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Evaluation of Renormalization Group Turbulence Models for Dynamic Stall Simulation

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Introduction

UNSTEADY stall phenomena are the result of airfoils and wings oscillating in pitch and having a maximum angle of attack greater than the static stall angle. The causes of this delay of stall, often accompanied with hysteresis in lift and moment coefficients, have challenged aerodynamicists for many years. As noted in the extensive studies by McCroskey[1] and McCroskey et al.,[2] the nonequilibrium nature of the separated turbulent boundary layer and the associated unsteady time-lag features are more difficult to analyze. Therefore an accurate turbulence model is required. In the evaluation of the turbulence models on dynamic stall, the renormalization group theory (RNG) algebriac model has demonstrated the efficiency and reasonable accuracy of the work of Srinivasan et al.[3] In the previous work,[4] the family of advection upwind splitting method (AUSM) schemes, together with the RNG-based algebraic model, is used for several steady-state and oscillating NACA 0012 airfoil flows. It was shown that AUSMD with a weighting function based solely on the density was robust and stable for the problem considered. Whereas in the light stall case numerical estimation of unsteady airload hysteresis was satisfactory, the deep dynamic stall case was not predicted successfully by the RNG-based algebraic model used. To continue this effort, two RNG-based algebraic models[5,6] and one RNG-based k-ϵ model[7] are selected for the present investigation of the deep stall case. Numerical results of one deep stall case of the NACA 0012 airfoil are compared with the experimental results of McCroskey et al.[2]

Numerical Models

The two-dimensional, Reynolds-averaged, Navier–Stokes equations with the kinetic energy and dissipation equations are written as

$$\frac{\partial \boldsymbol{Q}}{\partial t} + \frac{\partial \boldsymbol{F}}{\partial x} + \frac{\partial \boldsymbol{G}}{\partial y} = \left(\frac{\partial \boldsymbol{F}_v}{\partial x} + \frac{\partial \boldsymbol{G}_v}{\partial y}\right) + S \tag{1}$$

where x, y, and t are the Cartesian coordinates and time, $\boldsymbol{Q}$ the vector of the dependent variables, and $\boldsymbol{F}$ and $\boldsymbol{G}$ convective flux vectors. Also, the viscous flux vectors are represented by $\boldsymbol{F}_v$ and $\boldsymbol{G}_v$. In the implementation of the algebraic turbulence model, the kinetic energy and turbulence dissipation equations are not considered and the source term S is neglected. The governing equations are integrated with a dual-time-stepping procedure and discretized in the finite volume formulation with the AUSMD scheme. A second-order-accurate, three-point backward differencing is implemented for the physical time discretization, and a four-stage explicit Runge–Kutta scheme is implemented for the pseudotime evolution of solutions between the physical times.

RNG Turbulence Models

In the first RNG-based algebraic turbulence model, the eddy viscosity is expressed in the following formula:

$$\nu = \nu_t + \nu_l = \nu_l\left[1 + H\left(\frac{0.0192}{\nu_l^3}\epsilon L^{-4} - C\right)\right]^{\frac{1}{3}} \tag{2}$$

where the subscripts l and t refer to the laminar viscosity and turbulent viscosity, respectively; $C = \mathcal{O}(100)$ is the RNG constant; and H is the Heaviside step function. The length scale L is evaluated as

$$L = \frac{1}{y} + \frac{1}{0.225\delta} \tag{3}$$

The thickness parameter δ is defined as $\delta = 1.2y_{1/2}$ (Ref. 5), where $y_{1/2}$ is the normal distance from the wall at which the vorticity function attains its half-amplitude. The near-wall turbulence is reduced by implementing a dissipation rate ϵ:

$$\epsilon = \frac{2.5u_\tau^3}{y}\left[1 - \exp\left(-\frac{0.04\rho u_\tau y}{\mu_l}\right)\right] \tag{4}$$

where u_τ is the friction velocity.

In the so-called RNG algebraic Q4 model,[6] the eddy viscosity equation is obtained from a quartic equation:

$$Q_4(\nu) = \nu^4 + (C-1)\nu_l^3\nu - (\kappa^2\Omega\ell^2)^4 = 0 \tag{5}$$

where $C = \mathcal{O}(100)$ is the constant, κ the von Kármán constant, and Ω the vorticity function. This quartic equation has only one physically plausible root and is solved under the constraint $\nu = \max(\nu, \nu_l)$. In the determination of the length scale appearing in the quartic equation, $L = \min(y, \gamma y_{\max})$ is used by means of the normal distance $y_{\max}$ and the intermittency coefficient γ.

The RNG-based k-ϵ model[7] is also considered. An extra term R in the source term is required:

$$R = \frac{C_u\eta^3(1 - \eta/\eta_0)}{1 + \beta\eta^3}\frac{\epsilon^2}{k} \tag{6}$$

where $\eta = wk/\epsilon$, w is the magnitude of the rate of strain, and $C_u = 0.0845$.

The eddy viscosity is given by

$$\nu_t = \nu_l\left\{1 + \left[\left(\sqrt{C_u/\nu_l}\right)\left(k/\sqrt{\epsilon}\right)\right]\right\}^2 - \nu_l \tag{7}$$

Results

Two separated-flow cases of the NACA 0015 airfoil at high angles of attack are selected to evaluate the RNG turbulence models. The relevant parameters are $M_\infty = 0.3$, $Re_\infty = 3 \times 10^6$, and $\alpha = 13$ and 17 deg, the conditions reported in Ref. 4. Figure 1 compares the pressure coefficients from the computed and experimental results. In the mildly separated case ($\alpha = 13$ deg), the RNG-based algebraic model and the Q4 model give consistent surface pressure distributions that are also in close agreement with the data. However, the RNG k-ϵ model shows excessive numerical dissipation by smearing out the pressure coefficient distribution around the leading edge of the airfoil. In the strongly separated case ($\alpha = 17$ deg), the RNG model with the damping dissipation rate [Eq. (4)] gives a more reasonable prediction of the quasi-unsteady surface pressures than the other two RNG models. It is seen that the overall pressure coefficients are underpredicted by the RNG k-ϵ model but also additional computation cost is incurred. Among the selected RNG turbulence models, the RNG algebraic model with the damping dissipation function is shown to be the most cost effective in providing accurate solutions to the steady- and quasi-unsteady-statetest cases.

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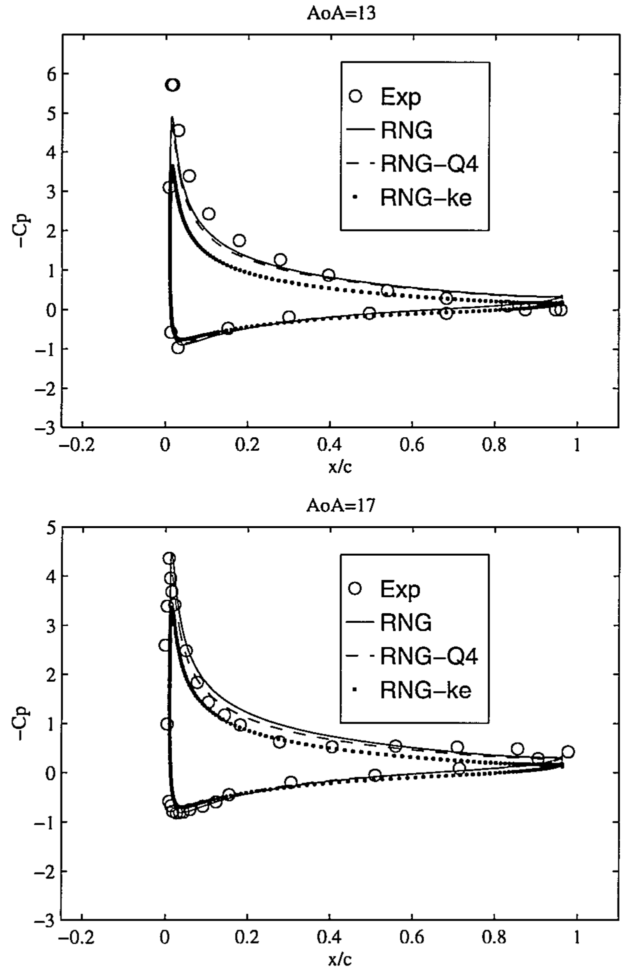

Fig. 1 Pressure coefficient distributions over a NACA 0015 airfoil; M = 0.29 with α = 13 and 17 deg by the RNG models.

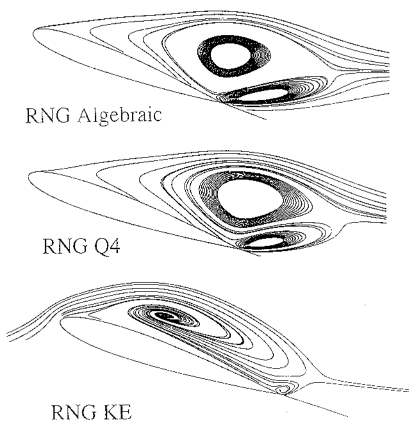

Fig. 2 Particle trace plots of the dynamic deep stall by different RNG models; the angle of the attack is 19 deg in the downstroke mode.

One of the deep dynamic stall cases in McCroskey et al.'s experiment[2] is chosen for validating the calculations. The parameters are $M_\infty = 0.3$ and $\alpha(t) = 15 + 10\sin(0.5t)$, oscillating about 0.25 chord. The unsteady calculations are started from the steady solutions at the mean pitching angle of attack on a 249 × 64 O-type grid. Figure 2 shows that the form of vortex at the maximum angle of attack captured by the algebraic model is close to the result of the Q4 model but is larger than the result of the k-ϵ model. Also, both algebraic RNG models give the consistent predictions of the vortex shedding into the downstream, but no obvious vortex shedding and a smaller separation zone are predicted by the k-ϵ model. Furthermore, Fig. 3 shows the numerical predictions of unsteady Cl and Cm vs angle of attack for the deep stall. The predicted unsteady airload hysteresis by the algebraic model agrees slightly better with the experimental data than the Q4 and k-ϵ models. Even with additional equations to solve in each unsteady time step, the expense needed in both the Q4 and k-ϵ models does not seem to pay off for the accuracy in this study. The algebraic model in conjunction with a damping dissipative rate function and a simple length scale provides simplicity, efficiency, and better accuracy than the other two RNG models considered. However, the reversed lift coefficient curve around the maximum angle of attack 25 deg in the experimental data is not captured in the numerical results, and the predicted negative moment coefficient is much smaller than the experimental data. Also, none of the chosen RNG models successfully predicts the near-wall transition behaviors.

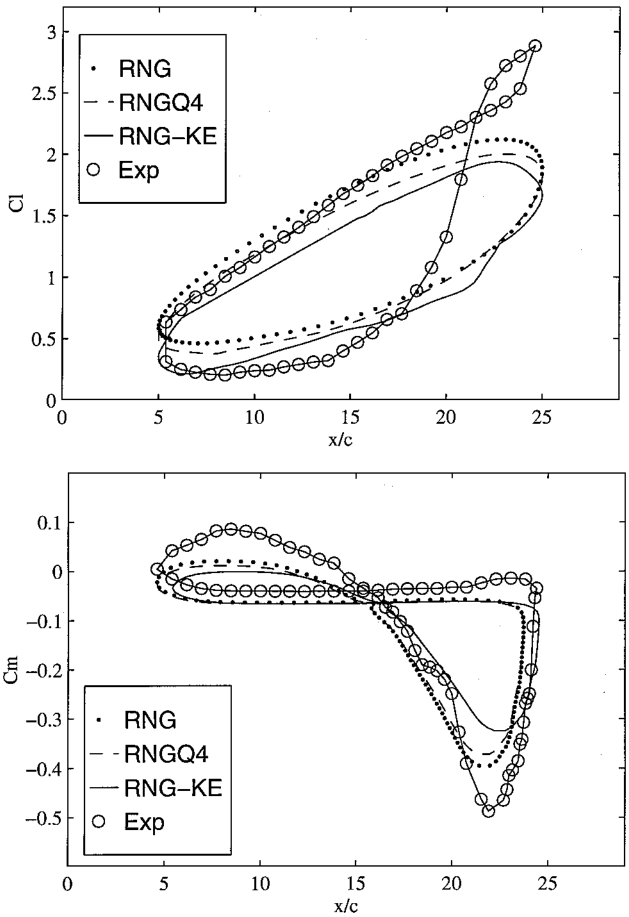

Fig. 3 Lift and moment coefficient hysteresis vs angle of attack of the dynamic deep stall case.

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