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Numerical investigations of the vortex interactions for a flow over a pitching foil at different stages

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The fluid–structure interaction is investigated numerically for a two-dimensional flow ($Re=2.5\cdot10^6$) over a sinusoid-pitching foil by the SST (Shear Stress Transport) k–ω model. Although discrepancies in the downstroke phase, which are also documented in other numerical studies, are observed by comparing with experimental results, our current numerical results are sufficient to predict the mean features and qualitative tendencies of the dynamic stall phenomenon. These discrepancies are evaluated carefully from the numerical and experimental viewpoints.

In this study, we have utilized Λ, which is the normalized second invariant of the velocity gradient tensor, to present the evolution of the Leading Edge Vortex (LEV) and Trailing Edge Vortex (TEV). The convective, pressure, and diffusion terms during the dynamic stall process are discussed based on the transport equation of Λ. It is found that the pressure term dominates the rate of the change of the rotation strength inside the LEV. This trend can hardly be observed directly by using the vorticity transport equation due to the zero baroclinic term for the incompressible flow.

The mechanisms to delay the stall are categorized based on the formation of the LEV. At the first stage before the formation of the LEV in the upper surface, the pitching foil provides extra momentum into the fluid flows to resist the flow separation, and hence the stall is delayed. At the second stage, a low-pressure area travels with the evolution of the LEV such that the lift still can be maintained. Three short periods at the second stage corresponds to different flow patterns during the dynamic stall, and these short periods can be distinguished according to the trend of the pressure variation inside the LEV. The lift stall occurs when a reverse flow from the lower surface is triggered during the shedding of the LEV. For a reduced frequency $k_f=0.15$, the formation of the TEV happens right after the lift stall, and the lift can drop dramatically. With a faster reduced frequency $k_f=0.25$, the shedding of the LEV is postponed into the downstroke, and the interaction between the LEV and TEV becomes weaker correspondingly. Thus, the lift drops more gently after the stall. In order to acquire more reliable numerical results within the downstroke phase, the Large Eddy Simulation (LES), which is capable of better predictions for the laminar-to-turbulent transition and flow reattachment process, will be considered as the future work.

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Nomenclature

Subscript i, j, k, m	Einstein notation [1]
C	Chord length [m]
C_L	Lift force coefficient [1]
C_N	Normal force coefficient [1]
C_p	Pressure coefficient [1]
F_1, F_2	Function in the turbulent model [1]
k	Turbulent kinetic energy [m^2/s^2]
k_f	Reduced frequency [1]
P	Pressure [Pa]
P_t	Turbulent production term [$kg/m/s^3$]
Q	Second invariant of velocity gradient tensor [$1/s^2$]
Λ	Normalized form of Q [1]
Re	Reynolds number [1]
Re_t	Turbulent Reynolds number [1]
S	Strain rate tensor [1/s]
S_C, S_P, S_V	Source terms in transport equation of Λ [1/s]
t	Time [s]
u	x-direction velocity [m/s]
u_i	Velocity in i-direction [m/s]
U	Free stream velocity [m/s]
x	Position [m]
α_1, α^*, β, β^*, σ_k, σ_ω , $\sigma_{\omega 2}$	Coefficient in turbulent model [1]
α	Angle of attack [°]
ρ	Density [kg/m^3]
μ, μ_t	Laminar and turbulent dynamic viscosity [kg/m s]
ν, ν_t	Laminar and turbulent kinematic viscosity [m^2/s]
ω	Specific turbulent dissipation rate [1/s]
ω_f	Angular velocity [1/s]
θ	Azimuthal angle [°]
η	Vorticity [1/s]
τ	Reynolds stress [Pa]

1. Introduction

For a fluid flow past a foil with rapid motions, such as the pitching, plunging, and flapping, the lift force still can be maintained even when the angle of attack (AoA) exceeds the normal static stall angle (Ekaterinaris and Platzer, 1997; Wang et al., 2012). This is so-called dynamic stall. The prediction of the dynamic stall is very important in the aerodynamics of aircraft, helicopter, wind turbine, and turbomachinery.

For maneuverable fighters and helicopter rotors, the vibration, high load, fatigue, and structural failure can be caused due to the unsteadiness of the dynamic stall phenomenon (Carr, 1988; Gompertz et al., 2011; Mulleners et al., 2012a). As for insect flights, the Reynolds number is very low due to their sizes, and hence the lift must be generated by the pitching, plunging, and flapping behaviors. The study of the dynamic stall of insects inspires the development of micro air vehicles (MAV) (Shyy et al., 2013; Kang et al., 2011). Empirical methods are often used in the corresponding industry during 1970s without knowing the details of the flow physics (Gormont, 1973; Harris et al., 1970; Wang et al., 2012). However, recent progress in Computational Fluid Dynamics (CFD) makes it possible to predict the dynamic stall process numerically in the turbomachinery and helicopter industry (Dawes, 2007; Doerffer and Szulc, 2008; Wang et al., 2012).

The formation of the leading edge vortex (LEV) plays an important role for the dynamic stall. During the convection of the LEV, the low-pressure area of the LEV provides extra lift force to delay the stall. When the shedding of LEV takes place, the lift force can drop dramatically. The LEV could interact with the surrounding fluid flow to induce multiple recirculation regions, such as the secondary vortex and trailing edge vortex (TEV) (Ekaterinaris and Platzer, 1997; Leishman, 1990; McAlister et al., 1978; McCroskey et al., 1976; Wang et al., 2010, 2012). The complicated interactions among the LEV, TEV, and secondary vortex could cause difficulties in numerical predictions and experimental measurements. Recently, the force-element method is applied to decompose the aerodynamic force into several components. The vorticity almost dominates the contributions of the lift during the entire stroke, which emphasizes the significance to study the vortex interactions during the dynamic stall (Niu and Chang, 2013). The dynamic stall characteristics could depend on the reduced frequency, the freestream flow condition, the Reynolds number, the Mach number, and the foil shape. These effects will be discussed hereafter in this section.

McAlister et al. (1978) and McCroskey et al. (1976) have experimentally investigated the dynamic stall with different reduced frequencies (k_f=0.05, 0.15 and, 0.25) at Reynolds number=$2.5 \cdot 10^6$ for a NACA0012 foil. As k_f=0.05, the shedding of the LEV and the secondary vortex both occur in the up-stroke, which correspond to two peaks of the lift force during the up-stroke. When k_f increases to 0.15, the shedding of the secondary vortex can be postponed into the down-stroke. The dynamic stall due to the shedding of the LEV typically still happens when AoA approaches its maximum amplitude in the up-stroke. For k_f=0.25, even the dynamic stall can be further delayed into the down-stroke. Recent experiments by Lee and Gerontakos (2004), and Sharma and Poddar (2013) also display the same trends. Similarly, Leishman (1990) has found out that the increasing reduced frequency could delay the onset of the flow separation and dynamic stall to a higher angle for a NACA23012 foil at Re=$1.5 \cdot 10^6$. Only small values of reduced frequency are required to significantly delay the dynamic stall since the flow separation does not have time to develop at this high Reynolds number. Further interactions between the maximum lift and the reduced frequency will be discussed in Section 8.

Gharali and Johnson (2013) have investigated the phase difference between the freestream velocity oscillation and pitching pattern oscillation numerically at Reynolds number ~10^5 for a NACA0012 foil. For in-phase oscillations, the lift