Study of hydrofoil boundary layer transition using different turbulence models

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Study of hydrofoil boundary layer transition using different turbulence models

C L Ye¹,², B P M van Esch³

1. College of Water Resources and Civil Engineering, China Agricultural University, Beijing 100083, China
2. Department of Mechanical Engineering, Eindhoven University of Technology, Eindhoven 5600MB, The Netherlands
E-mail address: ychl1994@cau.edu.cn

Abstract: Boundary layer transition is one of the key factors affecting the hydrodynamic characteristics of hydrofoil. In order to explore the capability of a transition model coupled to different turbulence models in the prediction of hydrofoil boundary layer transition, the flow field around the NACA0009 blunt-edge hydrofoil at 0° angle of attack was calculated using γ-Reθt transition model coupled with SST, SST-DES, SST-SAS, SST-DDES turbulence models. The characteristics of the hydrofoil boundary layer at Reₜ=2*10⁶ are analysed. The experimental data and numerical calculation results are compared. The results show that the four turbulence models differ quite a bit in simulating hydrofoil boundary layer transition at the same calculation conditions. The flow parameters of the hydrofoil boundary layer calculated by the transition model coupled with SST-DDES are closer to the experimental results.

1. Introduction

Transition on the blade surface of hydraulic machinery directly affects its characteristics. A hydrofoil is a simplified model of a hydro-mechanical blade. Under the condition of free inflow with low turbulence, there is a natural transition from laminar flow to turbulent flow in the boundary layer of smooth hydrofoil wall [1]. Therefore, a suitable computational model is necessary to investigate the characteristics of the boundary layer transition of the hydrofoil.

In order to predict transition accurately, the transition model by introducing the intermittent factor γ and the transition onset criteria in terms of momentum thickness Reynolds number was proposed by Menter[2]. At present, the computational model coupled by γ-Reθt transition model and SST turbulence model is widely used in boundary layer transition prediction[3], which has the characteristics of high computational efficiency, however, this model still has some problems in predicting the transition of hydrofoil [4]. Comparatively, considering the advantages of hybrid RANS/LES, γ-Reθt transition model coupled with hybrid RANS/LES was applied in aerodynamics research. Many researchers’ work [5-7] has confirmed the practical possibility and success of the combination of transition model with hybrid RANS/LES method, but there are still some unrevealed details in hydrofoil.

The aim of the present work is to assess the capability of γ-Reθt transition models coupled several turbulence models for predicting transition on hydrofoil NACA0009, for which experimental data are available in the literature[8]. In addition to SST turbulence models, three hybrid turbulence models (SST-DES, SST-SAS and SST-DDES) are selected to couple with the transition model. By comparing...
with the experimental results, the differences among these models in the prediction of hydrofoil boundary layer flow are analysed, and the applicability of the calculation model is verified.

2. Turbulence Modelling

2.1. SST k-ω

The turbulent kinetic energy and dissipation rate in SST model can be expressed as follows:

$$\frac{D}{Dt}(\rho k) = \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta' \rho \omega k + \frac{\partial}{\partial x_j}\left((\mu + \sigma_\omega \mu) \frac{\partial k}{\partial x_j}\right)$$

(1)

$$\frac{D}{Dt}(\rho \omega) = \gamma \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta \rho \omega^2 + \frac{\partial}{\partial x_j}\left((\mu + \sigma_\omega \mu) \frac{\partial \omega}{\partial x_j}\right) + 2(1-F_1) \frac{\rho \sigma_{k\omega}}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}$$

(2)

The meanings of the coefficients in the formula can be referred to [7].

2.2. SST-DES

In DES model, DES length scale \( l_{DES} \) is used to replace the length scale \( l_{RANS} \) in RANS model[7].

$$l_{DES} = \min(l_{RANS}, l_{LES}), \quad l_{RANS} = \frac{k^{3/2}}{\beta' \omega}, \quad l_{LES} = C_{DES} \Delta$$

(3)

\( \Delta \) is Local grid spacing, \( C_{DES} \) is defined as

$$C_{DES} = F_1 C_{DES}^{k-\omega} + (1-F_1) C_{DES}^{k-\omega}, \quad C_{DES}^{k-\omega} = 0.61, \quad C_{DES}^{k-\omega} = 0.78$$

(4)

The source term \( \beta' \rho \omega k \) in Formula (1) can be written as follows:

$$\beta' \rho \omega k = \frac{D^{k^{3/2}}}{l_{RANS}}$$

(5)

By replacing \( l_{RANS} \) with \( l_{DES} \), the DES method based on SST model is obtained.

2.3. SST-DDES

To counter the problem of premature separation caused by modeled stress depletion, Menter[7] ‘shielded’ the boundary layer using the existing parameters (function \( F_S \)) in the STT model

$$F_{DES} = \max\left[1 - F_S, \frac{l_{RANS}}{C_{DES} \Delta}, 1\right], \quad F_{SST} = 0, F_1, F_2$$

(6)

, essentially converting the DES to DDES.

2.4. SST-SAS

The SAS model introduces the second derivative of the velocity field and thereby \( l_{rk} \) into the turbulent scale equation. [7] The additional source term which plays an adaptive role in the \( \omega \) equation of the SST model is defined as

$$M_{SAS} = \rho \max \left[ \xi k^2 \left(\frac{L}{l_{rk}}\right)^2 - C \frac{2k}{\sigma \phi} \max \left(\frac{1}{\omega \phi} \frac{\partial k}{\partial x_j}, \frac{1}{k^2} \frac{\partial \omega}{\partial x_j}, \frac{1}{k^2} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}\right), 0\right]$$

(7)

$$l_{rk} = \frac{KS}{U'}, \quad C = 2.0, \quad \kappa = 0.41, \quad \xi = 3.51, \quad \sigma = \frac{2}{3}, \quad C_\gamma = 0.09$$

(8)

2.5. Coupling to the -Re \( \phi \)
The $\gamma$-Re$_0$ transition model obtains the intermittent factor $\gamma$ of the flow field by solving the intermittent factor $\gamma$ and the Reynolds number transport equation of the onset momentum thickness of the transition.[7] Considering the influence of the separation of the laminar boundary layer, the transition model is modified to obtain an effective intermittent factor, which will act on the generation and destruction terms of the turbulent kinetic energy transport equation in the turbulence model to control the development of turbulence.

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho U_k)}{\partial x_i} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \sigma_f \mu_f \right) \frac{\partial k}{\partial x_i} \right]$$

$$D_k = \min(\max(\gamma_{eff}, 0.1), 1.0)D_k'$$

3. Grid and Numerical Setup

3.1. Solution strategy
The transient N-S equation is discretized by the finite volume method and the implicit time integration scheme. The second-order central-difference scheme is used for the advection term and the diffusion term. The second-order backward Euler scheme is used for the transient term. The coupled solution method is used to solve the discretized equations. The dimensionless time step is set to $\Delta t^* = U \Delta t / L = 0.001$ (the average courant number is equal to 1), where $\Delta t$ is the physical time step and $U$ is the mean velocity at the inlet. The transient statistics are started after the solution goes into a steady state.

3.2. Mesh and boundary condition
Figure 1 shows the details of NACA0009 blunt trailing edge hydrofoil and the 2D computational domain. The hydrofoil chord length $L=100\, \text{mm}$, maximum thickness $9.9\, \text{mm}$, trailing edge thickness $h=3.22\, \text{mm}$, and inflow angle of attack $\alpha=0\, \text{degree}$ are measured. The upper boundary of the computational domain is $2L$ from the leading edge of the hydrofoil, and the lower boundary is $6L$ from the trailing edge of the hydrofoil. The height of the computational domain is $1.5L$, as shown in Figure 1. O-type grids are used in the normal 3mm area of the hydrofoil wall, and H-type grids are used in the other areas.

The grids are refined in the leading edge, trailing edge and wake area of the hydrofoil, as shown in Figure 2. Uniform velocity ($U=20\, \text{m/s}$, $Re_L=2*10^5$) and static pressure are set at the inlet and outlet respectively. The hydrofoil wall and the upper and lower boundaries of the computational domain are set as non-slip walls with a given inflow velocity at the inlet and a static pressure boundary condition at the outlet of the computational domain.

4. Result

4.1. Grid convergence analysis
A grid convergence analysis is conducted with controlling mesh parameters. The parameters is summarized in Table 1. For example, Grid5 is shown in Fig. 2; the foil surface nodes is discretized by 189 nodes and the whole 2D computational domain contains 105552 cells.
Table 1. Grid convergence

<table>
<thead>
<tr>
<th>Case</th>
<th>Ratio</th>
<th>Max. y+</th>
<th>Normal surface nodes</th>
<th>Along surface nodes</th>
<th>Cell number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid 1</td>
<td>1.2</td>
<td>0.32</td>
<td>48</td>
<td>189</td>
<td>108995</td>
</tr>
<tr>
<td>Grid 2</td>
<td>1.2</td>
<td>0.91</td>
<td>48</td>
<td>189</td>
<td>105658</td>
</tr>
<tr>
<td>Grid 3</td>
<td>1.2</td>
<td>1.73</td>
<td>48</td>
<td>189</td>
<td>104487</td>
</tr>
<tr>
<td>Grid 4</td>
<td>1.2</td>
<td>14.44</td>
<td>48</td>
<td>189</td>
<td>100056</td>
</tr>
<tr>
<td>Grid 5</td>
<td>1.1</td>
<td>0.89</td>
<td>48</td>
<td>189</td>
<td>105552</td>
</tr>
<tr>
<td>Grid 6</td>
<td>1.05</td>
<td>0.88</td>
<td>48</td>
<td>189</td>
<td>103321</td>
</tr>
<tr>
<td>Grid 7</td>
<td>1.1</td>
<td>0.73</td>
<td>72</td>
<td>189</td>
<td>111876</td>
</tr>
<tr>
<td>Grid 8</td>
<td>1.1</td>
<td>0.87</td>
<td>96</td>
<td>189</td>
<td>112654</td>
</tr>
<tr>
<td>Grid 9</td>
<td>1.1</td>
<td>0.74</td>
<td>72</td>
<td>370</td>
<td>135853</td>
</tr>
</tbody>
</table>

Comparison of the skin friction coefficient $C_f$ among all grids is shown in Fig. 3. The transition position of hydrofoil boundary layer predicted by transition SST model shifts downstream with the increase of $y+$ value, and the predicted transition position tends to be the same when the maximum $y+$ value is less than 1. The grid expansion ratio near the wall region has small impact of prediction. According to the calculation, Grid6 will be used to analyze the boundary layer.

![Figure 3. Grid sensitive for $C_f$](image)

4.2. boundary layer analysis

Comparison of the skin friction coefficient $C_f$ for different turbulence models is shown in Fig. 4. In order to make a comparative analysis, the calculation results of the full laminar flow model are given. It can be seen that the wall friction coefficient predicted by SST model is higher than that calculated by laminar flow model from the leading edge of hydrofoil, which indicates that SST model predicts the velocity gradient near the wall too high and does not capture the laminar boundary layer before transition. Transition SST, transition SAS, transition DES and transition DDES models can be used to solve the laminar boundary layer flow, and the transition onset positions predicted by the four models are 0.4 L, 0.12 L, 0.78 L and 0.82 L, respectively.

![Figure 4. $C_f$ prediction with different models](image)

![Figure 5. Intermittent factor $\gamma$ with different turbulence models](image)
Intermittent factor $\gamma$ is an important parameter to characterize the flow. In the laminar region of the boundary layer, $\gamma$ is 0, and outside the boundary layer, gamma is 1. In the transition region, gamma is between 0 and 1 with the change of turbulence intensity. Figure 5 shows the distribution of intermittent factors in the boundary layer. The results are consistent with skin friction coefficient. After 0.4L, the intermittent factor in the boundary layer increases rapidly, and the friction coefficient predicted by the transition SST model increases gradually. The boundary layer transits to turbulence and develops into a turbulent boundary layer near 0.6L.

Fig. 6 shows the boundary layer thickness distribution along the hydrofoil wall. Compared with the experimental results [8], the SST and transition SAS models predicted the boundary layer thickness over the whole hydrofoil wall. The boundary layer thickness predicted by transition DES and transition DDES models was close to the experimental values, especially in the range from the leading edge of hydrofoil to 0.7 L. The calculated results were in good agreement with the experimental results. In the range of 0.8L-0.99 L, the boundary layer thickness predicted by the two models was in good agreement. The degree is less than the experimental value.

![Figure 6. Boundary layer thickness profiles along hydrofoil chord](image6)

![Figure 7. Boundary layer form factor profiles along hydrofoil chord](image7)

![Figure 8. Boundary layer tangential time-averaged velocity profiles along hydrofoil chord](image8)

It is generally believed that the boundary layer is laminar when the form factor of the boundary layer is greater than 2.6, turbulent when it is less than 1.5, and transition when it is between the two [8]. Figure 7 shows that the $H_{12}$ predicted by transition SST is closer to the experimental value in the leading edge region of hydrofoil, but gradually deviates from the experimental value after $x=0.2L$, and drops to 1.5 near 0.6L. The boundary layer at this position is in turbulent state, which is ahead of the
completion of transition at 0.85L, while the $H_{12}$ predicted by transition DDES drops to 1.5 near 0.85L, which is in good agreement with the experimental measurement.

The time-averaged velocity profiles along hydrofoil chord are shown in Figure 8, including the data measured by the experiment [8] and the results calculated by the five models. In the figure, $d$ is the normal distance to the wall, and $U_t$ is the surface-tangent velocity, which is normalized by the external velocity, $U_{te}$. The good agreement between experiment and calculation means that the transition DDES model achieves better simulation for the transitional boundary layer.

5. Conclusions

The flow field around the NACA0009 blunt-edge hydrofoil at 0° angle of attack was calculated based on $\gamma$-Re$_\theta$ transition model coupled with SST, SST-DES, SST-SAS and SST-DDES turbulence model, the main findings in this paper are as follows:

The transition position of hydrofoil boundary layer predicted by transition SST model shifts downstream with the increase of $Y_+$ value in the first layer of the wall. When the maximum $y_+$ value is less than 1, the predicted transition position tends to be similar. The effect of grid expansion in the near wall region on transition prediction is relatively small.

Four transition models can solve laminar boundary layer and hydrofoil boundary layer transition. Transition DDES model can predict boundary layer accurately. The predicted boundary layer thickness is in good agreement with the experimental results.

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