hz, AoA =10º)

Wing	Averaged of lift coefficient ($C_{L\ avg}$)	% increment
Flat	4.4454	-
Camber 6%	5.1988	16.9479
Camber 9%	5.7673	29.7364
Camber 12%	6.5108	46.4615
Camber 15%	9.2142	107.2749

For comparison, Table 3 presents that the lift coefficients of wing camber 6% increased by a factor of 1.17 times compared to the flat wing, 1.30 times for camber 9%, 1.46 times for camber 12%, and the cambered wing 15%, which presents the greatest performance by a factor of 2.07 times compared to the flat wing. Figure 3 indicates a similar trend of drag increase with an increase of camber. Worth noting is that at low Re = 3600, the coefficient of the drag due to camber wing was found to be as high as 3.22, 3.46, 3.47, and 3.97 for the tested camber wing 6%, 9%, 12%, and 15%, respectively.

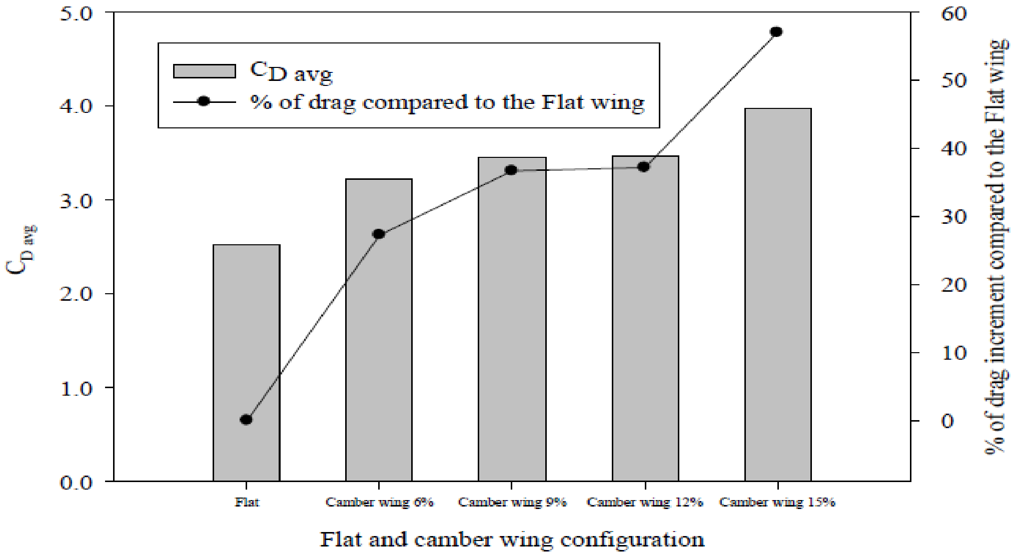

Figure 3: Time-averaged of drag coefficient from different configuration of camber at low Re = 3,600 for at flapping frequency 9Hz. (AoA 10º)

Table 4: Enhancement of CD avg based on camber condition at Re = 3600 (F = 9 Hz, AoA =10º)

Wing	**Averaged of drag coefficient (C_{Davg})**	**% increment**
Flat wing	2.5316	-
Camber 6%	3.2224	27.2871
Camber 9%	3.4610	36.7120
Camber 12%	3.4735	37.2057
Camber 15%	3.9759	57.0509

For comparison, Table 4 presents that the drag coefficients of wing camber 6% increased by a factor of 1.27times compared to the flat wing, 1.36 times for camber 9%, 1.37 times for camber 12%, and the cambered wing 15%, which presents a greater increment by a factor of 1.5705 times compared to the flat wing.

4.0 CONCLUSION

The main goal of the experiments is to study the aerodynamic effect of cambered wings for flapping-wing micro air vehicles (MAVs) at a low Reynold number. The result shows that the flapping motion of the tested wings with camber brings significant aerodynamic benefit specifically in lift enhancement 1.17 to 2.07 times compared to the flat wing. Drag coefficient, however, the camber wings considerably insignificant in overall drag production over the flat wing.

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