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Unsteady aerodynamic characteristics investigation of rotor airfoil under variational freestream velocity

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Numerical investigations based on CFD method have been accomplished to illustrate the unsteady aerodynamic characteristics of the SC1095 airfoil under conditions of coupled freestream velocity/pitching oscillation. In order to simulate the variational freestream velocity of airfoil, the moving-embedded grid method is employed to calculate the fluctuating velocity. The unsteady RANS equations coupling with the dual time-stepping approach are chosen as the governing equations to predict flowfield of airfoil under variational freestream velocity condition. The implicit Lower–Upper Symmetric Gauss–Seidel scheme and Spalart–Allmaras turbulence model are employed to improve the calculation efficiency and accuracy, respectively. Based on the present CFD method, the unsteady aerodynamic characteristics of the airfoil with variational freestream velocity are simulated under conditions of fixed angle and variational angle. The simulated results indicate that the peaks of lift coefficient, drag coefficient and pitching moment coefficient of airfoil are enlarged with the increasing of fluctuating velocity, and the start of airflow reattachment process on airfoil is delayed with the increasing of fluctuating velocities and reduced frequencies due to the effects of the airflow hysteresis and compressibility. Additionally, it is illustrated in the case of different phase angles that these peaks would be reduced by increasing phase angle.

1. Introduction

Due to the coupling of rotation velocity of rotor and forward flight velocity of helicopter in forward flight and maneuver flight, the relative freestream velocity of the rotor blade is a time-varying value for different azimuths of rotor, i.e., the freestream velocity relative to the rotor blade is larger on the advancing side than it is on the retreating side. In order to satisfy the rolling moment requirement of helicopter rotor, the cyclic pitching motion and flapping motion are used in the operation of helicopter. Therefore, the rotor blades work at unsteady environments compared with the fixed-wing aircraft, especially for the conditions of high-speed forward flight and maneuver flight, and a lot of bad influences, such as stall flutter, noise increasing, vibration increasing and so on, are exacerbated by the unsteady aerodynamic characteristics of rotor blade [1,2].

The dynamic stall usually occurs on the retreating blade since the rotor blade operates at higher angle of attack (AoA) in this region, and a lot of investigations have been accomplished to discover the physical characteristics of this phenomenon under the condition of steady freestream velocity, such as that some researchers in NASA have measured the aerodynamic loads of rotor airfoil [3–6], including the lift coefficient (Cl), drag coefficient (Cd), pitching moment coefficient (Cm) and pressure coefficient. With the developments of laser and computer technology, the particle image velocimetry (PIV) method is widely employed to illustrate the characteristics of flowfield structure of airfoil [7,8] under the condition of dynamic stall. In order to effectively overcome the shortcomings of the experiments method, the computational fluid dynamics (CFD) method is gradually used to simulate the unsteady aerodynamic characteristics of rotor airfoil under the dynamic stall condition [9,10] since it has advantages of shorter time consuming, lower cost, broader simulated environment and so on. As a result, at present the aerodynamic characteristics of airfoil under the conditions of dynamic stall with steady freestream velocity are well-studied. However, most of these historical studies seldom took account of the effects of variational freestream velocity on the unsteady aerodynamic characteristics of airfoil.

In order to develop a full understanding of airfoil dynamic stall under the condition of unsteady freestream velocity, Favier [11,12] preliminarily investigated the effects of incidence fluctuations combined with simultaneous velocity oscillations of the incoming airstream on the two-dimensional aerodynamic behavior of NACA0012 by experimental method. Later, Gursul [13,14] mea-

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sured the aerodynamic loads of NACA0012 airfoil under the condition of unsteady stream at a vertical unsteady water tunnel with a cross-sectional area of 45.7 × 45.7 cm. In recent years, Gharali [15] researched the effects of horizontal oscillations of freestream velocity superimposed on a pitch oscillating NACA0012 airfoil by employing the software of ANSYS Fluent under low-speed condition, and it was found that the phase delay between the oscillation of freestream and oscillation of airfoil could affect the formation of leading edge vortex (LEV) and the critical AoA of stall under the condition of dynamic stall coupling with unsteady freestream velocity. Meanwhile, the researchers in the Ohio State University (OSU) conducted some new experiments to measure the aerodynamic characteristics of SSC-A09 airfoil under the condition of coupled freestream velocity/pitch oscillations in unsteady transonic wind tunnel [16,17]. However, due to the restrictions of the wind tunnel or water tunnel, the maximum fluctuating velocity in these experiments is limited, such as in Ref. [16] and Ref. [17], the maximum fluctuating Mach number is 0.08 which is much smaller than the forward flight speed of helicopter. Meanwhile, the measured data in Ref. [17] under the conditions of dynamic stall with steady freestream velocity deviated from the measured data of Lorber [18] due to the three-dimensional (3-D) effects in these experiments. As a result, it could be noticed that the experimental methods still have some shortcomings to investigate the unsteady aerodynamic characteristics of airfoil under the conditions of variational freestream velocity. It is indicated that the variational freestream velocity close to the factual flow environment of the rotor airfoil is still not involved in these conventional investigations. Therefore, it is valuable to study this phenomenon more deeply by numerical simulations.

The purpose of the investigation in this work is to research the effects of variational freestream velocity on the aerodynamic characteristics of airfoil under the factual inflow environment of helicopter. In order to simulate the large fluctuating velocity (close to the actual forward flight velocity of helicopter), the CFD method with the moving-embedded grid method [19,20] is employed to investigate the unsteady aerodynamic characteristics of the SC1095 airfoil under the condition of variational freestream velocity. The fluctuating velocity is simulated by periodically back-and-forth moving the airfoil along the direction of basic freestream velocity. Meanwhile, the variational AoA of airfoil is also accomplished by periodically oscillating around the quarter chord position of airfoil. Based on this grid method, the unsteady RANS equations are chosen as the governing equations to predict the flowfield of airfoil, and the highly-efficient implicit scheme of Lower–Upper Symmetric Gauss–Seidel (LU-SGS) is adopted for temporal discretization. To capture the separated vortex of dynamic stall more accurately, the Spalart–Allmaras (S–A) turbulence model is employed to close the RANS equations. By comparisons of the simulated results with different fluctuating velocities, reduced frequencies and phase delay of variational freestream velocity, some meaningful results have been obtained in this investigation.

2. Numerical simulation method

2.1. Grid generational method

The C-topology computational grid around the SC1095 airfoil is generated by solving the Poisson equations [21], and the governing equations of the grid generation in two-dimensional condition can be written as

$$\begin{cases} \xi_{xx}+\xi_{yy}=P(\xi,\eta) \\ \eta_{xx}+\eta_{yy}=Q(\xi,\eta) \end{cases} \tag{1}$$

where, $P(\xi,\eta)$ and $Q(\xi,\eta)$ denote the control function. The angle between the grid line η of computational space and the boundary can be changed by varying $P(\xi,\eta)$. The space interval between the grid line ξ of computational space and the boundary can be changed by varying $Q(\xi,\eta)$. The discrete governing equations in the computational region can be rewritten as

$$\begin{cases} \alpha x_{\xi\xi}-2\beta x_{\xi\eta}+\gamma x_{\eta\eta}=-J^2(x_\xi p+x_\eta q) \\ \alpha y_{\xi\xi}-2\beta y_{\xi\eta}+\gamma y_{\eta\eta}=-J^2(y_\xi p+y_\eta q) \end{cases} \tag{2}$$

where, α, β and γ are the coefficient of coordinate transformation. The C-topology computational grid with 359 × 80 points and far-field boundary of 25 times of airfoil chord can be generated by iterating these equations. There are 240 control points layout on the upper surface and lower surface of the SC1095 airfoil. The Cartesian grid with 300 × 300 points is used to compose the background grid in this work, and the far-field boundary of the background grid is 50 times of airfoil chord. The hole boundary is identified by employing the Hole Map method, and the Inverse Map method is used to search the donor element [22]. The schematic diagram of the motions of airfoil in background grid is shown in Fig. 1.

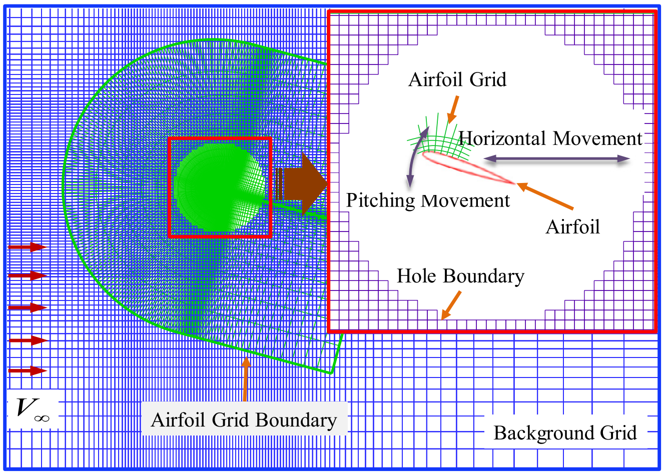

Fig. 1. Schematic diagram of moving-embedded grids.

2.2. CFD method

The integral form of the Navier–Stokes equations is employed to calculate the unsteady compressible flowfield around airfoil, it can be written as

$$\frac{\partial}{\partial t}\iiint_{\Omega}\boldsymbol{W}\,d\Omega+\iint_{\partial\Omega}(\boldsymbol{F}_c-\boldsymbol{F}_v)\,d\boldsymbol{S}=0 \tag{3}$$

where, $\boldsymbol{W}$ represents the vector of conserved variables, $\boldsymbol{F}_c$ denotes the vector of convective fluxes, and $\boldsymbol{F}_v$ denotes the vector of viscous fluxes, as follows

$$\boldsymbol{W}=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho E\end{bmatrix},\quad \boldsymbol{F}_c=\begin{bmatrix}\rho\boldsymbol{V}_r\\ \rho u\boldsymbol{V}_r+n_x p\\ \rho v\boldsymbol{V}_r+n_y p\\ \rho H\boldsymbol{V}_r+\boldsymbol{V}_t p\end{bmatrix},\quad \boldsymbol{F}_v=\begin{bmatrix}0\\ n_x\tau_{xx}+n_y\tau_{xy}\\ n_x\tau_{yx}+n_y\tau_{yy}\\ n_x\Theta_x+n_y\Theta_y\end{bmatrix} \tag{4}$$

where, $\boldsymbol{V}_r=\boldsymbol{V}-\boldsymbol{V}_t$, $\boldsymbol{V}$ denotes the absolute velocity, and $\boldsymbol{V}_t$ denotes the contravariant velocity. ρ, E, p and H represent the density, total energy, static pressure and total enthalpy, respectively. τ_{ij} represent the viscous stresses, and Θ_i are terms describing the work of the viscous stresses and the heat condition in the fluid.

In order to predict the flowfield of rotor airfoil under unsteady condition, the dual time-stepping approach is employed to solve