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Mechanism of unconventional aerodynamic characteristics of an elliptic airfoil

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Abstract The aerodynamic characteristics of elliptic airfoil are quite different from the case of conventional airfoil for Reynolds number varying from about 10^4 to 10^6. In order to reveal the fundamental mechanism, the unsteady flow around a stationary two-dimensional elliptic airfoil with 16% relative thickness has been simulated using unsteady Reynolds-averaged Navier–Stokes equations and the $\gamma - \overline{Re_{\theta t}}$ transition turbulence model at different angles of attack for flow Reynolds number of 5×10^5. The aerodynamic coefficients and the pressure distribution obtained by computation are in good agreement with experimental data, which indicates that the numerical method works well. Through this study, the mechanism of the unconventional aerodynamic characteristics of airfoil is analyzed and discussed based on the computational predictions coupled with the wind tunnel results. It is considered that the boundary layer transition at the leading edge and the unsteady flow separation vortices at the trailing edge are the causes of the case. Furthermore, a valuable insight into the physics of how the flow behavior affects the elliptic airfoil's aerodynamics is provided.

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1. Introduction

As the elliptic airfoil is applied on canard rotor/wing (CRW) aircraft,[1,2] more and more attention has been paid to the performance of this kind of airfoil in relatively low-Reynolds-number flows in recent years. In practice, people are especially interested in the elliptic airfoil with relatively large thickness. Kwon and Park[3] conducted an experimental study of flow over an elliptic airfoil with 16% relative thickness for the Reynolds number of 3×10^5 and found that its aerodynamic characteristics were very different from the case of conventional airfoil. Furthermore, in order to examine the influence of the Reynolds numbers, Zhan et al.[4] performed a series of experimental studies of flow over the same elliptic airfoil for a range of Reynolds number from 5×10^5 to 2.5×10^6 in the low speed wind tunnel in Northwestern Polytechnical University, by varying the wind speed from 10 m/s to 50 m/s. They also found the unconventional aerodynamic characteristics of elliptic airfoil at the Reynolds number of 5×10^5. Firstly, lift coefficient C_L increased nonlinearly with the angle of attack α, while at small angles of attack, the lift increased fast as α increased; secondly, unlike the conventional symmetrical airfoil, the minimum drag coefficient C_D was obtained at $\alpha = 4°$ rather than

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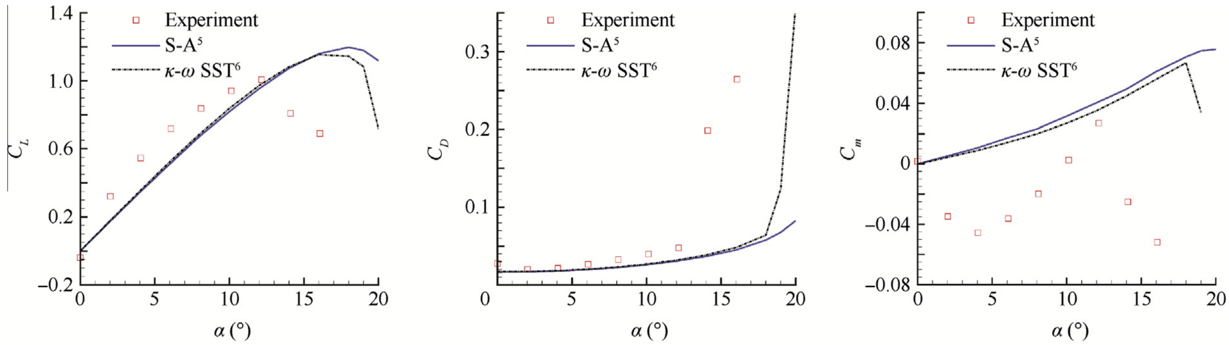

(a) Lift coefficients (b) Drag coefficients (c) Pitching moment coefficients

Fig. 1 Predicted lift, drag and pitching moment coefficients using fully-turbulent computations against experimental data.

$\alpha = 0°$; thirdly, the variation of the pitching moment about the quarter chord was very irregular and severe and two inflection points were found in the pitching moment coefficient C_m curve. The numerical results obtained from Reynolds-averaged Navier–Stokes (RANS) equations coupled with S–A[5] and κ–ω shear stress transport (SST)[6] fully turbulence models show apparent discrepancies compared with experimental data, which can be seen clearly in Fig. 1. It indicates that these unconventional aerodynamic characteristics are difficult to capture using traditional method.

The flow separation commonly occurs in engineering practices.[7] In aviation, the designers always try to avoid separation or control it on aircraft surface.[8] The flow past an elliptic airfoil has been studied as a typical example of flows around blunt body since a long time ago because of its significance in fundamental flow physics. Many studies have been accomplished, some of which are experimental,[9,10] while the majority of which are numerical and mostly at low Reynolds numbers.[11–13] Unlike general airfoils, the typical characteristic of an elliptic airfoil is the blunt trailing edge, which can cause flow separation and vortex shedding to form Karman vortex street aft of the airfoil. At small angles of attack, the boundary layer is primarily laminar over the airfoil surface, but as α increases, the laminar separation bubble[14–16] may form near the leading edge on the suction surface of the airfoil, which will result in laminar–turbulent transition. Fig. 2 shows a schematic diagram of the typical flow field structure of an elliptic airfoil. The flow separation near the blunt trailing edge and the transition inside the boundary layer have a great influence on the flow field and aerodynamic characteristics of elliptic airfoil and also pose huge challenges for computational fluid dynamics (CFD) simulation.

In order to reveal the mechanism of unconventional aerodynamic characteristics exhibited by the elliptic airfoil, a numerical simulation method is established by solving the two-dimensional compressible unsteady Reynolds-averaged Navier–Stokes (URANS) equations. A four-equation transition-sensitive turbulence model is used to close the governing equations. Numerical simulations have been performed on an elliptic airfoil with 16% relative thickness for the Reynolds number of 5×10^5. Combining with the experimental data from wind tunnels, the unconventional aerodynamic characteristics are investigated.

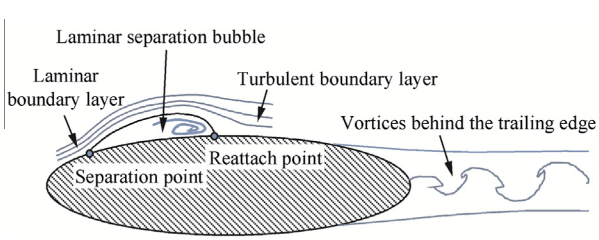

Fig. 2 Schematic of flow field of elliptic airfoil.

2. Computation scheme

2.1. Governing equation

In order to simulate the unsteady vortices in the flow field, the two-dimensional compressible URANS equations are chosen as the governing equations. The non-dimensional form of the equations in Cartesian coordinates can be written as follows:

$$\frac{\partial \boldsymbol{Q}}{\partial t} + \frac{\partial(\boldsymbol{E} - \boldsymbol{E}_{\text{v}})}{\partial x} + \frac{\partial(\boldsymbol{F} - \boldsymbol{F}_{\text{v}})}{\partial y} = 0 \quad (1)$$

where $\boldsymbol{Q} = [\rho, \rho u, \rho v, e]^{\text{T}}$ denotes the conservative variables, ρ, u, v, e denote density, components of velocity vector and total energy per unit volume respectively, $\boldsymbol{E}, \boldsymbol{F}$ denote the convective flux while $\boldsymbol{E}_{\text{v}}, \boldsymbol{F}_{\text{v}}$ denote the viscous flux, whose detailed expressions are

$$\begin{cases} \boldsymbol{E} = [\rho u, \rho u^2 + p, \rho uv, (e+p)u]^{\text{T}} \\ \boldsymbol{F} = [\rho v, \rho uv, \rho v^2 + p, (e+p)v]^{\text{T}} \\ \boldsymbol{E}_{\text{v}} = [0, \tau_{xx}, \tau_{xy}, \theta_x]^{\text{T}} \\ \boldsymbol{F}_{\text{v}} = [0, \tau_{yx}, \tau_{yy}, \theta_y]^{\text{T}} \end{cases} \quad (2)$$

The viscous shear stress τ and the heat fluxes θ are in the form of

$$\begin{cases} \tau_{xx} = 2\mu u_x - \frac{2}{3}\mu(u_x + v_y) \\ \tau_{xx} = 2\mu v_y - \frac{2}{3}\mu(u_x + v_y) \\ \tau_{xy} = \tau_{yx} = \mu(u_x + v_y) \\ \theta_x = u\tau_{xx} + v\tau_{xy} + \kappa T_x \\ \theta_y = u\tau_{yx} + v\tau_{yy} + \kappa T_y \end{cases} \quad (3)$$

where κ is the coefficient of thermal conductivity and the total viscosity μ is calculated as $\mu = \mu_{\text{l}} + \mu_{\text{t}}$, where μ_{l} is molecular viscosity calculated by Sutherland law and μ_{t} is eddy viscosity determined by turbulence model.

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