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Control of flow separation around an airfoil at low Reynolds numbers using periodic surface morphing

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ABSTRACT

The paper investigates experimentally the low Reynolds number flow ($Re_c = 50,000$) around a model that approximates a NACA 4415 airfoil and the control of separation using periodic surface motion. Actuation is implemented by bonding two Macro Fiber Composite patches to the underside of the suction surface. Time-resolved measurements reveal that the peak-to-peak displacement of the surface motion is a function of both the amplitude and frequency of the input voltage signal but the addition of aerodynamic forces does not cause significant changes in the surface behavior. The vibration mode is uniform in the spanwise direction for frequencies below 80 Hz; above this frequency, a secondary vibration mode is observed. The flow around the unactuated airfoil exhibits a large recirculation region as a result of laminar separation without reattachment and consequently produces relatively high drag and low lift forces. Various actuation frequencies were examined. When actuated at $V_{f^+} = 2.0$, the spectra in the vicinity of the trailing edge and near-wake were found to be dominated by the actuation frequency. Sharp peaks appear in the spectra suggesting the production of Large Coherent Structures at this frequency. The increased momentum entrainment associated with these enabled a significant suppression of the separated region. The result was a simultaneous increase in C_L and decrease in C_D and therefore a large increase in the L/D ratio. In addition, a delay in the onset of stall results in a significant increase in the maximum achievable lift.

1. Introduction

Aerodynamics at low Reynolds numbers, *Re*, is an increasingly active area of research (Mueller and DeLaurier, 2003). Primarily, this is a consequence of the increase in real-world engineering applications, such as wind turbines (Wright and Wood, 2004; McTavish et al., 2013), micro air vehicles (MAV) (Mueller and DeLaurier, 2003), small unmanned aerial vehicles (UAV) (Mueller and DeLaurier, 2003; Francis, 2012) and even a potential system for exploring Mars (Anyoji et al., 2014). Another reason for the interest in low *Re* aerodynamics is the enormously rich flow physics in this flight regime.

1.1. Low Reynolds number aerodynamics

At sufficiently low *Re*, which according to the classical review of Lissaman (1983) can be anything below $Re = 500{,}000$, laminar boundary layers form on an airfoil's upper surface which persist beyond the suction peak and into the pressure

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recovery region whereupon an adverse pressure gradient (APG) is encountered. Viscous effects close to the airfoil's surface slow down a fluid element thereby reducing its kinetic energy. Turbulent boundary layers can compensate for this by mixing the low momentum fluid close to the wall with high momentum fluid at the edge of the boundary layer. However, a laminar boundary layer has no mechanism for re-energizing the near-wall flow, making it incapable of overcoming even modest APG and therefore highly susceptible to separation (Lissaman, 1983; Mueller and Batil, 1982).

The flow around an airfoil operating at low *Re* is, to a large extent, controlled by the development of the separated shear layer (SSL) (Yarusevych et al., 2008; Yarusevych and Boutilier, 2011). Depending on the angle of attack and Reynolds number, two different scenarios are encountered: development of a Laminar Separation Bubble (LSB) with turbulent reattachment (Mueller and Batil, 1982; Hsiao et al., 1989; Yarusevych et al., 2009) or massive separation without subsequent reattachment (Mueller and Batil, 1982; Yarusevych et al., 2008; Wang et al., 2014; Alam et al., 2010). Flow separation results in low lift, C_L, and high drag C_D coefficients, leading to reduced performance of the engineering devices mentioned above. Control techniques could counter such unfavorable flow conditions and potentially lead to considerable performance improvements.

1.2. Flow control

Since separation is associated with significant performance losses, its mitigation becomes important. Separation can be affected by both passive and active devices. Passive control has the benefit of requiring no additional power. Two of the most popular methods are vortex generators (VG) and boundary layer trips (or Turbulators). Gopalarathnam et al. (2003) experimentally investigated the use of the latter and discovered that boundary layer trips can have a positive net effect on C_D. Using a similar concept (surface roughness), Mueller and Batil (1982) found an improvement in the lift-curve slope of a NACA $66_3 - 018$ airfoil at $Re = 40{,}000$, while Zhou and Wang (2012) managed to reduce the presence of LSB with leading edge bumps and consequently improve L/D. In addition, VG have also been found to have a positive effect of low *Re* airfoil performance (Lin, 2002; Kerho et al., 1993; Manolesos and Voutsinas, 2015).

The drawback of passive control is that it cannot adapt to changing flow conditions. Although Gopalarathnam et al. (2003) found that trips have a net drag benefit, the performance of this flow control method was only optimum for a given flight condition. Similarly, while VG were found to improve performance at certain conditions, they have also been found to exhibit a drag penalty at others (Lin, 2002; Manolesos and Voutsinas, 2015). A similar problem was reported by Mueller and Batil (1982) who found the same surface roughness elements that improved performance at $Re = 40,000$, simply increased drag at high *Re*, where laminar flow exists over a smaller portion of the airfoil surface. Abbas et al. (2013) concluded that VG were most suitable when the separation location was fixed so they could be optimally positioned upstream of this location. Similarly, for boundary layer trips Gopalarathnam et al. (2003) agree by stating that for a given airfoil, a single trip location is not optimum for different flight conditions.

Therein lies the drawback of passive control; a method that improves performance at one flight condition is likely to degrade performance at another. On the other hand, active approaches, while requiring additional power, offer the significant advantage of being aerodynamically innocuous when they are inactive. Some of the earliest active control devices were based on suction and blowing. In principle these are capable of improving performance, but in practice complex auxiliary compressors and extensive plumbing systems result in large power consumption that can often offset the aerodynamic benefits (Greenblatt and Wygnanski, 2000). Seifert et al. (1996) discovered that by modulating a steady blowing technique with a periodic jet, a power saving of 84% could be achieved.

The idea of active control based on periodic forcing originates from the discovery that the formation of Large Coherent Structures (LCS) is accelerated and regulated by periodic motion (Greenblatt and Wygnanski, 2000; Seifert et al., 1996). Moreover, LCS have been found to be the essential building blocks of the mixing layer and are responsible for transporting momentum across the layer (Kotapati et al., 2010). The production and manipulation of LCS is therefore an efficient way to control mixing in a separated shear layer. Periodic motion can increase the transfer of high momentum fluid by enhanced entrainment due to LCS and therefore reduce significantly the size of recirculation zones. This is the fundamental mechanism that explains the control authority of periodic actuation. The frequency of actuation is important and an optimum range of reduced frequencies $F^+ = fX_{te}/U_\infty$ (where X_{te} is the distance of the actuator to the trailing edge) between 2 and 4 has been identified as optimum to prevent separation (Greenblatt and Wygnanski, 2000).

1.3. Scope of this paper

The review paper (Cattafesta and Sheplak, 2011) presents various actuator types used in low-to-moderate speed flows. In recent years, synthetic-jet (Kotapati et al., 2010; Zhang and Samtaney, 2015; Buchmann et al., 2013) and plasma-based actuators (Sato et al., 2015; Jukes and Choi, 2009) have emerged as the most popular devices. Their effectiveness is largely determined by the receptivity of the flow to the imposed disturbances. These actuators have to be of the right scale and, most importantly, introduced at the right location (upstream of the separation point). Each type of actuator has advantages and disadvantages (refer to table 1 of Cattafesta and Sheplak (2011)). For example, synthetic jets require no external fluid source, but peak velocities are typically limited to low to moderate subsonic speeds. The orifices are also potentially subject to fouling. Plasma-based actuators are easily installed on models, but require high voltage and have low conversion efficiency from input energy to mechanical output energy (Seifert, 2013).