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Numerical Simulation of Turbulent Flow past Airfoils on OpenFOAM

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Abstract

The attached boundary turbulent flow around two different airfoils at low Mach number condition are numerically simulated using the v2-f and S-A RANS models, and the performance is evaluated. The numerical platform is an open source CFD code based on the Field Operation and Manipulation C++ class library for continuum mechanics (OpenFOAM). In the simulation, the pressure field is obtained with SIMPLE algorithm. The advective volume-face fluxes are approximated using second-order TVD scheme/ limited linear differencing. The velocity profile and the aerodynamic parameters of the conventional airfoil at 0° attack angle and the supercritical airfoil at 4° attack angle are simulated, and compared with the experiment data respectively. The result indicates that the solution of v2-f turbulence model is comparable with that of S-A model for conventional airfoil computation, but it is better for the supercritical airfoil computation, especially at the positions with strong pressure gradient and streamline curvatures.

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Keywords: Airfoil, Turbulence Model, OpenFOAM, Numerical Simulation

1. Introduction

Airfoils with better aerodynamic performances such as supercritical airfoil and multi-element airfoil always bring about highly complex flow phenomena. These include the combination of compressible effect,
pressure gradient, unsteady effect, separation, etc, the prediction of which presents great challenges to RANS. Ideally, these flow phenomena need to be studied separately; however, they usually appear with companions. Although there are plenty of previous studies concerning this subject, they always evaluate models under circumstances in which separations are significant and easy to capture, so the effects of pressure gradient cannot be intimately investigated. The examples with isolated flow phenomena distributed in different flow regions are proper test cases for the evaluation of RANS models.

2. Computational method

The v2-f model of Durbin [2, 3] is similar to standard k-ε, but incorporates some near wall turbulence anisotropy as well as non-local pressure-strain effects via two additional equations of v^2. v^2 can be thought of as the velocity fluctuation normal to the streamlines, which can provide the right scaling for the damped turbulence close to the wall, so the model is naturally a low-Re model. The elliptic relaxation function f governed by an elliptic Helmholtz equation can model the anisotropic wall effects. Due to the excellent features of v2-f, this model is suitable for the simulation of complex turbulence. Readers can refer to [4] for the details of v2-f model used in this paper. Additionally, a modification[5] is used to ensure that v^2 is the smallest one everywhere.

S-A model is a one-equation model which solves a transport equation for a turbulent viscosity-like variable. It is robust and can provide reasonable solutions for complex turbulence such as turbulence flow with adverse pressure gradient and shallow separation. It is one of the most widely used models in aeronautical and aerospace engineering.

In this paper, all the simulations are implemented on the open-source code OpenFOAM 1.7.1. SIMPLE algorithm for the pressure correction and Preconditioned (bi-) conjugate gradient method for solving the discrete equations are used in the studies. The advective volume-face fluxes are approximated using second-order TVD scheme/ limited linear differencing.

3. Results and discussion

To investigate the performance of the v2f model against widely used S-A turbulence model when applied to attached boundary layer of airfoils, the experiment of A. Nakayama in year of 1983 was chosen. It is Case11 stored in the European Research Community on Flow, Turbulence and Combustion (ERCOFTAC) Database Classic Collection, which is the turbulence flow over a conventional airfoil of 0° attack angle and a supercritical airfoil of 4° attack angle at low Mach number.

For both the conventional and supercritical airfoils, the chord length is C=0.61m and the magnitude of free-stream velocity is 30.5m/s. Free-stream Mach number is set to 0.1, so the flow field is approximately incompressible. Reynolds number is ReC=1.2×10^6, based on the chord length and the free-stream velocity. Computation domain is decuple of the chord length and a C-type grid is adopted. The grid sizes of the two airfoils are both 276×97.

3.1. Conventional Airfoil

The conventional airfoil at zero incidence is noted as model A. The pressure coefficient distribution on model A is represented in Fig.1. The both results using S-A and v2-f turbulence model agree well with the experimental data. The comparison of friction coefficient distribution on model A with experimental data is shown in Fig.2.
Fig. 3 shows the velocity profiles for five sections placed at x/c which equals to 0.593, 0.893, 1.0 on the upper part and 0.893, 1.0 on the lower part of model A. The overall results above show that there is no significant difference between S-A and v2-f turbulence model in simulating the flow fields around a near-symmetric conventional airfoil. This is because there are no considerable pressure gradient and curvatures. The experiment [1] indicates that flow over model A is a minor perturbation of a symmetric flat-plate flow with small wake curvature and weak viscous-inviscid interaction.

Table 2. Numerical and experimental data of the aerodynamic coefficients of conventional airfoil (model A) at 0° attack angle

|            | Drag Coefficient | Lift Coefficient | Moment Coefficient |
|------------|------------------|------------------|--------------------|
| EXP        | 0.010073         | 0.152375         |                    |
| S-A        | 0.0125671        | 0.160971         | 0.0790521          |

Fig. 1 Comparison of pressure coefficient of model A

Fig. 2 Comparison of friction coefficient of model A

Fig. 3 Nondimensional velocity u/uref distribution at x/c=0.593, 0.893, 1.0 on the upper part and x/c=0.893, 1.0 on the lower part of model A
Table 2 shows the aerodynamic coefficients of model A using both v2-f and S-A turbulence model, compared with results of k-ε turbulence model (as part of this work) and experimental data. Clearly, the results using v2-f turbulence model are slightly closer to the experimental data.

### 3.2. Supercritical Airfoil

In contrast with conventional airfoil, supercritical airfoil features a well-rounded leading-edge and a sharply down curving trailing edge. As the shape changes, the flow over supercritical airfoil can be more complex. The experiment indicates that the flow around the supercritical airfoil is in considerable contrast with strong streamwise pressure gradients, non-negligible normal pressure gradients, and large surface and streamline curvatures of the trailing-edge flow [1].

![Fig. 4 Comparison of pressure coefficient of model B](image1)

![Fig. 5 Comparison of friction coefficient of model B](image2)

![Fig. 6 Nondimensional velocity u/uref distribution for x/c=0.693,0.893,1.0 on the upper part and x/c=0.893,1.0 on the lower part of model B](image3)
Fig. 4 and Fig.5 represent the comparison of the computational simulation results, the experimental data of the pressure coefficient and friction coefficient of the supercritical airfoil at the attack angle of 4° (noted as “model B”). The pressure coefficients of model B using both v2-f and S-A agree well with experimental data. In Fig.5, v2-f performs better on both upper surface and lower suppert surface of model B. However, the friction coefficient depends on the velocity distribution, the result using v2-f is better than that using S-A as seen in Fig.5. Fig.6 shows the velocity profiles for five sections placed at x/c which equals to 0.693, 0.893, 1.0 on the upper part and 0.893, 1.0 on the lower part of model B. v2-f agrees well with the experiment data, especially in the two sections of the lower part. It is just around the sharply down curving trailing edge, with great pressure gradient and curvatures. Because it incorporates near-wall turbulence anisotropy as well as non-local pressure-strain effects, v2-f obtains satisfactory results on regions of adverse pressure gradient and curvature flows.

Table 3 shows the aerodynamic coefficients of model B using both v2-f and S-A turbulence model together with results of k-ε turbulence model (as part of this work) and experimental data. The error of lift coefficient with v2-f turbulence model is 1.8%, which is less than 3.9% with S-A.

### Table 3. Comparison of numerical and experimental data of the aerodynamic coefficients of the supercritical airfoil (model B) at 4° attack angle

|          | Drag Coefficient | Lift Coefficient | Moment Coefficient |
|----------|------------------|------------------|--------------------|
|          | CD               | CL               | CM                 |
| EXP      | 0.036343         | 0.7609075        |                    |
| S-A      | 0.0173165        | 0.790914         | 0.308521           |
| V2-F     | 0.0149759        | 0.775294         | 0.301365           |
| K-epsilon| 0.024594         | 0.710807         | 0.272221           |

### 4. Conclusion

This paper indicates that v2-f achieves overall satisfactory results on attached boundary turbulence flow over airfoils at low Mach number. The v2-f model, due to the incorporation of near-wall turbulence anisotropy as well as non-local pressure-strain effects, is better than S-A in complex flow with adverse pressure gradient and curvatures.

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