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Enhanced thrust performance of a two dimensional elliptic airfoil at high flapping frequency in a forward flight

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ABSTRACT

This study is motivated by our earlier investigation Lua et al. (2016) which shows that a two-dimensional elliptic airfoil undergoing sinusoidal flapping motion experiences thrust deterioration when the flapping frequency exceeds a certain critical value (or critical Strouhal number, St_{cr}). To alleviate this unfavorable thrust generation condition, we propose two novel effective angle of attack profiles, namely smooth trapezoid (STEA) profile and elliptic trapezoid (ETEA) profile. These profiles are designed to ensure that the airfoil still experiences the same effective angle of attack amplitude as the sinusoidal flapping while concurrently reducing the detrimental effect of high rotation rate. The effectiveness of these two proposed profiles is confirmed by our numerical and experimental studies. In particular, our results show that at low to moderate flapping frequency, thrust generation is almost invariant to the type of angle of attack profiles applied, but at high flapping frequency ($St > St_{cr}$), the proposed profiles produce higher thrust than the sinusoidal flapping. The thrust augmentation can be attributed to the suppression of the adverse low pressure region in the vicinity of the airfoil, which is a consequence of the reduced rotation rate. Of the two proposed profiles, the ETEA with its steep acceleration phase produces a higher time-average thrust than the STEA near the stroke reversal. Also, in line with our previous finding, thrust augmentation for both STEA and ETEA is a function of the base length of the trapezoid, with a broader one producing a better thrust performance.

1. Introduction

Understanding the aerodynamics of flapping airfoil is important in the design of various propulsive devices including bio–inspired autonomous aerial and underwater vehicles (Lua et al., 2016; Ellington, 1999; Shyy et al., 1999; Ansari et al., 2006; Rozhdestvensky and Ryzhov, 2003). Generally speaking, the flapping airfoils are energy efficient and offer superior low speed maneuverability than a fixed or rotary airfoil in small-scale bio-inspired vehicles (Pesavento and Wang, 2009; Maxworthy, 1981; Platzer et al., 2008; Shyy et al., 2007; Spedding and Maxworthy, 1986; Mueller, 2001; Hubel and Tropea, 2009). Typically, the propulsive or locomotive force in these bio–inspired vehicles is generated through interaction of a translating and rotating airfoil with its surrounding fluid. Previous numerical and experimental investigations (Ellington, 1999; Hubel and Tropea, 2009; Lewin and Haj-Hariri, 2003; Dickinson et al., 1999; Smith, 1996; Sun and Tang, 2002; Freymuth, 1988; Jones et al., 1998; Lua et al., 2007) have shown that thrust generation of an oscillating airfoil is associated with the creation of a reverse von-Karman vortex street (RKVS) whereby the vortices are arranged in such a way that the downstream time-averaged velocity profile yields a momentum surplus jet-like flow scenario.

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Triantafyllou et al. (1991, 1993) have characterized thrust performance of a flapping airfoil in terms of flapping frequency (f) or Strouhal number (St), and showed that low oscillating frequency f or St generates drag force which can be attributed to the presence in the wake region of the momentum deficit von-Karman vortex street (KVS). However, with increasing flapping frequency, the drag-producing KVS transforms into thrust producing RKVS and the transition between these regimes was identified by Koochesfahani (1989) and Triantafyllou et al. (2004) to be around $St = 0.1$ for a flapping airfoil. Along the same line of investigation, Anderson et al. (1998), Schnipper et al. (2009) and Mackowski and Williamson (2015) have characterized different wake regimes in terms of Strouhal number (St) of the flapping airfoil. Buchholz and Smits (2008) have investigated the thrust performance and associated wake structure of low aspect ratio pitching airfoils. By considering the airfoil flexibility, Heathcote and Gursul (2007) and Heathcote et al. (2004) have further characterized wake regime of oscillating airfoil in both forward flight and hovering conditions. On power–extraction by a flapping airfoil, the numerical and analytical studies by Kinsey and Dumas (2008), Ashraf et al. (2011) and Young et al. (2013) found that the maximum extraction efficiency occurs when the non-dimensional oscillating frequency (normalized by the chord length and the incoming flow velocity) is approximately 0.15 and that coincides with the frequency of most unstable mode for maximum growth rate of the wake region.

Other associated studies (Read et al., 2003; Hover et al., 2004) on a simple sinusoidal heaving and pitching airfoil show that higher flapping frequency (or St) produces higher time-average thrust, but there exists an upper frequency limit or critical Strouhal number (St_{cr}), above which thrust performance deteriorates considerably. Our recent investigations Lua et al. (2016) and Dash et al. (2015) identified the source of this degradation at high St to the presence of adverse suction effects caused by airfoil high rotation rate and the presence of the leading edge vortex generated in the previous stroke which remained attached to the airfoil. These factors result in the production of a multiple-peak non-parabolic type transient thrust profile with undesirable drag producing "valley" or region. It is also noticed that, at $St < St_{cr}$, the transient thrust profile is of a parabolic shape with a single peak, but when $St > St_{cr}$ the extent of the drag producing valley increases with St, which in turn leads to thrust degradation. One of the motivations of the present investigation is to ascertain *whether thrust degradation above the critical Strouhal number (St_{cr}) can be alleviated by reducing the drag producing valley in the multiple-peak transient thrust force profile.*

In a related experimental study by Hover et al. (2004) on a 2D oscillating NACA0012 airfoil at $Re = 30,000$ and St varying from 0.2 to 0.8, it is found that modifying the flapping kinematics such that the instantaneous effective angle of attack follows a square-wave or a cosine-wave profile can lead to thrust enhancement. The authors reason that the modification of effective angle of attack profile cause the wake vortices to revert from drag producing KVS to thrust producing RKVS. This finding is supported by the subsequent numerical studies of Xiao and Liao (2010) and Esfahani and Karbasian (2013). Although earlier studies have shed light on the salient factors responsible for thrust enhancement, the details of this enhancement are still not fully understood. Moreover, (Lua et al., 2016), in a recent study, showed that thrust performance of an oscillating airfoil is governed by how the vortex structures interact with the airfoil. They argued that the wake structure observed downstream of the airfoil, as noted by Hover et al. (2004), is merely an aftermath of the near-wake interaction that is responsible for thrust production. Hence, it would be more fruitful to examine the near-wake physics to appreciate the source of performance gain. Unfortunately, the previous investigations (Hover et al., 2004; Xiao and Liao, 2010; Esfahani and Karbasian, 2013) did not provide the flow field information around the airfoil. Also, one drawback of the square-wave effective angle of attack profiles adopted by Hover et al. (2004) is the presence of inherent sharp corners which inevitably leads to infinite acceleration in both the heaving or pitching kinematics; this is impractical to achieve.

The present study is an attempt to address the shortcomings of the previous investigations (Hover et al., 2004; Xiao and Liao, 2010; Esfahani and Karbasian, 2013), and our solution is guided by the earlier investigation by Lua et al. (2016), which shows that high rate of airfoil rotation is the primary cause of thrust deterioration at high flapping frequency as this leads to the generation of an adverse low pressure region on airfoil surface. Arising from these findings, we propose two novel trapezoidal effective angle of attack profiles, namely, (1) Smooth Trapezoid (STEA) and (2) Elliptic Trapezoid (ETEA) with the aim of reducing the adverse low-pressure region and therefore enhancing the thrust. The details of these flapping kinematic (i.e. STEA and ETEA) and associated modifications of the near wake structure will be discussed in later sections. At this juncture, it is worth mentioning here that the pitching profile in both STEA and ETEA reduces the unrealistically high rate of airfoil rotation inherent in Hover et al. (2004) flapping kinematics. In addition, the present study aims to characterize the thrust performance in terms of the base length of trapezoid STEA and ETEA profiles, and this is achieved by gradually transforming these profiles into a sinusoidal type.

The present study is conducted experimentally and numerically using a 2D elliptic airfoil. The experiments were performed in a re-circulating water channel using the same flapping mechanism previously used by Dash et al. (2015) and Lua et al. (2016, 2011). Since the mechanism has a maximum flapping frequency of about 1.0 Hz, numerical simulations are conducted to scan through higher frequency range to bridge the gap in the experimental data. Moreover, numerical study can generate vorticity fields at a much higher spatial resolution and provide unsteady pressure fields that are difficult to obtain experimentally. The numerical simulations were performed using a commercial CFD package (FLUENT v15.0) with laminar viscous flow model. The accuracy of this solver (FLUENT) has been tested by several past experimental and numerical studies (Lua et al., 2016; Bos et al., 2008; Lee et al., 2012; Tay et al., 2015). It is worth emphasizing that the present numerical study focuses on the fluid dynamics of flapping airfoil only, it is not our intention to develop numerical scheme. We use the CFD package only after it has been thoroughly validated against available experimental results. The simulation is conducted at $Re = 5000$, St from 0.1 to 0.9 and induced effective angle of attack amplitude (α_0) from 10° to 20°. The ability of the laminar