Chinese Journal of Aeronautics, (2015),28(2): 357–367

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Numerical analysis and optimization of boundary layer suction on airfoils

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Received 30 July 2014; revised 1 December 2014; accepted 29 December 2014
Available online 21 February 2015

KEYWORDS

Active control;
Hybrid laminar flow control (HLFC);
Neural network;
Optimization;
Radial basis function (RBF);
Transition prediction

Abstract Numerical approach of hybrid laminar flow control (HLFC) is investigated for the suction hole with a width between 0.5 mm and 7 mm. The accuracy of Menter and Langtry's transition model applied for simulating the flow with boundary layer suction is validated. The experiment data are compared with the computational results. The solutions show that this transition model can predict the transition position with suction control accurately. A well designed laminar airfoil is selected in the present research. For suction control with a single hole, the physical mechanism of suction control, including the impact of suction coefficient and the width and position of the suction hole on control results, is analyzed. The single hole simulation results indicate that it is favorable for transition delay and drag reduction to increase the suction coefficient and set the hole position closer to the trailing edge properly. The modified radial basis function (RBF) neural network and the modified differential evolution algorithm are used to optimize the design for suction control with three holes. The design variables are suction coefficient, hole width, hole position and hole spacing. The optimization target is to obtain the minimum drag coefficient. After optimization, the transition delay can be up to 17% and the aerodynamic drag coefficient can decrease by 12.1%.

1. Introduction

Drag reduction is a significant topic for transport airplanes as energy crisis and environment problems are becoming more and more serious. Since surface friction drag can be up to 50% of the total drag in the civil aviation airplane,[1] how to reduce the friction drag forms an important research field. Some studies indicate that the friction drag in the laminar boundary layer is 90% less than that in the turbulent boundary layer. Therefore, transition delay is vitally important for friction drag reduction.[2] Hybrid laminar flow control (HLFC) is a most forward-looking technique for transition delay and drag reduction.[3] HLFC technique combines natural laminar flow (NLF)[4] and laminar flow control (LFC) to stabilize the boundary layer by shaping wing planform and airfoil geometry, as well as boundary layer suction control, so as to realize transition delay and drag reduction. Suction control affects transition in two aspects: changing the average velocity in

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Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2015.02.011

the boundary layer makes first the velocity profiles much fuller, and second the displacement thickness Reynolds number lower.[5]

A lot of research at home and abroad has contributed to applications of HLFC technique. Joslin[1] introduced the applications of HLFC to wing, vertical tail and nacelle from 30's to 90's in the 20th century. Younga et al.[6] studied the effects of suction surface, suction hole width and spacing, and suction coefficient in detail, providing quantitative references for HLFC design. Wright and Nelson[7] proposed to lower the energy consumption through optimization of suction hole distribution. Risse et al.[8] proposed conceptual wing design methodology with HLFC, and the quasi 3-D method proposed by them can lower the difficulty and cost of numerical simulation. Liu et al.[9] studied the effects of suction parameters on transition position for Rae2822 airfoil, and the analysis results can be used for further study. Researchers have done great contributions to the applications of HLFC technique; however, the suction holes selected are microscopic. Currently, research on microscopic suction holes is mainly conducted via experiments, but not via numerical simulations, which are only used for 2-D questions. HLFC experiments performed on Boeing 757 aircraft [10] need millions of holes (0.06 mm), so the grid will be too big to work, and the numerical accuracy of the common Reynolds averaged Navier–Stokes (RANS) method is questionable. Microscopic suction holes make numerical simulation difficult in HLFC study.

Fortunately, Pehlivanoglu et al.[11] selected 35 mm hole to increase the lift-drag ratio, which inspires us to consider how the suction holes between 0.5 mm and 7 mm (much larger than microscopic holes) affect transition position. Suction control with 35 mm hole in Pehivanoglu's study increases lift coefficient as well as drag coefficient. In this paper, the main work is to explore the ability of holes between 0.5 mm and 7 mm to maintain laminar flow. Computations are performed on a well designed laminar airfoil, and one-hole suction on the airfoil is studied first. Then, suction control with three holes is optimized.

This paper focuses on 2-D airfoil and transition occurs owining to Tollmien-Schlichting (TS) wave, so Menter and Langtry's $\gamma - \widetilde{Re}_{\theta t}$ model can be properly used.[12] The modified radial basis function (RBF) neural network model is used to approximate the aerodynamic forces, so as to enhance design efficiency in multiple holes suction control. In Section 2 the numerical simulation method of $\gamma - \widetilde{Re}_{\theta t}$ transition model and the modified prediction model based on RBF neural network are discussed in detail, and the validation of the model is done on NACA66012 airfoil. Section 3 shows the results of both single and multi-hole suction control. Section 4 comes to the conclusion of the present study.

2. Numerical methodology and optimization tools

2.1. $\gamma - \widetilde{Re}_{\theta t}$ transition model

The correlation-based $\gamma - \widetilde{Re}_{\theta t}$ transition model is developed strictly based on local variables, thus this transition model is compatible with modern CFD techniques. The model is made up with two equations, one for intermittency and the other for momentum thickness Reynolds number:

$$\frac{\partial(\rho\gamma)}{\partial t} + \frac{\partial(\rho U_j \gamma)}{\partial x_j} = F_{\text{length}} c_{a1} \rho S (\gamma F_{\text{onset}})^{0.5} (1 - c_{e1}\gamma) - c_{a2}\rho\Omega\gamma F_{\text{turb}}(c_{e2}\gamma - 1) + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_f}\right)\frac{\partial \gamma}{\partial x_j}\right] \tag{1}$$

$$\frac{\partial(\rho \widetilde{Re}_{\theta t})}{\partial t} + \frac{\partial(\rho U_j \widetilde{Re}_{\theta t})}{\partial x_j} = c_{\theta t}\frac{\rho}{t}(Re_{\theta t} - \widetilde{Re}_{\theta t})(1.0 - F_{\theta t}) + \frac{\partial}{\partial x_j}\left[\sigma_{\theta t}(\mu + \mu_t)\frac{\partial \widetilde{Re}_{\theta t}}{\partial x_j}\right] \tag{2}$$

The first two terms of right-side hand in Eq. (1) and the first term in Eq. (2) are the production terms. The last terms in Eqs. (1) and (2) are the diffusion terms. c_{a1}, c_{a2}, c_{e1}, c_{e2}, σ_f, $c_{\theta t}$ and $\sigma_{\theta t}$ are constants, F_{onset} is used to trigger the intermittency production, the magnitude of intermittency production is controlled by F_{length}, $F_{\theta t}$ is used to turn off the source term in Eq. (2) and allows the transported scalar $\widetilde{Re}_{\theta t}$ to diffuse in from the freestream, and $Re_{\theta t}$ is the transition onset momentum thickness Reynolds number. The parameters in Eqs. (1) and (2) are given in detail in Ref. [13]. The maximum vorticity Reynolds number is proportional to momentum thickness Reynolds number, which can serve as a local environment.

To correct the deficiency in simulating separation-induced transition, a modification is given by

$$\begin{cases} \gamma_{\text{eff}} = \max(\gamma, \gamma_{\text{sep}}) \\ \gamma_{\text{sep}} = \min\left(s_1 \max\left[0, \dfrac{Re_v}{3.235 Re_{\theta c}} - 1\right]\right) F_{\text{reattach}}, 2) F_{\theta t} \\ F_{\text{reattach}} = \exp\left[-\left(\dfrac{R_T}{20}\right)^4\right], s_1 = 2 \end{cases} \tag{3}$$

where γ_{sep} represents separation intermittency and the other parameters in Eq. (3) are given in Ref. [13], Re_v is the vorticity Reynolds number, and $Re_{\theta c}$ the critical momentum thickness Reynolds number, R_T the viscosity ratio. Finally, the modified intermittency γ is coupled with the turbulence model as follows:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho U_j k)}{\partial x_j} = \widetilde{P}_k - \widetilde{D}_k + \frac{\partial}{\partial x_j}\left[(\mu + \sigma_k \mu_t)\frac{\partial k}{\partial x_j}\right] \tag{4}$$

$$\widetilde{P}_k = \gamma_{\text{eff}} P_k \tag{5}$$

$$\widetilde{D}_k = \min(\max(\gamma_{\text{eff}}, 0.1), 1.0) D_k \tag{6}$$

where P_k and D_k are the production and destruction for k equation turbulence model, respectively.

2.2. Modified RBF neural network prediction model

To avoid the deficiency of vast time consumption by numerical simulation, the modified RBF neural network model [14] is used to predict the aerodynamic forces.

The mapping between the input and output of the neural model is given by:

$$y_i = f_i(x) = \sum_{k-1}^{M} w_{ik}\phi_k(\boldsymbol{x}, \boldsymbol{c}_k) = \sum_{k-1}^{M} w_{ik}\phi_k(\|\boldsymbol{x} - \boldsymbol{c}_k\|) \tag{7}$$