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LIFT PERFORMANCE OF A CAMBERED WING FOR AERODYNAMIC PERFORMANCE ENHANCEMENT OF THE FLAPPING WING

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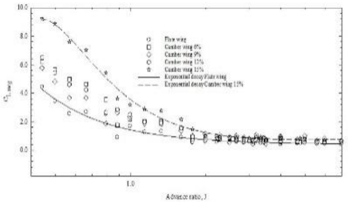
Graphical abstract



Abstract

Flapping-Wing Micro Air Vehicles (FW-MAVs) are small hand-held flying vehicles that can maneuver in constrained space owing to its lightweight, low aspect ratio and the ability to fly in low Reynolds number environment. In this study, the aerodynamic characteristics such as time-averaged lift of camber wings with different five wind tunnel test models with 6, 9, 12, and 15 percent camber were developed and the results were compared with time-averaged lift of a flat wing in order to assess the effects of camber wing on the aerodynamic performance for flapping flight applications. The experiments were performed in an open circuit wind tunnel with of 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 time-averaged lift as functions of advance ratio of the flapping motions with respect to 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 when the flapping flight is in unsteady state regime, with advance ratio less than 1.0. The aerodynamic benefits of camber are found to decay exponentially with the increasing advance ratio. Cambered wing shows significantly higher lift in comparison to the flat wing.

Keywords: Flapping wing, camber, lift, drag, micro air vehicle

1.0 INTRODUCTION

Micro Air Vehicles (MAVs) is defined as an unmanned aircraft that has a size limited to 15 mm and capable of operating a speed lower than 15 m [1]. MAVs have a wide of application 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 categorizes; fixed wing, rotary wing and flapping wings. Fixed wing is used for long endurance outdoors missions while rotary wing are used for shorter endurance outdoors missions with hover flight [2]. 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)[3,4]. Another limitation of the fixed wing is the inherit wingspan and surface area of the wing. This means that the MAV will have lower agility in avoiding indoor obstacles while rotary wings is relatively noisy and has poor efficiency at low Reynolds number [2,3]. Another type of wing is that can potentially overcome the short comings of these wings is the flapping wing MAV.

Quasi-steady state aerodynamic theory shows that it is a difficult to generate enough lift during hover while slowly flying forward [7]. 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 [8]. The incredible performance observed from some of nature's best flyers has inspired FW-MAV designers to employ membrane wings that have variable chamber or an adaptive wing surface to achieve improved agility and efficiency during maneuvering 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 [9]. Pervious works has shown that camber wing has the ability to provide additional enhancement 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 [6].

There are 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 [10, 11, 12, 14]. Even still, the effect of cambers in a flapping flight is still a relatively unexplored subject. Only recent works done by Shkarayev et al. [14] shows camber plays a crucial influence on the aerodynamic performance in flapping flights when compared with a conventional rigid flat wing.

In continuation of the work done by Shkarayev et al. [14], this study aims to explore the benefits of varying camber wing on an unsteady condition. This study will focus on camber flapping wings for MAV application by evaluating the aerodynamic benefits of camber wing compared to 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 10o and uses a flapping mechanism integrated with a novel electronic control system developed in our previous study [6].

2.0 EXPERIMENTAL DETAIL

2.1 Experimental Setup And Procedure

The airflow chamber is located in the School of Mechanical Engineering, University Sains Malaysia. The propeller at the rear of this chamber generates the required wind velocity. To avoid undesired turbulence, intake air is stored in a reservoir, before being channeled out through an open nozzle. The digital controller is used to control the air speed. The test chamber is an open section with non-return airflow; it has a 1 x 1 ft (0.3 x 0.3) m opening and capable of speed ranging from 0.5 to 30 m/s. In order to verify the uniformity of free stream velocity, the turbulence level of axial flow direction was tested using Laser Doppler Anemometry (LDA), which the free stream uniformity was rated at 0.3%. The lift and drag was measured using a high precision DELTALAB strain gauge sensor that was attached to the flapper system by an intermediate mount. The measurements are based on the displacement of a rigid parallelogram, composed of four beams subjected to bending or torsional loads where the strain gauge is fixed to the beam's surfaces. The displacements are very small and the test model is attached to the balance and will remain in the same plane and perpendicular to the flow direction. The precision of the force sensor's measurement has 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 300A model was carried out under default channel condition settings. And it has a range of 10000 μm/m, with calibration factor of 1.67 and a zero offset value (refer figure 1b for a diagram of the experiment set up). The LABVIEW 6.0 software provides the necessary user interface for sampling data from the DAQ device and exports the sampled raw data into Microsoft Excel spreadsheet for further aerodynamic analysis. The resolution of the DAQ was 8 bits. Low pass Butterworth filter with cutoff frequency of 5Hz and a second order iterative process was used to smooth the raw data. A total of 40,000 data points was collected for every point test condition, which was then used to find the time average value of the lift coefficient, CL avg. (Eq.1).

$$C_{L_{avg}} = \frac{L_{avg}}{0.5\rho V^2 \infty S} \qquad (1)$$

Where; Lavg. is the average lift force, S is wing platform area, V∞ is forward flight speed, and ρ is air density.

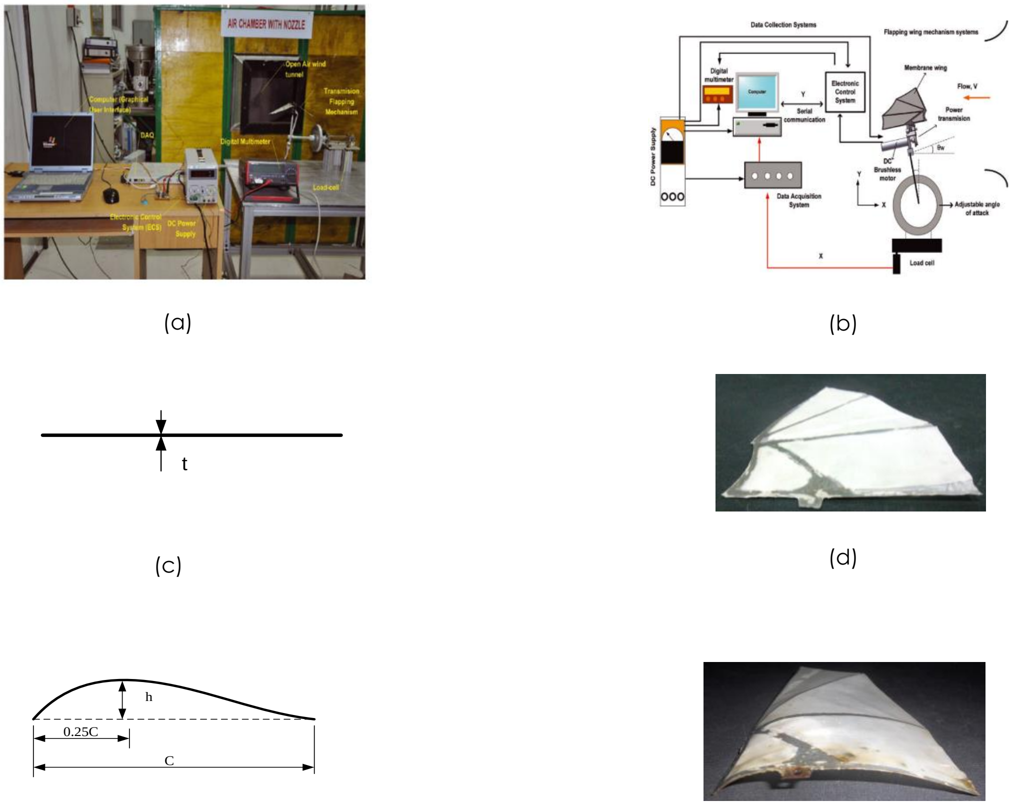
To accurately determine the flapping frequency, an Electronic Control System (ECS) consisting of microcontroller, motor driver, DC mini-motor with encoder, variable resistor power supply and a personal computer with GUI (Graphical User

Interface) [6]. This helped overcome some of the major issues associated with the traditional means of controlling and measuring the flapping frequency, and the relative error was reduced from 25–35% to 0.4–1.8%. Similar to the work done by Shkarayev et al. [14], this study used test models with 6, 9, 12, and 15 percent camber. The wing design that was used in this study is the same design that was used previously by the author in a different study [6]. These wings had same chord length (c), wing area (A), and thickness (t) (see also Fig. (1c to 1d). Table 1 shows the physical features for wings with different camber percentage. Fig. (1a to 1b) shows the experiment and schematic setup.

Table 1 Wings model geometry series.

Camber, (h/c) %	**6**	**9**	**12**	**15**	**Flat**
Wing area (A) [m²]	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	12	-
Thickness (t) [mm]	0.35	0.35	0.35	0.35	0.35

Each model was mounted in the wind tunnel and tested over a range of free stream velocity (V) from 1 to 7 m/s, corresponding to Reynolds number ranging from 3600 to 25,200 and flapping frequency (F) of 4 to 9 Hz. The pitch angle of the flapping axis (θw)was set with respect to the angle of attack of 100 and the direction of the free stream velocity by adjusting the test stand of the flapper system.



(a) (b)

(c) (d)

(e) (f)

Figure 1 (a) The apparatus of experimental (b) schematic of experimental setup by Yusoff et al. [6] (c)-(d) schematic of flat and photo wing, and (e)-(f) schematic of camber and photo wing.

3.0 RESULTS AND DISCUSSION

3.1 Unsteady Effects Of Lift And Drag Performance

Ho et al. [5] have shown that flapping flight mechanism was separated into two regimes: quasi-steady state and unsteady state regime. Quasi-steady state flapping flight refers to a wing flap at relatively low frequency, or hardly flapping at all, during flight; hence the wing tip speed is lower compared to the forward flight speed. Larger birds, such as eagles and seagulls, are usually considered to fly in quasi-steady regime since they usually flapped their wings quite slowly, tending to have soaring flight as their wings behave more like fixed wings. On the other hand, smaller birds and insects fly in the unsteady state regime with their wings flapping at much higher flapping frequency (e.g., flies and mosquitoes flap their wings at several hundred hertz), and their wingtip speed during the flapping motion is much faster than the forward flight speed. When a flapping flight is in unsteady state regime, the flow motion around the flapping wing is highly unsteady and cannot be approximated by quasi-steady-state assumptions. In accordance to the work of Ho et al. [5], a non-dimensional parameter called advance ratio 'J', which is widely used to characterize aerodynamics of a rotorcraft and was used in the present study in order to characterize the measurement data of the tested wings in flapping flight. Advanced ratio, 'J', which is defined as the ratio of forward flight speed (i.e., the incoming flow velocity) to the wingtip velocity during flapping flight, can be expressed as:

$$J = \frac{V_\infty}{2 fb\Phi} \tag{2}$$

Where; f is the wing flapping frequency, and ϕ is the peak-to-peak displacement of the wing tip during the flapping flight.

The flow around a flapping wing can be considered as a quasi-steady state when J > 1.0, while J < 1.0 corresponds to unsteady state regime [6]. For the ease of comparison, the exponential decay is also plotted on the same graph for the flat and 15% camber wings as shown in Fig. 2. The experimental results confirmed that the present set up belonged to the region of unsteady and quasi-steady flow. For an advance ratio lesser than 1, the value of CL avg. for all the wings increased exponentially. On the other hand, when the advance ratio increased, CL avg. values decreased rapidly which can jeopardize the aerodynamic benefits of flapping wings. It has been established that under quasi-steady regime with relatively large values of J, there is virtually limited or zero aerodynamic benefits to CL avg.

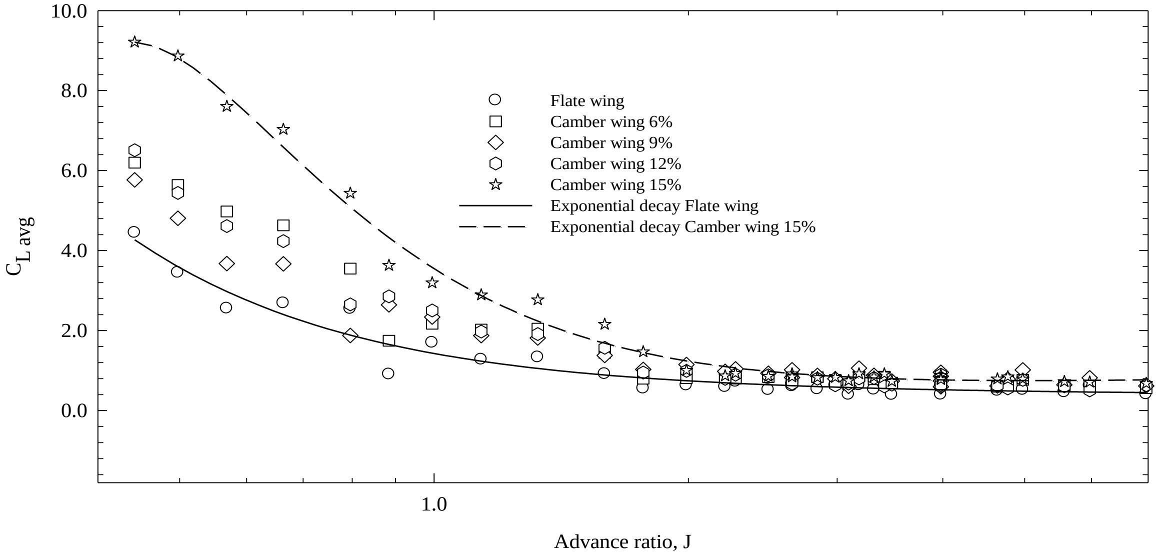


Figure 2 $C_{L\,avg.}$ respect to advance ratio (*J*).

Therefore, to compare the results of CL avg. for every increment in camber wing, a flat wing was utilized. It was found that the maximum camber wing 15% provided the best values for lift and drag coefficients. This was because, as the camber increases, the lift force also increases. The CL avg. value was enhanced 2 to 3 times, in comparison to the flat wing performance for an advance ratio less than 1. However, when the advance ratio was more than 1 (i.e. quasi-steady) the amount of lift increment for camber 15% did not show any significant benefits. The increase in lift was only around 0.5~0.7 times, much lesser than the case with lower values of advance ratio. This result indicates that the flapping wings have better aerodynamic benefits under unsteady flow regimes.

4.0 CONCLUSION

The main goal of the experiments is to study the aerodynamic advantages of cambered wings for flapping wing micro air vehicles (MAVs). The result shows that the flapping motion of the tested wings with camber bring significant aerodynamic benefit specifically in an unsteady state regime with the flapping flight advance ratio of 1.0 or less. At higher advance ratio however, the aerodynamic benefit of camber in flapping flight begins to decay rapidly. The camber wings considerably significant in overall lift production over the flat wing for both unsteady and quasi-steady.

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