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Control of low Reynolds number flows by means of fluid–structure interactions

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ABSTRACT

There is great interest in small aircraft known as Micro Air Vehicles and mini Unmanned Air Vehicles due to the wide range of possible applications. This article reviews recent work that aims to exploit the flexibility of the wing structure in order to increase lift and thrust, and delay stall. Wing flexibility has often been considered to be unwanted for large conventional aircraft and measures are taken to limit the deformation. In contrast, very small aircraft flying at low speeds are not necessarily subject to the same limitation. This approach is only applicable to small aircraft because the frequencies of the wing structure and fluid flow instabilities are close to each other. Consequently, small amplitude and high-frequency motions will be considered.

We first start with rigid airfoils and wings in forced plunging motion, which mimics the bending oscillations. The main advantage of this approach is the freedom to vary the frequency within a wide range. Two mechanisms of high-lift production on the oscillating rigid airfoils are discussed. In the first one, leading-edge vortex dynamics and different modes of vortex topology play an important role on the time-averaged lift and thrust at post-stall angles of attack. Existence of optimal frequencies and amplitudes are demonstrated, and their relation to other phenomena is discussed. In the second mechanism of high-lift, trailing-edge vortex dynamics leads to bifurcated/asymmetric flows at pre-stall angles of attack. Deflected wakes can lead to time-averaged lift coefficients higher than those for the first mechanism. Some aspects of lift enhancement can be sensitive to the airfoil shape. For three-dimensional finite wings, lift enhancement due to the leading-edge vortices and existence of optimal frequencies are similar to the two-dimensional case. Vortex dynamics of the leading-edge vortex and tip vortex is discussed in detail. Leading-edge sweep is shown to be beneficial in the reattachment of the separated flows over oscillating wings. Oscillating flexible wings can provide much higher lift coefficient than the rigid ones. Amplitude and phase variation in the spanwise direction result in much stronger leading-edge and tip vortices. Self-excited vibrations of flexible wings, including membrane wings, can excite shear layer instabilities, and thus delay stall and increase lift. Finally, thrust enhancement or drag reduction can be achieved by employing chordwise and spanwise flexibility. The effects of wing flexibility on the vortices and thrust/drag are discussed in relation to the characteristics of wing deformation.

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1. Introduction

Recent advances in micro-technology have created an opportunity to mount miniature surveillance equipment on small (wing span less than 15 cm) flying aircraft known as Micro Air Vehicles (MAVs). Such micro-technology includes tiny CCD cameras, infrared sensors, and computer-chip sized hazard detectors. Micro-flying robots could be suitable for reconnaissance and surveillance, as well as numerous other applications such as coastal surveillance, crop monitoring, telecommunications, news broadcasting, remote sensing and mineral exploration. MAVs have similar dimensions to birds and insects, and similar Reynolds numbers. Mini Unmanned Air Vehicles (UAVs) are slightly larger, with correspondingly larger Reynolds numbers.

As the length scale of small aircraft is small and flight speed is low, the Reynolds number is low, typically $Re = 10^3 - 10^5$. At these low Reynolds numbers, separated and vortical flows are dominant, making lift and thrust generation challenging due to the strong viscous effects as discussed in recent review articles [1–4]. Because of the poor lift generation in cruise flight, it will be necessary for fixed-wing MAVs to fly at relatively high angles of attack, close to stall conditions. In addition, it may be necessary to fly in the poststall regime during vertical gusts. Hence, the delay of stall is necessary for stable MAV flight. High angle of attack flows with large separated regions are also typical for flapping-wing MAVs. Leading-edge vortices are known to enhance lift in unsteady aerodynamics. Periodic excitation of the flow to generate leading-edge vortices for fixed-wing MAVs is therefore a sensible approach.

Consequently, active flow control will be necessary. This can be achieved by means of unsteady blowing, suction, moving surfaces, and plasma actuators. However, these conventional flow control techniques such as blowing are not necessarily practical at these small scales, and often, the space available is insufficient to place actuators or blowing chambers. In addition, weight, volume and power consumption of the potential actuation systems need to be considered. For example, plasma actuators, when the power supply is considered, may not be practical at these small scales. In this review article, we focus on the periodic excitation of separated flows by means of wing oscillations. Fluid–structure interactions can be exploited to control the separated flows, and thus increase lift and delay stall. Small aircraft are inherently light weight and flexible, hence vibrations of the wings can be used to excite the separated flows.

1.1. Frequencies of fluid instabilities and wing structure

Extensive research on active flow control of separated flows around airfoils and wings has shown that partial or full reattachment is possible when the inherent instabilities in the separated flow are excited [5]. Depending on the airfoil shape and excitation characteristics, at least three different instabilities may be important for effective excitation: (1) initial shear layer instability or its subharmonics, although this appears to be more effective for delta wings [6]; (2) instability of the separation bubble [7]; and (3) wake instability [8,9]. Flow control research on separated flows suggests that the optimal Strouhal number of unsteady excitation is on the order of unity, $fc/U_\infty = O(1)$. Typically, the frequencies of the instability of the separation bubble and wake instability are on this order of magnitude. An alternative control strategy relying on much higher frequencies was discussed by Glezer et al. [10].

Fig. 1 shows the qualitative variation of the frequency of the fluid instabilities (corresponding to $fc/U_\infty = O(1)$) as a function of wing span. As the wing span increases from very small (MAVs) to large (civil transport aircraft), the frequency of flow instabilities does not vary much once variations in the wing chord length and flight speed are taken into account. Also shown in Fig. 1 is the qualitative variation of the natural frequency of the wing structure. It decreases substantially with increasing wing span. For a typical civil transport, the structural frequency may be on the order of few Hertz, while typically this quantity is on the order of 10^2 Hertz for micro air vehicles. As illustrated in Fig. 1, structural frequencies and fluid instability frequencies are therefore close to each other for small aircraft. This presents an opportunity to exploit wing vibrations for flow control purposes. For small aircraft, small-amplitude wing vibrations could potentially excite characteristic frequencies of the fluid instabilities.

While one tries to suppress the vibrations for large aircraft because of fatigue and passenger comfort issues, this requirement is not necessary for small aircraft (MAVs), because they have limited (much shorter) life time and no passengers. Thus, exploiting the flexibility of the wing structure to excite the fluid for flow control becomes a possibility at low Reynolds numbers. In practical applications, this technique can be achieved by the torsional (pitching) and bending (plunging) vibrations of flexible wings by means of piezoelectric actuators and/or elastic mounting of rigid wings. For example, if a torsional spring used for mounting is tuned correctly, airfoil/wing oscillations are easier to produce. External excitation at resonant structural frequencies for less power input or self-excited wing vibrations for zero power input can also be considered.

1.2. Small-amplitude high-frequency oscillations

As the main objective is to exploit the fluid–structure interactions for flow control, naturally small-amplitude and high-frequency wing oscillations are relevant. Here we will discuss the range of dimensionless parameters and compare with the biological flows where pitching

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