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Effects of flexibility on the hovering performance of flapping wings with different shapes and aspect ratios

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ABSTRACT

The effects of isotropic homogeneous flexibility on the aerodynamic performance of flapping wings with different shapes and aspect ratios in hover at a Reynolds number of 400 have been studied numerically with a 3-D Navier–Stokes solver coupled with a structure solver. Three wing shapes, defined by the radius of the first moment of wing area, $\overline{r_1}$ (=0.43, 0.53 and 0.63), with four aspect ratios, AR (=1.5, 2.96, 4.5 and 6.0) are considered. We used a set of moderately flexible wings with an effective stiffness of 14 and 2.31 (for the mass ratio, $m^* = 4.0$ and 0.66 respectively) and a set of more flexible wings with an effective stiffness of 6.12 and 1.01 (for $m^* = 4.0$ and 0.66 respectively). The wings have a limited spanwise twist and a dominant chordwise flexibility because the leading edge is modeled as rigid. The results show that although the prescribed kinematics is advanced pitch rotation, it becomes symmetric or delayed pitch rotation depending on the value of $\overline{r_1}$, the degree of flexibility and the mass ratio. This change in pitch angle kinematics causes variations in the time histories of lift and power with flexibility including the timings and magnitudes of lift and power peaks. Flexible wings with high AR such as 4.5 and 6.0 produce less lift than rigid wings for both mass ratios because of lower pitch angles during the mid-stroke, but they are more efficient in terms of power economy; for example, 11% less lift but 33% higher power economy at AR = 6.0, $\overline{r}_1 = 0.63$ and $m^* = 0.66$. At $m^* = 4.0$, the low $\overline{r_1}$ and high AR wings maximize PE for a given lift. However, at $m^* = 0.66$, there is a limited range of lift for which low $\overline{r_1}$ and high AR wings are efficient, as $\overline{r_1} = 0.63$ wing at higher AR (=6.0) consumes lesser aerodynamic power than $\overline{r_1} = 0.43$ and 0.53 wings by flapping at a lower pitch angle; therefore, the PE of low $\overline{r_1}$ (=0.43 and 0.53) may drop below $\overline{r_1} = 0.63$ wing for a given lift.

1. Introduction

Conventional airplanes generate lift through fixed wings with a forward motion relative to the wind and thrust by their engines via exhaust gas or propellers. On the contrary, insects use not only forward motion relative to the wind but also a flapping motion, up and down or back and forth, to generate lift and thrust depending on the desired flight maneuver. In the early days of flapping studies, scientists soon realized that fixed-wing aerodynamics could not explain how a bumblebee could fly (Magnan, 1934; McMasters, 1989). Since then, aerodynamicists and biologists have collaborated to explore and mimic striking flight features of insects to develop flapping wing micro aerial vehicles (MAV). Critical reviews of flapping wing aerodynamics have been given by Lehmann (2004), Platzer et al. (2008), Sane (2003), Shyy et al. (2010, 2016), Tobalske (2007) and Wang (2005). There are on-going efforts (Armanini et al., 2016; De Croon et al., 2015; Ma et al., 2013; Phan and

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Park, 2016; Widhiarini et al., 2016) to improve the capabilities of future MAVs, which have the potential to revolutionize capabilities in a range of applications from sports to security and surveillance in inaccessible areas after a natural disaster.

The fundamental parameters for the aerodynamic performance of flapping wings can be categorized into wing geometry, kinematics and flexibility. Wing shape and aspect ratio (AR) are the two most extensively investigated wing geometry parameters. The AR is the ratio of the wingspan to the mean chord length. The time history, amplitude, and frequency of flapping angles, the timing and duration of wing rotation, and the timing of stroke reversal are some common kinematic considerations (Ansari et al., 2008a; Phillips and Knowles, 2011; Tang et al., 2008). For flexible wings in nature, researchers have explored different aspects of chordwise flexibility (Du and Sun, 2008; Gopalakrishnan, 2008; Gulcat, 2009; Heathcote and Gursul, 2007; Shahzad et al., 2016a), spanwise flexibility (Aono et al., 2009; Heathcote et al., 2008; Zhu, 2007) and combined chordwise–spanwise flexibilities (Agrawal and Agrawal, 2009; Aono et al., 2010; Young et al., 2009; Shahzad et al., 2017) in their experiments and numerical models.

Some experimental studies (Ozen and Rockwell, 2013; Phillips et al., 2010) on rigid wings have reported similar flow structures on various wing shapes, and this is supported by less than 5% difference in the instantaneous lift of ten wing shapes inspired from a fruit fly's wing (Luo and Sun, 2005). On the contrary, wings with greater outboard areas towards the wingtip are found to produce more lift while simultaneously consuming more aerodynamic power (Ansari et al., 2008b; Wilkins, 2008). Likewise, the findings of the study of AR are also inconsistent. While differences of less than 10% in the change in the lift coefficient for different AR were reported in some studies (Luo and Sun, 2005; Usherwood and Ellington, 2002) for rigid wings, low AR wings were found to produce more lift than high AR wings (Wilkins, 2008; Harbig et al., 2013). Ellington (1984) determined that the wing shapes of insects such as hoverfly, bumblebee, green lacewing, and hawkmoth could be approximated by $\overline{r_1}$ using the beta distribution (see Section 2.2 for details). In our previous work (Shahzad et al., 2016b) on rigid wing shapes and AR at three Reynolds number (*Re*) of 12, 400 and 13,500, the performance trend of wing shapes is observed to be independent of Re, and maximum power economy (PE) is achieved at AR = 2.96. While high $\bar{r}_1$ and AR wings produce more lift, low $\overline{r_1}$ and high AR wings maximize PE for a given lift. Here, PE, defined as the ratio of the mean lift coefficient to the mean aerodynamic power coefficient, is a measure of the efficiency of the hovering motion. Since the averaged inertial power is approximately zero over a flapping cycle, we use the mean aerodynamic power for PE calculation. As insect wings are flexible, it becomes imperative to explore the elusive role of flexibility in influencing the performance of wing shapes.

Earlier studies have shown that there exists an optimum range of flexibility (Heathcote and Gursul, 2007; Aono et al., 2009; Miao and Ho, 2006) for propulsion and it depends on factors such as the angle of attack, plunge frequency, amplitude, and *Re*. It is also known that flexibility not only alters the time evolution, size and strength of vortical structures (Pederzani and Haj-Hariri, 2006; Vanella et al., 2009; Zhao et al., 2010) around the wing, but also suppresses the flow separation and delays stall (Albertani et al., 2007; Hu et al., 2010; Rojratsirikul et al., 2009; Tamai et al., 2008; Visbal et al., 2009). Hamamoto et al. (2007) incorporated both chordwise and spanwise deformation by varying thickness in quadrilateral shell elements in a numerical model of a dragonfly wing. They observed in their numerical simulations that rigid and flexible wings produced almost similar lift, but that the rigid wing required 34% greater peak power, resulting in lower PE than the flexible wing. Similar lift for rigid and flexible wings was also obtained by Lua et al. (2010) in their experiments of isotropic wings with chordwise–spanwise flexibility. In an experimental study of isotropic and chordwise flexible airfoils at zero free stream velocity, Heathcote et al. (2004) found all flexible airfoils to have a higher thrust to power ratio than rigid ones. Vanella et al. (2009) performed fluid–structure interaction (FSI) simulations on a two-dimensional (2-D) two-link model at different frequency ratios (0.16–0.50) and confirmed a 28%, 23% and 21% higher lift to drag coefficient of a flexible wing with a frequency ratio of 0.33 at *Re* of 75, 200 and 1000 respectively; this improved performance is attributed to enhancement of wake capture mechanism resulting from a strong trailing edge (TE) vortex at the stroke reversal. Here, the frequency ratio is defined as the ratio of the flapping frequency (f) to the fundamental mode resonant frequency (f_n). In their study of chordwise and isotropic flexible wing sections under hovering kinematics, Eldredge et al. (2010) explained that although passive deflection in a mildly flexible wing leads to smaller drag and torque penalties, a premature detachment of the leading edge vortex (LEV) from very flexible wings leads to performance degradation. Du and Sun (2010) used deformation data of free-flying hoverflies (Walker et al., 2010) in numerical simulations and reported a 10% increase in the lift and 5% decrease in the aerodynamic power of the deformable wing compared to the rigid wing. The differences in lift and power were respectively attributed to camber deformation and spanwise twist. Similarly, the combined-chordwise–spanwise flexible wing in Nakata and Liu (2011) outperformed the rigid wing both in the lift and efficiency, due to strong downwash in the wake and the wing twist respectively. Sridhar and Kang (2015) concluded that a medium chordwise flexible wing (frequency ratio of 0.35) at the same scale as the fruit fly is the most efficient, but the highest lift coefficient is produced by the least stiff wing (frequency ratio of 0.7). In contrast to these findings, Tanaka et al. (2011) found that a rigid wing produces approximately 17% higher average lift than an at-scale model designed to mimic the stiffness, venation and corrugation profiles of a hoverfly wing.

The mass ratio ($m^* = \rho_s h_s / \rho_f c$, where ρ_s is the material density, h_s the wing thickness, ρ_f the fluid density and c the mean chord), representing the inertial to aerodynamic effects, varies appreciably among insects (San Ha et al., 2013). For instance, m^* of fruit fly (Shyy et al., 2013), dragonfly (Yin and Luo, 2010) and hawkmoth (Shyy et al., 2013; Combes and Daniel, 2003b) is 0.66, 1.0 and 4.0 respectively and the m^* of hoverfly (Dai et al., 2012) close to the wingtip is about 0.5. Combes and Daniel (2003b) performed experiments in air and helium (which is 85% less dense) to measure the bending of hawkmoth wings. They postulated that the inertial forces on a wing alone could produce the deformations observed in hawkmoths. Likewise, Ennos (1988b) observed the mass distribution and torsional axis of the two species of Diptera and concluded