

# An Experimental Study of Flexible Membrane Wings in Flapping Flight

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**An experimental study was conducted to assess the aerodynamic benefits of using flexible membrane wings for the development of flapping-wing Micro-Air-Vehicles (MAVs). The overall aerodynamic performances (i.e. time-averaged lift and thrust/drag generation) of two flexible membrane wings with different skin flexibility (i.e., a flexible nylon wing and a more flexible latex wing) were compared with those of a conventional rigid wing in order to assess the effects of skin flexibility (rigidity) of the tested wings on their aerodynamic performances for flapping flight applications. The measurement results revealed clearly that, for all the tested wings, flapping motion would bring significant aerodynamic benefits when the flapping flight is in unsteady state regime with advance ratio of the flapping flight being smaller than 1.0. The aerodynamic benefits of flapping flight were found to decay exponentially with the increasing advance ratio. Flapping motion was found to become detrimental for high speed flight applications. The skin flexibility (rigidity) of the tested wings was found to have considerable effects on their aerodynamic performances for both soaring flight and flapping flight applications: The flexible membrane wings were found to have better overall aerodynamic performance (i.e., lift-to-drag ratio) over the rigid wing for soaring flight, especially for high speed soaring flight applications. The rigid wing was found to have better lift production performance for flapping flight in general. The latex wing, which is the most flexible among the three tested wings, was found to have the best thrust generation performance for flapping flight. The less flexible nylon wing, which has the best aerodynamic performance for soaring flight applications, was found to be the worst for flapping flight applications.**

## Nomenclature

$$C_D = \text{Drag coefficient, } C_D = D / \left( \frac{1}{2} \rho V_\infty^2 S \right)$$

$$C_L = \text{Lift coefficient, } C_L = L / \left( \frac{1}{2} \rho V_\infty^2 S \right)$$

$$C_T = \text{Thrust coefficient, } C_T = T / \left( \frac{1}{2} \rho V_\infty^2 S \right)$$

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$D$	=	Drag force
$L$	=	Lift force
$OA$	=	Orientation angle
$S$	=	Wing platform area
$T$	=	Thrust force
$V_\infty$	=	Forward flight speed or incoming flow velocity
$\rho$	=	Air density

## I. Introduction

**M**ICRO-Air-Vehicles (MAVs), which are characterized by small vehicle size (<10 cm) and low flight speed (<10 m/s), have attracted a growing interest in aerospace engineering community due to their great potentials for various civil and military applications. Equipped with video cameras, transmitters, or sensors, these miniaturized aerial vehicles can perform surveillance, reconnaissance, targeting, or biochemical sensing tasks at remote, hazardous, or dangerous locations. Although scaled-down versions of conventional designs of “macro-scale” aircraft may be the obvious approach to MAV design and are being pursued for many outdoor applications, such flight platforms are unattractive for indoor flight for a number of reasons. Fixed-wing MAVs, for example, do not have the required agility for obstacle-avoidance in indoor flight, and are incapable of hovering. Although rotary-wing MAVs offer good agility and vertical-take-off-and-landing (VTOL) capability, they suffer from wall-proximity effects, are too noisy, and usually inefficient for low Reynolds number flight [1-2]. A plausible alternative, therefore, is flapping flight.

Flapping flight is one of the most complex yet widespread modes of transportation found in nature. Over a million different species of insects fly with flapping wings to produce lift and thrust, and more than 10,000 different kinds of birds and bats flap their wings for locomotion [3]. Flapping flight has undoubtedly been a sophisticated realm of flight and has intrigued human beings for hundreds of years. It has long been realized that steady-state aerodynamics does not accurately account for the aerodynamic forces produced by the flapping flight of natural fliers. This has prompted extensive studies to uncover underlying physics and to elucidate fundamental mechanisms employed by the natural fliers to produce enough aerodynamic forces needed for propulsion and maneuvering. Much progress has already been made in recent years associated with the flapping flight of the natural fliers. As summarized by Viieru et al. [4], the fundamental mechanisms responsible for high lift generations in flapping flight would include: 1). Weis-Fogh’s clap-and-fling [5-7]; 2). Delayed dynamic stall associated with leading-edge vortex attachment in flapping motion [8-9]; 3). Fast pitching-up rotation of flapping wings [10-12]; and 4). Wake capturing associated with wing-wake interaction during flapping flight [10-13]. Further information about unsteady aerodynamics of flapping flight can be found from the reviews of Ho et al. [14], Ansari et al. [15], Mueller [16], and Shy et al. [17].

Although much progress has already been made about flapping flight, most of the previous studies were conducted from a biologist’s point of view to try to understand the fundamental mechanism of the flapping flights of natural fliers. As described by Mueller & DeLaurier [16], there is a fundamental difference between an aerospace engineer’s interest in flapping flight and that of a biologist or zoologist. The primary motivation for studying the flight mechanics of natural fliers is to explain the physics for a creature that is known to fly. That is, the fact that it achieves successful thrust and propulsion is given. Therefore, various analytical models are adjusted to match the measurement results, and conclusions are reached regarding energetic, migration capabilities, etc. An aerospace engineer, in contrast, is trying to develop a flying aircraft, and its ability to achieve this is no given fact. What an aerospace engineer needs is a design-oriented analysis, which is not what can be offered from animal-flight studies.

Numerous experimental and numerical studies have been conducted in recent years to investigate the flow pattern and vortex structures in the wakes of flapping airfoil/wings. Much work has also been done to study the variations of the resultant aerodynamic forces (lift and thrust) acting on flapping airfoils/wings with phase angle of up-stroke and down-stroke within a flapping cycle. However, very little in the literature can be found to quantify the overall aerodynamic performances of flapping wings (i.e., how much time-averaged lift and thrust can be generated by flapping the airfoils/wings) as functions of flapping frequency, forward flight speed, as well as the orientation angle of the flapping plane with respect to incoming flows (i.e., flight direction). For the development of engineered flapping-wing MAVs, such information is extremely important because the performances of the MAVs, such as the vehicle size, payload, and flight speed, would be totally determined by the mean lift and thrust that can be produced by the flapping wings.

Thin and flexible membrane wings are unique to flying mammals such as bats, flying squirrels and sugar gliders. These animals exhibit extraordinary flight capabilities with respect to maneuvering and agility that are not observed in other species of comparable size. It has been suggested that a potentially useful feature for engineered maneuverable MAVs might be the incorporation of flexible membranes as lifting surfaces. With this in mind, we conducted the present study to try to leverage the unique feature of flexible membrane airfoils/wings found in bats and other flying mammals to explore the potential applications of such non-traditional bio-inspired flexible-membrane airfoils/wings to MAV designs for improved aerodynamic performance. It should be noted that several successful efforts have already been made in recent years to adopt flexible membrane airfoils/wings in the designs of functional MAVs [18-20]. It has been found that flexible membrane airfoils/wings are able to alleviate the effects of gust wind, delay airfoil stall, and provide additional advantages for morphing to achieve enhanced agility and storage compared to conventional rigid airfoils/wings for MAV applications [18-24]. However, most of the previous studies on flexible membrane wings/airfoils are targeted for fixed-wing MAV designs, the advantages or disadvantages of using flexible membrane airfoils/wings for flapping-wing MAV designs have not been fully explored.

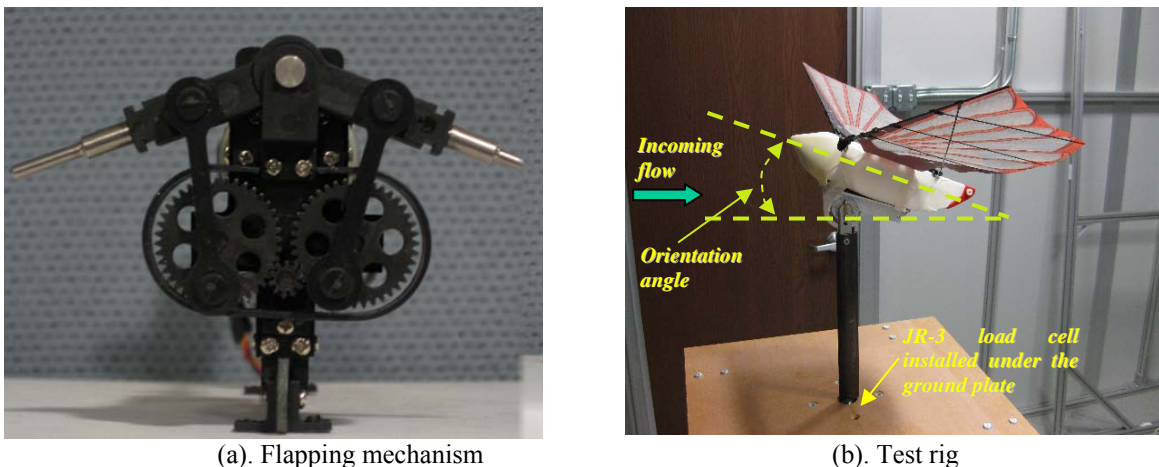
In the present study, an experimental investigation was conducted to assess the aerodynamic benefits of using flexible membrane airfoils/wings for flapping-wing MAV applications. The time-averaged lift and thrust generated by flapping two flexible membrane wings with different skin flexibility (i.e., a flexible nylon wing and a more latex wing) were compared with those of a conventional rigid wing to quantify the effects of the skin flexibility (rigidity) of the tested wings on their aerodynamic performances. During the experiments, the time-averaged lift and thrust generated by the tested wings as the functions of flapping frequency, forward flight velocity, and the orientation angle of the flapping motions with respect to the incoming flows were measured by using a high sensitivity force-moment sensor. Advance ratio, which is defined as the ratio of the forward flight speed to the wingtip velocity of the tested wings in flapping flight, was used to characterize the aerodynamic advantages of flapping flight over soaring flight (i.e., without flapping motion) for MAV applications.

## II. Experimental Setup and Studied Wings

The experiments were performed in a low-speed wind tunnel located in the University of Florida's Research & Engineering Education Facility (UF-REEF) near Air Force Research Laboratory at Eglin Air Force Base. As shown in Fig. 1, the wind tunnel has a bell mouth inlet with the inlet cross sectional being 12 ft  $\times$  12 ft. A flow conditioning section consisted of honeycomb screens and mesh structures was installed ahead of a contraction section to provide uniform, low-turbulent incoming flow to enter the test section. The exit of the contraction section is 42 ft  $\times$  42 ft square, which is the start of the open jet test section. The open jet test section has a rigid enclosure of 11 ft high  $\times$  12 ft wide  $\times$  15 ft long. A diffuser section is installed at the downstream of the open jet test section to make a transition from a square cross-section to a 60in circular axial fan driven by a 50 HP Reliance Electric motor.



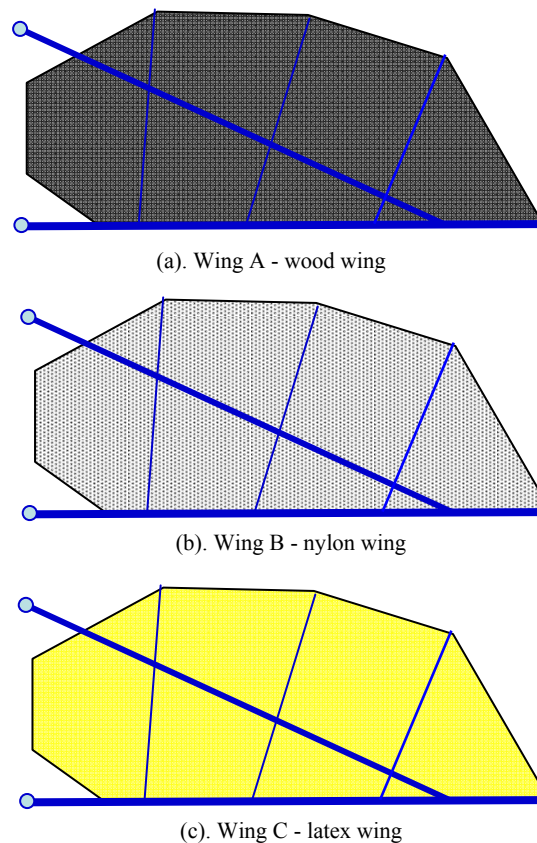
**Fig. 1:** Low-speed wind tunnel used in the present study



**Fig. 2:** Flapping mechanism and the test rig used in the present study

Fig. 2 shows the test rig and flapping mechanism used in the present study. Similar to the work of Hong & Altman [25], the flapping mechanism used in the present study was adapted from a Cybird P1 remote control ornithopter model, which is powered by a DC power supply. During the experiments, the flapping frequency of the mechanism is adjustable by changing output voltage of the DC power supply. The aerodynamic forces (lift, and thrust or drag) acting on the tested wings were measured by using a high-sensitive force-moment sensor cell (JR3, model 30E12A-I40). The force-moment sensor cell is composed of foil strain gage bridges, which are capable of measuring the forces on three orthogonal axes and the moment (torque) about each axis. The precision of the force-moment sensor cell for force measurements is about  $\pm 0.05\%$  of the full scale (40 N). During the experiments, the output signals from the force-moment sensor cell were scanned at 1,000 Hz for 60 seconds for each tested cases. The time-averaged lift and thrust produced by the tested wings in soaring and flapping flight were determined based on averaging the acquired 60,000 data samples.

Fig. 3 shows the schematic of the three wing models used in the present study. All the three tested wings have same rigid glass fiber frames (i.e., rigid leading edge spar and chordwise battens) and same elliptical wing planform shape and dimensions. The skin flexibility (rigidity) of the wings is quite different. The wing model-A is a rigid wing, which is made of a thin wood plate (thickness  $\sim 200\mu\text{m}$ ). The rigid wood wing was used as the comparison baseline in the present study in order to assess the aerodynamic benefits of using flexible membrane wings for soaring flight and flapping flight applications. The wing model-B is a flexible membrane wing, which is made of a thin nylon film (thickness  $\sim 70\mu\text{m}$ ) bonded to the rigid graphite frame. The skin of nylon wing is much easier to fold than to be stretched out. The skin of the nylon wing could deform along both chordwise and spanwise directions during soaring and flapping flight. The wing model-C is made of a thin latex sheet (thickness  $\sim 120\mu\text{m}$ ) bonded to the same rigid graphite wing frame. The skin of the latex wing is much easier to be stretched compared with the nylon wing. Therefore, the latex wing is the most flexible membrane wing among the three tested wings. It can deform significantly during soaring flight and flapping flight testing. Further information about the characteristics of the tested wings is given in Table 1.



**Fig. 3:** The tested wings

**Table 1: Characteristics of the tested wings**

TESTED WING	MASS (g)	AREA OF WING PLATFORM (cm <sup>2</sup> )	WING SPAN (cm)	CHORD AT MID-SPAN (cm)	FLAPPING ANGLE (Deg.)
Rigid wing	59.7	475.1	36.8	16.5	47.4
Nylon wing	15.1	475.1	36.8	16.5	47.4
Latex wing	30	475.1	36.8	16.5	47.4

### III. Experimental Results and Discussions

#### A. Aerodynamic performances of the tested wings in soaring flight

The aerodynamic performances of the three tested wings were compared at first for soaring flight (i.e., fixed wing) applications. During the experiments, the rigid leading edges of the tested wings were positioned horizontally. The incoming flow velocity in the test section (i.e., the forward flight speed) was varied from 1.0 m/s to 10.0 m/s, and the corresponding chord Reynolds number (based on the chord at wing mid-span)  $Re_C \approx 10,000$  to 100,000. For soaring flight, the orientation angle (OA) shown in Fig. 2 is actually the angle of attack of the tested wings with respect to the incoming flows. Some typical measurement results of the tested wings were given in Fig. 4 and Fig. 5 with the soaring flight speed  $V_\infty=2.0$  m/s ( $Re_C \approx 20,000$ ) and  $V_\infty=8.0$  ( $Re_C \approx 80,000$ ) m/s, respectively.

As revealed from the experimental data given in Fig. 4, when the flight speed is relatively low (i.e.,  $V_\infty=2.0$  m/s), all the three tested wings were found to have very comparable aerodynamic performances (in terms of both lift and drag coefficients) at relatively small orientation angles (i.e., OA <10.0 deg.). The flexible membrane wings were found to have slightly larger lift and drag coefficients compared with the rigid wood wing at relatively high orientation angles (i.e., OA >10.0 deg.).

This can be explained by that, when the forward flight speed is relatively low, the aerodynamic forces acting on the tested wings would be relatively small, especially at relatively low orientation angles (i.e., OA <10.0 deg.). No apparent deformations were found on the flexible membrane wings (for both the nylon wing and the latex wing). As a result, the flexible membrane wings were found to have very comparable aerodynamic performances to those of the rigid wood wing at low soaring flight speed with the orientation angle being relatively low (i.e., OA <10.0 deg.).

When the orientation angle becomes more significant (i.e., OA >10.0 deg.), obvious deformations were observed for the tested flexible membrane wings due to more significant aerodynamic forces acting on the flexible membrane wings. The straight chords of the flexible membrane wings were found to be curved slightly (i.e., to have small chordwise cambers) when the orientation angle becomes relatively high (i.e., OA >10.0 deg.). As a result, the flexible membrane wings were found to have slightly larger lift and drag coefficients compared with those of the rigid wood wing. Due to its more flexible skin, the latex wing was found to deform more seriously (i.e., the straight chord was curved more chordwise to have larger cambers) compared with the nylon wing. Therefore, the lift coefficients of the latex wing were found to be slightly larger than the nylon wing at relatively higher orientation angles. It was also found that the trailing edge of the flexible latex wing was fluttering when the orientation angle becomes relatively high during the soaring flight experiments. The fluttering of the trailing edge of the flexible latex wing was found to become more and more significant with increasing orientation angle. This is believed to be the reason why the drag coefficients of the latex wing were found to increase more rapidly with the increasing orientation angle compared with the rigid wood wing and the less flexible nylon wing.

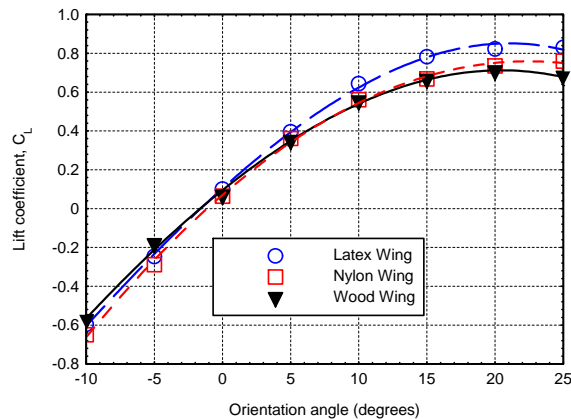
Although the straight chords of the flexible wings were found to be curved slightly to have small chordwise cambers, the induced deformations on the flexible membranes wings (for both latex and nylon wings) were still quite limited when the soaring flight speed is relatively low since the aerodynamic forces acting on the tested wings were still relatively weak. As revealed from the lift-to-drag ratio data given in Fig. 4(c), the overall aerodynamic

performances (i.e., lift-to-drag ratio) of all three tested wings were found to be very comparable for soaring flight with relatively low soaring flight speed.

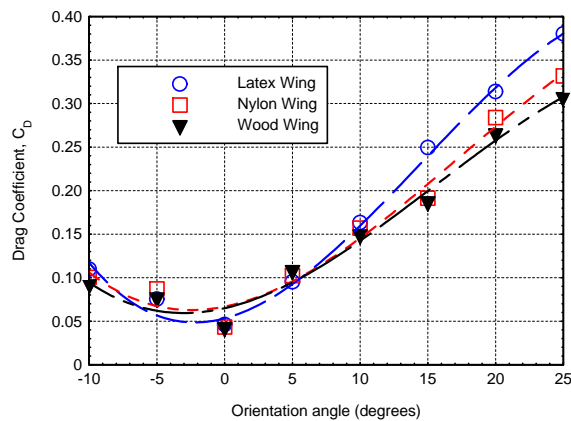
As the soaring flight speed increases, the aerodynamic forces acting on the tested wings would become larger and larger. As reported by Hu et al. [24], the significant aerodynamic forces acting on flexible membrane airfoils/wings would cause chordwise profile changes to adapt the incoming flows automatically (i.e., the chord profiles of the flexible membrane wings would be adjusted automatically) to balance the pressure differences between the upper and lower surfaces of the flexible membrane airfoils/wings. When the aerodynamic forces acting on flexible membrane airfoils/wings become more significant, the trailing edges of the flexible membrane airfoils/wings would be deflected and lifted up from its original designed position, which would reduce the effective angle of attack of the flexible membrane airfoils/wings with respect to incoming flows. Similar phenomena were also observed in the present study when the soaring flight speed becomes relatively high ( $V_\infty > 4.0$  m/s).

Figure 5 shows the measured lift coefficients, drag coefficients, and lift-to-drag ratio of the three tested wings at relatively high soaring flight speed (i.e.,  $V_\infty = 8.0$  m/s). During the experiments, the deformations on the tested flexible membrane wings (for both latex and nylon wing) were found to become very serious. Due to the more significant aerodynamic forces acting on the tested wings, in addition to having the straight chords of the flexible membrane wings curved more seriously, the trailing edges of the flexible membrane wings were also found to be deflected and lifted from their design position substantially, especially at relatively high orientation angles (i.e.,  $OA > 10.0$  deg.). Since the effective angles of attack of the tested flexible membrane wings with respect to the incoming flows were reduced considerably due to the trailing edge deflection, the lift coefficients of the flexible membrane wings were found to be slightly smaller than those of the rigid wood wing.

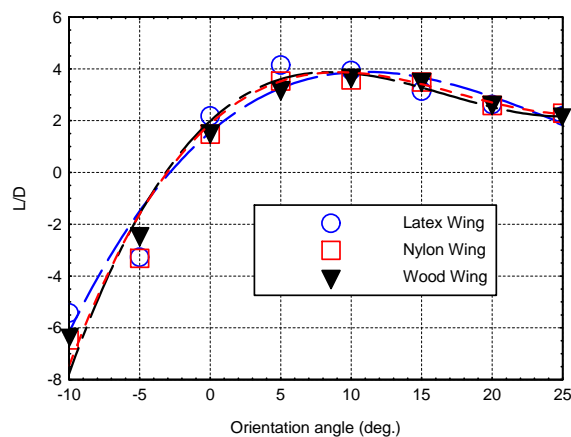
As revealed from the measurement results given in Fig. 5(a), the lift coefficient profile of the rigid wood wing was found to reach its peak value at  $OA \approx 20.0$  deg., then begin to decrease. It indicates that stall would occur at  $OA \approx 20.0$  degrees for the rigid wood wing. On the other hand, the lift coefficients of the flexible membrane wings (both the latex and nylon wings) were found to increase monotonically with the increasing orientation angle up to  $OA = 25.0$  deg. Such measurement results indicate that the flexible membrane airfoils could delay stall to a higher orientation angle, which agree with the finding of Stanford et al. [26], who conducted wind tunnel experiments to investigate the aerodynamic performance of flexible membrane airfoils/wings for fixed-wing MAV applications.



(a). lift coefficient



(b). Drag coefficient



(c). Lift-to-drag ratio

**Fig. 4:** The tested wings in soaring flight with forward flight speed  $V_\infty = 2.0$  m/s

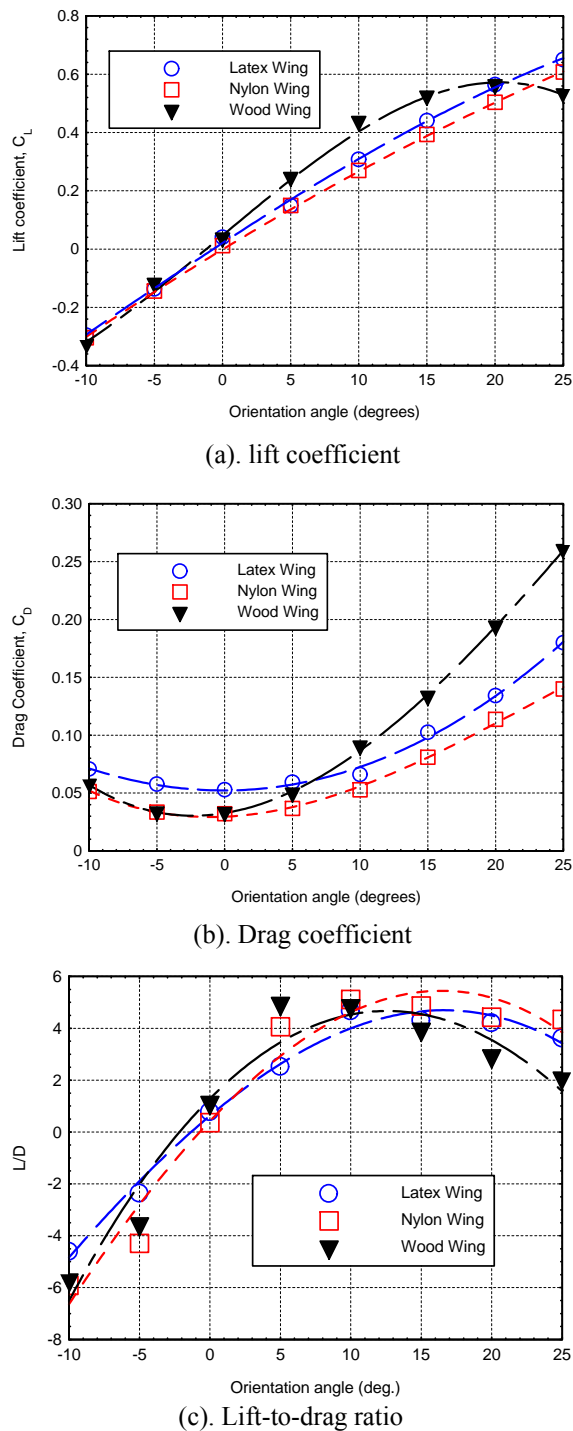
As visualized by the PIV measurements of Hu et al. [24], the flexible membrane wings would change their chordwise profiles automatically to adapt to incoming flows to suppress large flow separation. The deflection of their trailing edges would also reduce the effective angle of attack of the wings with respect to the incoming flows substantially. As a result, the drag coefficients of the flexible membrane wings were found to be much smaller compared with those of the rigid wing at relatively high orientation angles (i.e.  $OA > 10.0$  deg.). Since the trailing edges of the latex wing were found to be fluttering at almost all the tested orientation angles, therefore, the drag coefficients of the latex wing were found to be slightly bigger than those of the nylon wing.

Fig. 5(c) shows the overall aerodynamic performance (i.e., lift-to-drag ratio) of the three tested wings when the soaring flight velocity  $V_\infty = 8.0$  m/s. It can be seen clearly that flexible membrane wings would have better overall aerodynamic performances compared with the rigid wood wing, especially at relatively high orientation angles ( $OA > 10.0$  degrees).

In summary, the measurement results confirmed that flexible membrane wings could provide better aerodynamic performance compared with conventional rigid wing for soaring flight or fixed-wing MAV applications. The aerodynamic benefits of using flexible membrane wings for soaring flight are highlighted for the cases with relatively high soaring speed and high angles of attack, where the induced deformation on the flexible membrane wings become more obvious. The nylon wing, which is less flexible than the latex wing, was found to have the best overall aerodynamic performance among the three tested wings for soaring flight. This implies that it is important to choose a proper flexibility (or rigidity) of the membrane skins in order to achieve improved aerodynamic performance by using flexible-membrane airfoils/wings for fixed-wing MAV applications.

## B. Aerodynamic performances of the tested wings in flapping flight

For flapping flight experiments, the forward flight speed (i.e., the incoming flow velocity) was changed from 0.0 to 10.0 m/s. The orientation angle of the flapping motion with respect to the incoming flow was changed from -10.0 degrees to 20.0 degrees. Fig. 6 to Fig. 8 show the time-averaged lift and thrust produced by flying the three tested wings as functions of the flapping frequency with the orientation angle  $OA = 10.0$  deg.. It should be noted the negative thrust data shown in the plots represent that the aerodynamic forces acting on the tested wings are actually drag to try to slow the flight down instead of thrust to accelerate the flight. It should also be noted that the measurement results with zero flapping frequency (i.e.,  $f = 0.0$  Hz) actually represent those when the tested wings were in soaring flight. As expected, the drag (i.e., negative thrust) acting on the tested wings were found to increase with the increasing forward flight speed in soaring flight (i.e.,  $f = 0.0$  Hz cases).

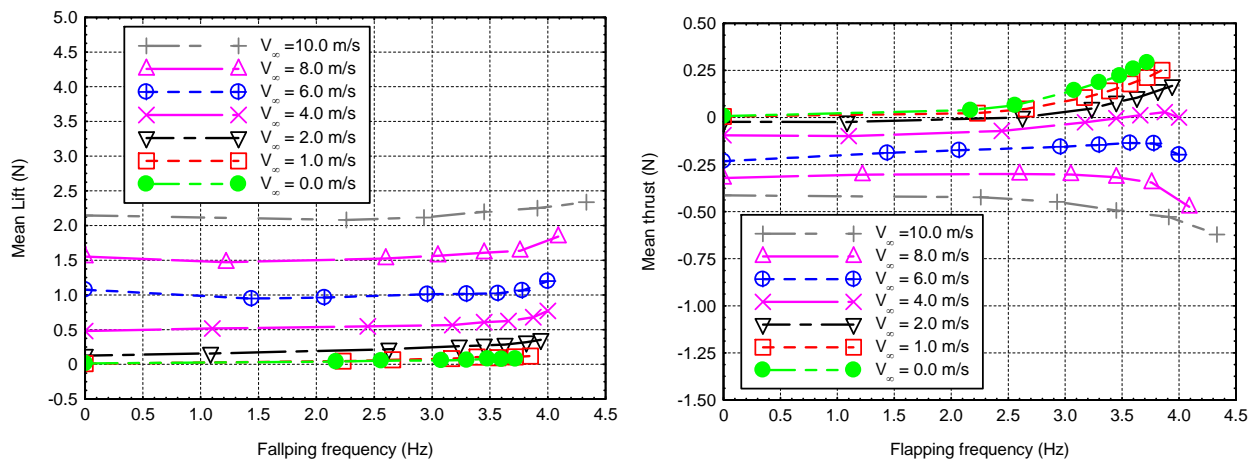


**Fig. 5:** The tested wings in soaring flight with forward flight speed  $V_\infty = 8.0$  m/s

The measurement results revealed that, with the same forward flight speed, the time-averaged lift produced by flapping the tested wings were found to increase monotonically with the increasing flapping frequency. For the same tested wings and the same flapping frequency, the time-averaged lift produced by flapping the wing were found to increase as the forward flight speed increases.

As revealed from the measurement data given in the Fig. 7(b), the time-averaged thrust generated by the nylon wing was found to increase monotonically with the increasing flapping frequency for all the tested cases with the forward flight speed changing from 0 (i.e., hovering flight) to 10.0 m/s. With the same flapping frequency, the time-averaged thrust generated by flapping motion was found to decrease rapidly with the increasing forward flight speed.

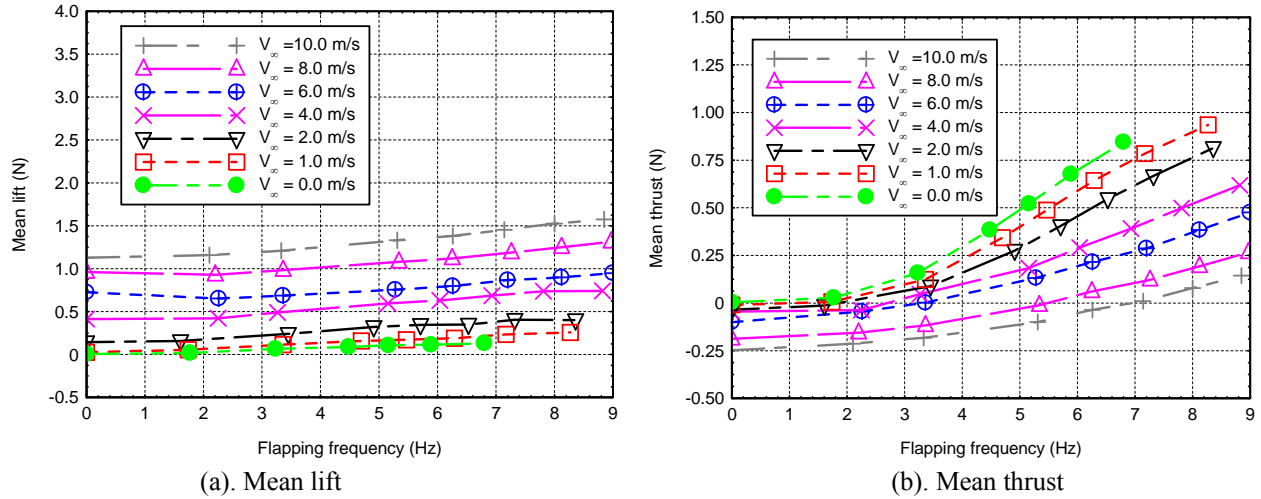
Surprisingly, the time-averaged thrust generated by flapping the rigid wood wing and the most flexible latex wing were found to increase with the increasing flapping frequency only when the forward flight speed is relatively low ( $V_\infty < 4.0$  m/s). When the forward flight speed becomes relatively high ( $V_\infty > 6.0$  m/s), the thrust generated by flapping the wings were found to be decreasing with the increasing flapping frequency. As mentioned above, the negative thrust data indicate that the aerodynamic forces acting on the tested wings are actually drag forces. The measurement results shown in Fig.6(b) and Fig.8(b) revealed that, when the forward flight speed became relatively high ( $V_\infty \geq 6.0$  m/s), it would produce much larger drag forces (instead of thrust) when the rigid wing and the latex wing were flapping with higher flapping frequency. Such measurement results revealed that additional drag will be induced by flapping the wings compared with those without flapping motion (i.e., soaring flight) when the forward flight speed becomes relatively high ( $V_\infty \geq 6.0$  m/s). Although the nylon wing was still found to generate thrust in flapping flight, the benefits of the flapping motion for thrust generation (i.e., the difference between the time-averaged thrust (drag) forces generated in flapping flight and those of the soaring flight) were found to decrease rapidly as the forward flight speed increases. All these measurement results indicate that the advantages of flapping flight for thrust generation would be diminished as the forward flight speed increases. Such finding may also be used to explain why small birds such as humming birds and insects are usually using flapping flight for propulsion since their flying speed are usually relatively low, while large birds such as eagles and seagulls flying with much higher speed seldom flap their wings with their wings behave more like fixed wings when they fly at high speed.



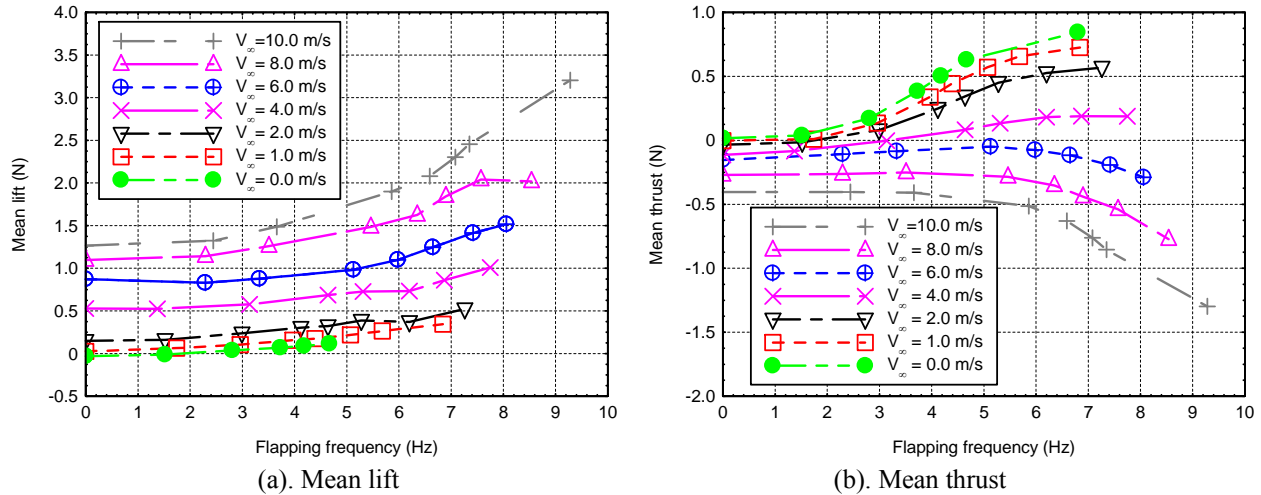
(a). Mean lift

(b). Mean thrust

**Fig. 6:** Time-averaged lift and thrust produced by the rigid wood wings in flapping flight at OA = 10.0 deg.



**Fig. 7:** Time-averaged lift and thrust produced by the flexible nylon wing in flapping flight at OA = 10.0 deg.



**Fig. 8:** Time-averaged lift and thrust produced by the flexible latex wing in flapping flight at OA = 10.0 deg.

In order to quantify the aerodynamic benefits of flapping flight more clearly, we introduce the concepts of lift augmentation and thrust augmentation for further data reduction of the flapping flight measurement results. The lift or thrust augmentation is referred to the increase of the time-averaged lift or thrust generated by a tested wing in flapping flight compared with those of the same wing in soaring flight (i.e., without flapping motion) with the same forward flight speed and same orientation angle. The augmentations of the lift and thrust forces due to flapping motion can be expressed as:

$$\Delta L_{flapping} = Lift_{flapping} - Lift_{soaring}$$

and

$$\Delta T_{flapping} = Thrust_{flapping} - Thrust_{soaring} .$$

Subsequently, the coefficients of the lift and thrust augmentations due to flapping motion for a tested wing can be expressed as:

$$\Delta C_L = \frac{\Delta L_{flapping}}{\frac{1}{2} \rho V_{\infty}^2 S} = \frac{Lift_{flapping} - Lift_{soaring}}{\frac{1}{2} \rho V_{\infty}^2 S}$$

and

$$\Delta C_T = \frac{\Delta T_{flapping}}{\frac{1}{2} \rho V_\infty^2 S} = \frac{Thrust_{flapping} - Thrust_{soaring}}{\frac{1}{2} \rho V_\infty^2 S}$$

As described above, for the flapping flight measurements as those shown in the Fig. 5, lift and thrust data in soaring flight were extracted from the measurement results with  $f=0.0$  Hz.

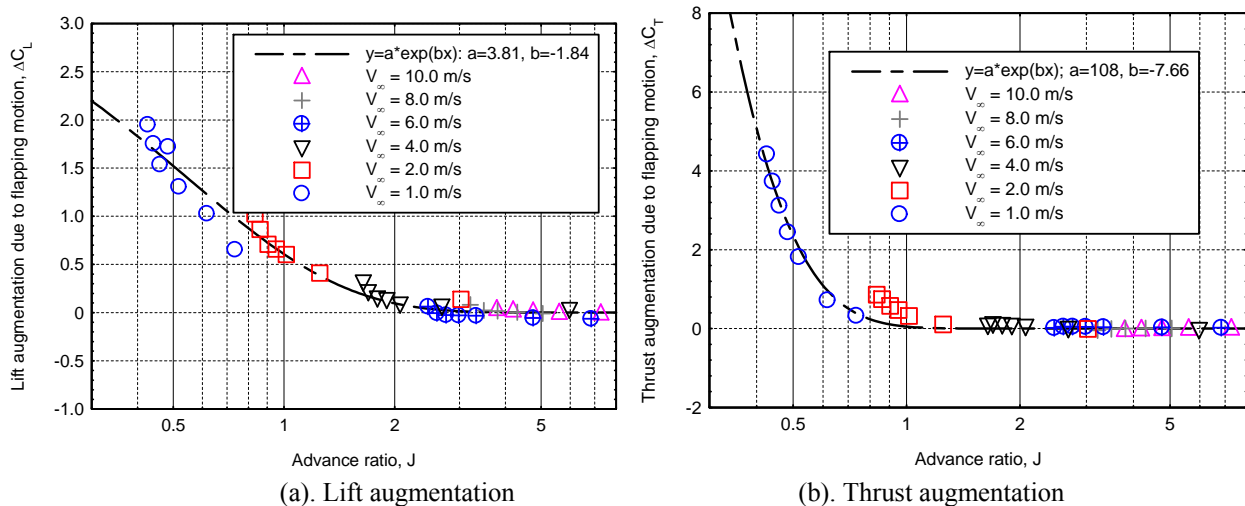
As described by Ho et al. [14], flapping flight can be separated into two regimes: quasi-steady state regime and unsteady state regime. Quasi-steady state flapping flight refers where a wing flaps at relatively low frequency (or hardly flapping at all) during the flight; hence the wing tip speed is low 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 flap they wing quite slowly to tend to have soaring flight and 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.

Following the work of Ho et al. [14], a non-dimensional parameter, advance ratio,  $J$ , was used in the present study to characterize the measurement data of the tested wings in flapping flight. Advance 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 expressed as:

$$J = \frac{\text{forward flight speed}}{\text{wingtip velocity}} = \frac{V_\infty}{2bf\Phi}$$

where  $b$  is the wing span;  $f$  is the wing flapping frequency, and  $\Phi$  is the total wing flapping angle. As decribed by Ho et al. (2003), the breakpoint between the quasi-steady state regime and the unsteady state regime for flapping flight is at  $J=1.0$ . When  $J > 1.0$ , the flow around the flapping wing can be considered quasi-steady, while  $J < 1.0$  corresponds to unsteady state regime.

Based on the flapping flight measurement data shown in Fig. 6 to Fig. 8, the coefficients of lift augmentation,  $\Delta C_L$ , and thrust augmentation,  $\Delta C_T$ , as functions of advance ratio of the flapping flight were calculated. The results were given in Fig. 9 to Fig. 11.



**Fig. 9:** Lift and thrust augmentations of the rigid wood wing in flapping flight at OA =10.0 deg.

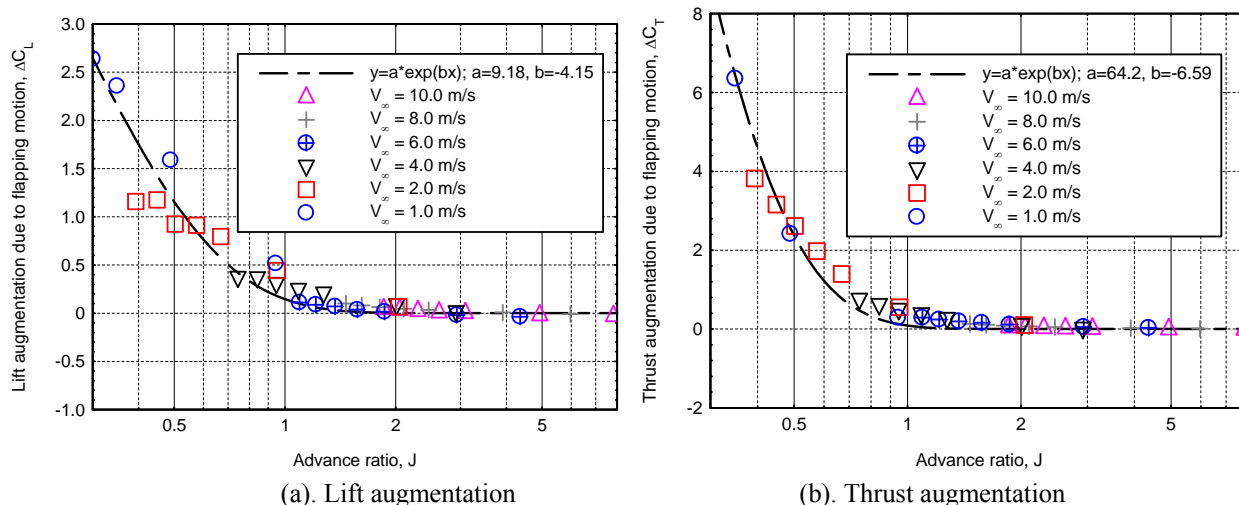


Fig. 10: Lift and thrust augmentation of the flexible nylon wing in flapping flight at  $OA = 10.0$  deg.

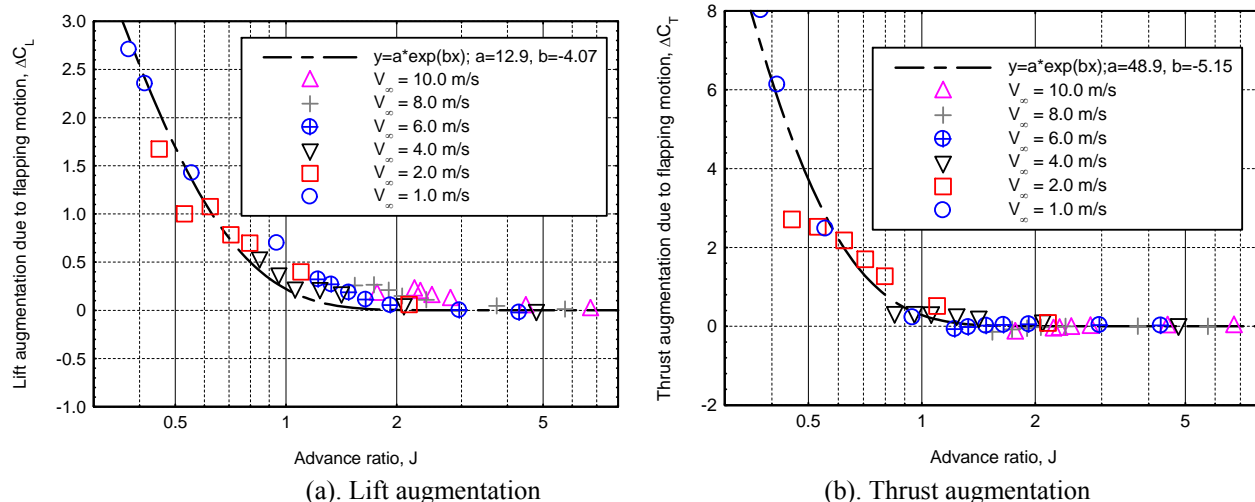


Fig. 11: Lift and thrust augmentation for the flexible latex wing in flapping flight at  $OA = 10.0$  deg.

It can be seen that, for all three tested wings, the lift and thrust augmentation data (i.e.,  $\Delta C_L$  and  $\Delta C_T$ ) with different experimental conditions (i.e., different forward flight speed and different flapping frequency) were found to align themselves nicely in the plots when advance ratio,  $J$ , was used to reorganize the measurement results. It should also be noted that, as shown in Fig. 9 to Fig. 11, the relationships between the lift and thrust augmentations (i.e.,  $\Delta C_L$  and  $\Delta C_T$ ) and the advance ratio,  $J$ , can be represented well by exponential functions for all the three tested wings. The exponential relationships between the lift and thrust augmentations (i.e.,  $\Delta C_L$  and  $\Delta C_T$ ) with advance ratio of the flapping flight were also confirmed from the measurement data at different orientation angles.

As revealed from the results shown in Fig. 9 to Fig. 11, flapping flight would bring significant aerodynamic benefits (i.e., generate much more lift and thrust) if the flapping flight is in unsteady state regime with the advance ratio  $J < 1.0$ . For example, for a flapping flight with the advance ratio  $J = 0.50$ , the lift augmentation due to flapping motion was found to be as high as  $\Delta C_T = 1.5$ ,  $1.2$ , and  $1.8$  for the tested wood wing, nylon wing, and latex wing, respectively. For comparison, as revealed in Fig. 4 and Fig. 5, the lift coefficients for the same tested wings in soaring flight (i.e., without flapping motion) were found to be only about  $0.3 \sim 0.6$  at the same orientation angle of  $OA = 10.0$  degrees. This means, for the same tested wings, the lift produced by the wings can be increased by a factor of  $2.0 \sim 6.0$  times by flapping the wings when the flapping flight is in unsteady regime with advance ratio  $J = 0.50$ . More lift can be generated for the same tested wings as the advance ratio of the flapping flight decreases.

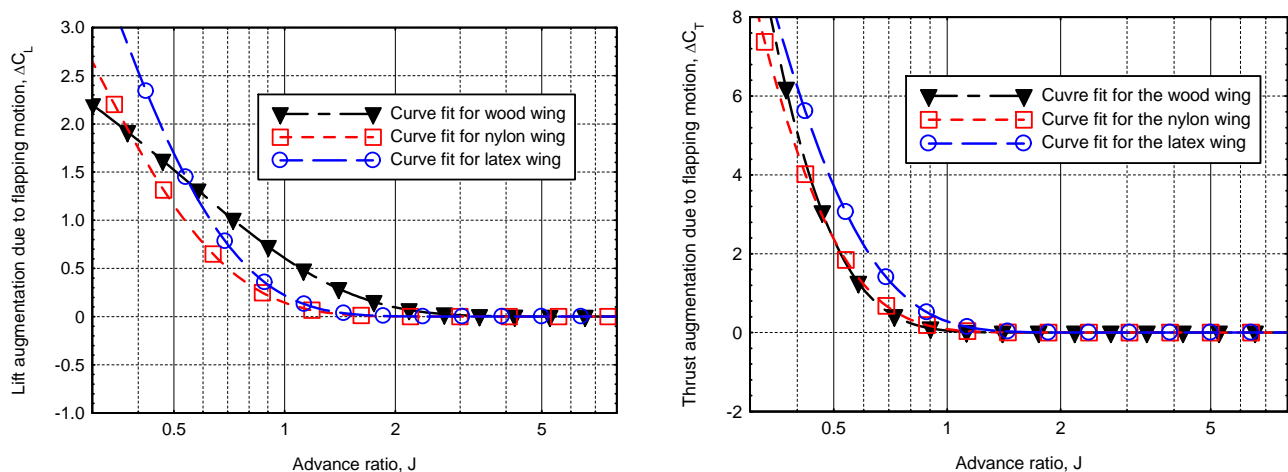
The measurement results also revealed that significant thrust would be generated by flapping the wings when the flapping flight is in unsteady state regime. According to the measurement data shown in the Fig. 4 and Fig. 5., the drag coefficients of the three tested wings in soaring flight would be about 0.05 ~ 0.10 at the orientation angle  $OA = 10.0$  degrees. The measurement data given in Fig. 9 to Fig. 11 revealed that, with the advance ratio  $J = 0.5$ , the thrust augmentation ( $\Delta C_T$ ) due to flapping motion would be 2.5, 2.4, and 3.7 for the tested wood wing, flexible nylon wing, and latex wing respectively. This indicates that the thrust generated by flapping the wings would be much larger than the drag acting on the wings. As a result, the resultant aerodynamic forces along the flight direction would be propulsive, which provide enough power to maintain the sufficient maneuverability or/and agility of the flapping flight. This may also be the reason why smaller birds such as humming birds and insects fly in unsteady state regime (for example, the advance ratio of the bumblebee, black fly and fruit fly in free flight is 0.66, 0.50, and 0.33 respectively) [14].

On the other hand, since the lift and thrust augmentations due to flapping motion was found to decrease exponentially with the increasing advance ratio of the flapping flight, aerodynamic benefits of flapping flight would be diminished rapidly as the advance ratio of the flapping flight increases. The flapping motion would make very limited or no contributions to either lift augmentation or thrust generation when the flapping flight is in quasi-steady regime with relatively large advance ratio values. For example, for a flapping flight with the advance ratio  $J=2.0$ , the aerodynamic benefits due to flapping motion would be almost negligible (i.e.,  $\Delta C_L < 0.08$ , 0.06 and 0.04, and  $\Delta C_T < 0.05$ , 0.06, and 0.03 for the tested wood wing, nylon wing, and latex wing respectively). It indicates that the aerodynamic forces produced by the tested wings in flapping flight would be almost as the same as those in soaring flight (i.e., without flapping motion).

In order to elucidate the effects of skin flexibility (rigidity) of the tested wings on their aerodynamic performances in flapping flight more clearly, the exponential curves best-fitted to the measurement data (both lift and thrust) of the three tested wings were plotted on same figures, which are shown in Fig. 12.

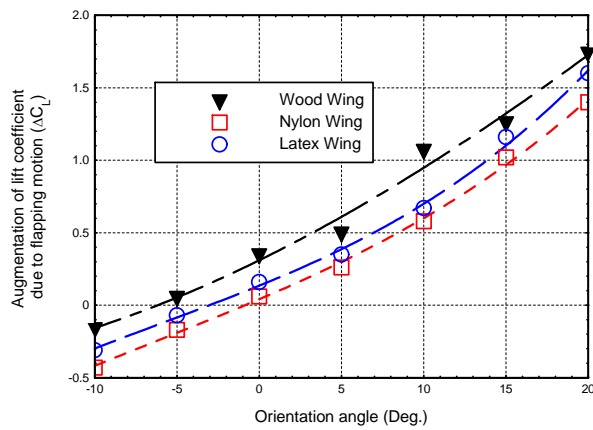
It can be seen clearly that, among the three tested wings flapping flight, the rigid wood wing was found to have the best lift generation performance for flapping flight until the advance ratio become quite small (i.e.,  $J < 0.55$ ). The latex wing, which is most flexible among the three tested wing and has the second highest lift production performance for flapping flight in the region  $J \geq 0.55$ , would overpass the rigid wing to produce the highest lift among the tested wings for highly unsteady flapping flight with advance ratio  $J < 0.55$ . The nylon wing, which has the best overall aerodynamic performance among the three tested wings for soaring flight, was found to have the worst lift production performance for flapping flight.

The results also revealed that, among the three tested wings, the most flexible wing, latex wing, was found to have the best thrust augmentation performance for flapping flight. The flexible nylon wing was found to have a comparable thrust generation performance as the rigid wing for flapping flight until highly unsteady flapping flight. The rigid wood wing was found to perform slightly better than the flexible nylon wing for thrust augmentation with flapping flight in highly unsteady regime.

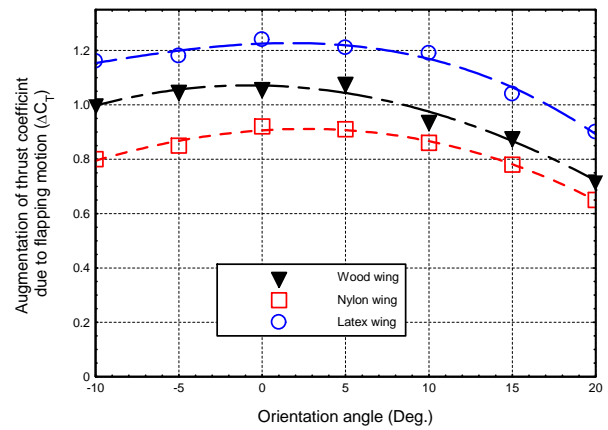


(a). lift coefficient augmentation (b). Thrust coefficient augmentation  
**Fig. 12:** Lift and thrust augmentation of the tested wings in flapping flight at  $OA = 10.0$  deg.

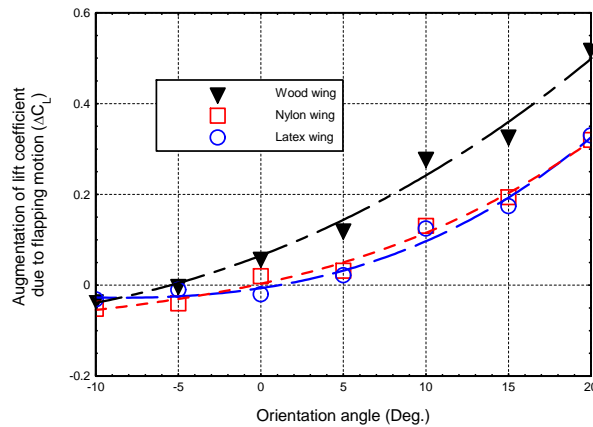
The effects of the orientation angle of the flapping flight on the aerodynamic performances of the tested wings in flapping flight were also investigated in the present study. During the experiments, the flapping frequency of the tested wings was kept as a constant, i.e.  $f=4.0\text{ Hz}$ , the forward flight speed was varied from  $V_\infty = 1.0\text{ m/s}$  to  $10.0\text{ m/s}$ . Fig. 13 shows some typical measurement results with the forward flight speed  $V_\infty = 2.0\text{ m/s}$ ,  $4.0\text{ m/s}$ , and  $8.0\text{ m/s}$  respectively. It should be noted that, for the tested cases with the forward flight speed  $V_\infty = 2.0\text{ m/s}$ , the corresponding advance ratio of the flapping flight is 0.80 (i.e.,  $J = 0.8$ ), therefore, the flapping flight is in unsteady state regime. When the forward flight speed increases to  $V_\infty = 4.0\text{ m/s}$  and  $8.0\text{ m/s}$ , corresponding advance ratios becomes 1.6 and 3.2, respectively (i.e.,  $J = 1.6$  and  $J = 3.2$ ), thus, flapping flight is in quasi-steady regime.



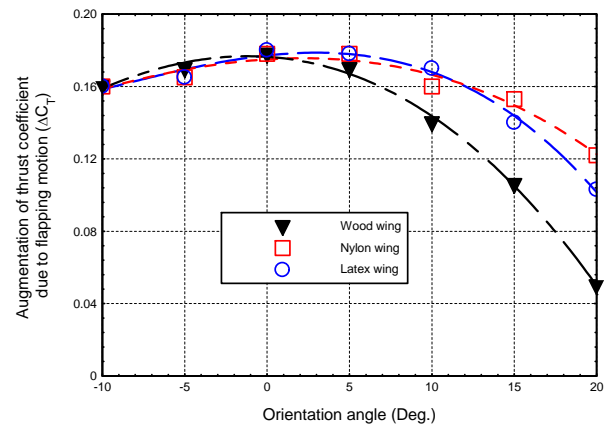
(a). Lift augmentation with  $V_\infty=2.0\text{ m/s}$



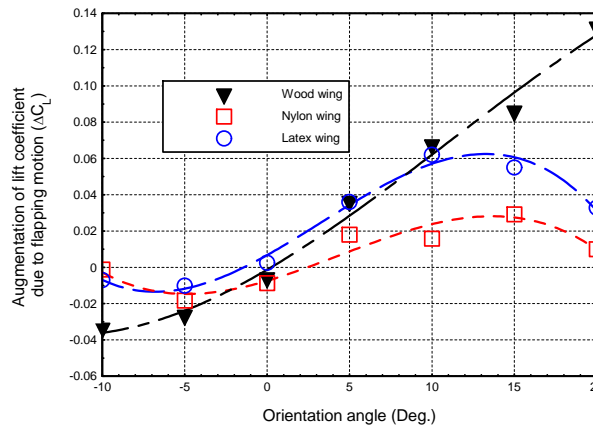
(b). Thrust augmentation with  $V_\infty=2.0\text{ m/s}$



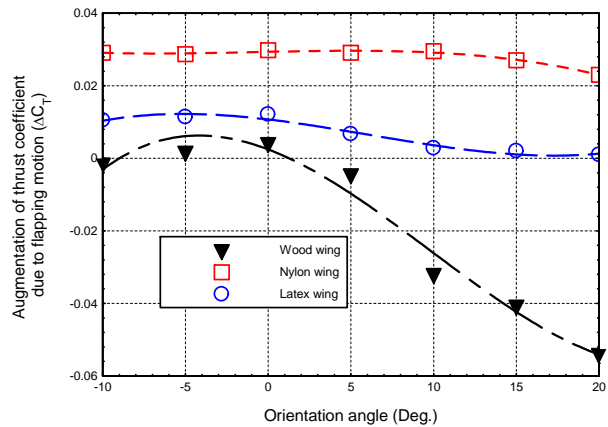
(c). Lift augmentation with  $V_\infty=4.0\text{ m/s}$



(d). Thrust augmentation with  $V_\infty=4.0\text{ m/s}$



(e). Lift augmentation with  $V_\infty=8.0\text{ m/s}$



(f). Thrust augmentation with  $V_\infty=8.0\text{ m/s}$

**Fig. 13:** Effect of orientation angle (flapping frequency  $f = 4.0\text{ Hz}$ )

As expected, with the same flapping frequency of  $f = 4.0$  Hz, since the flapping flight is in unsteady state regime with forward flight speed  $V_\infty = 2.0$  m/s, the lift and thrust augmentations of the flapping flights were found to be much higher than those in quasi-steady state regime (i.e., the tested cases with the forward flight speed  $V_\infty = 4.0$  m/s and 8.0 m/s) at all the tested orientation angles.

The measurement data shown in Fig. 13 revealed that, for all the three tested wings, the lift augmentations of all three tested wings in flapping flight were found to increase monotonically with the increasing orientation angle when the forward flight speed is relatively small ( $V_\infty < 6.0$  m/s). When the forward flight speed becomes relatively high ( $V_\infty > 6.0$  m/s), the lift augmentations of the two flexible membrane wings in flapping flight were found to increase at first, reach their peak values at  $OA \approx 10.0 \sim 15.0$  deg., then decrease with the increasing orientation angle, while the lift augmentation of the rigid wing was found to increase monotonically with the increasing orientation angle. Among all three tested wings, the rigid wood wing was found to have the best lift production performance for flapping flight at almost all the tested orientation angles. The two tested flexible membrane wings were found to have comparable lift generation performances with the latex wing performing slightly better.

The thrust augmentation data shown in the Fig. 13 revealed clearly that orientation angle would also affect the thrust generation of the tested wings in flapping flight greatly. Maximum thrust was found to be generated at  $OA \approx 0.0$  degree for all three tested wings. The thrust generated by flapping the tested wing was found to decrease with the increasing orientation angle. The latex wing, which has the most flexible skin, was found to have the best thrust generation performance among the three tested wings for the flapping flight in unsteady state regime. The nylon wing was found to have the best thrust generation performance when the flapping flight was in quasi-steady regime with relatively large advance ratio (i.e.,  $V_\infty = 8.0$  m/s and  $J = 3.2$  cases). It should also be noted that, for the rigid wing with relatively high forward flight speed (i.e.,  $V_\infty = 8.0$  m/s and  $J = 3.2$ ), the thrust augmentation data ( $\Delta C_T$ ) was found to become negative at most of the tested orientation angles. It indicates that flapping motion of the rigid wood wing would actually induce additional drag instead of generating thrust. Such measurement results confirmed again that flapping flight would be more aerodynamically efficient when the flapping flight in unsteady state regime. The advantages of flapping flight would diminish rapidly with the increasing advance ratio. Flapping flight would become detrimental for high speed applications.

#### IV. Concluding Remarks

An experimental study was conducted to assess the aerodynamic benefits of using flexible membrane wings for the development of flapping-wing Micro-Air-Vehicles (MAVs). The overall aerodynamic performances (i.e. time-averaged lift and thrust/drag generation) of two flexible membrane wings with different skin flexibility (i.e., a flexible nylon wing and a more flexible latex wing) were compared with those of a conventional rigid wing in order to assess the effects of skin flexibility (rigidity) of the tested wings on their aerodynamic performances for soaring flight and flapping flight applications. Advance ratio, which is defined as the ratio of the forward flight speed to the wingtip velocity of the tested wings in flapping flight, was used to characterize the aerodynamic advantages of flapping flight over soaring flight.

The measurement results revealed clearly that flapping motions could bring significant aerodynamic benefits when the flapping flight is in unsteady state regime with advance ratio  $J < 1.0$ . Since both lift and thrust augmentations due to flapping motion was found to decrease exponentially as the advance ratio increases, the aerodynamic advantages of flapping flight would diminish rapidly with the increasing advance ratio. Flapping flight was found to become detrimental for high speed applications.

The orientation angle of the flapping motion with respect to the incoming flow velocity was found to have considerable effects on both the lift and thrust generation performances of the tested wings in flapping flight. More lift was found to be generated as the orientation angle of the flapping motion increases. The tested wings were found to produce maximum thrust when the orientation angle is zero. The thrust generated due to flapping motion would decrease monotonically with the increasing orientation angle.

The skin flexibility (rigidity) of the tested wings was found to affect their aerodynamic performances significantly for both soaring flight and flapping flight. For soaring flight, the flexible membrane wings were found to have better overall aerodynamic performances (i.e., lift-to-drag ratio) in general. The benefits of using flexible membrane wings for soaring flight are much more highlighted at relatively high forward flight speed and large angle of attack, where the deformations of the flexible membrane wings were found to become more obvious. The

flexible nylon wing, which has the medium flexibility (or rigidity) among the three tested wings, was found to have the best overall aerodynamic performance (i.e., lift-to-drag ratio) for soaring flight.

The rigid wood wing was found to have the better lift generation performance compared with the two flexible membrane wings in flapping flight until the flapping flight in deeply unsteady regime. The latex wing, which is the most flexible wing among the three tested wings, was found to have the best thrust generation performance for flapping flight. The nylon wing, which has the best performance for soaring flight, was found to be the worst for flapping flight applications. Such measurement results imply that it is important to choose a proper flexibility (or rigidity) of the membrane skins in order to achieve improved aerodynamic performances by using flexible membrane airfoils/wings in soaring and flapping flight.

While the present study has revealed many interesting facts related to the aerodynamic performances of flexible membrane wings in soaring and flapping flight, further studies, such as detailed flow field measurements to quantify the vortex structures generated at the wakes of flapping wings with different structural flexibility, and quantification of the dynamic deformation on flexible membrane wings to elucidate flow-structure interactions in flapping cycles, are highly desirable in order to elucidate fundamental physics to further our understanding and to explore/optimize design paradigms for the development of novel flexible membrane-wing-based (either fixed-wing or flapping-wing) MAVs for improved aerodynamic performance.

### **Acknowledgments**

The authors also want to thank Mr. Bill Rickard and Mr. Matthew Burkhalter of Iowa State University, Capt. Judson Babcock of AFRL/RWGN, Eglin AFB, and Ms. Pamela Prater of University of West Florida for their help in conducting the experiments. The support of 2008 Air Force Summer Faculty Fellowship Awarded to Hui HU is gratefully acknowledged.

## References

- [1]. Bohorquez, F., Samuel, P., Sirohi, J., Pines, D., Rudd, L., and Perel, R., “Design Analysis and Hover Performance of a Rotating Wing Micro Air Vehicle,” *Journal of the American Helicopter Society*, Vol. 48, No. 2, April 2003, pp. 80–90.
- [2]. Ramasamy, M., Leishman, J. G., and Lee, T. E., “Flow Field of a Rotating Wing MAV,” 62nd Annual National Forum Proceedings of the American Helicopter Society, 2006.
- [3]. Dial, K.P., An inside look at how birds fly: experimental studies of the internal and external processes controlling flight. 1994 Report the Aerospace Profession, 38<sup>th</sup> Symposium Proceedings, The Beverly Hilton, Beverly Hills, CA, 1994
- [4]. Viieru, D., Tang, J., Lian, Y., Liu, H., and Shyy, W., “Flapping and Flexible Wing Aerodynamics of Low Reynolds Number Flight Vehicles”, AIAA paper 2006-0503, 44th AIAA Aerospace Sciences Meeting and Exhibit, Jan 9-12, 2006, Reno, NV.
- [5]. Weis-Fogh, T., “Quick Estimate of Flight Fitness in Hovering Animals, Including Novel Mechanisms for Lift Production,” *Journal of Experimental Biology*, Vol. 59, 1973, pp. 169-230.
- [6]. Lighthill, M. J., “On the Weis-Fogh Mechanism of Lift Generation,” *Journal of Fluid Mechanics*, Vol. 60, 1973, pp. 1–17.
- [7]. Maxworthy, T., “Experiments on the Weis-Fogh Mechanism of Lift Generation by Insects in Hovering Flight. Part 1. Dynamics of the ‘fling’,” *Journal of Fluid Mechanics*, Vol. 93, 1979, pp. 47-63.
- [8]. Ellington, C. P., Berg, C. van den, Willmott, A. P., and Thomas, A. L. R., “Leading-edge Vortices in Insect Flight,” *Nature*, Vol. 384, Dec. 1996, pp. 626-630.
- [9]. Dickinson, M. H., and Götz, K. G., “Unsteady Aerodynamic Performance of Model Wings at Low Reynolds Numbers,” *Journal of Experimental Biology*, Vol. 174, Jan. 1993, pp. 45-64.
- [10]. Dickinson, M. H., Lehmann, F.-O., Sane, S., “Wing Rotation and the Aerodynamic Basis of Insect Flight,” *Science*, Vol.284, Jun. 1999, pp. 1954-1960.
- [11]. Sun, M., and Tang, J., “Unsteady Aerodynamic Force Generation by a Model Fruit Fly Wing in Flapping Motion,” *Journal of Experimental Biology*, Vol. 205, Jan. 2002, pp. 55-70.
- [12]. Sun, M., and Tang, J., “Lift and Power Requirements of Hovering Flight in *Drosophila virilis*,” *Journal of Experimental Biology*, Vol. 205, Aug. 2002, pp. 2413-2427.
- [13]. Wang, Z. J., Birch, J. M., and Dickinson, M. H., “Unsteady Forces and Flows in Low Reynolds Number Hovering Flight: Two-dimensional Computations vs Robotic Wing Experiments,” *Journal of Experimental Biology*, Vol. 207, Jan. 2004, pp. 449-460.
- [14]. Ho, S., Nassef, H., Pornsinsirak N., Tai, Y., and Ho, C. M., “Unsteady aerodynamics and flow control for flapping wing flyers”, *Progress in Aerospace Sciences* Vol.39, 2003, pp635–68.
- [15]. Ansari, S.A., Zbikowski, R., and Knowles, K., “Aerodynamic modeling of insect-like flapping flight for micro air vehicles”, *Progress in Aerospace Sciences*, Vol. 42, 2006, pp129–172.
- [16]. Mueller, T. J. (ed.), *Fixed and Flapping Wing Aerodynamics for Micro Air Vehicle Applications*, Progress in Astronautics and Aeronautics, AIAA, Reston, VA, 2001
- [17]. Shyy, W., Lian, Y., Tang, J., Viieru, D., and Liu, H., *Aerodynamics of Low Reynolds Number Flyers*, Cambridge University Press, 2008.
- [18]. Albertani R., Stanford B., Hubner J.P., and Ifju, P.G., 2007, “Aerodynamic Coefficients and Deformation Measurements on Flexible Micro Air Vehicle Wings.” *Experimental Mechanics* (2007) 47:625–635.
- [19]. Abdulrahim, M. 2004, “Dynamic Characteristics of Morphing Micro Air Vehicles”, thesis for Master of Science, Department Mechanical and Aerospace Engineering, University of Florida.
- [20]. Shyy, W., Ifju, P. and Viieru, D., 2005, “Membrane Wing-Based Micro Air Vehicles” *Applied Mechanics Reviews*, Vol. 58, p.283-301.
- [21]. Shyy, W., Berg, M. and Ljunqvist, D., 1999, “Flapping and Flexible Wings for Biological and Micro Air Vehicles,” *Progress in Aerospace Sciences*, Vol. 35, pp. 455-506.
- [22]. Shyy, W., Jenkins, D.A. and Smith, R.W., 1997, “Study of adaptive shape airfoils at low Reynolds number in oscillatory flows”, *AIAA Journal*, Vol. 35, pp.1545-1548.
- [23]. Smith, R.W. and Shyy, W., 1995, “Computation of Unsteady Laminar Flow Over a Flexible Two-Dimensional Membrane Wing,” *Physics of Fluids*, Vol. 7, pp. 2175-2184.
- [24]. Hu, H., Tamai, M., and Murphy, J. T., “Flexible Membrane Airfoils at Low Reynolds Numbers”, *Journal of Aircraft*, Vol. 47, No. 5, pp1767-1778, 2008.
- [25]. Hong, Y. S. and Altman, A., “Lift from Spanwise Flow in Simple Flapping Wings”, *Journal of Aircraft*, Vol. 45, No. 4, July–August 2008.
- [26]. Stanford, B., Ifju, P., Albertani R. and Shyy W. “Fixed membrane wings for micro air vehicles: Experimental characterization, numerical modeling, and tailoring”, *Progress in Aerospace Sciences* Vol.44, 2008, pp258– 294.