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Aerodynamic shape optimization for alleviating dynamic stall characteristics of helicopter rotor airfoil

Wang Qing, Zhao Qijun *, Wu Qi

National Key Laboratory of Science and Technology on Rotorcraft Aeromechanics, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

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Abstract In order to alleviate the dynamic stall effects in helicopter rotor, the sequential quadratic programming (SQP) method is employed to optimize the characteristics of airfoil under dynamic stall conditions based on the SC1095 airfoil. The geometry of airfoil is parameterized by the class-shape-transformation (CST) method, and the C-topology body-fitted mesh is then automatically generated around the airfoil by solving the Poisson equations. Based on the grid generation technology, the unsteady Reynolds-averaged Navier-Stokes (RANS) equations are chosen as the governing equations for predicting airfoil flow field and the highly-efficient implicit scheme of lower–upper symmetric Gauss–Seidel (LU-SGS) is adopted for temporal discretization. To capture the dynamic stall phenomenon of the rotor more accurately, the Spalart–Allmaras turbulence model is employed to close the RANS equations. The optimized airfoil with a larger leading edge radius and camber is obtained. The leading edge vortex and trailing edge separation of the optimized airfoil under unsteady conditions are obviously weakened, and the dynamic stall characteristics of optimized airfoil at different Mach numbers, reduced frequencies and angles of attack are also obviously improved compared with the baseline SC1095 airfoil. It is demonstrated that the optimized method is effective and the optimized airfoil is suitable as the helicopter rotor airfoil.

1. Introduction

The motions of helicopter rotor blade include pitching motion, flapping motion, rotation and so on. Therefore the rotor blades work at extraordinary serious unsteady environment compared with the fixed-wing aircraft in normal forward flight, and the aerodynamic characteristics of rotor airfoil are more complex, especially in the maneuvering flight. As a result, a lot of bad influences, such as stall flutter, noise increasing,

* Tel.: +86 25 84893753.
E-mail addresses: mingqingwq@nuaa.edu.cn (Q. Wang), zhaoqijun@nuaa.edu.cn (Q. Zhao).
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vibration increasing sharply, etc. can be aroused by the unsteady characteristics of airfoil dynamic stall.[1] Therefore the dynamic stall characteristics of rotor airfoil have significant influences on the performance of aerodynamics, noise and vibration of helicopter. Therefore, the dynamic stall characteristics of the rotor airfoil have become a hotspot in the field of helicopter unsteady aerodynamics.

Consequentially, it is important to eliminate the dynamic stall effects of airfoil for helicopter rotor. A lot of investigations on the rotor airfoil dynamic stall have been accomplished in the last 40 years in order to understand the underlying unsteady flow physics and airfoil shape dependencies, including experimental researches[2–7] and theoretical researches.[8–11] Recently, the passive and active techniques,[12,13] such as vortex generators, leading edge droop, zero-mass jets and so on, have been successfully used to alleviate the unsteady aerodynamic characteristics. However, most of these schemes are designed at the steady aerodynamic states and the unsteady results are sometimes unpredictable when wind tunnel is tested.[14] What's more, the additional equipment used for active control would be installed in the helicopter blade. As a result, it is inevitable to increase the mass of blade and instability of rotor control system. Therefore, it is useful and important to design a new airfoil to alleviate the dynamic stall characteristics of rotor blades.

With the developments of computer technology in the past 30 years, the computational fluid dynamics (CFD) method has been employed to investigate the dynamic stall characteristics of airfoil.[15–18] Compared with the experimental methods, the CFD method has advantages of shorter time consuming and lower cost. Besides, this method can be used to predict the unsteady flowfield of aircraft. With these advantages, it is possible to quickly predict the dynamic stall characteristics of rotor blades in 2D or 3D conditions. Incorporated with optimization method, the CFD method may be employed to accomplish the optimization of aerodynamic shape of rotor airfoil under dynamic stall conditions.

Currently, the rotor airfoil is usually designed at the typical steady conditions.[19–22] As a result the aerodynamic performances of airfoil at unsteady conditions would have huge differences compared with steady states. In order to obtain a better unsteady aerodynamic performances of airfoil applied in the actual environment of helicopter rotor, the sequential quadratic programming (SQP) optimizing method incorporated with unsteady CFD method has been established in this paper to design a new rotor airfoil based on SC1095 airfoil aimed at alleviating the dynamic stall characteristics of rotor airfoil, especially to reduce the peaks of drag coefficient and pitching moment coefficient. Finally, a new airfoil suitable for the helicopter rotor has been designed. Compared with the baseline airfoil, the optimized airfoil has mild dynamic stall characteristics of drag coefficient and pitching moment coefficient at different Mach numbers, reduced frequencies and angles of attack.

2. Numerical method

2.1. Method of optimization

Because the computational cost of unsteady optimization of rotor airfoil is enormous, the choice of optimized method would be the key point in the process of optimization. Besides, the optimized method should be capable of dealing with the multiple constraint conditions. As a result, the SQP method[23] which is based on the gradient algorithm is employed in this paper to accomplish the optimized design process for rotor airfoil under the dynamic stall condition. The problem of optimization can be summarized as the form of nonlinear programming problem:

$$\begin{aligned} &\min \quad f(\boldsymbol{x}_n) \\ &\text{s.t.} \quad c_i(\boldsymbol{x}_n) \geqslant 0 \end{aligned} \tag{1}$$

where the vector of $\boldsymbol{x}_n$ denotes design variables which would be obtained from the parameters of the class-shape-transformation (CST) method. The subscript of n denotes the circulation of optimization. The subscript of i denotes the number of constraint condition. The purpose of the optimized case presented in this paper is to alleviate the divergence of the drag coefficient and pitching moment coefficient during the dynamic stall cycle while keeping the hysteresis loop of lift coefficient not being deviated from the original values of lift coefficient too much. As a result, the objective function and constraint conditions would be defined as

$$\begin{aligned} &\min \lg\left(\sum_{i=1}^{N}|C_{Di}|\right)+\lg\left(\sum_{i=1}^{N}|C_{mi}|\right) \\ &\text{s.t.}\begin{cases} \displaystyle\sum_{i=1}^{N}\left|\frac{2\pi\alpha}{\beta}-C_{Li}\right|-\sum_{i=1}^{N}\left|\frac{2\pi\alpha}{\beta}-C_{L0i}\right| \geqslant 0 \\ 0.95T_0^{\max} \leqslant T^{\max} \leqslant 1.05T_0^{\max} \end{cases} \end{aligned} \tag{2}$$

where $\beta=\sqrt{1-Ma^2}$; C_L, C_D and C_m represent the time variant lift coefficient, drag coefficient and pitching moment coefficient during each step of a dynamic stall cycle; $T^{\max}$ denotes the maximum thickness of rotor airfoil, subscript "0" the original airfoil, α the angle of attack of airfoil during the pitching cycle and N the number of physical time step in each dynamic stall cycle.

According to the Lagrange function, this nonlinear programming problem in Eq. (1) can be rewritten as a quadratic programming problem, i.e.,

$$\begin{aligned} &\min \quad \frac{1}{2}\boldsymbol{d}^{\mathrm{T}}\boldsymbol{B}\boldsymbol{d}+\nabla f(\boldsymbol{x}_n)^{\mathrm{T}}\boldsymbol{d} \\ &\text{s.t.} \quad \nabla c(\boldsymbol{x}_n)^{\mathrm{T}}\boldsymbol{d}+c(\boldsymbol{x}_n) \geqslant 0 \end{aligned} \tag{3}$$

where the vector of $\boldsymbol{d}$ denotes the search direction and it can be obtained by solving the quadratic programming problem in Eq. (3); $\boldsymbol{B}$ is the approximation of Hessen matrix and it would be renewed at each cycle of optimization. Finally, the new design variables can be calculated by

$$\boldsymbol{x}_{n+1}=\boldsymbol{x}_n+\sigma\boldsymbol{d} \tag{4}$$

where σ denotes the step length and it would be solved by using one-dimension searching. As a result, the new airfoil would be formed through these design variables.

2.2. CFD method for unsteady flowfield

The C-topology computational grid around rotor airfoil is generated by solving the Poisson equations. The control equations of the grid generation in two-dimension condition can be written as

$$\begin{cases} \xi_{xx}+\xi_{yy}=P(\xi,\eta) \\ \eta_{xx}+\eta_{yy}=Q(\xi,\eta) \end{cases} \tag{5}$$