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ITJ

ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 11 (12): 1758-1763, 2012
ISSN 1812-5638 / DOI: 10.3923/itj.2012.1758.1763

Effect of the Flexibility of Flapping Wings on Their Aerodynamic Characteristics

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Abstract: The effect of the flexibility of flapping wing on their aerodynamic characteristics are studied using numerical method, where the incompressible N-S equations coupled with a structural dynamic equation modeling the motion of the wing are solved. The flow structure around the wing, the aerodynamic forces and the energy consumption of the wing are examined for different flexibilities of the wing. It is found that the flexibility of the wing can influence its aerodynamic characteristics significantly and if the flexibility is at an appropriate level, it can increase the thrust and the energy efficiency of the wing while keep the mean lift force almost unchanged. The present results provide useful information for the development of flapping wing MAV.

Key words: Flapping wing, flexibility, energy efficiency

INTRODUCTION

The idea of Flapping Micro Air Vehicle (FMAV) is derived from the observation of insect flight. There have been a number of experimental and numerical studies carried out on the aerodynamic characteristics of insect flight, such as the studies by Ellington *et al.* (1996), Dickinson *et al.* (1999) and Wang (2000) and so on and it is understood that the aerodynamic characteristics of flapping wing may be enhanced through the interaction of three distinct yet interactive mechanisms: The delayed stall, the rotational circulation and the wake capture. It is known that nearly all of the insect wings are flexible and they can generate necessary dynamic deformation during flying (Cheng *et al.*, 2005; Wang *et al.*, 2003; Liu and Sun, 2008) and it is believed that the flexibility plays an important role in enhancing the aerodynamic characteristics.

Based on two-dimensional time-dependent Navier-Stokes simulation, Miao and Ho (2006) investigated the effect of chord-wise flexibility of a plunge wing on its aerodynamic characteristics. Their results indicated that the propulsive efficiency was improved when a degree of chord-wise flexibility was introduced to the wing. Vanella *et al.* (2009) used a two-link model to study the flexibility effect on the aerodynamic characteristics of a hovering wing. Their results showed that the flexibility can enhance the aerodynamic characteristics and the best performance was achieved when the wing was excited by a non-linear resonance at 1/3 of the natural frequency. Masoud and Alexeev (2010) performed a numerical study on the hovering aerodynamics of flexible planar wings oscillating at resonance. The results indicated that large-amplitude resonance oscillations of elastic wings can enhance the aerodynamic lift and efficiency of low-Reynolds-number plunging drastically. However, a recent experimental study on the effect of chord-wise flexibility of flapping wings on their aerodynamic force conducted by Zhao *et al.* (2009) showed that the flexible wings offered no aerodynamic advantage over a rigid wing under steady state circumstances.

The flexibility effect of a flapping wing on its flight performance still remains unclear though many experimental and numerical investigations have been carried out. The objective of this study was to investigate the effect of flexibility on the aerodynamic characteristics of flexible flapping wings. A 2-D flexible flapping wing in forward flight is studied for the purpose where the Navier-Stokes solver for fluid flow around the wing coupled with a structural dynamics solver for the wing motion is solved so that the fluid-structure interaction can be taken into account properly. The flow field, the lift and thrust forces of the wing are examined in detail.

COMPUTATION MODEL

A similar model to the one studied by Vanella *et al.* (2009) is adopted where a NACA0012 airfoil configuration is used. To simulate the flexibility of flapping wing, the tail part of the airfoil separated at point O is considered to be flexible and it can rotate around the point O passively as shown in Fig. 1, where c is the chord length of the airfoil, h (t) is the displacement specified at rigid leading part of wing and θ is the deformation angle of the tail part of the wing to simulate the flexibility of the wing. The point O is located at 0.25 c from the leading edge. The leading part of the airfoil is kept as rigid and experiences a plunging motion h(t) and the tail part, in addition to the plunging

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motion, rotates around point O passively to simulate the flexibility of wing. The plunging motion is described by the following equation:

$$h(t) = h_0 \cos(2\pi f t) \tag{1}$$

where, h_0 and f are the amplitude and the frequency of the plunging motion respectively and the deformation angle is governed by the following equation:

$$\ddot{\theta} + (2\pi f_s)^2 \theta = (Q_v + Q_p + Q_m)/J \tag{2}$$

where, J is the inertia moment of tail wing, Q_v, Q_p and Q_m are the torques generated by viscous force, pressure force and inertia force, respectively. f_s is the system natural frequency and:

$$f_s = \sqrt{K/J}/(2\pi)$$

where, K is the torsion stiffness. Only aerodynamic torque is considered.

Four important nondimensional parameters are concerned including Reynolds number Re, reduce frequency k, frequency ratio ω^* and mass ratio m^* and they are defined as:

$$Re = \frac{\rho U_\infty c}{\mu}, k = \frac{\pi f c}{U_\infty}, \omega^* = \frac{f}{f_s}, m^* = \frac{\rho}{\rho_s} \tag{3}$$

where, U_∞ is the uniform forward flight velocity, μ the fluid kinematic viscosity, ρ the fluid density and ρ_s the structure density.

Lift force coefficient C_L, thrust force coefficient C_T and energy coefficient C_P are defined as:

$$C_L = \frac{F_L}{0.5\rho U_\infty^2 c} \tag{4}$$

$$C_T = \frac{-F_D}{0.5\rho U_\infty^2 c} \tag{5}$$

$$C_P = \frac{F_L \dot{h}(t)}{0.5\rho U_\infty^3 c} \tag{6}$$

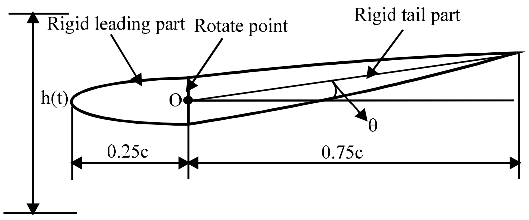


Fig. 1: Schematic representation of computation model

where, F_L is the lift force of the wing and F_D is the drag force of the wing. The energy efficiency is then determined by:

$$\eta = \frac{\overline{C_T}}{\overline{C_P}} \tag{7}$$

where, $\overline{C_T}$ and $\overline{C_P}$ are the mean thrust force and energy coefficients, respectively.

NUMERICAL METHOD

The Reynolds number 1000 is considered. Therefore, the fluid flow is assumed to be laminar and incompressible. The fluid flow solution is obtained using CFD software Fluent 6.3.26 which solves the Navier-Stokes equations based on the finite volume method and the dynamic mesh technique for moving boundary problem is used to simulate the motion of the flexible wing. The structural dynamics governing equation is solved using the finite difference method. The solutions for the fluid flow and the structure dynamics are coupled by using the User Defined Function (UDF) in the software, i.e., at each time step, the fluid field is solved first using Fluent where the aerodynamic torque on the wing is obtained and then the displacement of the tail wing can be determined under the aerodynamic torque using the finite difference solver which is embedded in Fluent using the UDF. In the next time step, the fluid flow is solved with the new location of the wing updated by using the dynamic mesh technique. The fluid flow and the wing's motion are solved alternatively and in such a way the fluid and the structure are coupled so that the fluid-structure interaction is taken into account properly.

A hybrid mesh system of computational domain is applied where an oval shape computational domain containing an inner domain, a middle domain and an outer domain is employed, as shown in Fig. 2. Quadrilateral cells

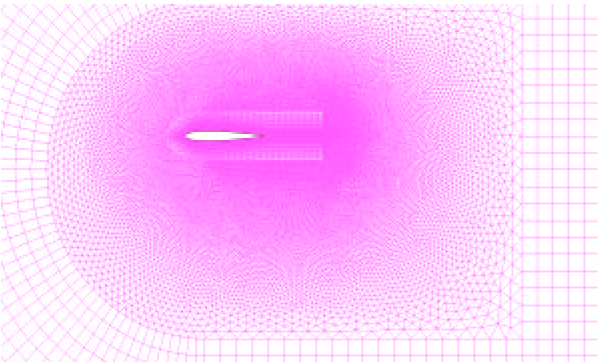


Fig. 2: Schematic representation computational mesh system

are used in the inner domain to encompass the entire wing and the inner domain moves according to the wing kinematics. Triangular cells are used in the middle domain where remeshing takes place at each time step to adapt the moving of inner domain. Quadrilateral cells are used in the outer domain and they keep still during the computation.

To validate the computation code, four different mesh systems are examined for a rigid wing. The results indicate that a mesh system with 15600 quadrilateral cells around the wing surface is sufficient to capture the characteristics of the flow field and a value of 0.001c for the height of the first grid above the wing surface is small enough for the purpose.

RESULTS AND DISCUSSION

In order to study the effect of flexibility on the aerodynamic performance of a flapping wing in forward flight, ten different cases are tested for which the frequency ratio ω^* is set at 0.00, 0.25, 0.33, 0.40, 0.50, 0.67, 0.80, 1.00, 1.33 and 2.00 but the flapping amplitude h_0, the Reynolds number Re, the reduce frequency k and the mass ratio m^* are kept unchanged for all cases and are set at the values of 0.4c, 1000, 0.86 and 120, respectively. Especially the case with the frequency ratio $\omega^* = 0$ which indicates a rigid wing is also tested.

Normally a steady state can be reached after ten initial flapping cycles as the results of the time variation of deformation angle shown in Fig. 3 for the cases of ω^* = 0.40, 0.80, 1.33, 2.00. All the analysis is based on the data obtained when the steady state is established.

The mean thrust, lift, energy coefficient and energy efficiency are shown in Fig. 4. It can be seen from

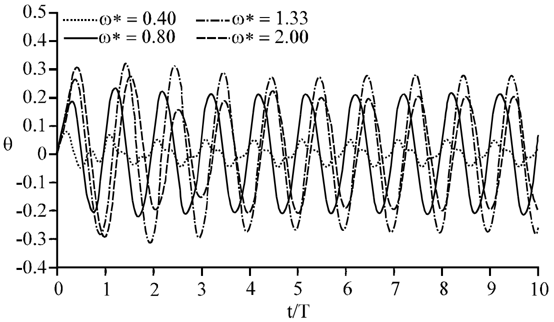


Fig. 3: Variation of deformation angle with time for ω^* = 0.40, 0.80, 1.33, 2.00

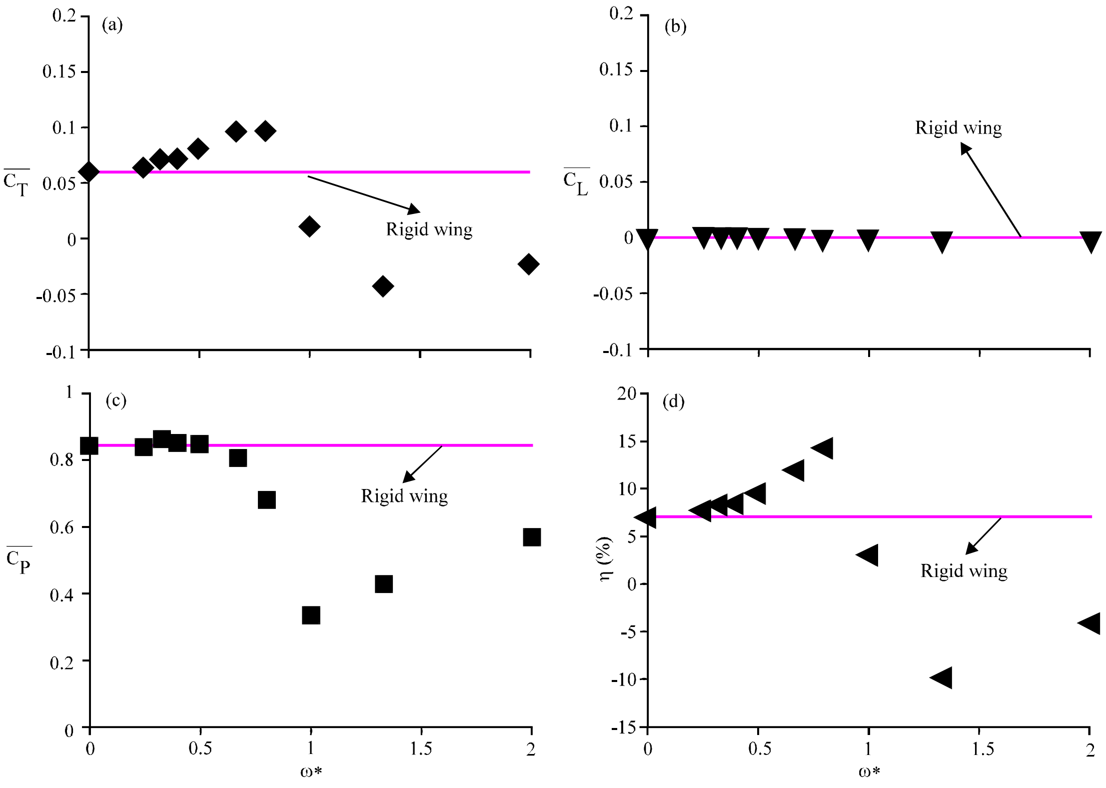


Fig. 4(a-d): Variation of four different coefficients with frequency ratio, (a) Mean energy thrust coefficient, (b) Mean lift coefficient, (c) Mean energy coefficient and (d) Energy efficient

Fig. 4a-d that the mean thrust force coefficient and the propulsive efficiency are affected by the frequency ratio largely comparing to the rigid wing. Both the mean thrust force coefficient and the energy efficiency increase with the frequency ratio when the ratio is smaller than 1.00 and reach a maximum just before $\omega^* = 1.00$. However, they drop sharply when ω^* crosses over 1.00 and reach a minimum value at $\omega^* = 1.33$ for the cases studied. In the frequency ratio larger than 1.00, a negative thrust i.e., drag force is generated which indicates that the flexibility of the wing deteriorates the aerodynamic characteristics of the wing at this frequency ratio range. Also, it is seen from Fig. 4b that the mean lift force coefficient almost remains unchanged which indicates that the flexibility has little effect on the mean lift force for the cases studied. Similar to the mean lift force coefficient, the mean energy coefficient (Fig. 4c) is almost kept as a constant which closes to the value for the rigid wing when the frequency ratio is less than 0.67 and it drops sharply when the flexibility level increases and reaches a minimum value at $\omega^* = 1.00$ for the cases studied. Generally, the mean energy coefficient for a flexible wing ($\omega^*>0.67$) is smaller than that for a rigid wing.

In order to analyze the mechanism of how the flexibility influence on the aerodynamic characteristics of flapping wing in detail, the results of lift force coefficient and thrust force coefficient for $\omega^* = 0.80$ and a higher flexibility $\omega^* = 1.33$ which show the two extreme aerodynamic characteristics cases i.e., the best and the worst for the cases studied (Fig. 4d) are presented in Fig. 5 and the results for a rigid wing are also presented in the Fig. 4 for comparison. It is seen from the figure that the positive lift force mainly generates in the down flapping duration and the thrust force generates in both down and up flapping durations. Obviously the lift force for flexible wing has smaller peak amplitude than the rigid wing, but the mean value is almost unchanged (Fig. 4b). The time variation curve of the lift force coefficient is smoother than that for the rigid wing which is beneficial for flight stability. Also, it can be seen from the Fig. 5b that the flexible wing with $\omega^* = 0.80$ has larger thrust force coefficient than the rigid wing almost during the whole flapping cycle, on the contrary the flexible wing with $\omega^* = 1.33$ has smaller thrust force coefficient than the rigid wing, which indicates that if the flexibility of wing is at an appropriate level, it can increase the thrust force generating.

Furthermore an inverse Karman vortex street is observed (Fig. 6a, b) in the wake of the flexible wing with

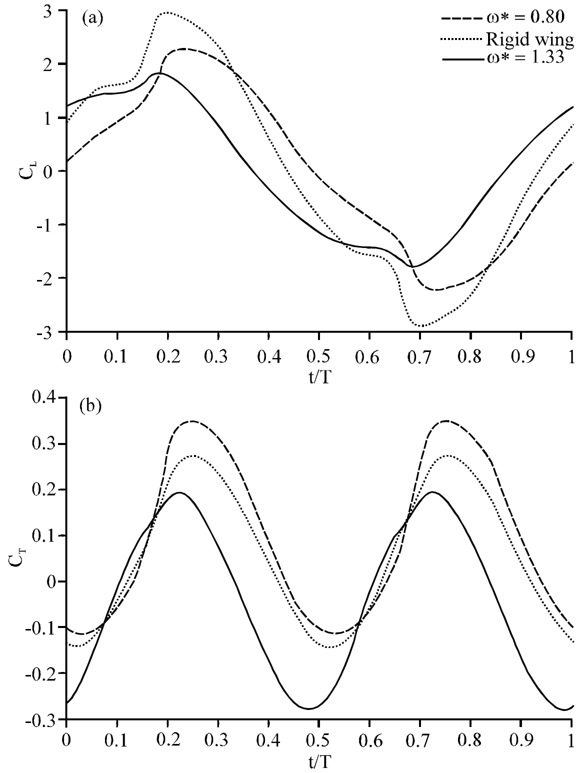
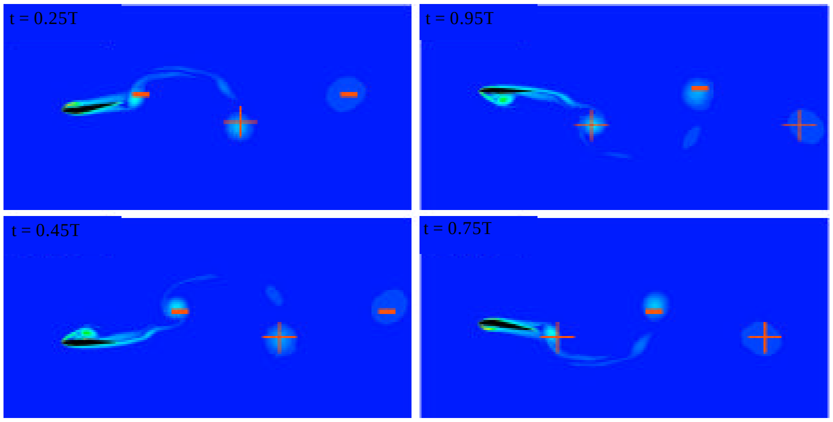
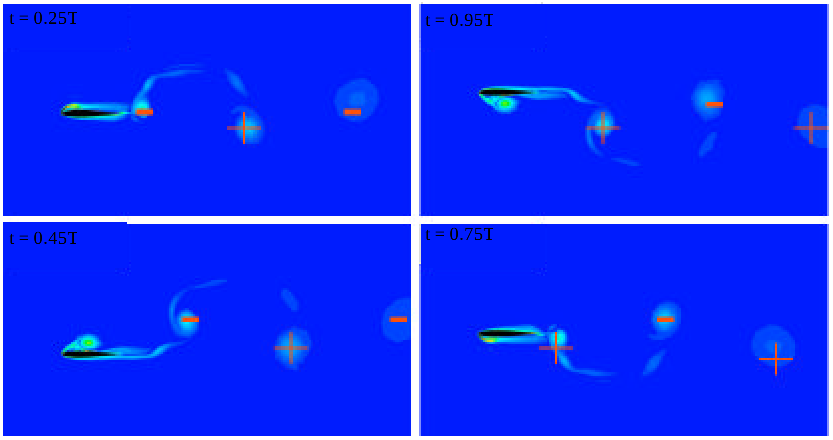


Fig. 5(a-b): Variations of lift force coefficient in one flapping cycle, (a) Lift force and (b) Thrust force

(a) Flexible wing with T* = 0.80



(b) Rigid wing



(c) Flexible wing with T* = 1.33

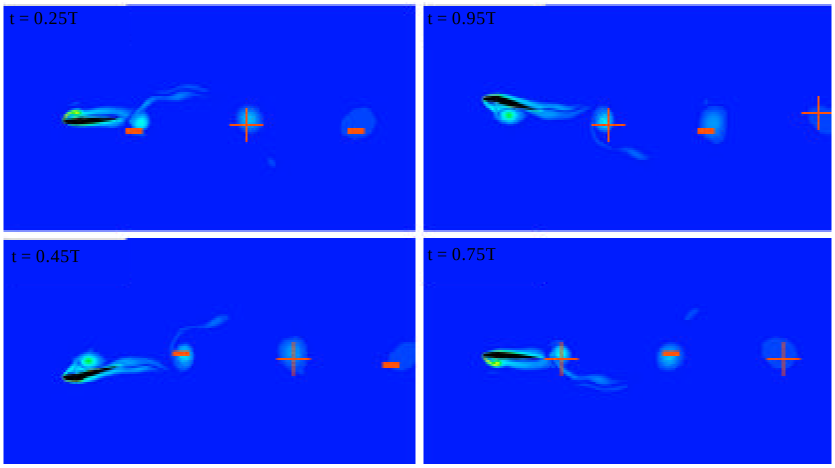


Fig. 6(a-c): Vortex patterns around the rigid and flexible wings, +: Represents positive vortices (clockwise), -: Represents negative vortices (anticlockwise)

ω^* = 0.80 as well as the rigid wing, which indicates that a thrust force is generated in the flapping cycle. However, a normal Karman vortex street is observed in the wake of the flexible wing with ω^* = 1.33 (Fig. 6c) where a drag force is produced in the flapping cycle, which shows too much flexibility can deteriorate the aerodynamic characteristics of the wing. The pressure contour around rigid and flexible wing with ω^* = 0.80 at t = 0.25T which show the peak values of thrust force (Fig. 5b) are presented in Fig. 7 to look into why the flexible wing with

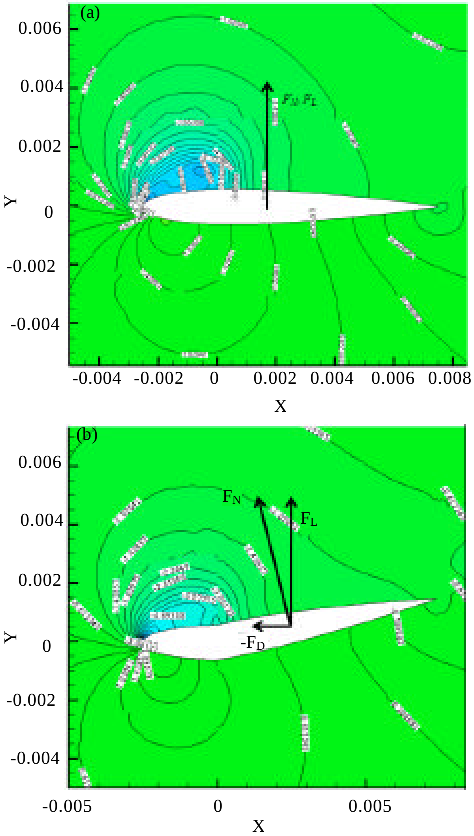


Fig. 7(a-b): The pressure contour around, (a) Rigid and (b) Flexible wing

$\omega^* = 0.80$ poses better aerodynamic characteristics than the rigid wing, where F_N is the normal force of tail wing. It is obvious that the up surface has negative pressure and the down surface has positive pressure for both considered wing, therefore, the wing will generate lift force at this moment, however, an angle incline is observed in the tail part of flexible wing normal force, which lead a horizontal component force and result the flexible wing with $\omega^* = 0.80$ generate more thrust force than rigid wing.

CONCLUSION

The effect of flapping wing's flexibility on its aerodynamic characteristics is studied by solving the incompressible N-S equations coupled with a structural dynamic equation for the motion of the wing. A computation model of a NACA0012 airfoil with a flexible trailing part in forward flight is investigated for the purpose. The results show that the flexibility can largely influence the aerodynamic characteristics of a flapping wing and if the wing has an appropriate flexibility the flexibility can decrease the fluctuation of lift force, increase the thrust force and energy efficiency and keep the mean lift force almost unchanged. Therefore, appropriate flexibility can improve the aerodynamic characteristics of a flapping wing. The present results provide useful information for the design of FMAV.

ACKNOWLEDGMENT

This study was supported by Natural Scientific Research Innovation Foundation in Harbin Institute of Technology (Project number HIT.NSRIF.2010122).

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