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Research paper

Lift Generation of Compliant Wing Mechanism of Flapping Wing

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Abstract

Flapping wing micro air vehicles are small, lightweight and can fly in a low Reynolds Number environment. They are capable of flying at low Reynolds number environment with amazing agility by imitating natural flyers like bats and have compliant wings while flapping. The primary goal of this study is to design and fabricate the compliant mechanism of flapping wing for improvement of lift performance of a MAV. The test was carried out in an open-air wind tunnel. Furthermore, the compliant wing mechanism is measured based on Angle of attack, Reynolds number and flapping frequency. The result shows, lower angle of attack produces lower lift coefficient while higher angle of attack (40°) produces higher lift coefficient until it reaches stall where the lift decreases drastically. The compliant wing mechanism at Reynolds number 20000 produces higher lift coefficient compared to higher Reynolds number, 36000. The best flapping frequency for the compliant wing mechanism is 9 Hz which is the highest frequency used in this experiment. The trend of the flapping frequency shows that the lift coefficient increases when flapping frequency increases. The highest lift produced for compliant wing mechanism is at 40° angle of attack, 9 Hz flapping frequency and 20000 Reynolds number.

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

1. Introduction

A micro air vehicle (MAV) is a class of miniature UAVs that has a size restriction of a wing span that is smaller than 15 centimetres. Its purpose can be for research, commercial, and, military purposes; smaller size aircraft will be expected in the future [1]. MAVs offer the potential to fly in a tight space and can manoeuvre in low Reynolds Number (Re), which cannot be accomplished by a larger flying vehicle.

Reducing the size of a UAVs will have a set of new challenges for researchers to create smaller UAVs with smaller wingspan, smaller thrust and lift force values will be generated from a single flapping cycle. Smaller UAVs will have to face complex air flow characteristics, such as wake capture, due to flight conditions bounded within the low Reynolds number regime (Re < 15000).

There are three type of MAV which are rotary, flapping and fixed wing. One of the most promising of these wings are flapping wings because this type of flight has provided unmatched manoeuvrability in nature. When the sizes decrease, it is additionally considerably more effective than rigid wing flight [2].

As the size of these MAVs gets smaller, the amount of lift and thrust force that can be produce during flapping will also decrease, which cause the load capacity of the MAV is limited. For very small MAVs with fixed wing designs, this will require critical air velocities that limit the manoeuvrability of the MAV. This problem can be overcome by using flapping wings. However, the flapping motion produce by flapping wing designs can produce unsteady thrust and lift forces compare to fixed wing MAVs, which means new method need to the design of the flapping mechanism. Several techniques have been developed by past researchers to measure the flapping motion and used these techniques in MAVs to show that these instruments can be utilised to accomplish flapping wing flight. The primary goal of this study is to design and fabricate the compliant mechanism of flapping wing for improvement of the lift performance of MAV.

2. Literature Review

The closest previous attempt at a flapping wing based on bat wings to this study is a previous work done by the author. In that study a four-bar slider crank was used as a transmission method to produce the flapping motion [3]. Similar previous work that uses a four-bar crank rocker as a transmission system is one work done by Ebrahimi et al. [4]. Another similar attempt at the design of a flapping wing is a MAV design based on ravens done by Decroon et al. [5] where the wings actuate independently to each other using actuators. Also, a previous study that uses actuators as a transmission system to produce the flapping motion is a work done by Beasley [6].

However, most of the previous researchers focused on insect wing but they can still be helpful to this study. A research on revolving hawkmoth wing to test the aerodynamics performance base on insect was done by Nguyen et al. [7]. The study investigated revolving hawkmoth wings that can produce high vertical lift and horizontal drag force coefficient because of leading edge vortex.

They reported that radical changes in wing give slight effects on aerodynamic properties.

In terms of aerodynamics of a flapping wing, the aerodynamic effect of wing platform shape on the flow which researcher use four type of wing platform shapes which are 'reverse-ellipse', rectangle, 'four-ellipse', and ellipse [8]. These design gives many geometric variations including tip width, leading and trailing edge sweep, and area distribution. Their main objective is to understand and observe the effects of platform shape on air flow generated. Based on the experiment, the flow structure of the four wing platform shapes is very similar despite of geometry difference. This show that platform shape wings gives smaller effect on the flow.

Bio-inspired flexible flapping wings with elastic deformation by making an artificial wing that mimic which features deformation and twisting was studied by Phillips et al. [9]. The report was about the development and characterisation mimicking artificial wings using elastic material at the wing which can cause twisting deformations. By replacing the elastic material at the wing root vein, the root vein would bend upward and inward generating an angle of attack, camber and twisting deformation while the wing was flapping due to the aerodynamic and inertial forces acting on the wing. The flexibility characteristics of the wing is investigated by natural frequencies. Shape of the wing deformed a little due to high frequency.

Aerodynamic comparisons of membrane wings with cambered and flat frames at a low Re which examines the effect of frame camber on the aerodynamic characteristics of membrane wings [10]. The fabricated the membrane by using silicone rubber and test it on a low Reynolds number flow (Re ~ 50,000). The author tried to mimic the wing of a bats which has a good flexibility. They discovered that 6% chambered frame and 6% thickness produces less drag compared to flat frames. The author also concludes that membrane wings with cambered frames give greater lift than flat frames. They also reported that drag is low when the angle of attack is 6° and increasing frame camber will increase the aero induced membrane camber relative to chord line.

The effect of chord-wise flexibility of the fluid and structural dynamics approaches for the aero elastic analysis of flapping wing was presented by Wrist et al. [11]. From the study, an aero elastic framework was developed for the analysis of low Re flows and their interactions with flexible flapping wings. The aero elastic coupled solution is based on a time-domain partitioned solution process in which the nonlinear partial differential equations modelling the dynamic behaviour of both fluid and structure were solved independently with boundary information. Within a suitably selected range of span wise flexibility, both mean and instantaneous thrust forces of a plunging wing could be enhanced due to wing deformation.

Design fabrication and camber trailing edge for testing in high altitude and long endurance aircraft was studied by Aono et al. [12]. They used adaptive structural trailing edge MACW which has used during natural laminar flow airflow. The characteristic of the MACW which are lightweight, small, less energy, variable geometry of the lower and upper flap which optimised maximise laminar boundary layer and lift coefficient for endurance aircraft application. They concluded that MACW effectively control the top surface distribution pressure and large transition radius is maintain into the recovery region.

Design and application of compliant mechanisms for morphing aircraft structures by applying trailing edge mechanism which can gives high attitude, long endurance air vehicle was studied by Kotacet al. [13]. Their main objective is to design a novel compliant mechanism which increased the efficiency and aerodynamically of the morph aircraft structures. They reported that compliant mechanism gives an aerodynamic benefit by minimising wing drag over a wide lift range. The geometry of the compliant wing gives a good lift performance advantage over trailing edge flap by deflecting a conventional flap downward.

Design compliant structures trailing edge for shape changing under distributed pressure load Kota et al. [14]. They managed to complete their objectives which to design morphing compliant mechanism of trailing edge with standing external loads. These report gives an idea on how to apply compliant mechanism by optimising the distributed pressure load to move the design and to remove the element possessive of very low stresses. The main function of the compliant mechanism in aircraft is to reduce lift coefficients.

Thrust and lift force are measured on compliant flapping wing for MAV was studied by Shili et al. [15]. They reported that compliant wing gives a good manoeuvre on drag force during high frequency operation using new test stand measurement. They reported that compliant wing generated extra thrust during down strokes and reduced negative lift during upstrokes compared to rigid wing during flapping. They concluded that compliant wing minimises dynamic response and frictional effects while isolating a single component of force generated by flapping.

Passive morphing ornithopter wing constructed using a novel compliant spine was designed and tested by Mueller et al. [16]. The objective of the work was to the execution of ornithopter can be improved by implementing compliant spine. The author reported that positive and negative lift during the down and up strokes is the same as the symmetrical between the upstrokes and down strokes of the ornithopter which lead to zero lift. The author concluded that the present of the compliant spine in the ornithopter wing was found to introduce an asymmetry between the upstroke and the downstroke.

3. Methodology

During the experiment, the MAV model was tested in an air tunnel with capable of producing air velocity between 5 m/s – 9 m/s. The MAV model's mechanical movement was driven by a DC powered motor. This allows for accurate and repeatable variable for the wing motion. The tested wind observed variable was the generated lift of the wing

The generated lift was measured by attaching the bare MAV model to a mount which is connected to a Delta Lab strain gauge. The secured connection translates flapping wing force into the gauge as electrical signals. The Delta Lab strain gauge itself was modified from the stock setup by neglecting its own digital readout unit and connecting it to the Kyowa data acquisition system, the PCD 300A. Analog signals from the strain gauge were fed into the data acquisition system to be conditioned into useful digital data, and only then, would the signal serve as an input to the computer for data analysis. The entire test system is presented in Fig. 1.

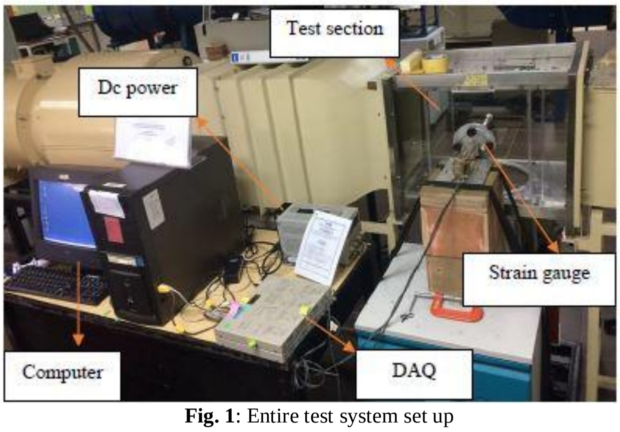
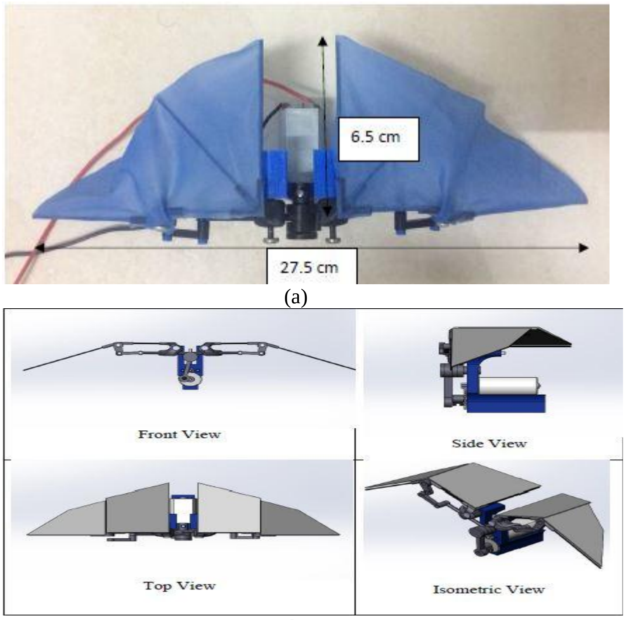


Fig. 1: Entire test system set up

3.1. Compliant Wing Mechanism

The design of MAV model is presented in Fig. 2. The body is fabricated by using 3D printer with Polylactic Acid (PLA) as its base material. The wing span is made by carbon fibre which is strong and has high elasticity. Finally, the wing skin is made from cotton, polyester, nylon, and rayon. The wing skin is the most important part which prevent the air to pass through the particle on the wing. The model simply serves as a model for lift study which has compliant flapping mechanism. With a total wingspan of 27.5 cm the MAV model is too large to be considered as a MAV. Despite its size, this model serves full purpose of this study. However, for purpose of experiment the only function used is the flight speed control; increasing or decreasing flapping frequency to suit experimental parameters.



(a)

(b)

Fig. 2: (a) Fabricated MAV model, (b) CAD drawing for the MAV model

3.2. Strain Gauge Balance

The Delta lab strain gauge balance was used for lift measurements with high accuracy. It was used by attaching the flapping wing system to an intermediate mount. The initial manufacturer's system has been wired and configured to provide measurements for lift, lift moment and drag. However, the purpose of this paper, only lift was measured. Measurements are based on the displacement of a rigid parallelogram, composed of four beams subjected to bending or torsional loads. The strain gauges were fixed to the beam surfaces. The displacements were very small and the test model was attached to the balance remains in the same plane and perpendicular to the flow direction. The balance was mechanically independent of the test section to avoid internal damping effects. Strain gauge balance unit is as shown in Fig. 3.

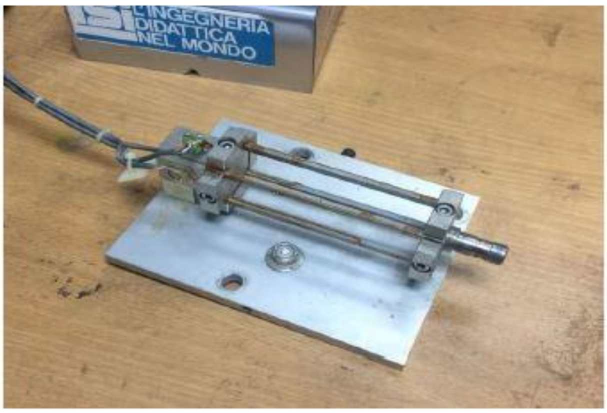


Fig. 3: Strain gauge balance unit

3.3. Kyowa PCD-300A Data Acquisition System

The Kyowa data acquisition system (DAQ-type of PCD 300A model) was used to acquire analogue signal from the strain gauge which later converted into a digital data set. The calibration of the PCD 300 A model was done at default channel condition settings with a range of 10000 μm/min with calibration factor of 1.45 and zero offset value. As the experiment only involves lift measurements, only one is activated and connected with the strain gauge balance. The Kyowa DAQ unit is shown in Fig. 4.

Fig. 4: Kyowa PCD-300A Data Acquisition unit

The Subsonic Open Circuit Wind Tunnel in Fig. 5 is in the School of Aerospace at Universiti Sains Malaysia. The wind tunnel consists of two section suction and blow. The turbine located at the middle of the wind tunnel which function to generate the required wind velocities. The air velocities can be controlled by using a control unit. The control unit increase and decrease the turbine rotational speed in rotational per minute, but we can detect the velocity by using anemometer.

The test equipment used during the experiment include a force measurement, air chamber, DC power supply, flapping mechanism, data acquisition devises and a computer with acquisition software. Starting test, the Delta Lab strain gauge balance was calibrated with weights to check validity of real world data outputs and its changes with respect to the succession of added weights. Calibration factor is set at channel settings to decrease the noise (calibration factor 1.4).

Fig. 5: The open circuit wind tunnel

With the calibration process completed, all parameters (calibration factor, range, sampling frequency, number of recording data) in the PCD-30A software can be set and testing can commence as

shown in the main screen. On this main screen, various operations were conducted, for example, controlling PCD-300A, setting measuring conditions, graphically and numerically displaying the measured data, confirming the PCD-300A connected state, etc.
The MAV model is placed at the centre of the testing section of the wind tunnel, the body axis is parallel to the air flow. The angle of attack was set before running the experiment then turn on the wind tunnel at the required speed by using it control unit. The speed of air is determined by using anemometer. After obtaining the required set of data, the process is repeated at different angles of attack and wind speeds based on the parameter given in Table 1.

Table 1: Test parameters

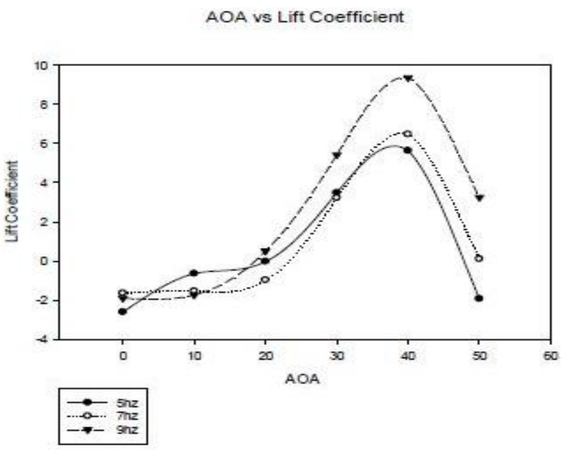
Parameter	Values
Flapping frequencies	4.0 Hz - 9.0 Hz
Angle of Attack (AoA)	0° - 50°
Reynolds number	20000 – 36000

The experiment was conducted with three different variables which are; air velocity, flapping frequency and angle of attack. In this experiment, Reynolds number used was 20000, 28000 and 36000. For flapping frequency from 5 Hz to 9 Hz and finally the angle of attack from 0° to 50° with 10° increment. For the first result, the MAV model is measured at increasing angle of attack at the same frequency and the same air velocity. Data was collected at sampling frequency of 1000 Hz.

4. Results

4.1. Aerodynamics Performance of MAV Wing

In general, all wings demonstrated a comparative pattern with increasing lift coefficient, which rises monotonically with increasing AoA for all Re until reaching the peak value at AoA between nearly 35° to 40°, and then the lift decreases. It can be clearly observed from Fig. 6 that lift force increases linearly with the increase in angle of attack until 40° which the MAV model has reach it stall. The increase in lift associated with higher angles of attack is theorised to be caused by delayed stall which is caused by translational mechanism. At high AoA, a flow structure forms on the leading edge of a wing that can generate circulatory forces more than those supported under steady-state conditions. From the data, 9 Hz produce the highest lift force at a constant air velocity. This is because the higher the flapping frequency the higher the lift force.
For changes in angles of attack, lift is higher at lower air velocity. This is shown in the graph which compare between each Re, Re = 20000 produce the highest lift force next is Re = 28000 and last is Re = 36000. This is because the higher the air velocity the higher the resistance for the flapping wing to produce lift force.



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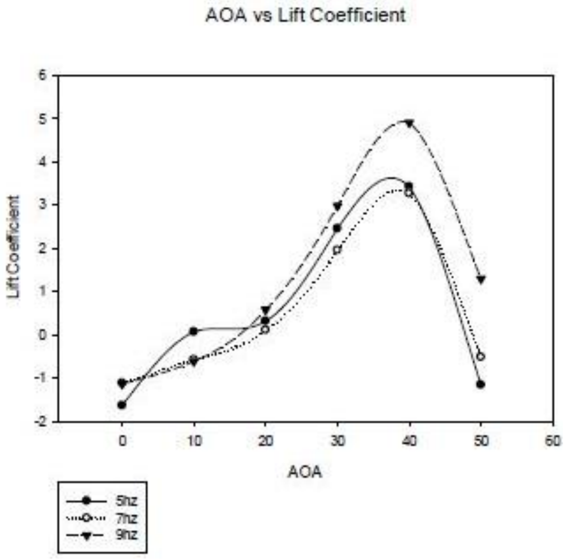

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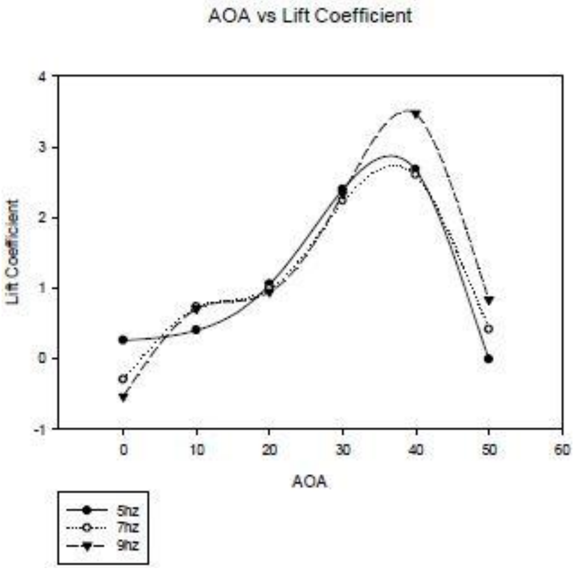
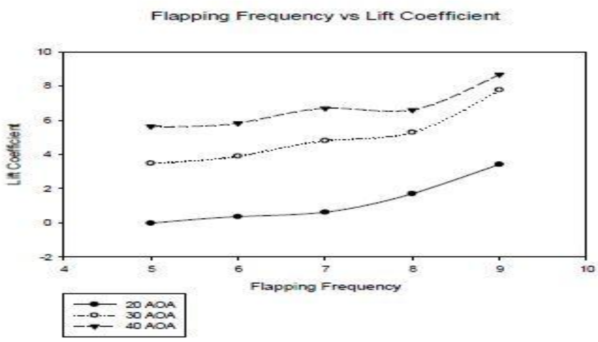


(c)

Fig. 6: Lift coefficient over change of Angle of Attack at (a) Re = 20000, (b) Re = 28000, and (c) Re = 36000

Based on the result lift coefficient versus flapping frequency Fig. 7, it can be clearly observed that 40° angle of attack for every flapping frequency has the highest lift force which is the best condition for compliant wing MAV. The lift force keeps increasing since the higher flapping frequency the higher the lift force. Angle of attack 40° is the best flapping condition for compliant wing mechanism. This is shown in Fig. 7 which is at angle of attack 40° produce the highest lift coefficient before reaching stall.



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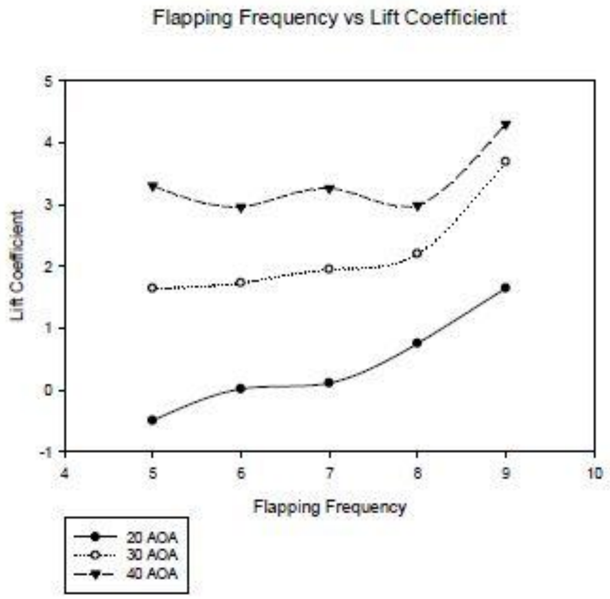

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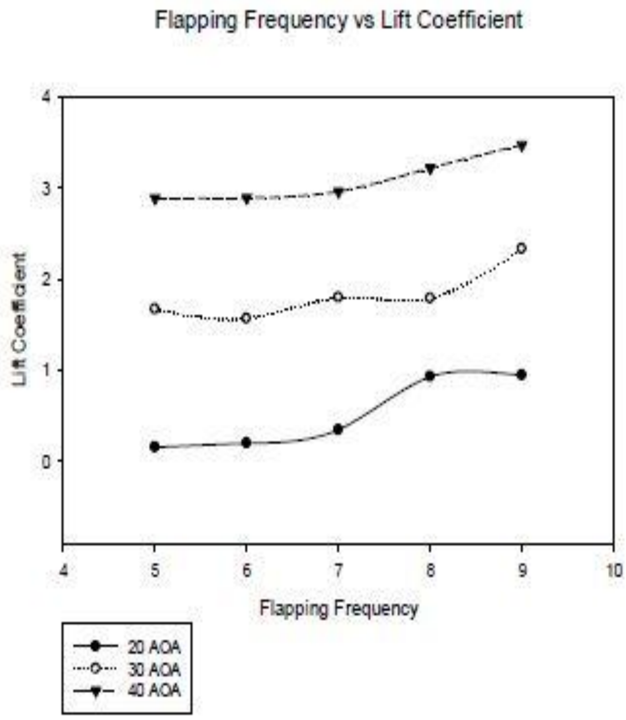
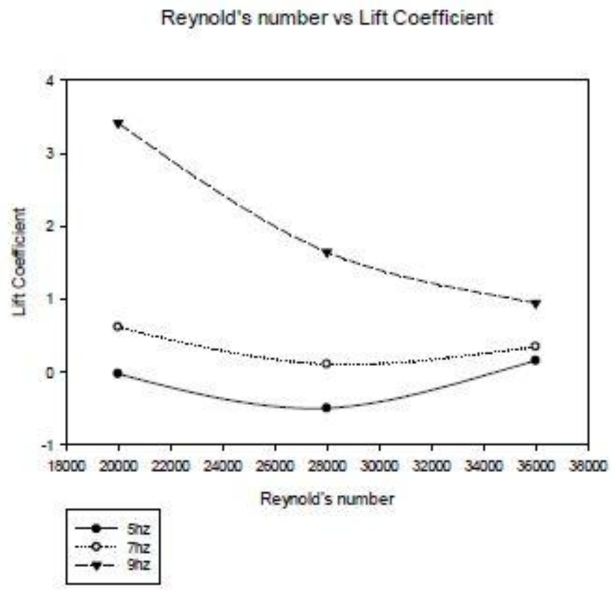


(c)

Fig. 7: Lift coefficient for different flapping frequencies at (a) Re = 20000, (b) Re = 28000, and (c) Re = 36000

Fig. 8 shows that the $C_{L\ avg}$ decrease exponentially during $20000 < Re < 36000$ and remain constant for each flapping frequencies. The result shows that Re = 20000 air velocity produces the highest lift coefficient. The lift force decreases as the air velocity increase which lower air velocity produce higher lift force compare to higher air velocity. This is because of the air resistance which disturb the flight of flapping wing. However, the results indicate that difference angle of attack for all the Re range of $20000 < Re < 36000$ gives a huge difference on the performance of compliant wing mechanism.



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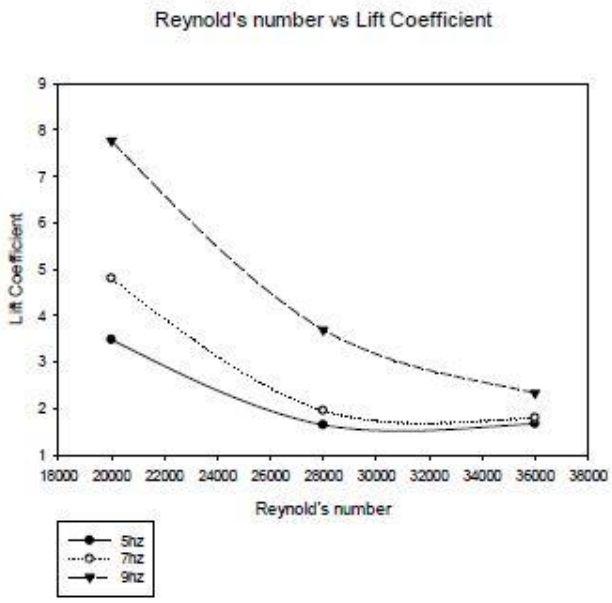

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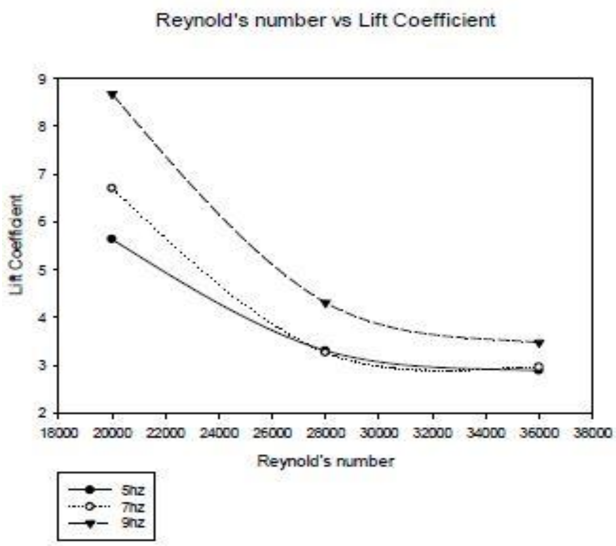

(c)

Fig. 8: Lift coefficient against Reynolds numbers at(a) AoA = 20^{o}, (b) AoA = 30^{o}, and (c) AoA = 40^{o}

To analyse the mechanism in terms of compliant wing influencing the aerodynamic characteristic of flapping wing, the results needs to show which is of the condition produce the best and the worst for compliant flapping wing.

The first comparison is between different Re 20000 < Re < 36000 at the same Angle of Attack. Based on the observation, Re = 20000 produce the most stable lift performance compared to other Reynolds number, based on Fig. 8. The stability of flight is based on theory which lift coefficient increase when angle of attack increase until it reaches stall. Re = 28000 also produce a stable lift performance, but the lift coefficient is lower than Re = 20000 conditions.

During flight of compliant wing in a different Reynolds number certain angle of attack is compared to ensure which angle is suitable for the changes in Reynolds number. Based on the result on Fig. 8, 40° angle of attack produce the highest lift coefficient compare to 20° and 30°. Basically, the best condition for compliant wing is at 40° angle of attack at 9 Hz flapping frequency and Re = 20000 which produce the highest lift coefficient which is 8.6.

5. Conclusions

The aerodynamic performance of compliant flapping wing mechanism for MAV was investigated in this work. Both experimental studies were completed with the objectives to analyzing the effects of compliant wing mechanism during flight. The performances of the compliant wing were measured as a function of several parameters, such as angle of attack, flapping frequency, and air velocity. Maximum lift produced by the compliant wings at 9 Hz is approximately 8.6 lift coefficient. Lift generated increases with flapping frequencies. However, the trend shows that high frequencies and low Reynold's number will produce better lift change.

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