Aerospace Science and Technology 72 (2018) 476–485

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Numerical research on the effect of variable droop leading-edge on oscillating NACA 0012 airfoil dynamic stall

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ARTICLE INFO

Article history:
Received 10 May 2017
Received in revised form 16 November 2017
Accepted 16 November 2017
Available online 22 November 2017

Keywords:
Airfoil
Dynamic stall
Variable droop leading-edge
RBF mesh deformation
Unsteady flow
Numerical simulation

ABSTRACT

Dynamic stall occurs when an airfoil is in unsteady motion and the angle of attack is far beyond the static-stall angle. In dynamic stall, lift and pitching moment will fluctuate in a wide range, and the performance of airfoil will get worse. By using the variable droop leading-edge (VDLE), local angle of attack near the leading-edge dynamically decreases when the overall angle of attack gets too large, then the adverse pressure gradient can be reduced. As a result, the formation of leading-edge vortex will be restricted, as well as the flow separation and dynamic stall. In this paper, two VDLE modes are proposed and a series of investigations are performed on the effect of different modes and parameters on dynamic stall control of NACA 0012 airfoil in pitching oscillation. The unsteady Reynolds-averaged Navier–Stokes equations and γ–Re_θ turbulence model are employed as the governing equations, and the shape modification is realized by the DCP-RBF mesh deformation method. The results suggest that the VDLE modes proposed in this paper can effectively reduce the dynamic stall and significantly improve the aerodynamic characteristics of NACA 0012 airfoil.

1. Introduction

The term dynamic stall means a series of events that result in the dynamic delay of stall. This phenomenon occurs when the airfoil experiences unsteady motion and the angle of attack gets far beyond the static-stall angle of attack [1]. The delay of stall, along with the usually consequent large excursions of lift and pitching moment, remains a challenge in aerodynamic research. On helicopter rotor blades, rapidly maneuvering fixed-wing aircraft, wind turbines and jet engine compressor blades, dynamic stall can happen and becomes a main limiting factor of performance [1]. When the helicopter operates in high-thrust conditions, as a result of the dynamically large angle of attack and the low speed relative to the free stream, dynamic stall occurs on the retreating blade, then the blade torsion moments and thus control loads increase rapidly, which is harmful for flight. Besides, for the fixed-wing aircraft, the aeroelastic flutter and buffet induced unsteady flow separation also limits the operating envelope [2,3].

To overcome the drawbacks of aerodynamic parameter fluctuation, some approaches have been applied to relieve or eliminate dynamic stall, including the application of leading-edge slat [4–6], trailing-edge flap [7,8], synthetic jet/periodic excitation [9–12], plasma actuator [13], vortex generator [14] and dynamically deformed leading-edge (DDLE) [15]. Since the local shape near the airfoil leading-edge has an important influence on the formation and development of dynamic stall vortex [16], it is a more efficient way to change the shape of the leading-edge to eliminate dynamic stall. Active flow control technique based on the variable droop leading-edge (VDLE) device can reduce the local Mach number and improve the pressure distribution near the leading-edge, thus postpones or eliminates the dynamic stall, without compromise of lift [17,18].

Perry et al. [19] carried out researches on the leading-edge droop of the FX63-137 airfoil at low Reynolds numbers. The results showed that drooping the leading-edge 5 degrees could increase the maximum lift coefficient, and the stall angle was substantially increased, as the effective angle of attack of the leading-edge was 5 degrees smaller than the other part of the airfoil. The deflection of the leading-edge could improve the pressure distribution and decrease the adverse pressure gradient thus delay the flow separation. Lee et al. [20] combined the leading-edge droop and the Gurney flap to improve the aerodynamic characteristics of dynamic stall and post stall of a rotor airfoil. The results showed that the dynamic stall was postponed with 20 degrees leading-edge droop and 0.5% chord Gurney flap. Besides, the maximum lift coefficient increased obviously and the magnitude of negative pitching moment reduced, thus the lift-to-drag ratio increased accordingly. Chandrasekhara et al. [21] expanded the leading-edge

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https://doi.org/10.1016/j.ast.2017.11.030

droop to the dynamic situation, and investigated the approach of dynamic stall control via VDLE by experiment. The results showed that the magnitude of dynamic stall vortex was significantly reduced. Large reductions of drag and pitching-moment coefficients, ranging from 50% to 75%, were obtained with acceptable lift coefficients, and the positive damping could eliminate the torsional instabilities. Bain et al. [22] investigated the airfoil VDLE with numerical methods, and found a dramatic reduction of the drag and moment rise associated with dynamic stall. Furthermore, these test results were applied to the UH-60A rotor. Through a numerical approach based on the loosely coupled computational fluid dynamics and comprehensive structural dynamics, a satisfying improvement in the performance and rotor efficient was obtained.

As for VDLE, a comprehensive investigation of different droop modes and parameters remains hardly seen in literature. To restrain the formation and development of leading-edge vortex and flow separation, thus prevent the airfoil from dynamic stall, in the present study, a systematic research is carried out for the dynamic stall control with VDLE on an oscillating NACA 0012 airfoil using unsteady Reynolds-averaged Navier–Stokes equations. Two different droop modes are proposed and investigated with a series of test conditions, and the optimal cases are found. The results suggest that the VDLE modes proposed in this paper can effectively reduce the dynamic stall and significantly improve the aerodynamic characteristics of NACA 0012 airfoil, which can be valuable for some practical engineering applications.

In this paper, firstly, the numerical method is introduced, and a validation is made based on the NACA 0012 airfoil pitching oscillation. The numerical results show well agreement with the experiment, hence a fine credibility can be guaranteed. Then two droop modes and the corresponding parameters are presented. A series of test cases of these two droop modes are studied. Through the analyses and discussions about the results, the optimal cases and some regularities are found. Some useful conclusions are drawn in the end.

2. Numerical methods

2.1. Governing equations and turbulence model

The process of airfoil dynamic stall is an unsteady state, in which flow transition or boundary layer separation may occur. To simulate the time-variant flow field with sufficient accuracy, the dual-time step method is employed, and the unsteady Reynolds-averaged Navier–Stokes equations in the integral form – Eq. (1) are used as the governing equations.

$$\frac{\partial}{\partial \tau}\int \mathbf{W} d\Omega + \frac{\partial}{\partial t}\int \mathbf{W} d\Omega - \oint (\mathbf{F}_c - \mathbf{F}_v) dS = 0 \qquad (1)$$

In Eq. (1), the vector $\mathbf{W}$ contains the conserved variables, $\mathbf{F}_c$ and $\mathbf{F}_v$ are the convective flux item and viscous flux item, respectively. The variables τ and t are the pseudo time and physical time, respectively, and Ω is the volume of mesh cell, S denotes the boundary of the mesh cell.

To solve the flow field around an object with complex geometry, as the direct numerical simulation (DNS) method and large eddy simulation (LES) method are both computationally expensive, the turbulence is usually approximated with a turbulence model in practical engineering applications. The γ–Re_θ model is based on the coupling of shear-stress transportation model and other two transportation equations, one of which is the intermittent factor, and another is the transition onset condition based on the momentum thickness Reynolds number [23,24]. This model is a good compromise of accuracy and robustness that can resolve the flow details from the near wall region to the far field. As a result, the γ–Re_θ model is utilized as the turbulence model in this paper.

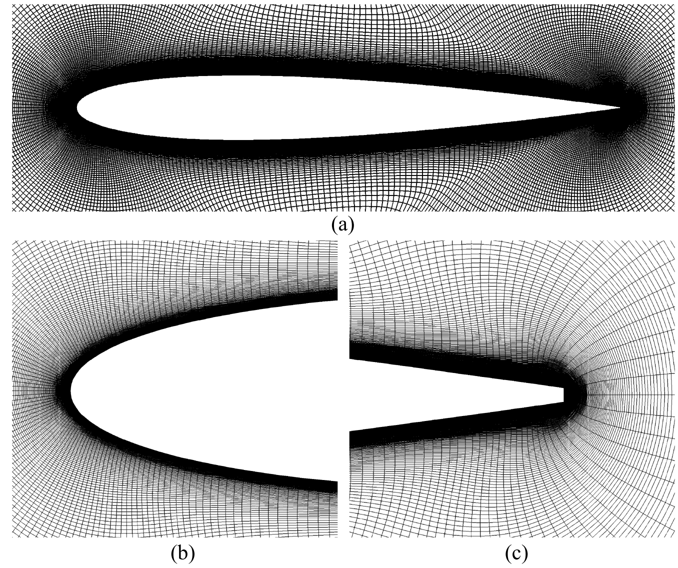

Fig. 1. Structured mesh around the airfoil (a) mesh around the airfoil; (b), (c): close-up views near the leading and trailing-edges.

2.2. Dynamic mesh technique

In the process of airfoil pitching oscillation and dynamic droop of the leading-edge, the location and shape of the airfoil in the computational domain will also change, and the mesh also need to adapt to the changes accordingly. Besides, in consideration of the demand of precisely resolving the dynamic stall process with γ–Re_θ model, the nondimensionalized first cell height y^+ should be kept around 1, hence a reliable mesh deformation method is needed. This requirement can be fulfilled by the DCP-RBF method proposed by Niu et al. [25]. The basic process of RBF mesh deformation method is to interpolate the displacements of the boundary mesh points to the internal mesh points through a radial basis function equation system. After the update of mesh points coordinates, mesh deformation is completed. Based on the RBF method, the DCP-RBF method uses a data-reduced control point set, and this set is dynamically updated in each time step. As a result, fine mesh quality is realized with a compromise of efficiency and robustness.

2.3. Numerical method validation

The validation refers to the experiment of NACA 0012 airfoil dynamic stall in pitching oscillation in Ref. [26]. In the experiment, the free stream Mach number is $Ma_\infty = 0.3$, and the Reynolds number based on the chord length is $Re = 3.86 \times 10^6$. The center of pitching oscillation is the one quarter point on the chord, and the mean angle of attack is $\alpha_0 = 9.96°$, the amplitude is $\alpha_1 = 4.90°$, and the reduced frequency is $k = 0.099$. According to the relationship among the reduced frequency k, the angular frequency ω and the free stream velocity V_∞: $k = \omega c / 2V_\infty$, the oscillation angular frequency is $\omega = 36.72$. Thus the instantaneous angle of attack in the motion is

$$\alpha(t) = \alpha_0 + \alpha_1 \sin(\omega t) = 9.96 + 4.90 \sin(36.72t) \qquad (2)$$

The mesh for calculation is a set of structured mesh of O topology, and the amount of cells is 400 × 350. The first cell height is about 4×10^{-6} times the chord, and the requirement of $y^+ \approx 1$ is fulfilled. The mesh around the airfoil and the close-up views near the leading and trailing-edges are shown in Fig. 1.