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Numerical study of separation on the trailing edge of a symmetrical airfoil at a low Reynolds number

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Abstract This study focuses on the trailing-edge separation of a symmetrical airfoil at a low Reynolds number. Finite volume method is adopted to solve the unsteady Reynolds-averaged Navier–Stokes (RANS) equation. Flow of the symmetrical airfoil SD8020 at a low Reynolds number has been simulated. Laminar separation bubble in the flow field of the airfoil is observed and process of unsteady bubble burst and vortex shedding from airfoil surfaces is investigated. The time-dependent lift coefficient is characteristic of periodic fluctuations and the lift curve varies nonlinearly with the attack of angle. Laminar separation occurs on both surfaces of airfoil at small angles of attack. With the increase of angle of attack, laminar separation occurs and then reattaches near the trailing edge on the upper surface of airfoil, which forms laminar separation bubble. When the attack of angle reaches certain value, the laminar separation bubble is unstable and produces two kinds of large scale vortex, i.e. primary vortex and secondary vortex. The periodic processes that include secondary vortex production, motion of secondary vortex and vortex shedding cause fluctuation of the lift coefficient. The periodic time varies with attack of angle. The secondary vortex is relatively stronger than the primary vortex, which means its influence is relatively stronger than the primary vortex.

1. Introduction

Low-Reynolds-number aerodynamics is very important for both military and civilian applications. Typical applications are wind turbines, remotely piloted vehicles, sailplanes, human powered vehicles, high altitude devices.[1–3] Recently, there is an increasing interest in the unmanned aerial vehicles (UAVs) and micro air vehicles (MAVs), which demands a deep and wide research on the aerodynamics of two-dimensional airfoils and three-dimensional wings.

It is well-known that many significant aerodynamics problems occur below chord Reynolds numbers of about 5×10^5. Compared to high Reynolds numbers, low Reynolds number aerodynamics is quite different. At high Reynolds numbers, the lift curve for airfoil is nearly linear with a slope of 2π. However, for low Reynolds numbers less than 5×10^5, the nonlinear features in the lift curve about 0° angle of attack (AOA) emerge for symmetrical airfoils; the maximum lift-to-drag ratio of airfoil deteriorates rapidly when the chord Reynolds numbers decrease in the vicinity of 5×10^5; besides, hysteresis

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can be seen in the lift characteristics of some airfoils at low Reynolds numbers.

Characteristics of laminar separation at low Reynolds numbers have been widely studied by analytical, experimental and computational methods for decades. From analytical and experimental aspects, Lissaman[4] gave a common review on the low Reynolds numbers airfoil aerodynamics from different perspectives such as the concept of low Reynolds numbers airfoil, fundamental fluid mechanics, experimental testing and theoretical design of airfoils. Horton[5] combined theoretical and experimental method to study the short type of bubble in two and/or three dimensional flow around airfoil and/or wing at low Reynolds numbers. He developed a semi-empirical theory for the prediction of the growth and bursting of two-dimensional short bubble and put an emphasis upon the conditions governing reattachment. Selig et al.[6,7] conducted tests on 34 different airfoils at low Reynolds numbers and acquired the lift and drag data of different airfoils at low Reynolds numbers. He analyzed the phenomena of the laminar separation bubble and its effects on the lift characteristics. He found a plateau in the lift curve of symmetrical airfoils in the vicinity of an angle of attack of 0° to be common in the Re range of 4×10^4 to 1×10^5. He also found hysteresis loops in the lift curve for some airfoils and considered whether counterclockwise or clockwise hysteresis loop can occur for a given Re. Yang et al.[8] conducted an experimental study on the aerodynamic characteristics of GA (W)-1 airfoil and investigated the aerodynamic hysteresis of airfoil at a low Reynolds number. Mueller and Batill[9] investigated the separation on a two-dimensional NACA66-018 airfoil using smoke visualization method and classified it as the leading-edge separation bubble. From simulation aspects, Refs. [10,11] simulated the flow around a two-dimensional airfoil and observed periodic vortex shedding. Lee et al.[12] classified airfoils according to the type of pattern shown by its corresponding lift coefficient curve and explained the reasons contributing to the abnormal behavior of the lift curves for various airfoils using computational fluid dynamics (CFD). Bai et al.[13,14] conducted a simulation on the flow around symmetrical and non-symmetrical airfoil at low Reynolds number and proposed a trailing-edge separation bubble model. He applied the model to explain the aerodynamic characteristics of the symmetrical airfoil at small angle of attack under low Re and mechanism of the nonlinear effect in the lift curve at small angle of attack. Ye et al.[15,16] carried out a direct numerical simulation (DNS) on the separation mechanism of two-dimensional airfoil and described the rules of vortex interaction. Zhang and Yang[17] simulated the unsteady two-dimensional low Reynolds number flow over Epper387 airfoil with an unsteady RANS solver and the transition point is fixed for different turbulence models. He also analyzed the effect of transition on the low-Reynolds-number flow. Sheng[18] discussed the characteristics of four types of airfoils with analytical, computational and experimental method and gave some suggestions on the shapes of airfoils at low Reynolds numbers. The present paper conducts a numerical simulation on the flow around a symmetrical SD8020 airfoil and studied the trailing-edge separation bubble mechanism by analyzing the flow field structure and surface pressure distribution. The shedding process of the vortex of the symmetrical airfoil is analyzed and the pattern of vortex shedding is also given.

2. Computation scheme

2.1. Governing equation

For the two-dimentional, unsteady and incompressible flow, we consider that the governing equations are the RANS equations without the gravity and the body force items in Cartesian tensor form:

$$\begin{cases} \frac{\partial u_i}{\partial x_i} = 0 \\ \frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + v\frac{\partial^2 u_i}{\partial x_j \partial x_j} - \frac{\partial \overline{u_i' u_j'}}{\partial x_j} \end{cases} \tag{1}$$

where u_i is the mean velocity, v the kinematic viscosity of the air, ρ the density of air, p the pressure, and $-\overline{u_i' u_j'}$ the Reynolds stress.

2.2. Turbulence model

The shear stress transport (SST) k-ω turbulence model[19] is a two-equation turbulence model which can precisely predict adverse pressure gradient flows and airfoil flows. It effectively combines the robust and accurate formulation of the k-ω model in the near-wall region with the free-stream independence of the k-ε model in the far field.

$$\begin{cases} \frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\Gamma_k \frac{\partial k}{\partial x_j}\right) + \widetilde{G_k} - Y_k \\ \frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho \omega u_i) = \frac{\partial}{\partial x_j}\left(\Gamma_\omega \frac{\partial \omega}{\partial x_j}\right) + G_\omega - Y_\omega + D_\omega \end{cases} \tag{2}$$

where $\widetilde{G_k}$ represents the generation of turbulence kinetic energy due to mean velocity gradients and G_ω the generation of ω, Γ_k and Γ_ω represent the effective diffusivity of k and ω, respectively, Y_k and Y_ω represent the dissipation of k and ω due to turbulence, D_ω represents the cross-diffusion term.

In order to simulate transition from laminar to turbulence, a low-Reynolds-number correction is used by which three closure coefficients α^*, α, β^* are added to the turbulent viscosity μ_t, G_ω and Y_k when the k-ω model is activated in the near-wall region.

$$\mu_t = \alpha^* \rho k / \omega \tag{3}$$

$$G_\omega = \alpha \frac{\omega}{k} \cdot \tau_{ij} \frac{\partial u_j}{\partial x_j} \tag{4}$$

$$Y_k = \rho \beta^* k \omega \tag{5}$$

For detailed information about the low-Reynolds number correction method in the k-ω model, readers can refer to Ref. [20].

2.3. Model, grid and boundary conditions

The present paper conducts a simulation on the flow around the SD8020 airfoil. The model and the established Cartesian coordinate are shown in Fig. 1(a). The airfoil is symmetrical and smooth, with its chord length c = 0.3048 m.

A C-type mesh generated by elliptical method is adopted to discrete the flow field of the airfoil. The C-type grid constitutes 82000 nodes with 290 grid points on the airfoil surface and the external computational boundaries are set to be 20c from the airfoil. The partial mesh of the domain is shown in Fig. 1(b). The height of the first row of the cells bounding the airfoil is