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Effects of relative thickness on aerodynamic characteristics of airfoil at a low Reynolds number

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Abstract This study focuses on the characteristics of low Reynolds number flow around airfoil of high-altitude unmanned aerial vehicles (HAUAVs) cruising at low speed. Numerical simulation on the flows around several representative airfoils is carried out to investigate the low Reynolds number flow. The water tunnel model tests further validate the accuracy and effectiveness of the numerical method. Then the effects of the relative thickness of airfoil on aerodynamic performance are explored, using the above numerical method, by simulating flows around airfoils of different relative thicknesses (12%, 14%, 16%, 18%), as well as different locations of the maximum relative thickness (x/c = 22%, 26%, 30%, 34%), at a low Reynolds number of 5×10^5. Results show that performance of airfoils at low Reynolds number is mainly affected by the laminar separation bubble. On the premise of good stall characteristics, the value of maximum relative thickness should be as small as possible, and the location of the maximum relative thickness ought to be closer to the trailing edge to obtain fine airfoil performance. The numerical method is feasible for the simulation of low Reynolds number flow. The study can help to provide a basis for the design of low Reynolds number airfoil.

1. Introduction

High-altitude unmanned aerial vehicles (HAUAVs) develop rapidly with the gathering attention of the near space flight platform in recent years. The HAUAVs cruise in the near space and have been advanced to enable higher operational altitudes, longer durations with greater payloads and increased autonomy. The atmosphere there has low density and high viscosity, which leads to the aerodynamics problem at low Reynolds number *Re* (generally less than 1 million).

As early as the 1900s, researchers found that flows behave in strange ways at Reynolds number below 1 million, compared with high Reynolds number. In low Reynolds number regime, the lift curve of symmetrical airfoil around the angle of attack of 0° acts undesirable peculiar nonlinear features. Some other airfoils produce a different type of hysteresis loop in the lift and drag forces.[1,2] Laminar separation bubble (LSB) shown in Fig. 1, which was presented by Horton in 1968, characterizes the low Reynolds number airfoil aerodynamics.[3] The bubble involves the separation of the laminar boundary layer

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from the surface due to a strong adverse pressure gradient and the reattachment of the shear layer shortly downstream. The region between the separation and the reattachment point is called the separation bubble. Carmichael[4] carried out the survey of low Reynolds number airfoils in 1982. He made a research on airfoil performance as well as flow separation in low Reynolds number and gave the further explanation of laminar separation bubble in detail. Mueller[2] presented an experimental study of the Lissaman 7769 and Miley M06-13-128 airfoils at low chord Reynolds numbers in 1985 and found that each airfoil produces a different type of hysteresis loop in the lift and drag forces when operated below chord Reynolds numbers of 300000. He claimed that it is the relative location of laminar separation and transition, which depends upon the shape of airfoil, that affects the type of hysteresis loop. Selig et al.[1] took lift and drag measurements on 34 airfoils at low Reynolds number in 1996. A plateau in the lift curve of symmetrical airfoil in the vicinity of an angle of attack 0° was found to be common in the Reynolds number range of 40000 to 100000. The nonlinearity can be reduced owing to a reduction in the size of the laminar separation bubble by the use of zig-zag type boundary-layer trip. Langley research center[5,6] made an experimental study of the Eppler387 airfoil in the Langley Low-Turbulence Pressure Tunnel in both 1988 and 1990, focusing on the laminar separation bubble. The tests were conducted over the chord Reynolds number ranging from 60000 to 460000. Oil flow visualization was used to determine laminar separation and turbulent reattachment locations. Lots of experimental results, such as lift and pitching-moment data, were obtained. Sahin et al.[7] carried out time-dependent unsteady calculations of low Reynolds number flows over the Eppler387 airfoil in both two- and three-dimensions, using unstructured grid associated with method of direct numerical simulation. Lift and drag coefficients calculated in each case show good agreements with extensive experimental results.

Few domestic researches focus on the low Reynolds number area. Bai et al.[8] conducted a numerical simulation on the laminar separation of the Eppler387 airfoil near the trailing edge at low Reynolds number ranging from 60000 to 200000 and gave the conclusion that the laminar separation bubble is actually the periodical shedding of the vortex. The researches of peculiar nonlinear phenomenon of symmetrical airfoil studied by Bai[9], Lei et al.[10] described the micro vortex structure of laminar separation bubble in detail by numerical methods. Ran et al.[11] made numerical computations for the symmetrical airfoils at low Reynolds number ranging from 500 to 50000. The dynamic aerodynamic characteristics were studied as to different values of maximum relative thickness and position.

Computational fluid dynamics (CFD) can be used where low Reynolds number flows are too difficult to investigate experimentally.[12] Extensive previous work has proved the accuracy and effectiveness of numerical methods. The HAUAVs usually adopt the high aspect ratio design, which leads to a more crucial matter of airfoil performance. However, few researches are aiming at the airfoil of HAUAVs. In this paper, low Reynolds number flow mechanism is expounded by the numerical simulation of several airfoils using Reynolds-averaged Navier–Stokes (RANS) equations combined with transition model. In addition, water tunnel tests are carried out in order to further testify the numerical method, in the meantime, to observe the laminar separation bubbles along with the flow regime in low Reynolds number. Finally, the numerical method is applied to calculate aerodynamic characteristics of airfoils of different relative thicknesses, to investigate the effects of relative thickness on airfoil performance. The airfoil used for HAUAVs is usually designed in big maximum relative thickness for the sake of structural strength, which would bring with the loss of aerodynamic forces. Meanwhile the laminar separation bubble would change according to the variation of thickness, which affects the airfoil performance. The study of thickness is carried out in this paper, which may help to provide a basis for the design of low Reynolds number airfoil.

2. Computation scheme

2.1. Governing equation

The governing equations are the RANS equations and the continuity equations without the gravity and the body force item in Cartesian tensor form:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=0$$

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}(\rho u_i u_j)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu\frac{\partial u_i}{\partial x_j}-\rho\overline{u_i'u_j'}\right)+S_i \tag{1}$$

where ρ is the density, u_i the velocity component of i direction, p the pressure, μ the dynamic viscosity of the fluid, $-\rho\overline{u_i'u_j'}$ the Reynolds stress, and S_i the generalized source term.

2.2. Transition model

Transition prediction is a difficult and key topic in low Reynolds number flows. Transition empirical formula, hydrodynamic stability theory and transition prediction formulation of the e^N type are three main transition prediction methods. Langtry and Menter proposed transition shear stress transport (SST) model, which is combined with the SST $k-\omega$ the calculation model, readers can refer to Ref model and the $\gamma-\widetilde{Re}_{\theta t}$ model at 2005.[13] The model is based on the coupling of the SST $k-\omega$ transport equations with two other transport equations, one for the intermittency and one for the transition onset criteria, in terms of momentum-thickness Reynolds number. The transport equation for the intermittency, γ, reads:

$$\frac{\partial(\rho\gamma)}{\partial t}+\frac{\partial(\rho U_j\gamma)}{\partial x_j}=P_{\gamma 1}-E_{\gamma 1}+P_{\gamma 2}-E_{\gamma 2}+\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\gamma}\right)\frac{\partial \gamma}{\partial x_j}\right] \tag{2}$$

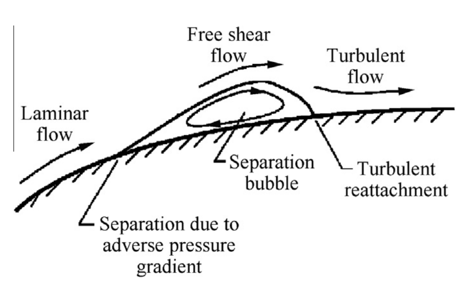

Fig. 1 Laminar separation bubble.[3]