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Numerical analysis of pitching-rotor aerodynamics

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ABSTRACT

The influence of periodic blade pitching on rotor aerodynamics is numerically investigated at a Reynolds number typical of micro-air vehicles. Blade pitching motion is parameterized using three variables, giving rise to a large parameter space that is explored through 74 test cases. Results show that a relevant tuning of pitching variables can lead to an increase in rotational efficiency and thrust, which is found to be primarily related to the occurrence of reversed von Karman street, leading edge vortex (LEV) formation and dynamic stall phenomenon. In addition, for cases where reversed von Karman street occurs, the flow is found to be quasi-two-dimensional, suggesting that quasi-two-dimensional approaches can provide relevant approximations of the global aerodynamics. Overall, the analysis demonstrates that blade pitching can be beneficial to the aerodynamic performance of micro-air vehicles and helps draw guidelines for further improvements of flapping-rotor concepts.

1. Introduction

Micro- (MAVs) and nano-air vehicles (NAVs) operate at Reynolds numbers roughly ranging from 10^3 to 10^5. At these Reynolds numbers, aerodynamic performance of conventional fixed and rotary wing concepts drastically decreases due to the increased importance of flow viscous forces with respect to inertial forces. Basically, increased viscous effects tend to increase viscous drag and to promote flow separation, which leads to a reduction in airfoil efficiency and maximum achievable lift respectively. Early examples of such reduced aerodynamic performance on NACA airfoils can be found in Jacobs and Sherman (1937). Reduction in airfoil efficiency and maximum achievable lift results in low endurance and limited payloads. Such issues significantly restrict the spectrum of applications, in a worldwide rapidly growing market. Therefore, the question is how can we tackle those issues?

The observation of nature can potentially bring an answer to this question. Indeed, conversely to conventional aircraft and helicopters which operate in the 'attached flow' regime, insect wings, for example, operate in the 'separated flow' regime. Flow separation is detrimental to conventional aircraft and helicopters but can be beneficial to insects, birds or fishes, where the resulting formation of vortices is used as high lift and locomotion mechanisms. Overall, two principal mechanisms emerge.

First mechanism is referred to as dynamic stall. When a high (fixed) angle of attack airfoil is impulsively started from rest in a quiescent fluid, the flow separates at the leading edge and rolls up into a leading edge vortex (LEV). The latter induces a low pressure region on the upper surface of the airfoil, which enhances lift. However, such a vortex is generally not stable in that its growth up to a critical size triggers its shedding from the airfoil, hence causing a drastic drop in the aerodynamic lift.

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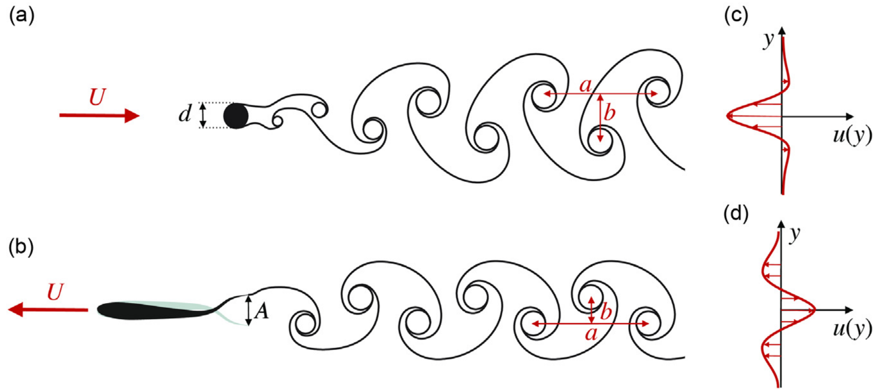

Fig. 1. Illustration of von Karman (a) and reversed von Karman (b) vortex street (reproduced from Eloy, 2012).

Then, a new LEV is formed and the scenario repeats itself, leading to an unsteady oscillating lift and a wake pattern known as a von Karman vortex street. The lowest angle of attack at which such an unsteady scenario occurs is referred to as the static stall angle. The mean value of the oscillating lift is lower than the steady lift obtained at lower angle of attack, in the absence of flow separation and vortex shedding. An interesting feature here is that the first LEV that develops immediately after the impulsive start remains attached to the airfoil longer than subsequent LEVs do (Wang, 2000). Thus, a longer plateau in high lift is observed at the impulsive start. A direct outcome is that airfoil angle of attack can be tuned to benefit from this plateau. In other words, if the angle of attack is increased above the static angle of attack to generate a ‘first’ LEV and then reduced below the static angle of attack before LEV shedding occurs, the airfoil can benefit from lift plateau while avoiding drastic drops in lift. If such a change in airfoil angle of attack is repeated, the lift still exhibits an unsteady behavior but its mean value is relatively high, i.e. higher than the maximum lift achievable on a static airfoil. This dynamic stall mechanism is intrinsically unsteady as it results from the unsteady motion of the airfoil. A fascinating example of dynamic stall mechanism can be found in nature, where insects and birds tune their flapping wings kinematics to benefit from the LEV and thus generate enough lift to keep them aloft (Dickinson et al., 1999). In a more general sense, dynamic stall phenomenon usually occurs on wings that undergo rapid changes in effective angle of attack (e.g. retreating helicopter rotor blades and highly maneuverable aircraft) and has therefore been extensively studied in the literature (e.g. McCroskey, 1982; Visbal, 1990; Eldredge et al., 2009).

Second mechanism is referred to as reversed von Karman street. As previously mentioned, a high (fixed) angle of attack airfoil translating in a quiescent fluid experiences low lift and its wake exhibits a von Karman vortex pattern due to periodic shedding of leading (LEVs) and trailing edge vortices (TEVs). von Karman vortex street is associated with wake velocity deficit which is indicative of drag. This drag generating mechanism can be clearly correlated with the position and circulation of LEVs and TEVs, as illustrated in Fig. 1. Therefore, a high angle of attack translating airfoil experiences both low lift and high drag, hence low aerodynamic efficiency. However, the position and orientation of the shed vortices can be altered *via* a time variation of the airfoil angle of attack, turning the wake pattern into a reversed von Karman street. Such a pattern is associated with a wake velocity surplus which is indicative of a propulsive force (Fig. 1). Reversed von Karman street is an ubiquitous feature in nature and explains the locomotion of fishes.

Overall, dynamic stall and reversed von Karman street appear as unconventional high lift and locomotion mechanisms respectively. These result from a time variation in airfoil angle of attack, which is generally achieved through pitching and plunging unsteady motions. During the past decades, MAVs relying on dynamic stall mechanism were developed using flapping wings concept (e.g. the Nano Hummingbird from AeroVironment, Keennon et al., 2012; RoboBee from Harvard University, Wood, 2008). The flapping wings concept is a prospectively relevant solution for low Reynolds number hovering flight where conventional concepts exhibit very poor aerodynamic performance. However, a major drawback of flapping wings concept is that the flapping motion is characterized by stroke reversal phases (pronation and supination phases) where the wing velocity approaches zero. Although additional mechanisms such as wake capture or Kramer effect (Dickinson et al., 1999) tend to mitigate the effect of stroke reversal phases, the latter are still detrimental to aerodynamic performance. On the other hand, MAVs relying on the reversed von Karman street mechanism were also developed using flapping wings concept to achieve propulsion for forward flight (e.g. the Naval Postgraduate School MAV, Jones et al., 2005). However, it is important to emphasize that, as in nature, reversed von Karman street obtained from flapping wings is dedicated to forward flight rather than hovering flight.

In this paper, an innovative concept is investigated that can theoretically (1) allow both dynamic stall and reversed von Karman street to promote hovering flight performance while (2) avoiding zero wing velocity phases. The concept, generally referred to as the flapping-rotor (or flotor), consists in coupling both rotating and flapping motions. It was first introduced by Theodoor (2002) on a medium scale rotor. In the authors' work, the flapping motion was defined as a finite amplitude oscillating rotation of the rotor blade around an axis perpendicular to both blade and rotor axis. The flapping motion was powered while the rotating motion was induced by the flapping motion (probably through the generation of reversed von