

A comparative study of dragonfly inspired flapping wings actuated by single crystal piezoceramic

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Abstract. A dragonfly inspired flapping wing is investigated in this paper. The flapping wing is actuated from the root by a PZT-5H and PZN-7%PT single crystal unimorph in the piezofan configuration. The non-linear governing equations of motion of the smart flapping wing are obtained using the Hamilton's principle. These equations are then discretized using the Galerkin method and solved using the method of multiple scales. Dynamic characteristics of smart flapping wings having the same size as the actual wings of three different dragonfly species *Aeshna Multicolor*, *Anax Parthenope Julius* and *Sympetrum Frequens* are analyzed using numerical simulations. An unsteady aerodynamic model is used to obtain the aerodynamic forces. Finally, a comparative study of performances of three piezoelectrically actuated flapping wings is performed. The numerical results in this paper show that use of PZN-7%PT single crystal piezoceramic can lead to considerable amount of wing weight reduction and increase of lift and thrust force compared to PZT-5H material. It is also shown that dragonfly inspired smart flapping wings actuated by single crystal piezoceramic are a viable contender for insect scale flapping wing micro air vehicles.

Keywords: piezofan; single-crystal; non-linear vibrations; smart materials; aerodynamics; dragonfly; flapping; micro air vehicles

1. Introduction

Research interest in flapping flight has accelerated due to the need to develop a class of very small flight vehicles called micro air vehicles (MAVs). MAVs have a large number of potential applications ranging from civil search-and-rescue missions to military surveillance missions. In order to perform these tasks, MAVs should be able to fly slowly, maneuver with a high degree of precision and navigate through complex environments. Nature provides flapping flyers such as birds and insects which routinely exhibit such performance (Ganguli *et al.* 2010). These natural flapping flyers represent biomimetic design for intelligent MAVs with much superior performance relative to conventional wings and rotors (Ansari *et al.* 2006). Hence, birds and insects are available as a natural source of inspiration for the development of MAVs. Flapping wings design for MAV represents one of the major challenges to efficient flight in the low Reynolds-number regime as the wings are not only responsible for lift, but also for propulsion and maneuvers (Rosenfeld and Wereley 2009).

To mimic the wing movement of the natural flapping flyers, several biomimetic flapping wing mechanisms were developed. Researchers have developed flapping wing mechanisms to capture

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bird's wingbeat kinematics. Two electrodynamic linear shaker actuators were used, by Raney and Slominski (2004), to approximately match the wingbeat patterns of hummingbirds. Their avian flapping system consisted of a 3-degree of freedom ball-and-socket connection between a fixed rigid test stand and a rigid beam element. McIntosh *et al.* (2006) developed a flapping mechanism for biaxial rotation of an ornithopter wing using a single actuator and spring-loaded cam-follower system. The mechanism, driven by a small DC motor, was designed to capture the wing motion of the hummingbird and hovering insects. Feathering motion was generated by a cam-follower system and flapping motion of the wing was generated by a simple four-bar mechanism. Issac and Agrawal (2007) investigated the effect of using springs and wing motions to minimize the power required by a pigeon-like mechanical bird to fly. The wing was connected to the body using two revolute joints in series. The proximal revolute joint was used for flapping and the distal joint was used to generate feathering motion. Yang *et al.* (2009) developed flapping wing micro air vehicles named 'Eagle II' and 'Golden Snitch'. Flapping motion of the wing was generated using the four-bar linkage transmission mechanism. Aluminum-alloy 7075 was chosen as the main structural material and electrical-discharge wire cutting (EDWC) technique was chosen to construct the gear transmission module which was driven by a commercial polylithium battery powered motor.

Several flapping wing mechanisms were developed to mimic the insect's wingbeat kinematics. To mimic the complex movements of the wings of a hovering hawkmoth, VandenBerg and Ellington (1997) made a scaled up robotic insect (the 'flapper'). In another study, Dickinson, Lehmann and Sane (1999) built a dynamically scaled model of the fruit fly, *Drosophila melanogaster*. Yamamoto and Isogai (2005) developed a mechanical flapping wing apparatus that dynamically simulates the tandem wing configuration of a dragonfly in hovering flight. The flapping and feathering motion were induced by electric sliders and stepping motors, respectively. In order to study the aeroelastic effects associated with the lightweight and highly flexible wing, Singh and Chopra (2008) developed an insect based flapping mechanism. They found that the thrust generating capability of MAV scale flapping wings is highly depended on wing flexibility. Recently, Nguyen *et al.* (2010) designed and fabricated a prototype of a flapping-wing device that can mimic some characteristics of the beetle *Allomyrina dichotoma*. In the design, they used a combination of a Scotch yoke and a linkage mechanism to transform the rotary motion of the motor into a large output flapping angle. Passive wing rotation was incorporated into the flapping-wing system by means of a flexible member. It can be noticed from the above studies that these dynamically scaled flapping wing mechanisms are bulky and flap at very low frequency. Moreover, current flapping wing mechanisms rely on pneumatic and motor-driven flapping actuators which lead to high weight and system-complexity (Syaifuddin *et al.* 2006). Additionally, it may not be easy to mimic the complex wingbeat kinematics of the natural flyers with these conventional actuators. Use of actuators made of smart materials to design flapping wing mechanism may be a plausible alternative.

Smart materials, such as piezoelectric materials, shape memory alloys, magneto rheological fluid etc., are being considered for various engineering applications. Piezoelectric materials have been widely used as sensory and active materials in many applications in the area of adaptive structures because they have several attractive features such as high bandwidth, high output force, compact size and high power density (Chopra 2002, Zehetner and Irschik 2008). Several researchers have used piezoelectric actuators to develop biomimetic flapping wing mechanisms (Cox *et al.* 2002, Sitti 2003). Syaifuddin *et al.* (2006) have introduced a flapping wing mechanism actuated by a unimorph piezoceramic actuator, LIPCA (lightweight piezo-composite actuator). In the flapping system, the limited actuation displacement produced by bending motion of the simply supported actuator was

transformed into a large flapping angle by using a four-bar linkage system. A passive wing rotation mechanism was also implemented in the flapping system. In a further study, Nguyen *et al.* (2008) introduced an insect-mimicking flapping-wing system actuated by unimorph piezoceramic actuator LIPCA, where the rotation, corrugation, and clapping of insect wings were mimicked. Kim *et al.* (2008) developed a smart flapping wing with a macro-fiber composite (MFC) as a surface actuator to generate the camber motion of a local wing section. The flapping motion was generated using an electric DC motor and a transmission system with a reduction gear system that converts the rotary motion of the motor into the flapping motion. The twisting motion was induced passively by the flexibility of the wing during up and down strokes. In another study, Kim *et al.* (2009) developed a biomimetic flexible flapping wing of a real ornithopter scale by using macro-fiber composite (MFC) actuators. They performed aerodynamic tests in a low-speed wind tunnel to investigate the aerodynamic characteristics, particularly the camber effect, the chordwise flexibility effect and the unsteady effect.

Most research on flapping wing mechanisms were developed using conventional PZT ceramics. Single crystals piezoceramic are the potential new generation materials being proposed in many engineering applications as sensors and actuators (Sitti 2003, Thakkar and Ganguli 2006a,). Recently, lead-zinc-niobate-lead-titanate, $\text{Pb}(\text{Zn}_{1/3}\text{Nb}_{2/3})\text{O}_3\text{-PbTiO}_3$ (PZN-PT) have attracted considerable attention due to superior electromechanical properties (Thakkar and Ganguli 2006b, Pawar and Jung 2008). Specifically, piezoelectric properties of PZN-PT type single crystals with (0 0 1) orientation have been found to possess large direct piezoelectric coefficients (d_{33} , d_{31}) than soft piezoceramic like PZT-5H. Material properties of PZN-PT single crystals varies with the amount (%) of PT present in the piezoceramic. PZN-7%PT has the PT composition slightly away from the morphotropic phase boundary composition and remains in the rhombohedral phase at room temperature. So, its electromechanical capacity is higher and materials properties fluctuation is much smaller compared to other varieties of PZN-PT single crystal systems. Therefore, PZN-7%PT single crystal is one of the most suitable piezoceramics for engineering applications (Zhang *et al.* 2002).

Unfortunately, the piezoelectric effect is intrinsically small and leads to a small deflection when expected directly from the bending piezoelectric unimorph/bimorph (Syaifuddin *et al.* 2006, Chung *et al.* 2009). Therefore, some kind of motion amplification mechanisms is necessary in order to obtain large deflection. Piezoelectric fan (piezofan) is one of the simple motion amplification mechanisms. The concept of the piezofan was first proposed by Toda and Osaka (1979). Piezofan has potential usages in cooling applications in modern portable electronics such as laptops, cellular phones, automobile multimedia boxes etc. (Yao and Uchino 2001, Wait *et al.* 2007). Piezofan was also used in flapping wing applications by several researchers. Chung *et al.* (2008) used two coupled piezofans in their experiments and showed that the bending amplitude of the wing reduced with the increasing phase delay and the twisting movement increased with an increasing phase delay. In another study, selection of the best piezofans for flapping wing MAV applications based on design optimization was proposed by Chung *et al.* (2009). They used using the Strouhal number and a limited numbers of material parameters for the optimization. These studies used a linear analytical model to analyze the performance of piezofan structure at dynamic operation. It is clear from the flight of the natural flyers that they move their wings through a large angle. Therefore, linear model is inadequate to capture and analyze the large wing movement which can be obtained using piezofan through large deflection. Therefore, non-linear dynamic model is needed to perform dynamic analysis (Mukherjee and Ganguli 2010). Mahmoodi and Jalili (2007) derived the non-linear equations of motion of a non-homogenous piezoelectrically actuated microcantilever beam. The non-linear terms appeared in the form of quadratic expression due to presence of piezoelectric

layer, and cubic form due to geometrical non-linearities. In addition to these structural aspects, aerodynamic model is needed to consider the piezofan for flapping wing applications.

Aerodynamic analysis of flapping wing is mainly performed with quasi-steady models and unsteady models (Betteridge and Archer 1974, Rayner 1979, Philips *et al.* 1981, Norberg 1985). Numerical simulation of flapping flight using computational fluid dynamics (CFD) was performed by several researchers (Roget *et al.* 2009, Chandar and Damodaran 2010). However, CFD simulations are computationally intensive and often not suitable for preliminary design studies. DeLaurier (1993) proposed an unsteady aerodynamic model which can be used to estimate the aerodynamic performances of harmonically flapping wings in the phase of preliminary design and development (Ke *et al.* 2008). This model is based on modified strip theory and is useful for estimating the lift generated by a flapping wing.

In this paper, an energy method is used in order to derive the non-linear equations of motion of a smart flapping wing. The flapping wing is actuated from the root by a PZT-5H and PZN-7%PT single crystal unimorph in the piezofan configuration. Insects, such as the dragonfly, are very efficient flyers and its flight satisfies the entire flight envelope required for an MAV. Dragonflies are one of only a few species of insects that are capable of gliding flight and they are among the largest of the flying insects. Flight mechanics of different dragonfly species have been studied extensively by many researchers (Bao *et al.* 2006, Kim *et al.* 2009, Zhang and Lu 2009). The different dragonfly species provide different biomimetic designs for a flapping wing which can lead to the discovery of better configurations for engineering use. Therefore, dragonfly characteristics can provide design guidelines for the development of flapping wing MAVs. Dynamic characteristics of piezoelectrically actuated flapping wings, having the same size as to the actual wings of three different dragonfly species, are analyzed using numerical simulations. An unsteady aerodynamic model is used to obtain the aerodynamic forces. Finally, a comparative study of performances of three piezoelectrically actuated flapping wings is performed.

2. Structural model

In this study, a piezoelectric unimorph is attached to the uniform flexible wing in piezofan configuration. The schematic diagram of the flapping wing actuated by supplying a voltage, $P_e(t)$ is shown in Fig. 1.

To describe the dynamics of the wing, two coordinate systems are utilized: the (x, y, z) system is considered to be inertial and the $(\xi, \tilde{\theta}, \zeta)$ system is the local principal system (Mahmoodi and Jalili

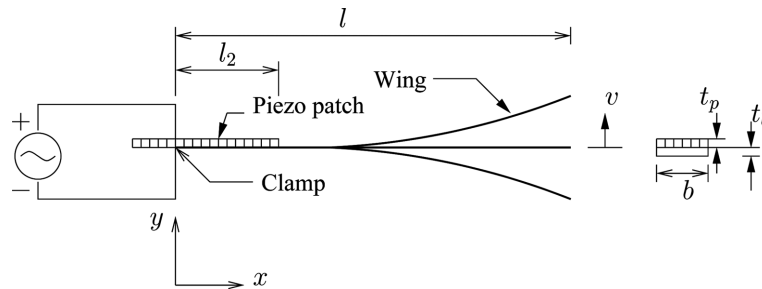


Fig. 1 Schematic of the piezoelectrically actuated flapping wing

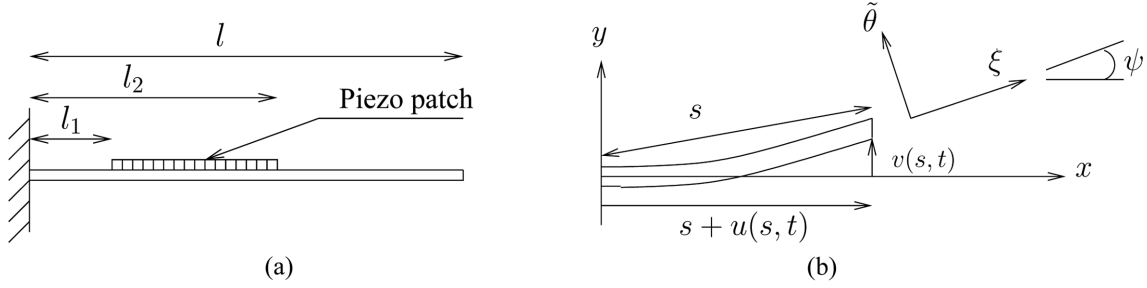


Fig. 2 (a) Schematic diagram of flapping wing geometry used for modeling and (b) principal and inertial coordinate systems

2007). Schematic diagram of the wing geometry used for the structural modeling is shown in Fig. 2(a). Fig. 2(b) shows a wing segment of length s .

The Euler rotation, $\psi(s, t)$, represents the relationship between the principal and the inertial coordinates. Using Fig. 2(b), angle $\psi(s, t)$ for an element of length ds can be written as

$$\psi = \tan^{-1} \frac{v'}{1+u'} \quad (1)$$

where the over prime denotes derivative with respect to the arc length. The longitudinal and transverse displacements are described by $u(s, t)$ and $v(s, t)$, respectively. Utilizing Green's strain theory, strain of the neutral axis (ε_0) is given by (Hsieh *et al.* 1994)

$$\varepsilon_0 = \sqrt{(1+u')^2 + v'^2} - 1 \quad (2)$$

Inextensibility condition can be used to relate longitudinal and bending vibration as it demands no relative elongation of the neutral axis. Using the Taylor series expansion, Eq. (2) reduces to

$$u' = -\frac{1}{2}v'^2 \quad (3)$$

The neutral surface, y_n , changes for each section and can be obtained as

$$y_n = \begin{cases} 0, & s < l_1 \text{ or } s > l_2 \\ \frac{E_p t_p (t_p + t_b)}{2(E_p t_p + E_b t_b)}, & l_1 < s < l_2 \end{cases} \quad (4)$$

The total kinetic energy ($\mathcal{T}$) of the system can be expressed as (Mahmoodi and Jalili 2007)

$$\mathcal{T} = \frac{1}{2} \int_0^l [m(s)(\dot{u}^2 + \dot{v}^2) + J(s)(\dot{v}'^2 - 2\dot{v}'^2 u' - 2v' \dot{u}' \dot{v}' - 2\dot{v}'^2 v'^2)] ds$$

where

$$m(s) = b(\rho_b t_b + (H_{l_1} - H_{l_2}) \rho_p t_p) \quad (6)$$

Here, $H(s)$ is the Heaviside function and $J(s)$ is the mass moment of inertia of the wing.

Similarly, the total potential energy ($\mathcal{V}$) of the system can be written as (Mahmoodi and Jalili 2007)

$$\begin{aligned} \mathcal{V} = & \frac{1}{2} \int_0^{l_1} \iint_A \sigma_{11}^b \varepsilon_{11}^b dA ds + \frac{1}{2} \int_{l_1}^{l_2} \iint_A \sigma_{11}^b \varepsilon_{11}^b dA ds + \frac{1}{2} \int_{l_1}^{l_2} \iint_A (\sigma_{11}^p \varepsilon_{11}^p + Q_2 D_2) dA ds \\ & + \frac{1}{2} \int_{l_2}^l \iint_A \sigma_{11}^b \varepsilon_{11}^b dA ds + \frac{1}{2} \int_0^l EA(s) \left(u'^2 + u' v'^2 + \frac{1}{4} v'^4 \right) ds \end{aligned} \quad (7)$$

The following fundamental assumptions are made for the analysis:

- (a) The wing is inextensible,
- (b) Bonding layer is assumed to be perfect,
- (c) Both, the piezoelectric layer and the wing have same width,
- (d) The wing is initially straight and it is clamped at one end and free at other end, and
- (e) The Euler-Bernoulli beam theories are followed, where shear deformation and rotary inertia terms are negligible.

Considering all the assumptions and applying the extended Hamilton's principle, governing equations of motion can be obtained as

$$\begin{aligned} m(s) \ddot{v} + \frac{\partial^2}{\partial s^2} (C_\zeta(s) v'') + \frac{\partial}{\partial s} \left[v' \int_l^s m(s) \int_0^s (\ddot{v} v' + \dot{v}'^2) ds ds \right] + \left[v' \frac{\partial^2}{\partial s^2} (C_\zeta(s) v'' v') + v'' \frac{\partial}{\partial s} (C_\zeta(s) v'' v') \right] \\ + v' \frac{\partial}{\partial s} \left(\frac{C_d^2(s)}{C_\beta(s)} v'' v' - \frac{b C_c(s)}{C_\beta(s)} P_e(t) v' \right) - \frac{\partial^2}{\partial s^2} \left[\frac{b C_d(s)}{C_\beta(s)} P_e(t) \left(1 - \frac{1}{2} v'^2 \right) + \frac{C_d^2(s)}{C_\beta(s)} v'' \right] = 0 \end{aligned} \quad (8)$$

with the boundary conditions

$$v(0, t) = v'(0, t) = v''(l, t) = v'''(l, t) = 0 \quad (9)$$

where

$$\begin{aligned} C_\zeta(s) = & (H_0 - H_{l_1}) E_b I_b + (H_{l_1} - H_{l_2}) E_b (I_b + b t_b y_n^2) \\ & + (H_{l_1} - H_{l_2}) E_p I_p + (H_{l_2} - H_l) E_b I_b \end{aligned} \quad (10)$$

$$C_d(s) = (H_{l_1} - H_{l_2}) h_{12} I_d \quad (11)$$

$$C_\beta(s) = (H_{l_1} - H_{l_2}) b t_b \beta_{22} \quad (12)$$

$$I_p = b \left(t_p y_n^2 + (t_p^2 + t_b t_p) y_n + \frac{1}{3} \left(t_p^3 + \frac{2}{3} t_b t_p + \frac{3}{4} t_b^2 t_p \right) \right)$$

$$I_d = \frac{b}{2} (t_b t_p + t_p^2 - 2 t_p y_n)$$

$$I_b = \frac{b t_b^3}{12} \quad (13)$$

Coupling of electrical and mechanical fields introduces quadratic and cubic nonlinearities due to piezoelectric effect. Cubic non-linear terms of inertia and stiffness, resulting from the geometry of the vibrating wing, appear in the equations of motion. The Galerkin method is utilized to discretize the system as

$$v(s, t) = \sum_{n=1}^{\infty} v_n(s, t) = \sum_{n=1}^{\infty} \phi_n(s) q_n(t) \quad (14)$$

where ϕ_n are companion functions and q_n are generalized time-dependent coordinates. In order to solve the equations of motion utilizing the method of multiple scales (Nayfeh and Mook 1979), Eq. (8) is rewritten in the form

$$\ddot{q}_n + \varepsilon \mu \dot{q}_n + \omega_n^2 q_n + \varepsilon^2 k_{1n} f(t) q_n^2 + \varepsilon k_{2n} q_n^3 + \varepsilon k_{3n} (q_n^2 \ddot{q}_n + q_n \dot{q}_n^2) + \varepsilon k_{4n} f(t) = 0 \quad (15)$$

where

$$\omega_n^2 = \frac{g_{2n}}{g_{1n}}, k_{1n} = \varepsilon^{-1} \frac{g_{3n}}{g_{1n}}, k_{2n} = \varepsilon^{-1} \frac{g_{4n}}{g_{1n}}, k_{3n} = \varepsilon^{-1} \frac{g_{5n}}{g_{1n}}, k_{4n} = \varepsilon^{-1} \frac{g_{6n}}{g_{1n}}, f_n(t) = \varepsilon^{-1} P_e(t) \quad (16)$$

$$g_{1n} = \int_0^l m(s) [\phi_n(s)]^2 ds \quad (17)$$

$$g_{2n} = \int_0^l C_\zeta(s) \phi_n''(s) ds - \frac{h_{12} I_d (\phi_n'(l_2) - \phi_n'(l_1))}{b t_p \beta_{22} (l_2 - l_1)} \int_0^l C_d(s) \phi_n''(s) ds \quad (18)$$

$$g_{3n} = \frac{1}{t_p \beta_{22}} \int_0^l C_d(s) \phi_n''(s) [\phi_n'(s)]^2 ds \quad (19)$$

$$g_{4n} = 2 \int_0^l C_\zeta(s) [\phi_n''(s)]^2 ds - \frac{h_{12} I_d ([\phi_n'(l_2)]^3 - [\phi_n'(l_1)]^3)}{b t_p \beta_{22} (l_2 - l_1)} \int_0^l C_d(s) \phi_n''(s) ds \\ - \frac{h_{12} I_d (\phi_n'(l_2) - \phi_n'(l_1))}{b t_p \beta_{22} (l_2 - l_1)} \int_0^l C_d(s) \phi_n''(s) [\phi_n'(s)]^2 ds \quad (20)$$

$$g_{5n} = 2 \int_0^l \phi_n(s) [m(s) \phi_n'(s) \int_l^s 2 [\phi_n'(s)]^2 ds ds]' ds \quad (21)$$

$$g_{6n} = \frac{1}{t_p \beta_{22}} \int_0^l C_d(s) \phi_n''(s) ds \quad (22)$$

The linear mode shapes of a cantilever beam are considered here to be the following companion functions

$$\phi_n(x) = \cosh(z_n x) - \cos(z_n x) + [\sin(z_n x) - \sinh(z_n x)] \frac{\cosh(z_n) + \cos(z_n)}{\sinh(z_n) + \sin(z_n)} \quad (23)$$

where z_n are the roots of the frequency equation

$$1 + \cos(z_n) \cosh(z_n) = 0 \quad (24)$$

Now, $q_n(t)$ can be expressed by order of ε as (Nayfeh 1973)

$$q_n(t; \varepsilon) = q_{0n}(T_0, T_1) + \varepsilon q_{1n}(T_0, T_1) + \dots \quad (25)$$

where, T_0 and T_1 are the time scales. $T_1 = \varepsilon t$ is defined shift in the natural frequencies because of the non-

linearity, while $T_o=t$ demonstrates motion occurring at the natural frequencies, ω_n . Frequency response of the system can be expressed as

$$\left(\frac{1}{2}\mu\omega_n a_n\right)^2 + \left(\frac{3}{8}k_{2n}a_n^3 - \omega_n^2 \sigma a_n\right)^2 = k_{4n}^2 f^2 \quad (26)$$

where σ is a detuning parameter and a_n is the amplitude of the generalized coordinate $q_n(t)$. Finally, the deflection at the tip of the wing is obtained by

$$v(l, t) = \phi_n(l) a_n(t) \cos(\beta_n t + \beta_0) = \phi(l) q(t) \quad (27)$$

where a_n and β_n are real functions of time scale.

3. Aerodynamic model

The aerodynamic model is based on the modified strip theory as proposed by DeLaurier (1993), in which the aerodynamic forces of the flapping wing are obtained by integrating the sectional aerodynamic forces calculated in each section. Recently, Kim *et al.* (2011) improved modified strip theory to consider dynamic stall for a high relative angle of attack and compared the present aerodynamic model's results with the experimental data of a flat plate wing with oscillating motion. Further, Lee *et al.* (2011) used this model to study the flapping frequency-dependent trim flight characteristics of a bioinspired ornithopter. In the present study DeLaurier's aerodynamic model is used for the aerodynamic analysis and DeLaurier's model is a well validated model and several researchers (Madangopal *et al.* 2005, Ke *et al.* 2008) have used it in order to estimate the aerodynamic performance of harmonically flapping wings in the phase of preliminary design and development. In this unsteady aerodynamic model, the kinematics for a section of the wing is represented by a plunging velocity $\dot{h}$ and a pitch angle of the chord θ relative to the free stream velocity, as shown in Fig. 3.

The aerodynamic forces acting on each section of the wing are divided into the normal force dN , and the chordwise force, dF_x . The local parameters determining the forces includes the section's geometry, relative angle of attack at the $3/4$ -chord location, pitch rates and the dynamic pressure at the $1/4$ -chord location. The components of the normal force are: (i) dN_c , a circulatory force normal to the chord at the $1/4$ -chord location and (ii) dN_a , an apparent-mass force normal to the chord at the $1/2$ -chord location. The expressions for the normal force components are as follows

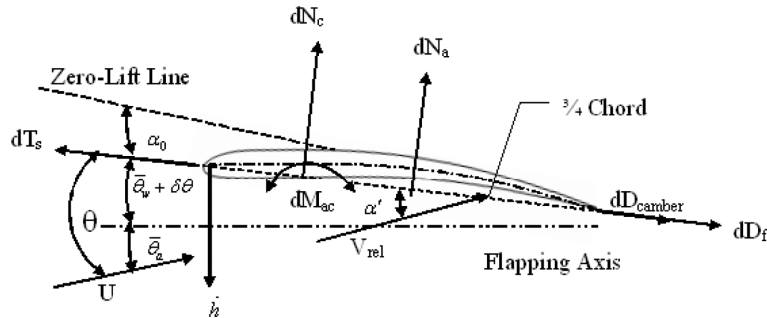


Fig. 3 Aerodynamic forces and motion variables of a wing section

$$dN_c = \frac{\rho_{air}UV}{2} C_n c dy \quad (28)$$

$$dN_a = \frac{\rho_{air}\pi c^2}{4} v_2 dy \quad (29)$$

Therefore, the section's total attached flow normal force is

$$dN = dN_c + dN_a \quad (30)$$

The components of the chordwise force are: (i) dT_s , a chordwise leading edge suction force, (ii) dD_{camber} , a chordwise drag due to camber, and (iii) dD_f , a chordwise drag due to skin friction. The expressions for the chordwise force components are as follows

$$dT_s = \eta_s 2\pi \left(\alpha' + \bar{\theta}_a - \frac{c\dot{\theta}}{4U} \right)^2 \frac{\rho_{air}UV}{2} c dy \quad (31)$$

$$dD_{camber} = -2\pi\alpha_0(\alpha' + \bar{\theta}_a + \bar{\theta}_w) \frac{\rho_{air}UV}{2} c dy \quad (32)$$

$$dD_f = (C_d)_f \frac{\rho_{air}V_x^2}{2} c dy \quad (33)$$

Thus, the total chordwise force is

$$dF_X = dT_s - dD_{camber} - dD_f \quad (34)$$

The equations for the segment's instantaneous lift dL and thrust dT are

$$dL = dN \cos \theta + dF_X \sin \theta \quad (35)$$

$$dT = dF_X \cos \theta + dN \sin \theta \quad (36)$$

These may be integrated along the span to give the whole wing's instantaneous lift and thrust:

$$L(t) = 2 \int_0^{\frac{b}{2}} \cos \gamma dL \quad (37)$$

$$T(t) = 2 \int_0^{\frac{b}{2}} dT$$

where $\gamma(t)$ is the section's dihedral angle at that instant in the flapping cycle.

The wing's average lift and thrust are obtained by integrating $L(t)$ and $T(t)$ over the cycle. Integrating with respect to cycle angle, ϕ , instead of time, t , where

$$\phi = \omega t \quad (39)$$

so that the average lift and thrust are expressed as

$$\bar{L} = \frac{1}{2\pi} \int_0^{2\pi} L(\phi) d\phi \quad (40)$$

$$\bar{T} = \frac{1}{2\pi} \int_0^{2\pi} T(\phi) d\phi \quad (41)$$

The complete details of the aerodynamic model are given by DeLaurier (1993).

4. Results and discussion

The results of the numerical simulations are shown in three sections. First, the implementation of the nonlinear analysis for the piezoelectrically actuated microcantilever beam is discussed. Next, the model is used to perform dynamic analysis of dragonfly inspired flapping wings. Finally, the aerodynamic analysis of the flapping wing is done and best design for the flapping wing is identified and evaluated.

4.1 Validation of numerical analysis

In order to validate the dynamic model, numerical analysis is carried out for a structure which is used by Mahmoodi and Jalili (2007) as shown in Fig. 4. The physical properties, used for this analysis are given in Table 1.

Fig. 5 shows the tip deflection due to the excitation voltage of 0.5 Vpp. Excitation voltage is

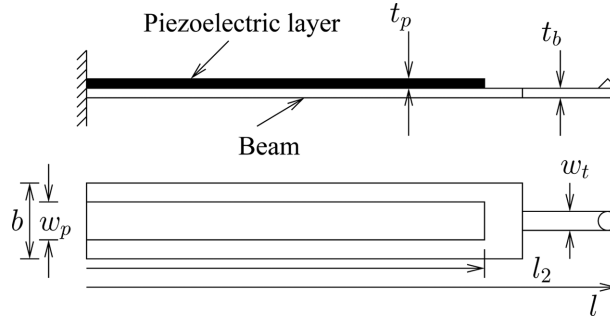


Fig. 4 Geometry of the microcantilever beam

Table 1 Material and geometric properties used for model validation

Microcantilever beam		Piezoelectric layer	
Parameter	Value	Parameter	Value
Young's modulus	105 GPa	Young's modulus	104 GPa
Beam length	500 μm	Piezoelectric length	375 μm
Width	250 μm	Width	130 μm
Tip mass width	55 μm	Coupling coefficient	500 MV/m
Poisson's ratio	0.28	Poisson's ratio	0.25
Density	2330 Kg/m^3	Density	6390 Kg/m^3
Thickness	4 μm	Thickness	4 μm

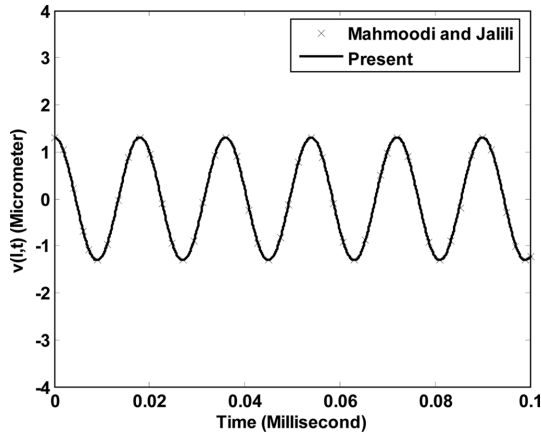


Fig. 5 Tip deflection due to 0.5 Vpp excitation

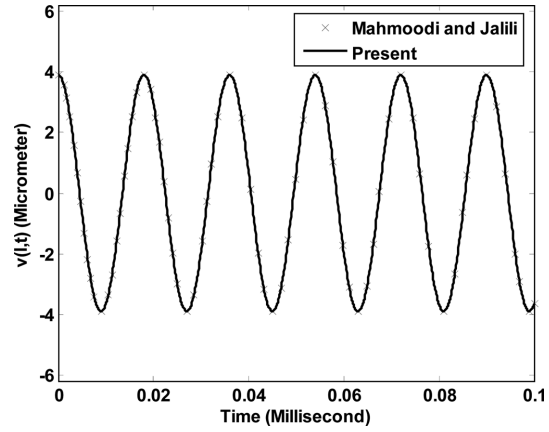


Fig. 6 Tip deflection due to 1.5 Vpp excitation

increased to 1.5 Vpp and the corresponding tip deflection is shown in Fig. 6. It can be seen from Fig. 5 and Fig. 6 that tip deflection is sensitive to the input excitation voltage. Moreover, the results of this analysis match well with the results presented in Mahmoodi and Jalili (2007). Therefore, the model implementation is validated and subsequently used for dynamic analysis of dragonfly inspired smart flapping wings.

4.2 Dynamic analysis of flapping wing

In the present study, the sizes of the flapping wings are chosen at an insect scale. Insects, such as the dragonfly, fly with unusual aerial agility. Dragonfly flight satisfies all the requirements of an MAV flight envelope therefore providing inspiration for MAV design. Dragonfly wing size shows substantial variations among the different species due to demographical reasons. Fig. 7 shows the picture of three different dragonfly species. Planforms of wings of three different dragonfly species and their typical average values are shown in Fig. 8. These three species provide wings with considerably different lengths and widths. Thus, they are different biomimetic designs for flapping wing MAVs.

Flapping wing corresponding to each dragonfly species is considered for dynamic analysis. Wings



(a) Dragonfly *Aeshna Multicolor*

(b) Dragonfly *Anax Parthenope Julius*

(c) Dragonfly *Sympetrum Frequens*

Fig. 7 Picture of three different dragonfly species used for biomimetic inspiration

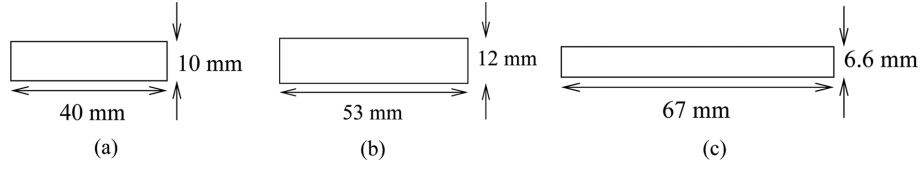


Fig. 8 Schematic diagram of the planform of smart wings having the same size as (a) *Aeshna Multicolor* wing (Combes and Daniel 2003), (b) *Anax Parthenope Julius* wing (Sunada *et al.* 1998) and (c) *Sympetrum Frequens* wing (Azuma *et al.* 1985)

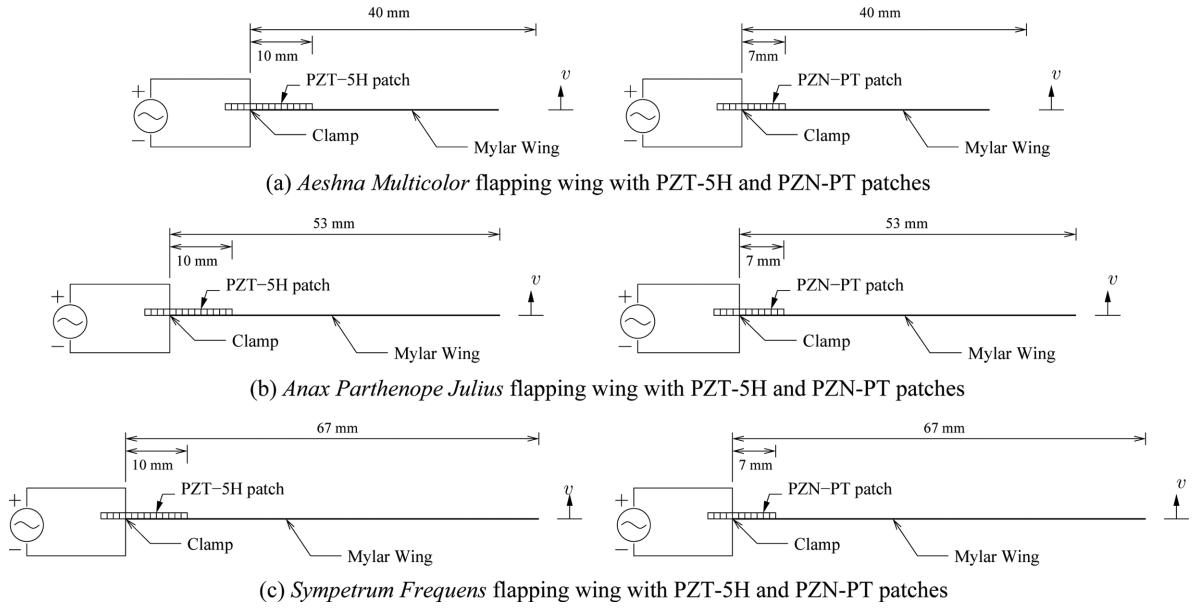


Fig. 9 Schematic diagram of smart flapping wings inspired by three dragonfly species

Table 2 Material properties of the flapping wings

	Parameter	Value
Mylar (Wait <i>et al.</i> 2007)	Young's modulus	4.6 GPa
	Density	1240 Kg/m ³
	Poisson's ratio	0.44
PZT-5H (Chung <i>et al.</i> 2009)	Young's modulus	62 GPa
	Density	7800 Kg/m ³
	Piezoelectric constant (d_{31})	-320×10^{-12} m/V
PZN-7%PT (Zhang <i>et al.</i> 2002) (Zeng <i>et al.</i> 2008)	Young's modulus	126.5 GPa
	Density	8350 Kg/m ³
	Piezoelectric constant (d_{31})	-1204×10^{-12} m/V

are made of Mylar and actuated from the root by a piezoceramic unimorph in the piezofan configuration as shown in Fig. 1. In the present study, both PZT-5H and PZN-7%PT single crystal piezoceramics are considered for flapping wing actuation and they are schematically shown in Fig. 9. Input excitation voltage is assumed to be harmonic to generate flapping motion. Material properties

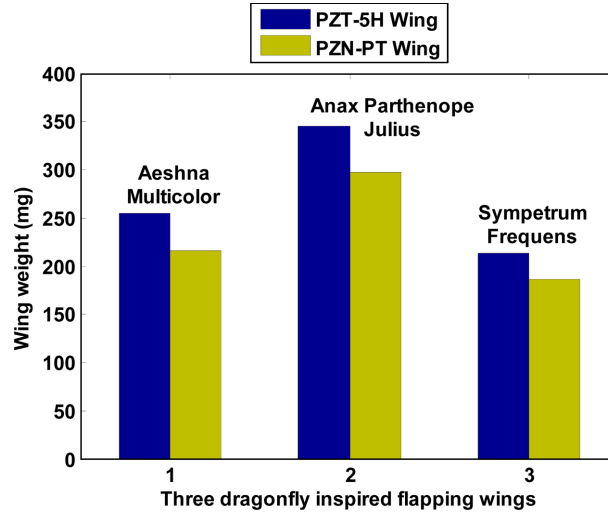


Fig. 10 Wing weight of three dragonfly inspired smart flapping wings

pertaining to each flapping wing are given in Table 2. Here, the thickness of piezo layer and Mylar wing is considered to be $200\ \mu\text{m}$. These properties are used to analyze the performances of the dragonfly inspired flapping wings.

It is clear from Table 2 that the piezoelectric constant (d_{31}) of PZN-7%PT is nearly 4 times higher than that of PZT-5H. Therefore, it is possible to reduce the amount of piezoceramic material used for PZN-7%PT wings as can be seen from Fig. 9. It is shown in Fig. 10 that the use of PZN-7%PT can lead to a wing weight reduction up to 15%, 13% and 12% as compared to that of *Aeshna Multicolor*, *Anax Parthenope Julius*, *Sympetrum Frequens* PZT-5H wings, respectively. The length of the PZN-PT patch was reduced from 10 mm to 7 mm to approximately match the amplitude of the tip deflections in dynamic analysis, as discussed next. Numerical experiments with different piezo patch lengths were used to arrive at this design.

4.2.1 Wing tip deflections

The first set of results compares the tip response of the flapping wings inspired by the three different dragonfly species when actuated by the two different smart materials. Fig. 11 shows the tip deflections of the three different smart flapping wings actuated by PZT-5H and PZN-7%PT at an excitation voltage of 60 V and excitation frequency corresponding to their respective first natural frequencies. A tip deflection of 21 mm is obtained for *Aeshna Multicolor* PZT-5H wing at 41 Hz, as can be seen from Fig 11(a). Fig. 11(a) also shows that tip deflection of *Aeshna Multicolor* PZT-7%PT is 24 mm at 38 Hz. Fig. 11(b) shows the maximum tip deflection of *Anax Parthenope Julius* PZT-5H wing is 37 mm and it occurs at 29 Hz. Fig. 11(b) also shows that tip deflection of *Anax Parthenope Julius* PZN-7%PT wing is 40 mm at 27 Hz. Similarly, Fig. 11(c) shows that the maximum tip deflection of *Sympetrum Frequens* PZT-5H wing is 59 mm and it occurs at 21 Hz. Fig. 11(c) also shows that tip deflection of *Sympetrum Frequens* PZT-7%PT wing is 68.58 mm at 19 Hz. It can be noted from the above results that a slightly higher tip deflection is obtained when the flapping wings are actuated by PZN-7%PT as compared to PZT-5H. Thus we can see that good actuation performance can be obtained even after using less piezoelectric material, when single

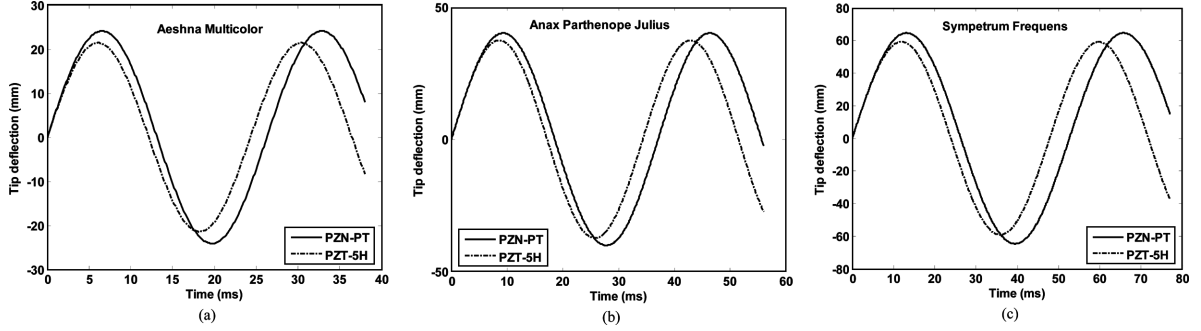


Fig. 11 Tip deflections of three dragonfly inspired smart flapping wings

crystal actuation is used.

It can be noted from the above results that the magnitude of the maximum tip deflection and frequency at which it occurs are different for each wing although their input excitation voltage is identical, i.e., 60 V. This happens because of the difference between the wing geometries and the material properties. In turn, the flapping frequency of each wing and the flapping angle produced by each wing will also be different. We will see in a later part of this section that these parameters have substantial effect on the performance of each wing in terms of aerodynamic forces.

4.2.2 Wing flapping angles

The flapping angle is a good measure of the actuation performance of the smart materials used. The flapping angle can be obtained from the tip deflection following the procedure explained schematically in Fig. 12.

Fig. 13 shows the flapping angle variations of smart flapping wings at an excitation voltage of 60 V for the flapping wings corresponding to the three different dragonfly species and two different piezoceramic materials. Fig. 13(a) shows that the *Aeshna Multicolor* wing produces flapping angles of 28° and 31° for PZT-5H and PZN-7%PT wings, respectively. Fig. 13(b) shows that *Anax Parthenope Julius* wing with PZT-5H and PZN-7%PT patch can produce flapping angles of 35° and 37° , respectively. Fig. 13(c) shows that flapping angles reach up to 41° and 44° for *Sympetrum Frequens* wing with PZT-5H and PZN-7%PT patch, respectively. The more flexible wings of *Sympetrum Frequens* with PZN-7%PT patch are most suitable for high levels of flapping. Moreover, the above results show that the flapping angles produced by these wings belong to nonlinear regime. Therefore, nonlinear dynamic model is required to predict the response of these flapping wings accurately (Mukherjee and Ganguli 2010). While the dynamic analysis shows the high actuation capacity of smart materials, the key issue for MAV application is the lift generating capacity of the

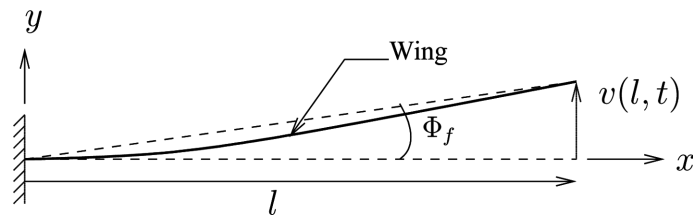


Fig. 12 Schematic diagram of calculating flapping angle

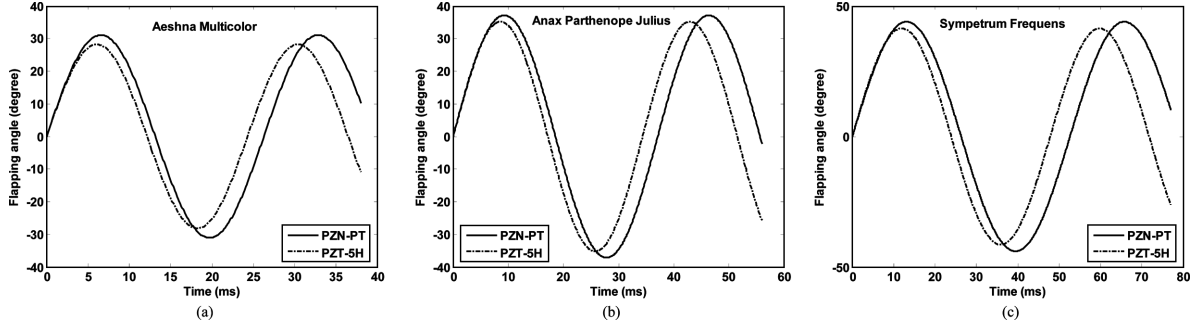


Fig. 13 Flapping angle variations of three dragonfly inspired smart flapping wings

wing. Aerodynamic forces are obtained using an unsteady aerodynamic model as described in the next section.

4.3 Aerodynamic analysis of flapping wing

For aerodynamic modeling, kinematics pertaining to the wing section located at 75% of the wing span is considered for calculation of the aerodynamic forces. The aerodynamic forces are calculated at different pitch angles and different flight speeds and the net lift force generated by the flapping wing is found.

4.3.1 Aerodynamic forces at different pitch angles

Fig. 14 shows the average lift pertaining to each wing at different pitch angle ($\bar{\theta}_a$) at a flight speed of 3 m/s which is a typical flight speed for dragonflies. Average thrust at different pitch angles is shown in Fig. 15 where the wings inspired by the three different dragonfly species and two piezoceramic materials are compared. Fig. 14(a) shows that maximum average lift for *Aeshna Multicolor* wing occurs at the pitch angle of 7.8° for both PZT-5H and PZN-7%PT wings. Fig. 14(b) shows that the maximum average lift for *Anax Parthenope Julius* wing occurs at the pitch angle of 7.7° for both PZT-5H and PZN-7%PT wings. Similarly, Fig. 14(c) shows that *Sympetrum Frequens* PZT-5H and PZN-7%PT wing occur at the pitch angle of 7.7° and 7.8° , respectively. However, it can be seen from Fig. 15 that thrust corresponding to each pitch angle, at which average lift reaches maximum, has a negative value. Since average thrust force must be positive to

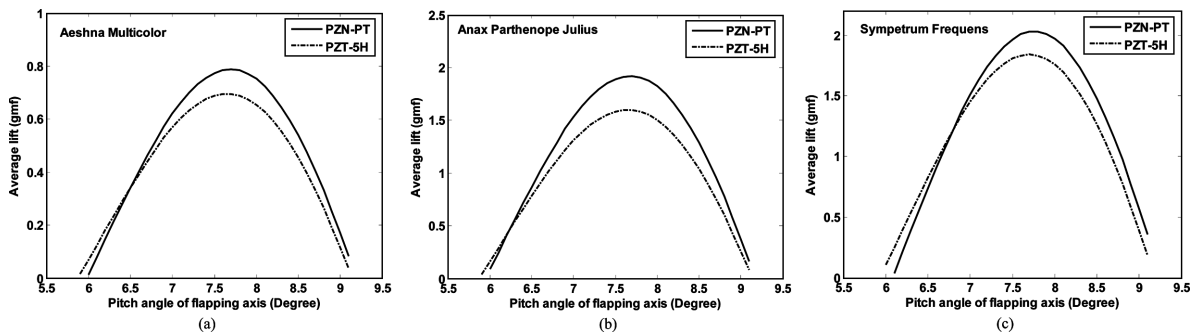


Fig. 14 Average lift of three dragonfly inspired smart flapping wings for different pitch angle

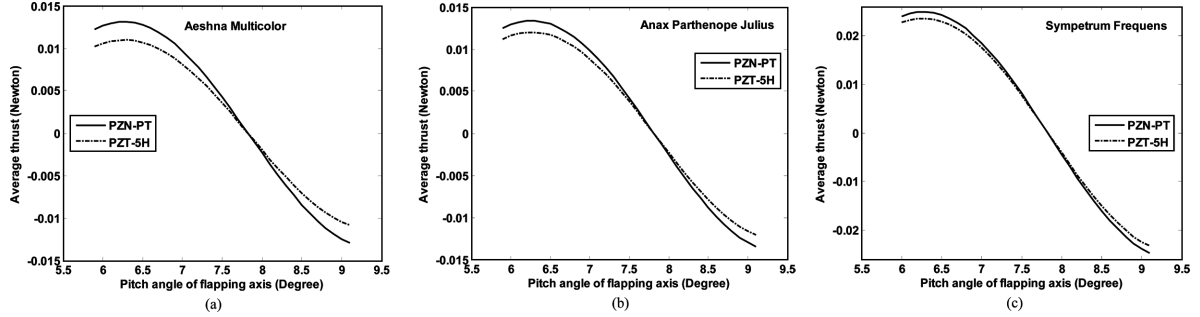


Fig. 15 Average thrust of three dragonfly inspired smart flapping wings for different pitch angle

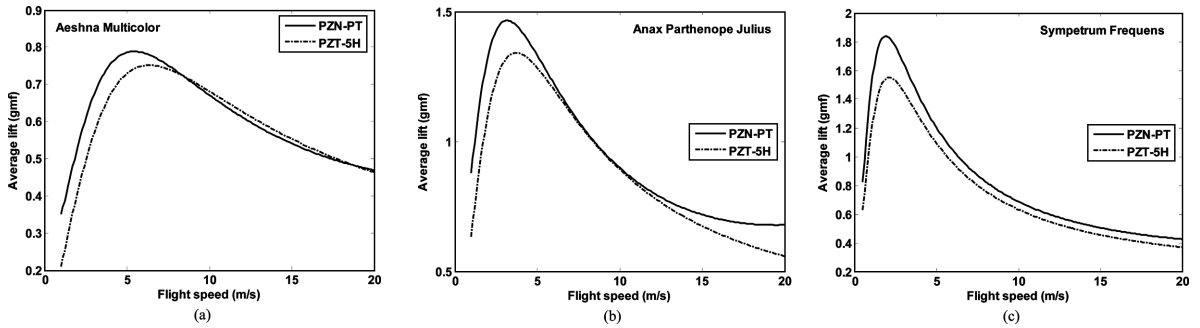


Fig. 16 Average lift of three dragonfly inspired smart flapping wings for different flight speed

satisfy the condition for cruise flight, the value of pitch angle is selected as 7° for each wing. From Figs. 14 and 15, it can be seen that the pitch angle of 7° results in a reasonable level of lift along with positive thrust. After selecting the pitch angle of the flapping axis, average lift and thrust are obtained for each smart flapping wing by varying the flight speeds.

4.3.2 Aerodynamic forces at different flight speeds

Fig. 16 shows the average lift produced by smart flapping wings at different flight speeds. In all these cases, a pitch angle of 7° is used. It can be seen from the Fig. 16(a) that the maximum lift force for *Aeshna Multicolor* PZT-5H and PZN-7%PT wing are 0.75 g and 0.79 g at the flight speed of 6.2 m/s and 5.4 m/s, respectively. It can also be noted from Fig. 16(b) that the maximum lift force for *Anax Parthenope Julius* PZT-5H and PZN-7%PT wing are 1.34 g and 1.46 g at the flight speed of 3.7 m/s and 3.2 m/s, respectively. Fig. 16(c) shows that the maximum lift force for *Sympetrum Frequens* PZT-5H and PZN-7%PT wing are 1.55 g and 1.82 g at the flight speed of 2.1 m/s and 1.9 m/s, respectively.

Average thrust force at different flight speeds are shown in Fig. 17. It can be seen from Fig. 17(a) that the average thrust force for *Aeshna Multicolor* PZT-5H and PZN-7%PT wing are found to be 0.0075 N and 0.0084 N at the flight speed of 6.2 m/s and 5.4 m/s, respectively. Fig. 17(b) shows that the thrust force for *Anax Parthenope Julius* PZT-5H and PZN-7%PT wing are 0.0066 N and 0.0069 N at the flight speed of 3.7 m/s and 3.2 m/s, respectively. Similarly, thrust force for *Sympetrum Frequens* PZT-5H and PZN-7%PT wing are found to be 0.01 N and 0.012 N at the flight speed of 2.1 m/s and 1.9 m/s, respectively.

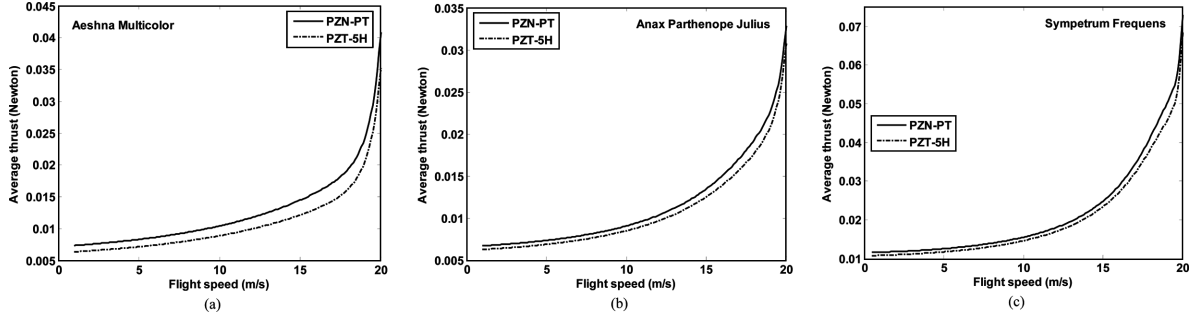


Fig. 17 Average thrust of three dragonfly inspired smart flapping wings for different flight speed

4.3.3 Net lift forces

Net lift force, obtained by subtracting the total wing weight from the total lift force, when two smart flapping wings are used for each species is shown in Fig. 18. It can be seen from Fig. 18(a) that the net lift produced by the *Aeshna Multicolor* PZT-5H wing is 0.99 g and it occurs at 6.2 m/s. Moreover, the net lift produced by the *Aeshna Multicolor* PZT-7%PT wing at the flight speed of 5.4 m/s is 1.14 g which is 15% more than that of PZT-5H wing. Fig. 18(b) shows that net lift obtained for the *Anax Parthenope Julius* PZT-5H and PZT-7%PT wing are 1.99 g and 2.33 g at a flight speed of 3.7 m/s and 3.2 m/s, respectively. Therefore, the *Anax Parthenope Julius* PZT-7%PT wing can produce 17% more net lift compared to the PZT-5H wing. Similarly, net lift for *Sympetrum Frequens* PZT-5H and PZT-7%PT wing reach up to 2.68 g and 3.27 g at the flight speed of 2.1 m/s and 1.9 m/s, respectively, as shown in Fig. 18(c). Hence, *Sympetrum Frequens* PZT-7%PT wing can produce 22% more net lift than the corresponding PZT-5H wing.

From the numerical results in the paper, it can be seen that the dynamic and aerodynamic performances of smart flapping wing based on the geometry of the dragonfly *Sympetrum Frequens* wing is best among the three boimimetic flapping wings. Use of PZN-7%PT single crystal piezoceramic can lead to considerable amount of wing weight reduction and increase of lift and thrust force compared to PZT-5H material. Specifically, there is a wing weight reduction and an increase of net lift of 12% and 22%, respectively, for *Sympetrum Frequens* PZT-7%PT wing, compared to when PZT-5H is used. Therefore, biomimetic smart flapping wings based on the geometry of the dragonfly *Sympetrum Frequens* PZT-7%PT wing represents an attractive design for insect scale flapping wing vehicles.

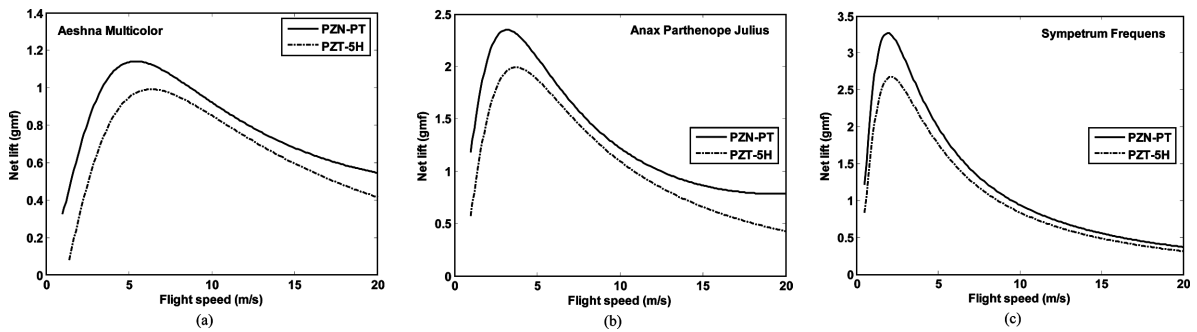


Fig. 18 Net lift of three dragonfly inspired smart flapping wings for different flight speeds

We would like to mention that the present study mainly focuses on the feasibility study of the flapping wing actuated by single crystal piezoceramic. There is a need for full aeroelastic consideration for more accurate prediction of aerodynamic forces as the forces produced by the flapping wing may change in the presence of aerodynamic loading. Moreover, the effects of the wing twist, due to aerodynamic loading, on the aerodynamic force generation need to be studied. These aspects of the problem have been taken up as a future work.

5. Conclusions

The Hamilton's principle is used in order to derive the non-linear equations of motion of a smart flapping wing. These equations are then discretized using the Galerkin method and solved using the method of multiple scales. Flapping wing is actuated from the root by a PZT-5H and PZN-7%PT unimorph in the piezofan configuration. Dynamic characteristics of smart flapping wings, having the same size corresponding to the actual wings of three different dragonfly species, are analyzed using numerical simulations.

Dynamic characteristics of all the three different piezoelectrically actuated flapping wings are studied for an input excitation voltage of 60 V. An unsteady aerodynamic model is used to obtain the aerodynamic forces. It is observed from the numerical results that net lift and thrust force produced by smart *Sympetrum Frequens* wing are highest among the three dragonfly inspired flapping wings considered in this study. Moreover, smart *Sympetrum Frequens* flapping wing is suitable for low speed flight. Use of PZN-7%PT single crystal piezoceramic can lead to a weight reduction of 12% for smart *Sympetrum Frequens* flapping wing as compared to PZT-5H wing. At the same time, there is an increase of net lift of 22% for *Sympetrum Frequens* PZN-7%PT wing as compared to PZT-5H wing. This net lift may be used to carry several sub-systems, such as power supply unit, control unit, sensory systems etc., required for autonomous flight. Therefore, PZN-7%PT flapping wing based on geometry of dragonfly *Sympetrum Frequens* wing represents a potential candidate for use in insect scale micro air vehicles.

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Notation

b	: Wing width
c	: Airfoil chord
c_n	: Normal force coefficient
$(C_d)_f$	: Drag coefficient due to skin friction
D	: Electrical displacement vector
E_b	: Wing modulus of elasticity
E_p	: Piezoelectric modulus of elasticity
$f(t)$	: Harmonic excitation voltage
h	: Coupling co-efficient matrix
l	: Wing length
l_2-l_1	: Piezoelectric layer length
m	: Mass per unit length of the wing with piezoelectric layer
Q	: Electrical field vector
t	: Time
t_b	: Wing thickness
t_p	: Piezoelectric layer thickness
U	: Flight speed
V	: Relative velocity
α_0	: Angle of section's zero lift line
α'	: The flows relative angle of attack at the $\frac{3}{4}$ chord location
ε	: Perturbation parameter
ε_{33}^S	: Dielectric constant at constant strain
η_s	: Leading edge suction efficiency
$\bar{\theta}$	: Pitch angle of chord with respect to U
$\bar{\theta}_a$	: Pitch angle of flapping axis with respect to U
$\bar{\theta}_w$	: Mean pitch angle of chord with respect to flapping axis
μ	: Damping co-efficient
ρ_{air}	: Atmospheric density
ρ_b	: Volumetric mass density of the wing
ρ_p	: Volumetric mass density of the piezoelectric layer
v_2	: Mid-chord normal velocity component due to the wing's motion
Φ_f	: Flapping angle
$()^b$	: Parameters pertaining to the wing
$()^p$	: Parameters pertaining to the piezoelectric layer
$()_n$	: Parameters pertaining to the neutral axis