UNSTEADY AERODYNAMIC CHARACTERISTICS OF THE FLAPPING WING MICRO AIR VEHICLE (MAV)

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Abstract

Flapping wing propulsion is center of attention in the field of micro air vehicle research in recent years. Knowledge in unsteady aerodynamics is insufficient to design an efficient wing that produces the required lift and thrust force for the flapping wing micro air vehicle. The unsteady aerodynamic effects on aerodynamic wing design parameters were discussed in this paper. The effect of aspect ratio and the wing planform shape on lift and thrust force were determined experimentally. The experiments were conducted in an open jet low speed wind tunnel having test section 350 mmx350 mm. A rack and gear type new flapping mechanism was designed and fabricated and this was used as test bed for all the experiments. Also an experiment was conducted to determine the effect of torsional flexibility of the wing. The result shows that the chord wise flexible wing produces more lift and thrust than the other wing.

Nomenclature

a_o = two dimensional lift curve slope
AR = aspect ratio
b = semi wing span
c = chord length
C_{Lo} = two dimensional lift coefficient
C_L = three dimensional lift coefficient
C_t = coefficient of thrust
f = flapping frequency
J = advance ratio
k = reduced frequency
S = wing area
U = free stream velocity
α = angle of attack
ϕ = flap angle
ω = wing angular velocity

Introduction

Micro Air Vehicles (MAVs) are the small aircrafts that has its application [1] in military and civil missions. The primary missions of interest for MAVs include surveillance, detection, communications, and the placement of unattended sensors. Surveillance missions include video, infrared images of battlefields and urban areas. These real-time images can give the number and location of opposing forces in battlefield. Detection missions include the sensing of biological agents, chemical compounds, and radioactivity. MAVs may also be used to improve communications in urban or other environments where full-time line-of-sight operations are important. The placement of acoustic sensors on the outside of a building during a hostage rescue or counter-drug operation is another possible mission. Micro air vehicles should have an overall size of 15cm in all the three coordinates (length, span and height) and maximum weight of 50g.

The main advantage of flapping wing propulsion over other types of propulsion system is the generation of lift force and thrust without excessive size or weight. By flapping wings, the birds and insects effectively increase the Reynolds number without increasing the forward speed. Another advantage of flapping wing is its ability to perform short takeoff and landing and is extremely maneuverable at low speed flight. Also it is inaudible if the wing's beat frequency is less than 20Hz.

The aerodynamics of insect wings is entirely different from the conventional wings. Kesel [2] showed that the wings of dragonfly is comparable with conventional profiles in a steady flow, but in dragonfly the negative pressure occurs on both the upper and lower surfaces of the wing at angles of attack from -10 to 0º. The higher values of C_L produced by insects are due to some special high lift mechanisms [3]. Reduced frequency increases with increase in unsteady effects and for an insect it will be greater than 0.75. But in case of birds [4] the reduced frequency is lesser than 0.75. For low velocity flight, the

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reduced frequency is high and gives rise to unsteady flow. It is most often described by the vortex wing theory. The upstroke contributes no useful aerodynamic forces.

De Laurier [5] had shown that the thrust generation in plunging motion is due to the leading edge suction and for significant suction force the leading edge has to be adequately shaped. With pitch articulation, thrusting can be generated not only by leading-edge suction, but also by the stream wise component of the wing's normal force. During down stroke as the wing reaches the mean position of the flapping amplitude (i.e., when the wing span is parallel to the ground), maximum suction occurs and the maximum thrust is produced [6]. The propulsive efficiency attains maximum at certain values of reduced frequency. By increasing the reduced frequency beyond this, results in a small decrease in efficiency [7]. Jones [8] shows that the static thrust decreases with increase in aspect ratio up to an aspect ratio of 4.5, and it remains fixed for higher values of aspect ratio.

The objective of present work is to determine the effects of aspect ratio, wing planform and wing torsional flexibility on lift and thrust force. The flapping mechanism follows a simple harmonic motion and symmetrical flapping. The flap angle (the angle traveled by the wing for one flap) is fixed as constant 70º for all the experiments.

Flapping Mechanism Description

The rack and gear flapping mechanism, which was used as a test bed for conducting experiments was designed and fabricated [10] using Plastic and Aluminium plates which is shown in Fig.1. It consists of a crank, which is connected to the motor shaft and the other end of the crank is connected with connecting rod. The connecting rod is connected with double side-toothed rack, which is constrained by Aluminium support, only to slide up and down. The either side of the rack is meshed with spur gears. The wings are attached to these gears through wing attachments that are fixed with spur gear as shown in Fig.2. As the motor rotates, the rack is pushed and pulled vertically by the crank and connecting rod links. On the other hand the rack actuates the gears on its either side to move in opposite direction i.e., one of the gears rotates in clockwise direction and the other in counter clockwise direction. These opposite movements of gears cause symmetrical flapping action in the wing planforms.

The important parameters of the mechanism that affects the lift and thrust directly are the frequency of the flap and the angle of flap. Variation in the input voltage to the electric DC motor controls the flapping frequency of the wing. The flap angle depends on two variables and they are gear radius (r_g) and crank radius (r_c). The flap angle can be related to them by,

$$\phi_{max} = 2\frac{r_c}{r_g} \qquad (1)$$

ϕ_{max} - Maximum Flap angle in radians.

The flapping angle of the wing vastly influences the instantaneous angular velocity of the wing. Generally as the maximum flap angle increases the instantaneous angular velocity and there by the linear velocity of the wing increases. The expression for instantaneous flap angle is given below. In this the crank angle and the flap angle are measured from the maximum upstroke position.

$$\phi = \frac{r_c\,(1 - \cos(\pi - \theta))}{r_g} \qquad (2)$$

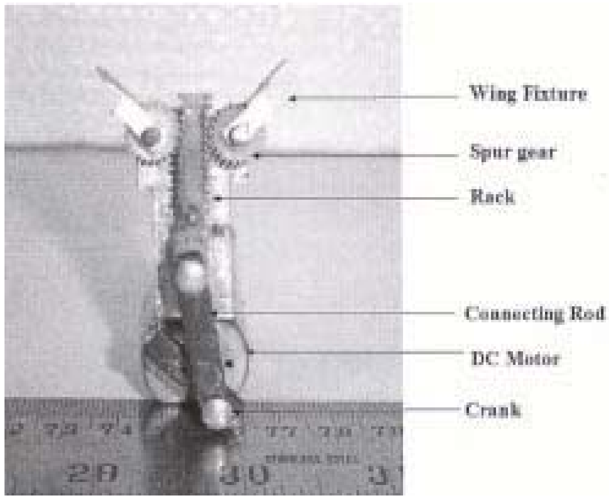

Fig. 1 Rack and gear mechanism

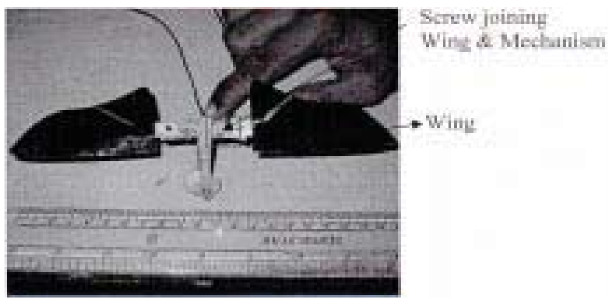

Fig. 2 Mechanism with wing attachment

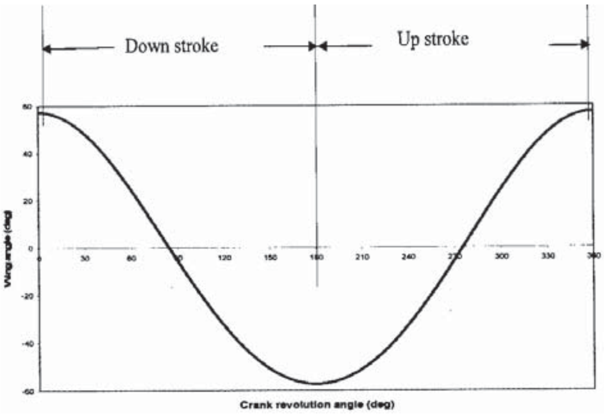

Fig. 3 Wing angle with crank revolution angle

where,

ϕ - Instantaneous flap angle in radians.

θ - Instantaneous Crank angle in radians.

The wing rotation angle variation with respect to the angular position of crank disc for the flap angle of 58º is shown in Fig.3. The maximum value of wing angle is the flap angle. One revolution of crank (360º rotation of motor) produces one flapping cycle i.e., one upstroke and one down stroke. The down stroke starts from the crank rotation angle of 0º, while the wing is at +58º with the horizontal and this stroke ends at the crank rotation angle of 180º, while wing is at -58º with the horizontal and at this point the upstroke beings.

Wing Planform Development

All the wings are constructed by using Mylar sheet for skin and Balsa wood for spar. A thin flat plate was used for all the wings and that eliminates the effect of camber, airfoil shape, thickness effect etc. For the aspect ratio experiment, three pairs of wings with aspect ratio of 4, 12 and 20 were considered. The planform of these wings were elliptic shape since efficiency factor of 1 in steady aero-dynamics. Various wing planforms considered are shown in Fig.4. Basically, two insect wings (butterfly and drag-onfly) and two bird wings (humming bird and pigeon) were selected for experiment. The wing planform specifi-cations are given in Table-1. Wings are also fabricated and tested for the effect of torsional flexibility and a schematic diagram of arrangement is shown in Fig.5. By arresting the motion of flaps, the same wing could be used as rigid wing and single flap wing, which is shown in Figs.5(a) and (b). The double flap arrangement is similar to that of a wing with a control surface (which is the first flap) and tab

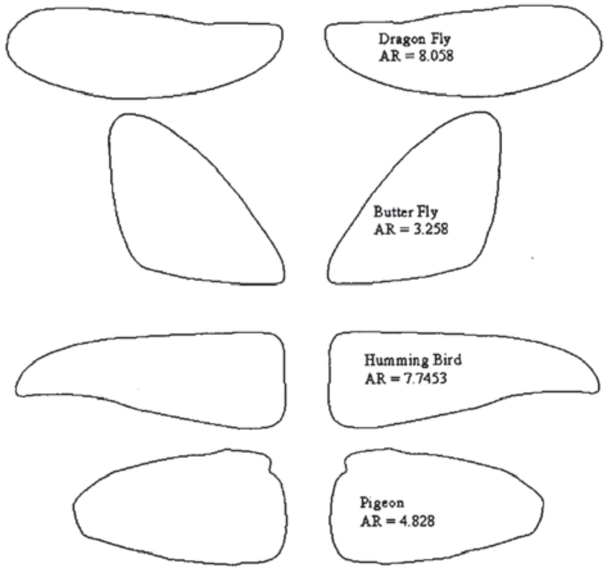

Fig. 4 Wing tested for planform effect

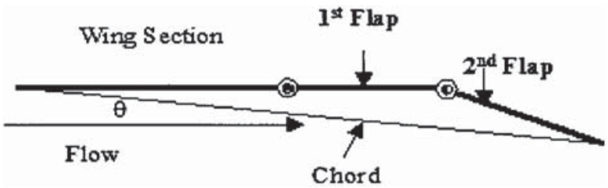

Fig. 5a Schematic diagram of torsionally flexible wing

Fig. 5b Torsionally flexible wing

(second flap) in stick free condition in conventional wing. Here the area of first and second flaps and the fixed part of the wing are equal. The angle of attack and camber are indicated in Fig.5(a) and it depends on the flap deflection. The maximum values of the camber and the angle of attack at root and tip are given in Table-2. The values of The angle of attack here refers the virtual angle of attack and not the actual angle of attack due to flow. While flapping at certain degree of flap angle the chord line of flexible wing makes an angle 'θ' to horizontal plane and this angle is referred as virtual angle of attack as shown in Fig.5(a).

Table-1 : Wings Specifications tested for Aerodynamic Parameters

Sl.No.	Planform Shape	Wing Area (mm2)	Aspect Ratio
Wings Tested for Aspect Ratio			
1	Ellipse	967.61	4
2	Ellipse	955.04	12
3	Ellipse	620.465	20
Wings Tested for Planform			
1	Dragon Fly	1000	8.058
2	Butterfly	1000	3.258
3	Humming Bird	1000	7.7453
4	Pigeon	1000	4.828

Table-2 : Angle and Camber Variations for Flexible Wing

Wing	Virtual Angle of Attack (deg)		Camber (%)	
	Root	Tip	Root	Tip
Rigid	3	6	3	0
Single Flap	9	20	10.77	13.85
Double Flap	25	37	20	0

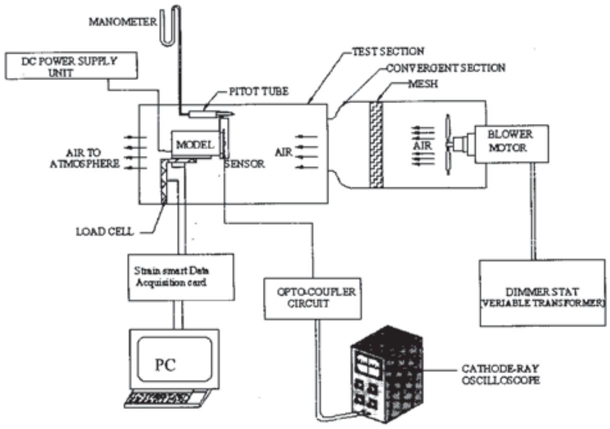

Fig. 6a Schematic diagram of experimental setup

Fig. 6b Experimental setup

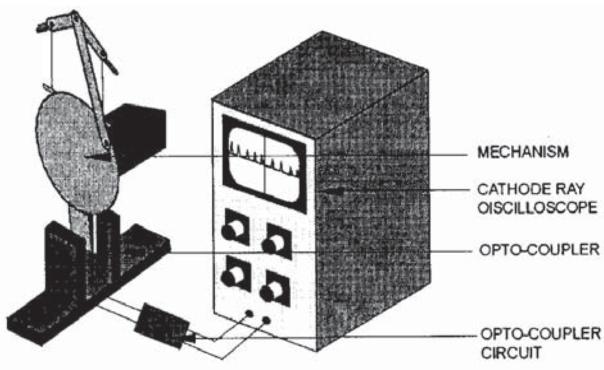

Fig. 7 Opto-Coupler sensor arrangement

Test Setup and Procedure

The experimental setup is shown in Fig.6(a) - Schematic diagram and Fig.6(b) - Test Setup. It consists of an open jet low speed wind tunnel with velocity uniformity of 0.5% and speeds from 1 m/s to 10 m/s. The wind tunnel has a 350x350x600 mm test section with a 2:1contraction. Lift and thrust forces were measured using low capacity 2-D force strain-gauge base load cell. A two-component strain gauge load cell was designed and fabricated to measure the lift and thrust force simultaneously. The load cell [10] consists of an inverted 'L' shaped frame with strain gauges attached at the bend and also at the root. The output of the load cell has been interfaced with PC through STRAINSMART DAQ (Data Acquisition) interface card, which has the strain-gauge signal conditioner with 16-bit Analog-to-Digital Converter (ADC). The free stream velocity was measured using 'U' tube manometer through Pitot-static tube. An opto-coupler non-contact sensor was used to measure the flapping frequency. The sensor output is interfaced to the oscilloscope through simple opto-coupler circuit as shown in Fig.7.

The flapping frequency of the mechanism can be varied by changing the input voltage to the DC motor, which is used to drive the mechanism. The experiments were conducted for various values of free stream velocity and flapping frequency for different planforms. Another important parameter that affects the lift and thrust is the flap angle and that was fixed for the entire experiments as Φ=70º. All the tests were carried out in a full-scale model. Tests were conducted for different combinations of flapping frequency (between 4Hz to 20Hz) and free stream velocity (from 1m/s to 5m/s).

Results and Discussion -Aspect Ratio Effect

The effect of aspect ratio on lift force is shown in the graph plotted between reduced frequency and the coefficient of lift in Fig.8. As the aspect ratio increases the coefficient of lift also increases as in case of steady flow. To find the effect of aspect ratio on lift, the equation (3) that gives the effect of aspect ratio in steady aerodynamics has been modified with experimental results to get an empirical relation shown in equation (4).

$$C_{Lo} = C_L \left[1 + \frac{\alpha_o}{\pi AR} \right] \quad (3)$$

$$C_{Lo} = C_L \left[\frac{\alpha_o^2}{2\,\pi^2\,AR^2} + \frac{3\alpha_o}{2\,\pi\,AR} + 1 \right] \quad (4)$$

This equation relates the two-dimensional lift coefficient with the three-dimensional lift coefficient for an unsteady case. By replacing the C_L (y-axis) of previous graph by C_{Lo}, which is calculated by using equation (4) results in a plot shown in Fig.9. This graph is useful in validating the equation (4). The term aspect ratio used in this paper is the effective aspect ratio. The reduced frequency can be crudely defined as number of vortex generated per unit distance movement of a body. And the advance ratio is the distance moved per unit flap of wing per unit span.

$$k = \frac{2\,\pi f c}{U} \quad (5)$$

$$J = \frac{U}{4 b f \phi} \quad (6)$$

The thrust variation with aspect ratio is depicted in Figs.10 and 11. The coefficient of thrust increases with increase in aspect ratio (Fig.10(a)) and with reduced frequency and decreases with increase in aspect ratio (Fig.10(b)) and with advance ratio.

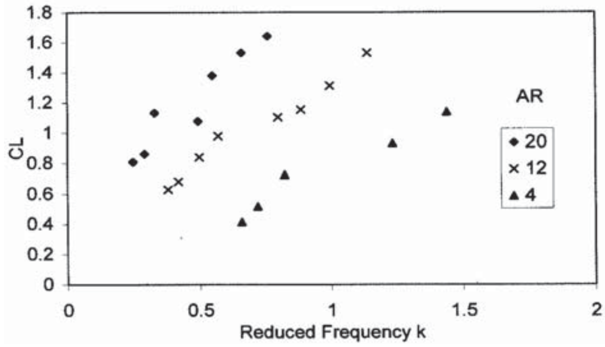

Fig. 8 Effect of aspect ratio on C_L.

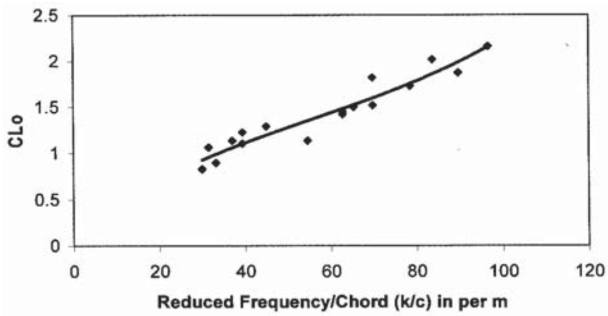

Fig. 9 Elimination of effect of aspect ratio

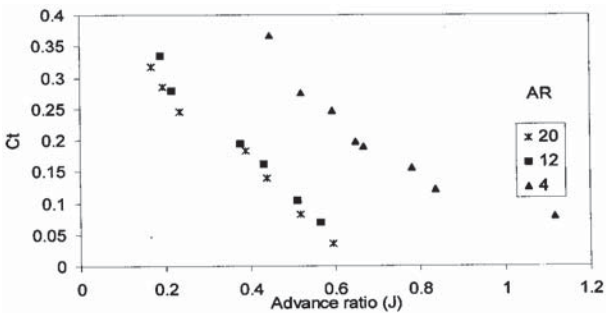

Fig. 10a Variation of C_t with advance ratio

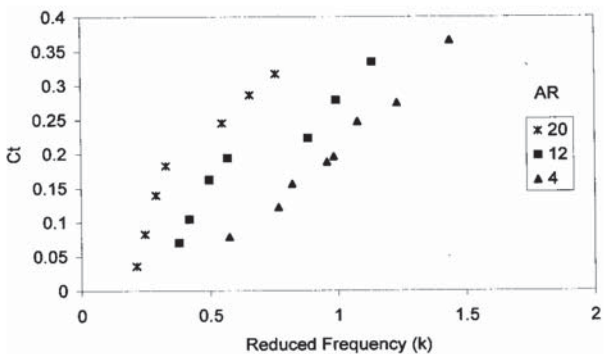

Fig. 10b Variation of Ct with reduced frequency

Since flap angle is constant, the inverse of reduced frequency is very much similar to that of advance ratio equation. The length dimensions (i.e., chord and semi wing span) in these two equations affect the effect of aspect ratio. Hence one more set of curves are plotted by omitting the length dimensions i.e., the x-axis is taken as reduced frequency per unit chord for Fig.11(a) and product of advance ratio and span is taken in Fig.11 (b). In these two graphs all the curves merges in to one and shows that there is no effect of aspect ratio on thrust force (for an aspect ratio ≥ 4).

The variation in curves of Fig.10(a) and 10(b) is only due to the length dimensions, which shifts the curve along x-axis and not in the y-axis i.e., the coefficient of thrust remains same. In brief, for all these three elliptic wings of different aspect ratios the coefficient of thrust remains same for the same flapping frequency and free stream velocity.

Results and Discussion on the Effect of Wing Planform Shape

The effect of wing planform on lift and thrust forces are shown in Fig.12 to 14. From the Fig.12 the dragon fly wing shows better lift characteristics than others. The increasing order of performance inclines much on the aspect ratio rather than the wing planform shape of the wing. Hence in order to isolate the planform effect and to eliminate the effect of aspect ratio, the results shown in Fig.12 were modified with the equation (4) and the final graph is shown in Fig.13. This graph eliminates the effect of aspect ratio and holds the planform shape effect on the coefficient of lift under the flapping motion.

The butterfly and dragonfly wing performs better than that of the other two wings at a reduced frequency around one, which is shown in Fig.13. In general the planform of insects seems to be better than that of the bird's wing at higher flapping frequency. The root chord of an insect wing is much smaller than that of tip chord but the bird's wing has smaller tip chord as that of conventional aircrafts wing. Owing to the shape of the insect's wing, they are highly aeroelastic and have lesser divergence and flutter velocity. Hence a highly aeroelastic wing could produce much higher lift than that of a rigid wing with same aspect ratio and wing area.

The effect of wing planform shape on thrust force is depicted in Fig.14. Since the thrust coefficient remains same for the same flapping frequency and free stream velocity combination for different aspect ratio, the graph in Fig.13 was plotted in a similar way as like Fig.11. Fig.14 shows that the butterfly and pigeon wing has better thrust characteristics than the dragonfly and humming bird wing shapes. In this case neither higher aspect ratio nor aeroelastic wing shows better characteristics.

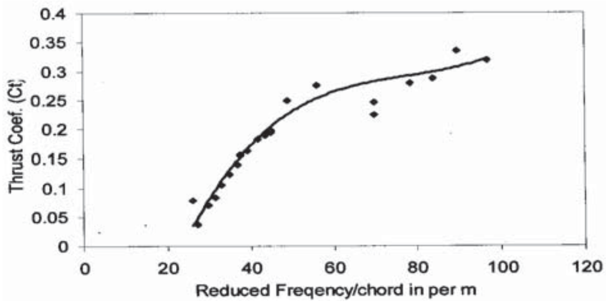

Fig. 11a Effect of aspect ratio C_t

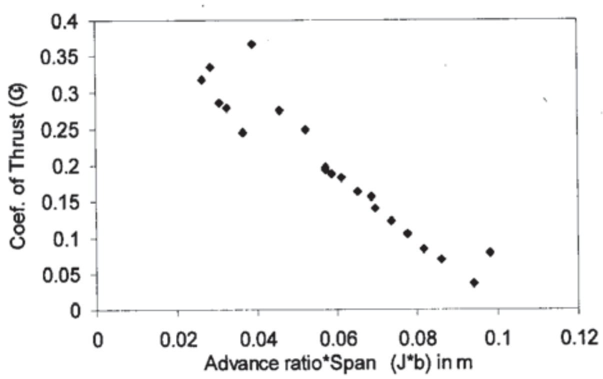

Fig. 11b Effect of aspect ratio on C_t

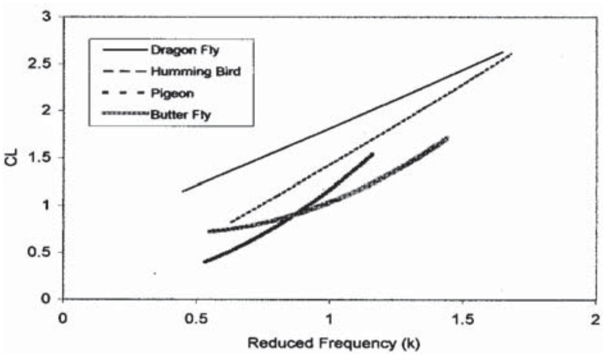

Fig. 12 Performance of planforms

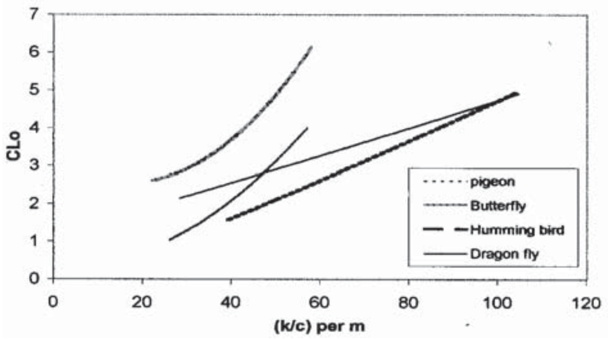

Fig. 13 Effect of planform shape on lift

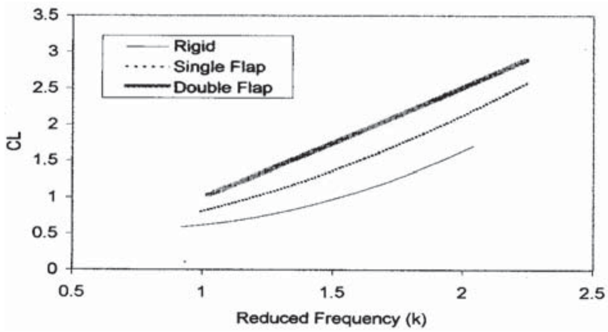

Fig. 15 Effect of flexibility on lift

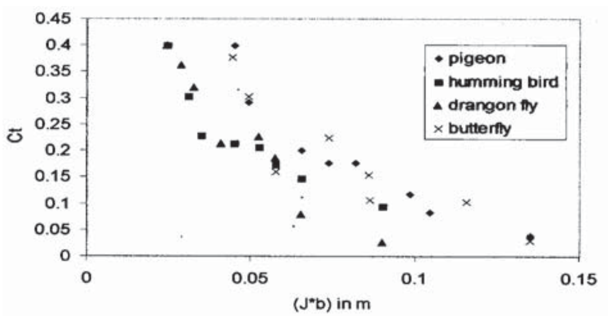

Fig. 14 Effect of planform on thrust

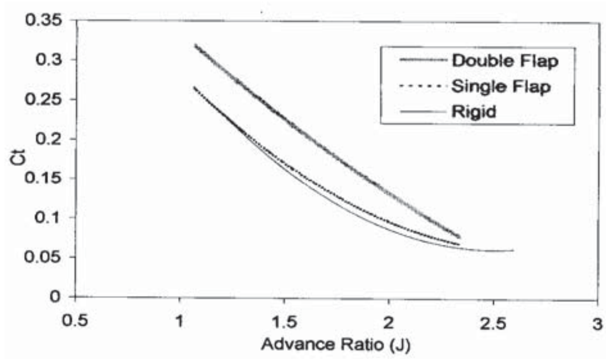

Fig. 16 Effect of flexibility on thrust

Effect of Torsional Flexibility - Results and Discussions

The effect of torsional flexibility on lift force is shown in Fig.15. As the torsional flexibility increases the lift force also increases. The C_L produced by double flap wing is approximately 1.5 times greater than that of the rigid wing. Even though the camber distribution of single flap wing is in opposite sense to the other types, this does not affect the increase in lift force. The variation of coefficient of thrust force due to torsional flexibility is depicted in Fig.16. Double flap wing shows better C_t than the other two types. The C_t produced by the double flap wing is approximately 1.2 times greater than that of the rigid wing. Even though the single flap wing is flexible in torsion there is no detectable difference in thrust coefficient compared with rigid wing and this is because of the camber distribution. Hence the torsional flexibility distribution also affects the thrust force.

Conclusion

In this study, the effects of wing aspect ratio, wing planform shape and torsional flexibility of the wing on lift and thrust force are investigated for various flapping frequency and free stream velocity. The lift force increases with increase in aspect ratio and also with the torsional flexibility. The thrust force also increases with increase in torsional flexibility, but it is not affected by the aspect ratio of the wing (with same wing area and wing shape). The butterfly wing planform shape shows better lift and thrust characteristics. A wing with less flutter speed (highly aeroelastic) can generate much higher lift and thrust force than a rigid wing.

Reference

1. Muller, T. J., "Fixed and Flapping Wing Aerodynamics for Micro Air Vehicle Applications", Progress in Astronautics and Aeronautics, 2001.

2. Kesel, A. B., "Aerodynamic Characteristics of Dragonfly Wing Sections Compared with Technical Aerofoils", The Journal of Experimental Biology 203, pp.3125-3135, 2000.

3. Sane, S. P., "The Aerodynamics of Insect Flight", The Journal of Experimental Biology, 206, pp.4191-4208, 2003.

4. Shyy, W., Berg, M. and Ljungqvist, D., "Flapping and Flexible Wings for Biological and Micro Air

Vehicles", Progress in Aerospace Sciences, 35, pp.455-505, 1999.

5. DeLaurier, J.D. and Harris, J.M., "Experimental Study of Oscillating-wing Propulsion", Journal of Aircraft, Vol. 19, No. 5, May 1982.

6. Tuncer, I.H. and Platzer, M.F., "Thrust Generation Due to Airfoil Flapping", AIAA Journal, Vol.34, No.2, February1996.

7. Guglielmini, L. and Blondeaux, P., "Propulsive Efficiency of Oscillating Foils", European Journal of Mechanics B/Fluids, 23, pp.255-278, 2004.

8. Jones, K.D., and Platzer, M.F., "Flapping Wing Propulsion for Micro Air Vehicle (MAV)", 38th Aerospace Sciences Meeting and Exhibit, AIAA, 2000-0897.

9. Dally, J.W. and Riley, W.F., Experimental Stress Analysis, McGraw Hill Inc., New York, 1978.

10. Duriyanandhan, V., Muniappan, A. and Baskar, V., "Development of Rack and Gear Mechanism for Flapping Wing Micro-Air Vehicle and Effects of Wing Planforms on the Lift Characteristics", 18th NCAE, Indian Institute of Technology Kharagpur, 17-19 November 2004.

11. Bisplinghoff, R.L., Ashley, H. and Halfman, R.L., "Aeroelasticity", Addinson-Wesley Publishing Company, Cambridge.

12. Fung, Y.C., "The Theory of Aeroelasticity", Dover Publications, New York.