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Flow patterns and efficiency-power characteristics of a self-propelled, heaving rigid flat plate

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ABSTRACT

The aim of the present study is to characterize the flow patterns, propulsion efficiency and power requirements associated with a self-propelled-heaving thin flat plate in a quiescent medium. In this regard, a numerical model using a shifting discontinuous-grid and based upon multi-relaxation-time lattice Boltzmann method is developed to probe the resulting aerodynamics. The influence of kinematic parameters namely flapping Reynolds number Re_f $(20-100)$ and plunging amplitude β (0.2–1), and the density ratio ρ^* (10^1-10^2) on forward flight is pursued. Depending on the kinematics, various periodic vortex shedding characteristics of the plunging plate are observed that lead to modification of the angle of attack as a result of wing-wake interaction and downward jet. The presence of strong vortex dipole at the trailing edge with an attached leading edge vortex are factors responsible for maximum thrust generation. A wing-wake interaction which occurs at low β and high Re_f due to weak vortex dissipation and presence of vortex dipole at the trailing edge acting in tandem can lead to achieving high propulsion efficiency. Through surrogate modelling, a set of Pareto-optimal solutions that describe the tradeoff between efficiency and input power for forward flight is presented and offers insight into the design and development of next generation flapping wing micro-air vehicles.

1. Introduction

With a dimension span of 15 cm or smaller and flight speed of ~10 m/s or lower, micro-air vehicles (MAVs) operate in low Reynolds number ($Re < 10^4$) regimes and experience aerodynamic conditions with low lift-to-drag ratios (Shyy et al., 2008, 2013, 2010). These are rapidly evolving as modern defense gadgets for performing surveillance and reconnaissance operations with prerequisites of high-maneuverability, stable hover, vertical take-off/landing capability, swiftness and noiseless locomotion (Shyy et al., 2008, 2013, 2010; Tsai and Fu, 2009; Muller, 2001). While alternative MAV concepts based on fixed wing, rotary wing and flapping wing have been explored, flapping flight has carved its superiority over other designs with excellent maneuverability through space, navigation and control capabilities, stimulating researchers to develop and design this class of MAVs, including Nano-humming bird (Keennon et al., 2012), Microrobot (Fuller et al., 2014; Ma et al., 2015) and Delfly (Croon et al., 2016).

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Nevertheless, as discussed by Shyy et al. (2016) and Chin and Lentink (2016), significant milestones are yet to be achieved for establishing comprehensive predictive capabilities of flapping flight concepts towards development of MAVs capable of covering the wide range of flight conditions encountered in practical operation. In addition, the flight of insects and birds which involves complex flapping motions do not follow the classical aerodynamics based quasi-steady mechanisms of lift generation without taking into account of the flow characteristics surrounding the flapping wing (Shyy et al., 2009; Trizila et al., 2011; Shyy et al., 1999; Sane, 2003; Alexander, 2002; Dickinson et al., 1999; Arora et al., 2014). Developing a better understanding of this process which addresses the issues of scaling and energy optimization (Kang et al., 2011; Kang and Shyy, 2013, 2014; Lee et al., 2015; Quinn et al., 2013) is expected to assist in simplified MAV design.

The phenomenon of thrust generation in birds was first reported by Knoller (1909) and Betz (1912), and hence is known as the *Knoller–Betz effect.* By considering a vertically heaving airfoil as a representation of bird wings, they stated that due to the plunging motion of wing an effective angle of attack was created which provided a force component in the horizontal direction and was responsible for thrust production, which was later experimentally proved by Katzmayr (1922). Many experimental and computational studies on rigid wing performing pure plunging motion (some studies also included active pitching) were conducted which supported the above argument (Freymuth, 1988, 1990; Triantafyllou et al., 1991; Lai and Platzer, 2000; Jones et al., 1998; Anderson et al., 1998; Lewin and Haj-Hariri, 2003). In all these studies either the wing flapped at a fixed position with an oncoming flow or the wing cruised through the flow whose speed could be controlled independently. Taking it further, the present study is conducted on a rigid self-propelled heaving airfoil (the forward translation is produced only due to flapping motion and both of them are interdependent or coupled) to mimic the operation of a biological flyer.

Some of the key findings of previous studies on an auto-propelled wing (Vandenberghe et al., 2004; Vandenberghe et al., 2006; Alben and Shelley, 2005; Lu and Liao, 2006; Zhang et al., 2009; Benkherouf et al., 2011; Hu and Xiao, 2014) are summarized here. Vandenberghe et al. (2004, 2006) experimentally revealed the presence of a stability limit beyond which a pure oscillating rectangular plate mounted on an axle can rotate in the transverse direction, indicating the onset of the generation of thrust. Alben and Shelley (2005), using an elliptical wing, numerically investigated the earlier (Vandenberghe et al., 2004) experiment and showed that beyond a critical Reynolds number (based on flapping frequency), unidirectional locomotion can be achieved for an initially non-locomoting body. Lu and Liao (2006) quantified the critical Reynolds number by varying the amplitude of an elliptical membrane and studied the dynamical behavior of the foil with different density ratios, and classified it as (a) steady, or (b) oscillatory movement. Zhang et al. (2009) studied the effect of varying the chord-thickness ratio (CR) for an elliptical and rectangular flapping foil between 1 and 100 on the symmetry breaking bifurcation. Hu and Xiao (2014) examined the propulsive performance of a three-dimensional plunging elliptical airfoil by varying the density and aspect ratio (defined as the span to chord ratio) and showed that the translational velocity and thrust coefficient increase with an increase in the aspect ratio.

These earlier studies demarcate the zones of stability/instability and quantify the critical plunging frequency or flapping Reynolds number beyond which pure plunging motion leads to thrust generation, as a function of amplitude, density and chord-thickness ratio. Furthermore, power requirements and efficiency for propulsion of a self-propelled airfoil due to interplay of flapping Reynolds number Re_f, plunging amplitude β and wing-fluid density ratio ρ^* need to be addressed. We aim to present a quantitative assessment of such issues for the zone in which propulsion is attained, develop their reduced-order models and highlight the relative impact of the governing parameters for a thin, rigid and plunging flat plate. Hence, the following are the key objectives of this work:

1. investigate the impact of flapping Reynolds number Re_f, plunging amplitude β and density ratio ρ^* on the propulsion velocity and energy requirements of a rigid-flat plate,
2. highlight the dominant flow structures that capture and explain the dynamics of thrust generation in a self-propelled plunging plate, and
3. formulate reduced-order models through surrogate modelling to establish a relationship between performance (power and efficiency) and system parameters (Re_f, ρ^* and β). Thereafter, identify the optimum operating conditions in forward flight including any tradeoff between these two performance parameters.

To the best of our knowledge, impact assessment of the chosen variables on propulsive performance of a plunging wing with the help of reduced-order models has not been pursued so far.

2. Problem description

2.1. Plunging kinematics and parameters

We consider an auto-propelled heaving rigid flat plate, unconstrained to translate in the horizontal direction, whereas plunging takes place in the vertical direction. The following parameters which are expected to play a vital role in propulsion are introduced to conduct a parametric study on the plunging airfoil. Chord C has been chosen as the length scale and flapping duration T (where $T = 1/\gamma$ and γ is the plunging frequency) as time scale for non-dimensionalizing them.

The dimensionless vertical displacement of the flat plate is given as