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Parametric analyses for synthetic jet control on separation and stall over rotor airfoil

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Abstract Numerical simulations are performed to investigate the effects of synthetic jet control on separation and stall over rotor airfoils. The preconditioned and unsteady Reynolds-averaged Navier–Stokes equations coupled with a $k-\omega$ shear stream transport turbulence model are employed to accomplish the flowfield simulation of rotor airfoils under jet control. Additionally, a velocity boundary condition modeled by a sinusoidal function is developed to fulfill the perturbation effect of periodic jets. The validity of the present CFD procedure is evaluated by the simulated results of an isolated synthetic jet and the jet control case for airfoil NACA0015. Then, parametric analyses are conducted specifically for an OA213 rotor airfoil to investigate the effects of jet parameters (forcing frequency, jet location and momentum coefficient, jet direction, and distribution of jet arrays) on the control effect of the aerodynamic characteristics of a rotor airfoil. Preliminary results indicate that the efficiency of jet control can be improved with specific frequencies (the best lift-drag ratio at $F^{+} = 2.0$) and jet angles (40° or 75°) when the jets are located near the separation point of the rotor airfoil. Furthermore, as a result of a suitable combination of jet arrays, the lift coefficient of the airfoil can be improved by nearly 100%, and the corresponding drag coefficient decreased by 26.5% in comparison with the single point control case.

1. Introduction

The retreating blades of a rotor are usually manipulated with large pitch angles. Therefore, flow separation and dynamic stall occur frequently during the forward flight of a helicopter. The dynamic stall of retreating blades is one of the typical unsteady aerodynamic characteristics of a helicopter rotor, and it induces the loss of lift, the increase of drag and pitching moment of the rotor, which significantly impacts the aerodynamic performance of a helicopter, threatening the stability of the rotor and restricting the speed envelope of the helicopter. Strategies for delaying the flow separation and stall of the rotor (airfoil) and further extending the post stall envelope of the rotor (airfoil) have been an active topic in the field of helicopter technology for many years. The active flow control (AFC) method is a new approach in improving the aerodynamic characteristics of the rotor (airfoil), and is considered one of the innovative technologies for the next generation of

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rotorcraft.[1] Furthermore, AFC has the potential to significantly improve the aerodynamic characteristics of airfoils without any deflecting control surfaces, which helps to retain a minimum radar cross section.

Recently, a novel method of AFC by using synthetic jet actuators has been experimentally demonstrated to be one of the most promising AFC methods, especially for rotary wing aircraft.[2] It is because the synthetic jet actuator generates a high-frequency jet from the flow with zero net mass injection. The synthetic jet actuator was manufactured by Smith and Glezer in 1994. A synthetic jet is created by driving one side of a cavity using a piston or piezoelectric diaphragm in a periodic manner, and the jet is synthesized by the interactions of counter rotating vortex pairs formed at the edge of an orifice.[3] The fluid driven out of the cavity forms a shear layer between the expelled fluid and the surrounding fluid. This layer of vorticity rolls up to form two parallel vortices in the case of a rectangular actuator. By the time the diaphragm begins to move away from the orifice to pull the fluid back into the cavity, the vortices have moved far away enough. Thus a train of vortex pairs are created by the actuator. Therefore, a synthetic jet requires no mass injection, but only electrical power. It is feasible for the flow control on the rotor and airfoil. Many experimental and numerical results demonstrate that a synthetic jet with appropriate combinations of parameters can reattach the separation flow over the rotor airfoils or delay its separation,[1,4–10] resulting in improving the aerodynamic characteristics of airfoils and delaying stall by enlarging the stall angle.

Seifert et al. carried out active flow control experiments on a NACA 0015 airfoil by placing a synthetic jet actuator at the leading edge,[11] and the results indicated that a jet placed just upstream of the separation location was effective on controlling the flow separation of an airfoil. In the aspect of numerical simulations for synthetic jet control, Donovan et al. used Reynolds-averaged Navier–Stokes (RANS) equations to investigate the effect of synthetic jet on the flowfield of an airfoil just according to the experiments,[12] and good agreements were obtained between the numerical results and the test data. The results give us the confidence that the RANS approach can be used to investigate the active flow control on rotor airfoils by using unsteady synthetic jets. Lorber et al. conducted numerical and experimental investigations on avoiding or delaying retreating blade stalls by a directed synthetic jet (DSJ) over helicopter rotor airfoil SC2110.[13] The results indicated that the DSJ was valuable on controlling the post and dynamic stall of a rotor retreating blade. Kim et al. numerically investigated the flow control using a synthetic jet to improve the aerodynamic performance of tiltrotor airfoils under various flight conditions,[14] and the calculated results revealed that the download could be efficiently reduced by using both the leading edge and trailing edge jets in the hovering flight mode.

Although the synthetic jet has a good potential in applications for active flow control on rotors and airfoils, there are some problems that have not been resolved.[15] The interactions of jet vortex pairs with low speed and viscous boundary layer are still not very clear yet, and the applications of the synthetic jet on a rotor airfoil still remain theoretical because of the large number of controlling parameters,[16] such as actuator location, forcing frequency, blowing magnitude and direction, etc. Additionally, there are some disagreements among different references. For example, He et al. pointed out that the synthetic jet was not sensitive to the blowing directions,[16] while Hassan considered that the synthetic jet had the best performance when the jet angle was about 25°.[17] Furthermore, the numerical conclusions of Hassan preliminarily indicated that a jet array with two synthetic jet actuators could help improve the benefits of the enhancement of aerodynamic characteristics for rotor airfoils.[17] However, the research work only involved a two point AFC control with the actuators at a fixed location, while the control mechanism of synthetic jet arrays at various locations and with more than two actuators has not been taken into consideration.

This paper aims at obtaining in depth the effects of several parameters (especially jet angle and jet array) about the synthetic jet on the control efficiency of the aerodynamic characteristics of a rotor airfoil (measured by the increment or decrement rates of the aerodynamic forces of the rotor airfoil under control compared with the baseline case or a specified jet controlled case). Quite a number of numerical simulations have been conducted to investigate the effects of synthetic jet control on the separation and stall over rotor airfoils. To improve the accuracy of prediction on low speed flow induced by a synthetic jet with strong adverse pressure gradients and pressure-induced boundary layer separation, preconditioned RANS equations and a $k-\omega$ shear stream transport (SST) turbulent model are adopted to investigate the characteristics of the synthetic jet and the effectiveness of periodic jet control on the separation and post-stall for rotor airfoils. The feasibility and efficiency of this method are evaluated and demonstrated. Then, based on the present method, parametric analyses of synthetic jet control for rotor airfoil OA213 are carried out to study the control mechanism of the synthetic jet on the aerodynamic characteristics of the rotor airfoil, and some significant conclusions are obtained.

2. Numerical methods

2.1. Governing equations

Based on the CFD method developed by the author of this paper,[18] and to overcome the stiffness of the solution system and improve the computational efficiency when the local Mach number is low, flows around a rotor including unsteady perturbations induced by a synthetic jet are simulated by solving the unsteady preconditioned RANS equations. The preconditioned Navier–Stokes equations in a control volume Ω in the integral form by using pressure p, flow velocity u, v, and temperature T as parameters $\boldsymbol{W} = [p, u, v, T]^{\mathrm{T}}$, can be written as

$$\boldsymbol{\Gamma}\frac{\partial}{\partial t}\int \boldsymbol{W}\mathrm{d}\Omega + \oint(\boldsymbol{F}-\boldsymbol{F}_{\mathrm{v}})\cdot\boldsymbol{n}\mathrm{d}S = 0 \tag{1}$$

where $\boldsymbol{F}$, $\boldsymbol{F}_{\mathrm{v}}$ denote respectively the vectors of convective and viscous fluxes, $\boldsymbol{n}$ is the unit vector normal to surface element $\mathrm{d}S$, $\boldsymbol{\Gamma}$ the preconditioning matrix, and the Weiss–Smith matrix is employed in this paper.[19]

$$\boldsymbol{\Gamma} = \begin{bmatrix} \Theta & 0 & 0 & \rho_T \\ \Theta u & \rho & 0 & \rho_T u \\ \Theta v & 0 & \rho & \rho_T v \\ \Theta H - 1 & \rho u & \rho v & \rho c_p + \rho_T H \end{bmatrix} \tag{2}$$