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MEMS flexible thermal flow sensors for measurement of unsteady flow above a pitching wind turbine blade

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ABSTRACT

MEMS (Micro-Electro-Mechanical System) thermal flow sensors have been applied widely in boundary-layer studies and aerodynamic flow sensing due to high spatial resolutions and fast response times as well as minimal interference with fluid flow. In this study, self-made MEMS thermal flow sensors were designed and fabricated on a flexible skin. The steady laminar separation was investigated on two-dimensional LS (1) 0417 airfoil by using thermal flow sensors at various angles of attack with validation by hot wires and flow visualization. The unsteady flow on the pitching airfoil was experimentally investigated to simulate the dynamic stall condition of VAWT (Vertical Axis Wind Turbine). Based on variations of the mean value and standard deviation of the thermal flow sensor signals, nine stages of unsteady flow developing events are identified with further evidence from flow visualization. As the reduced frequency (k) increases, the incipient transition is delayed to higher angles of attack during the pitch-up motion; the re-laminarization is postponed to lower angles of attack during the pitch-down motion. The hysteresis is more pronounced at higher k where the oscillating time scale plays a more significant role in determining the unsteady flow pattern than the convective time scale. The phase difference between transition and re-laminarization was enlarged from $\Delta\alpha \approx 4.9°$ for $k = 0.009$ to $\Delta\alpha \approx 13.5°$ for $k = 0.027$ at $Re = 6.3 \times 10^4$.

1. Introduction

The fact of strong growth in utilizing wind energy in the past decade stimulates extensive research work in wind turbines nowadays. Studies of the vertical axis wind turbine (VAWT) have attracted a great deal of attention because of their potential applications in urban environments. For instance, installing a small wind turbine on the roof of a building has been explored [1,2]. However, VAWT faces a critical challenge, especially operating in a low tip speed ratio [3]. The angle of attack of the blades will exceed the static stall angle at low tip speed ratio leading to the aerodynamics of VAWT which involves highly unsteady flow fields. Dynamic stall is an inherent phenomenon of the low tip speed ratio impacting on power, loads, and fatigue of the blades [4–6]. Therefore, the unsteady aerodynamic behavior and phenomenon of dynamic stall of VAWT blades represent a challenging subject to be investigated.

Dynamic stall phenomena have attracted a number of studies for years with a wide range of practical applications such as wind turbines, helicopter blade, and mini aviation vehicle. These phenomena are associated with pitch oscillating airfoils have been simulated above practical applications. On the other word, the complex dynamic stall phenomena can be employed in a simplified configuration of pitching airfoil to study its main characteristics [7–9]. Dynamic stall can be considered as delay of flow separation on wings and airfoils caused by rapid variations in the angle of attack beyond the critical static stall angle due to a different type of unsteady motion [10]. The conditions of dynamic stall can be divided into four distinct regimes which are under-stall, stall-onset, light-stall and deep-stall, respectively [7]. Under stall is the regime in which the pitching angle of the airfoil is below the static stall angle. In the stall onset regime, pitching angle of airfoil reaches the static stall angle. It represents the limiting case of the maximum unsteady lift that can be obtained with no significant penalty in pitching moment or drag. This further slightly increase in its pitching angle, the stall condition enters the light stall regime and it develops the first dynamic stall vortex. This vortex is sensitive to the unsteady parameters such as reduced frequency

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and pitching angle. The vertical extent of the viscous area tends to maintain the scale of the airfoil thickness and this is generally less than static stall. In the deep stall regime, pitching amplitude well in excess of the static stall angle begins with the formation of a strong vortex in the leading edge. This vortex sheds from the boundary layer and moves downstream over the upper surface of the airfoil where large amounts of hysteresis occur during the rest of the cycle.

There are a few significant parameters affecting the dynamic stall process, such as reduced frequency, pitching amplitude and geometry of the airfoil [11]. Carr et al. [12] described the dynamic stall phenomenon with sequence events for rapidly pitching NACA 0012 airfoil. From low to moderate pitching motions at the range of $Re = 10^3$ to $Re = 10^5$, the typical flow topologies undergoing dynamic stall are demonstrated in Fig. 1. The dynamic stall development is based on the flow visualizations carried out in the water tunnel by the authors [13]. In general, the dynamic stall angle exceeds the static stall angle [7,8,11].

At the beginning of a pitch upstroke at small angles of attack, the flow field can be described as a typical laminar boundary layer. A small trailing vortex begins to form as the angle of attack increases as shown in Fig. 1(a). As the angle of attack increases, the apparent thickening of the boundary layer occurs. Meanwhile, the trailing vortex grows and propagates upstream as shown in Fig. 1(b). A laminar to turbulent boundary layer transition may occur depending on the pitching rate, the angle of attack [11]. The lift force increases linearly and the center of pressure moves upstream with increasing pitching angles. The region of reversed flow develops with increasing angles of attack and moves toward the leading edge. As shown in Fig. 1(c), multiple clockwise vortices

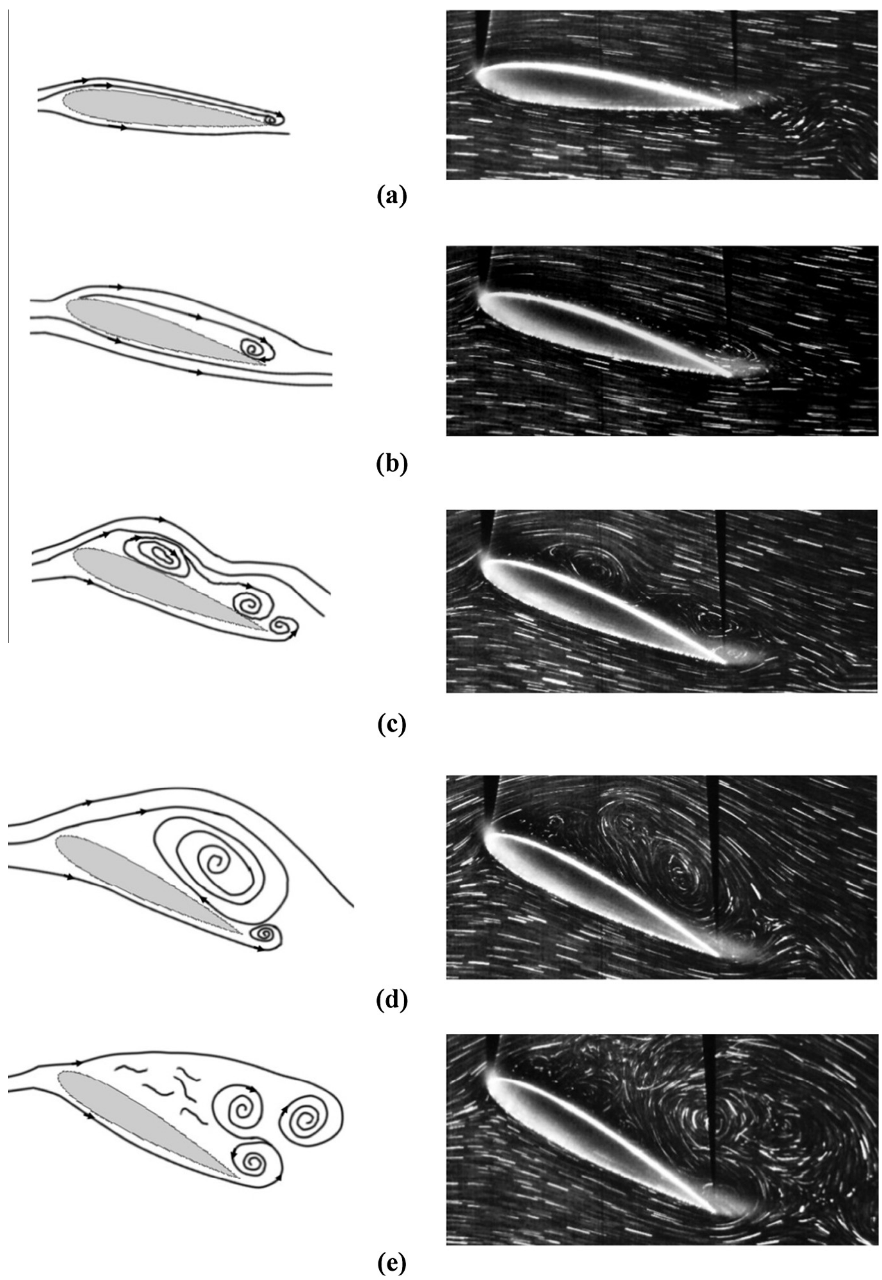

Fig. 1. Flow topologies of pitching airfoil undergoing dynamic stall at the range of Reynolds number. from $Re = 10^3$ to $Re = 10^4$. (a) Laminar boundary layer, (b) trailing vortex growing and moving toward the leading edge, (c) flow reversal with multiple vortices with center of lift moving toward the leading edge, (d) dynamic stall vortex growing and moving downstream and (e) detachment of dynamic stall vortex causing abruptly drop of lift.