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Dynamic stall control optimization of rotor airfoil via variable droop leading-edge

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ABSTRACT

A novel strategy of dynamic stall control for rotor airfoil via variable droop leading-edge (VDLE) has been conducted based upon the optimization method. As foundations, body-fitted grids around oscillatory rotor airfoil with VDLE are regenerated by solving Poisson equations, and flowfield around airfoil is simulated based on unsteady Reynold averaged Navier–Stokes (URANS) equations. To improve computational accuracy and efficiency, ROE-MUSCL scheme, S–A turbulence model and implicit LU-SGS scheme are adopted. The verified results of VR-12 airfoil indicate that dynamic stall vortex could be remarkably suppressed by VDLE control. Additionally, parametric analyses for dynamic stall control of airfoil indicate that aerodynamic characteristics of an oscillatory airfoil could be significantly improved when non-dimensional frequency (k^*) of VDLE is about 1.0 and mean droop angle (δ_0) and angular amplitude (δ_m) of VDLE are between 2° and 7°. Furthermore, multi-objective optimizations are conducted by employing the surrogate model. The maximum drag and negative moment coefficients of VR-12 airfoil can be reduced by about 79.2% and 81.2% respectively via control of VDLE with $k^* = 1.06$ and $\delta_m(\delta_0) = 8.46°$. By multi-objective optimization, it indicates that "upward" leading-edge at some instant helps to optimize control effects of VDLE on dynamic stall of rotor airfoil.

1. Introduction

To avoid large rolling moment of helicopter in high-speed forward flight, retreating blade of rotor is often operated under large angle of attack (AoA) [1,2], while AoA of blade in advancing side is much lower. The periodic variation of AoA often leads to dynamic stall on retreating side of rotor. Dynamic stall of rotor and airfoil always accompanies with formation of dynamic stall vortex close to the leading-edges in the upstroke motion [3]. The scale of dynamic stall vortex increases rapidly with its convection along suction surface of airfoil, as a result, the lift of rotor airfoil could obtain an extra value comparing to the static maximum lift [4]. However, the aerodynamic forces of rotor airfoil might encounter sudden deteriorations as the vortex sheds off, such as substantial loss of lift and obvious peaks of drag and nose-down moment. Consequently, dynamic stall might bring on excessive vibration load and flutter of rotor, and further limit the operational envelope of airfoil or rotor. Therefore, it has become imperative that the performance of rotor (airfoil) should be enhanced by suppressing or postponing the formation of dynamic stall vortex.

For alleviating dynamic stall of rotor (airfoil), active flow control should be taken into account in the next generation of helicopter [5]. It has been indicated that local curvature of leading-edge is an important area of concern on impacting the intensity and evolution of dynamic stall vortex [6]. Several leading-edge control strategies for postponing airfoil dynamic stall have been proposed and investigated, such as leading-edge slat method [7,8], variable droop leading-edge (VDLE) device [9,10], sharp leading-edge concept [11,12], and rotating leading-edge of airfoil [13]. The leading-edge slat is at the same time a very important element to achieve the necessary high lift performance and the dominant noise source of a high lift system [14], comparing to leading-edge slat, VDLE could significantly reduce the slat noise and recover the losses of high lift system without a slat [15]. Additionally, the sharp leading-edge is a passive control method for post stall control of fixed wing, and the rotating leading-edge might lose its efficiency when flow is compressible. Among these methods, active flow control of VDLE has shown its capability in decreasing large drag and pitching moment of a dynamic airfoil without loss of lift [16,17].

In 1987, Perry et al. [18] experimentally investigated the effectiveness of a droop leading-edge on enhancing aerodynamic characteristics of FX63-137 airfoil at low Reynolds numbers. The

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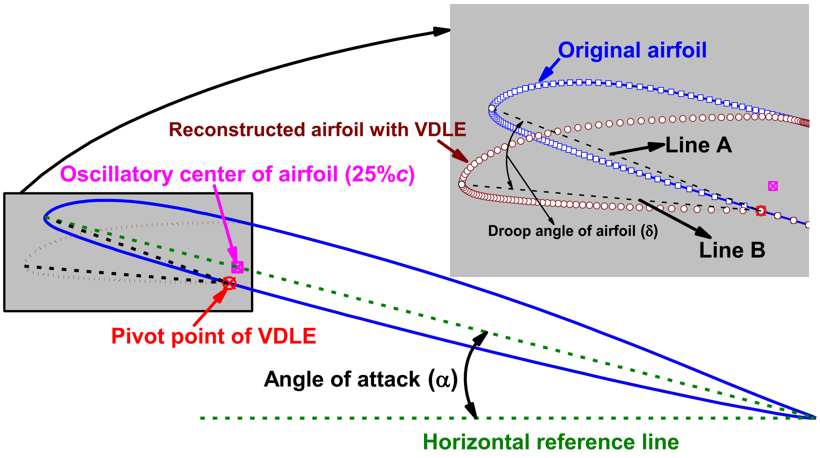

Fig. 1. Sketch of centers for oscillatory airfoil and droop leading-edge.

results showed that a fixed droop leading-edge could increase the maximum lift coefficient and critical angle of FX63-137 airfoil, and the maximum lift coefficient $Cl_{\max}$ of airfoil could be increased by up to 9.2% when the droop angle of leading-edge was 5°. Furthermore, Lee [19] numerically investigated the control effects of a fixed droop leading-edge on airfoil dynamic stall. He indicated that the droop leading-edge could significantly reduce the absolute values of the maximum nose-down moment coefficient $Cm_{\max}$ and the maximum drag coefficient $Cd_{\max}$, and better control effects could be obtained when the droop angle of leading-edge was 20°. For the investigations of dynamic stall control via VDLE, the experimentally and numerically incompressible results of NASA Ames research center [20] indicated that aerodynamic characteristics of airfoil suffered in dynamic stall could be enhanced more effectively by control of VDLE rather than control of fixed droop. By further considering the compressibility of flow, experimental investigations were conducted by Chandrasekhara [21] on airfoil dynamic stall control by using a VDLE. The results showed that VDLE could reduce the absolute values of peak pitching-moment and drag of airfoil more significantly than the fixed droop in the compressible state.

Though VDLE has shown its effectiveness on suppressing dynamic stall vortex of airfoil and further improving performance of airfoil during dynamic stall, the comprehensively parametric analyses of VDLE on delaying dynamic stall of rotor airfoil are still lacking, especially optimal design of VDLE. By now, only the leading-edges with positive drooped angle were considered in the subsequent investigations on parametric analyses of dynamics stall control via VDLE [22–24], nevertheless, the “upward” leading-edge (with the angular amplitude of the VDLE larger than its mean droop angle, resulting in a negative droop angle at some time of the whole period) were not taken into account. Additionally, few works were conducted for optimization of VDLE aiming at achieving better control effects on dynamic stall of rotor airfoil, especially, optimization investigations taking the mean droop angle and angular amplitude of VDLE as independent variables have been not carried out.

In this paper, the comprehensively parametric analyses on dynamic stall control of rotor airfoil via VDLE are carried out, and the optimization of VDLE parameters are further conducted for maximizing its control effects on dynamic stall of rotor airfoil. Based upon reconstruction strategy of airfoil with VDLE and regeneration of grid system, the simulation methods for dynamic stall of rotor airfoil and its control via VDLE are established by solving the URANS equations. To improve the accuracy of the solution, the ROE-MUSCL scheme and S–A turbulence model are adopted for computation of convective and viscous fluxes of URANS equations respectively. The effectiveness of the numerical method is validated by simulation of dynamic stall control of VR-12 airfoil via VDLE, and then systemic analyses on dynamic stall control of VR-12 airfoil via VDLE are conducted by considering different parameters such as non-dimensional frequency, mean droop angle and angular amplitude of VDLE. According to the results of parametric analyses, multi-objective optimizations are further employed to obtain optimal parameters of VDLE for maximizing its control effects on delaying dynamic stall of rotor airfoil in a large Mach number range. Besides, a new control concept is proposed by considering the mean droop angle and angular amplitude of VDLE as independent parameter, and the “upward” leading-edge is introduced when the angular amplitude is greater than the mean droop angle of VDLE. The optimal results could help to expand the investigations on active control for dynamic stall of rotor (airfoil) via VDLE for further applications.

2. Numerical methods

2.1. Reconstruction of surface points on airfoil

To simulate the dynamic stall characteristics of an oscillatory rotor airfoil, only mean AoA α_0 and the 1st-order sinusoidal component of AoA are taken into account for the motion of airfoil, so variation of AoA α is written as

$$\alpha = \alpha_0 + \alpha_m \sin(2kt) \tag{1}$$

where α_m is the amplitude of oscillation, and k is the reduced frequency of rotor airfoil.

For simplification, the pivot point of VDLE is set to a surface point of airfoil, and the droop angle δ varies as

$$\delta = \delta_0 + \delta_m \sin\left(2k^* kt\right) \tag{2}$$

where δ_0 is the mean droop angle of VDLE, and δ_m is the angular amplitude of VDLE variation. It should be noted that the negative value of δ denotes that VDLE is not drooped in the strict sense but “upward” in practice. k^* is the non-dimensional frequency of VDLE with respect to the reduced frequency of the oscillatory rotor airfoil.

As configuration of rotor airfoil is changed due to VDLE, the distribution of airfoil points is reconstructed based on the B-splines interpolation function. Fig. 1 illustrates the schematic for pivot point of VDLE, oscillatory center of airfoil, droop angle of VDLE and AoA of airfoil respectively, and it also shows the distributions of grid points on both original airfoil and airfoil with a VDLE. It is necessary to point out that transient AoA of an airfoil with VDLE