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Nonequilibrium Turbulence Modeling Study on Light Dynamic Stall of a NACA0012 Airfoil

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A computational study on the nonequilibrium turbulence modeling effects for the prediction of the light stall phenomenon has been done for the NACA0012 airfoil. For this, an unsteady thin-layer Navier-Stokes solver was developed that is capable of solving the flowfield around an airfoil undergoing unsteady harmonic motion. In the program, the Baldwin-Lomax and Cebeci-Smith turbulence models were used as baseline models, and the Johnson-King turbulence model was used to study the nonequilibrium effects. It was found that the non-equilibrium effects are important for the prediction of the light stall, and only the Johnson-King model yields light stall hysteresis loop that is similar to the experiment. It was also found that the wind-tunnel wall effects are important, and a mean angle-of-attack increase in the computation was necessary to yield a better agreement with the experiment.

Introduction

In recent years, in parallel with the improvement in computer hardware and software, calculation of the viscous unsteady flows have become possible. An important area in this field is the dynamic-stall phenomenon that occurs around airfoils undergoing unsteady motion beyond critical angle of attack. One active area that is in urgent need of improved numerical, experimental, and empirical methods, is the design of the helicopter blades. In general, dynamic stall is encountered in a variety of aeronautical, hydrodynamic, and wind-energy problems, and the associated unsteady lift augmentation offers various advantages to designers including aircraft supermaneuverability. A majority of the unsteady aerodynamics and dynamic stall research has been focused on the case of airfoils undergoing harmonic motions of moderate amplitude. During such motions, when the angle of attack reach high values, airfoils experience massive unsteady separation accompanied by large-scale vortical structures.[1,2]

Prediction of such flowfields offer great challenges for the numerical methods because of the many interdependent parameters that must be accounted for. For instance, airfoil shape, reduced frequency, amplitude, and mean angle of the unsteady motion are important parameters in addition to usual parameters like the Mach number and Reynolds number. Also, other types of motions such as a ramp motion or rapidly pitching motion have their own complexities and importance. Recognizing the need for systematic computational studies to cover all aspects of this field, increasing number of publications are appearing in the literature. For instance, various aspects of the dynamic stall was studied for the incompressible flow in Refs. 3 and 4, and for the compressible flow in Refs. 5–8 for rapidly pitching and oscillating airfoils. The authors of these articles assumed laminar or turbulent flow for various reasons.

The aerodynamic characteristics of an aircraft in some regimes are very sensitive to viscous effects and the selection of the turbulence model for a prediction method is as important as the selection of the numerical algorithm. Satisfactory results can be obtained with the so-called "equilibrium" turbulence models for weak interaction cases (i.e., cases where separation is relatively small). However, this is not the situation for cases where there is a massive separation in results of a strong shock at high speeds or high angle of attack at low to high speeds. The equilibrium models[9,10] are not suitable for cases with massive separation, and it is in fact dangerous to use these models (i.e., airfoil design). Use of these models can result in unduely optimistic projections of aircraft performance at off-design conditions.[11]

Significant improvements in the accuracy of the numerical predictions methods are achieved through better turbulence modeling without necessarily adding any significant complication to these methods. Recently, a "nonequilibrium" algebraic turbulence model was formulated[11,12] that attempts to capture this important characteristic of turbulence. This "nonequilibrium" algebraic model (i.e., the Johnson-King model) employs an ordinary differential equation (o.d.e.) to model slow response of the turbulence to changes in local flow conditions. The performance of the turbulence model relative to popular "equilibrium" models was illustrated for three airfoil test cases of the 1987 AIAA Viscous Transonic Airfoil Workshop, Reno, Nevada. It was observed that the Johnson-King model exhibited impressive improvements in the prediction of the transonic separated flows. Since then, this model was further improved to account for some of the deficiencies in the original model.[13] In the present article, a major trust for using the Johnson-King model to study the dynamic stall comes from the observation that this model seems to be good for the low-speed, massively separated flows induced by a strong adverse pressure gradient, such as a low speed diffuser flow.[11]

The majority of the numerical simulations encountered in the literature seems to be conducted for laminar flows. For turbulent flows, a computational study was made by Rumsey and Anderson[14] for unsteady airfoil motion. In their study, significant differences between the Baldwin-Lomax[10] and Johnson-King[11] models were apparent and showed a need for further studies on this line. An attempt was made in the

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present work to shed some more light on this aspect of the problem. Here, the light dynamic stall has been chosen as a test case among four categories of the dynamic stall given by McCroskey and Pucci[15]: 1) no stall (weak interactions), 2) stall onset (mild interaction), 3) light stall (strong interactions), and 4) deep stall (viscous dominated). The choice of the light stall was made because of the fact that coupled with its practical importance, it is probably the one that most warrants concentrated research efforts.[15] In this regime, the vertical extend of the viscous zone tends to remain on the order of the airfoil thickness, generally less than for static stall. Consequently, this class of oscillating airfoil problems should be within the scope of the zonal methods or thin-layer Navier-Stokes calculation.

However, the light stall seems to be more difficult to capture for numerical methods because, unlike the deep stall case, the leading-edge vortex is not well-organized. In deep stall, the vortex is well-organized and even low-order methods such as the vortex lattice method can capture the peak moments. For this reason, all published computational-experimental comparisons seem to be in the deep-stall regime. In the light stall, the problem is to accurately predict the beginning of the stall. This may be indicative of the importance of the transition and turbulence, because it may be the turbulence that sets up the strength of the vorticity that is shed from the leading edge. This gives us impetus to investigate the nonequilibrium turbulence effects in the light stall.

Numerical Method

The strong conservation form of the Navier-Stokes equations is used for shock capturing purposes. In high-Reynolds number flows, the viscous effects are confined to thin layer near rigid boundaries. Also, one generally does not have enough grid resolution in the streamwise direction due to computer limitations. Hence, for many Navier-Stokes computations the viscous terms along the body can be dropped. This leads to the thin-layer Navier-Stokes equations that seem to be suitable for computing light dynamic stall. The unsteady formulation in this work is achieved in the following way. The governing thin-layer Navier-Stokes equations are written in an inertial frame of reference and the motion of the body can be provided by means of a general time-dependent coordinate transformation, $\tau = t$, $\xi = \xi(x, y, z)$, $\eta = \eta(x, y, z)$. In order to eliminate the need for generating a grid at each time step, a fixed grid is rotated with the airfoil (Fig. 1). After the time-dependent coordinate transformation, the thin-layer Navier-Stokes equations in strong conservation form are written as

$$\partial_\tau \hat{Q} + \partial_\xi \hat{E} + \partial_\eta \hat{F} = Re^{-1} \partial_\eta \hat{S}$$

where $\hat{Q} = J^{-1}[\rho, \rho u, \rho v, e]$ is the vector of the dependent variables. The inviscid and viscous flux vectors are not given here and can be found in Ref. 17.

A body-fixed grid is harmonically oscillated around the quarter chord of the airfoil with angular velocity determined from the nondimensional pitch rate. New points at each time step are found by using a rotational transformation matrix, and time metrics are computed from

$$\xi_t = -\xi_x x_t - \xi_y y_t, \qquad \eta_t = -\eta_x x_t - \eta_y y_t$$

at each time step where $x_t = \dot{\alpha} y$ and $y_t = -\dot{\alpha} x$, and $\dot{\alpha}$ is the instantaneous angular velocity that is the time rate of change of the angle-of-attack variation given by $\alpha(t) = \alpha_0 + \alpha_1 \sin(wt)$. Here α_0 is the mean angle of attack, α_1 is the amplitude, and ω is the circular frequency of the oscillation. The initial condition for the unsteady calculation is a steady converged solution for a suitable mean angle of attack. In this study, implicit approximate factorization algorithms of LU-ADI due to Obayashi and Kuwahara[16] and diagonal algorithm due to Pulliam and Chaussee[17] were used. The algorithms are first-order accurate in time and second-order accurate in space.

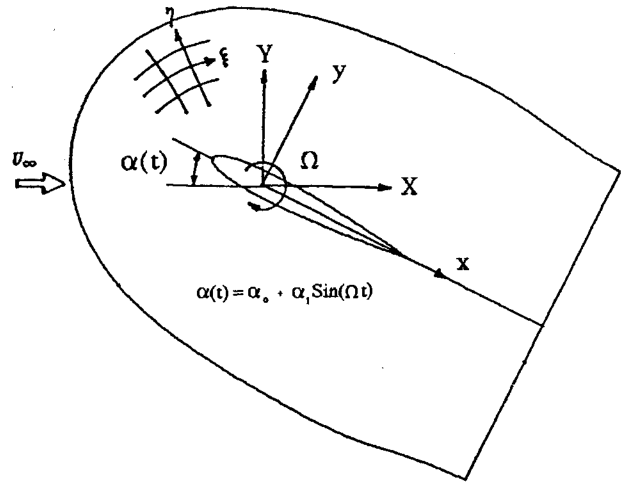

Fig. 1 Unsteady airfoil motion (*X-Y* inertial coordinate system, *x-y* rotating coordinate system).

For more information the reader is referred to the original papers.

In this study, the Cebeci-Smith[9] and Baldwin-Lomax[10] models are used as the equilibrium turbulence models and the Johnson-King model[11] is used as the nonequilibrium turbulence model. The present method implements a simple zonal turbulence model that uses the Baldwin-Lomax model in the wake for both the equilibrium and nonequilibrium models. Thus, the nonequilibrium effects were not yet carried to the wake. The Baldwin-Lomax model was patterned after that of Cebeci-Smith and it is more straightforward to use with the Navier-Stokes flow solvers. This is due to the fact that the Baldwin-Lomax model removes the necessity of finding the boundary-layer edge. However, simple formulas[18] based on numerical experimentation or more elaborate techniques such as the one developed by Stock and Haase[19] help turbulence models, like Cebeci-Smith or Johnson-King, by determining the boundary-layer edge quite accurately. The Johnson-King model accounts for the convection and diffusion effects by solving an o.d.e. governing the streamwise development of the maximum shear stress derived from the turbulent kinetic energy equation. In this study, the Cebeci-Smith method is used as the base model for the Johnson-King model. Also, the Baldwin-Lomax, Cebeci-Smith, and Johnson-King models will be called as B-L, C-S and J-K in short.

Results and Discussion

Unsteady calculations were performed for the NACA0012 airfoil that is rotated around the quarter chord point with a fixed grid around it. A hyperbolic C-type grid was generated with dimensions 157 × 57 (Fig. 2). A minimum normal spacing of 0.00001 c (c is chord length) at the airfoil was chosen to guarantee at least one or two grid points in the viscous sublayer. Outer extend of the grid was exponentially stretched to 20 chord lengths from the solid surfaces to avoid reflection of boundary conditions. Although, a much finer grid is desirable for better resolution of viscous effects, current computational cost of the calculations confines us to use a rather medium grid. Temporal scales were resolved by using sufficiently small time step (0.001). Therefore, a complete cycle of motion took about 100,000 time steps.

The C-S and J-K models in this study use boundary-layer quantities as scaling parameters for computing the eddy viscosities that necessitate the accurate prediction of the boundary-layer edge. For this purpose, we either used a technique developed by numerical experimentation[18] or the one suggested in Ref. 19. Both techniques were consistent with each other.[18] Before unsteady computations, the code has been validated for steady state (see Ref. 18).

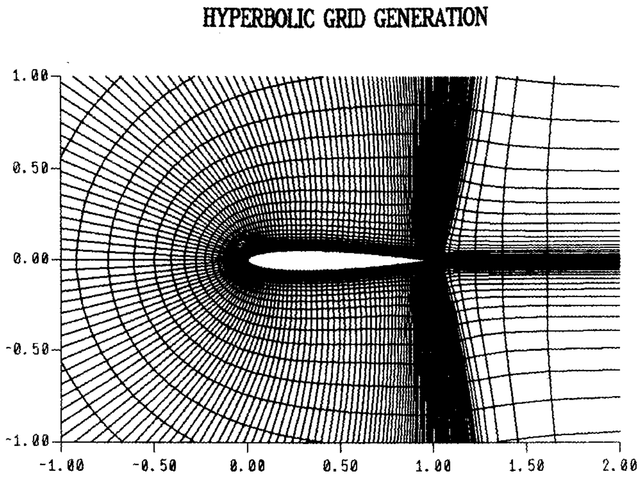

Fig. 2 C-type hyerbolic grid.

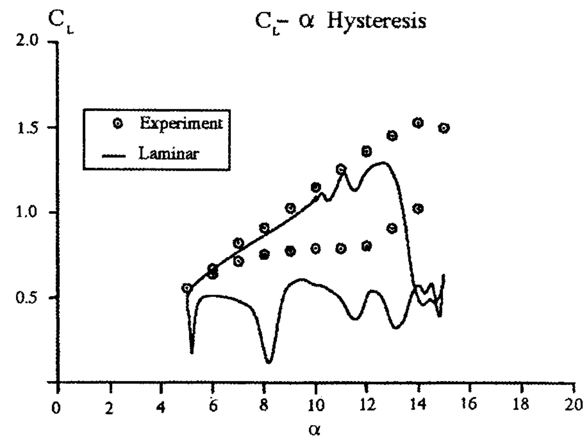

Fig. 3 Comparison of predicted and experimental C_L—α hysteresis for the light dynamic stall of the NACA0012 airfoil, M_∞ = 0.3, $\alpha(t)$ = 10 deg + 5 deg $\sin(2M_\infty kt)$, k = 0.1, Re_∞ = 4 × 10^6, laminar.

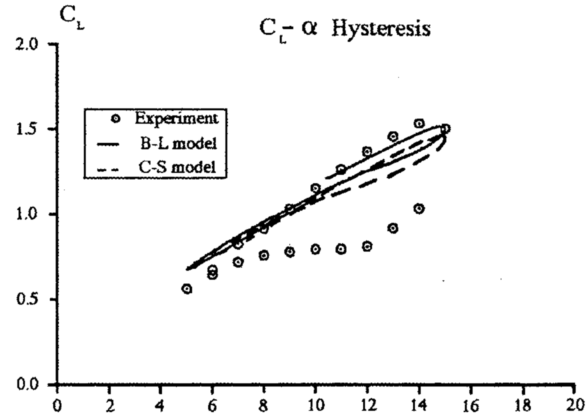

Fig. 4 Comparison of predicted and experimental C_L—α hysteresis for the light dynamic stall of the NACA0012 airfoil, M_∞ = 0.3, $\alpha(t)$ = 10 deg + 5 deg $\sin(2M_\infty kt)$, k = 0.1, Re_∞ = 4 × 10^6, B-L and C-S models.

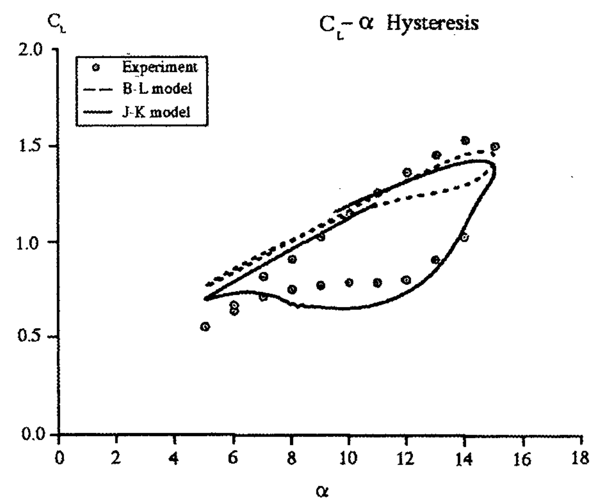

Fig. 5 Comparison of predicted and experimental C_L—α hysteresis for the light dynamic stall of the NACA0012 airfoil, M_∞ = 0.3, $\alpha(t)$ = α_0 + 5 deg $\sin(2M_\infty kt)$, $\alpha_{0,\text{exp}}$ = 10 deg, $\alpha_{0,\text{comp}}$ = 11 deg, k = 0.1, Re_∞ = 4 × 10^6, B-L and J-K models.

Case 7 of Ref. 15 for the light stall of the NACA0012 airfoil was chosen as the test case. The flow conditions for this case were $M_\infty = 0.3$, $Re = 4 \times 10^6$. The airfoil is oscillated according to the formula $\alpha(t) = \alpha_0 + \alpha_1 \sin(2M_\infty kt)$ where $k = \omega c/2U_\infty$ is the reduced frequency, ω is the circular frequency, and α_0 and α_1 are the mean angle and the amplitude of the oscillation. The parameters of the harmonic motion for this case are $k = 0.1$, $\alpha_0 = 10$ deg, and $\alpha_1 = 5$ deg.

To demonstrate the importance of the turbulent diffusion, first a laminar run was made for this case. A suitable starting angle of attack was chosen as an initial condition and a steady-state solution was obtained first. Later, the angle of attack was changed according to the harmonic motion formula given above. In Fig. 3, C_L—α hysteresis loop compared with the experiment, and the results are far from the experiment. However, we should not be too surprised with this result because in this Reynolds number the flow cannot stay laminar. Similar results were independently obtained in Ref. 20 for a deep-stall case. Turbulent flow calculations for this case using Baldwin-Lomax and Cebeci-Smith models are shown in Fig. 4. During the upstroke motion of the airfoil, both models give similar trends lying close to experiment. The difference between the two models during the upstroke motion comes from using different initial conditions. This is for numerical experimentation, and results would have shown similar trends, if they had been started from the same initial conditions. Also, one cycle was completed because of the computer time limitations. Although the upstroke motion was captured, the downstroke motion and the overall hysteresis loop are very inaccurate in both models.

In all these calculations, the similar features of the flow, is that around the maximum angle of attack a very tiny region of separation was forming at the trailing edge, but due to inadequately modeled viscous and turbulent interaction, the light stall hysteresis loop could not be obtained. One may tend to conclude this is because of the inadequacy of the turbulence models, but use of free-air grid without corrections on the experimental data could also be a restricting point. To check this aspect of the problem it was decided to increase the mean angle of attack of the harmonic motion by 1 deg so that some kind of wall corrections are included. A result of such a computation using the Baldwin-Lomax model for a mean angle-of-attack α_0 of 11 deg is shown in Fig. 5. The solution is basically the same as its counterpart in Fig. 4. At this point, it was concluded that probably the equilibrium turbulence model was inadequate and nonequilibrium effects might be important. The use of the Johnson-King model proves this point as shown in Fig. 5. The hysteresis loop produced by this model is quite similar to the experiment demonstrating the need to include nonequilibrium behavior of the Reynolds shear stress in the calculations. The moment hysteresis curves for the B-L and J-K models are given in Fig. 6. Whereas the B-L model gives a very inaccurate prediction, J-K model produces the correct shape of the curve, including the negative-pitch damping.

To further illuminate this point, the ratio of the nonequilibrium and equilibrium outer eddy viscosities called σ is given

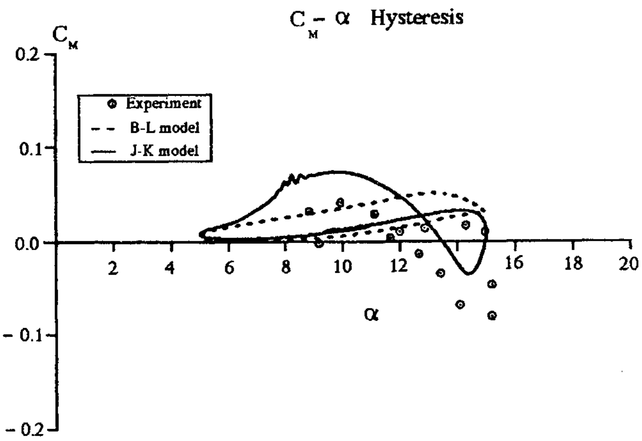

Fig. 6 Comparison of predicted and experimental C_M—α hysteresis for the light dynamic stall of the NACA0012 airfoil, $M_\infty = 0.3$, $\alpha(t) = \alpha_0 + 5\ \text{deg}\ \sin(2M_\infty kt)$, $\alpha_{0,\text{exp}} = 10$ deg, $\alpha_{0,\text{comp}} = 11$ deg, $k = 0.1$, $Re_\infty = 4 \times 10^6$, B-L and J-K models.

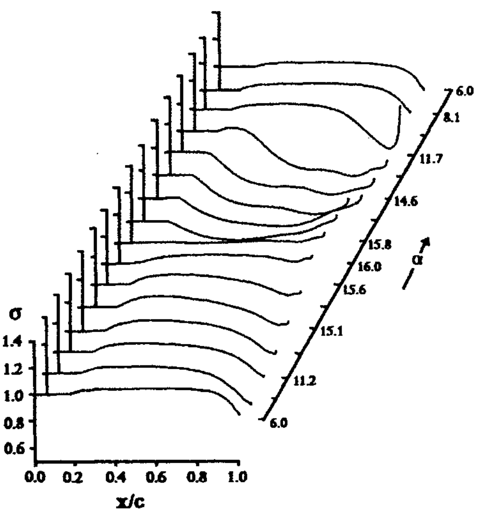

Fig. 7 Computed σ—α sequence ($\sigma = \nu_{t0,n}/\nu_{t0,\text{eq}}$) during the light dynamic stall of the NACA0012 airfoil, $M_\infty = 0.3$, $\alpha(t) = \alpha_0 + 5\ \text{deg}\ \sin(2M_\infty kt)$, $\alpha_{0,\text{exp}} = 10$ deg, $\alpha_{0,\text{comp}}$, $= 11$ deg, $k = 0.1$, $Re_\infty = 4 \times 10^6$, J-K model.

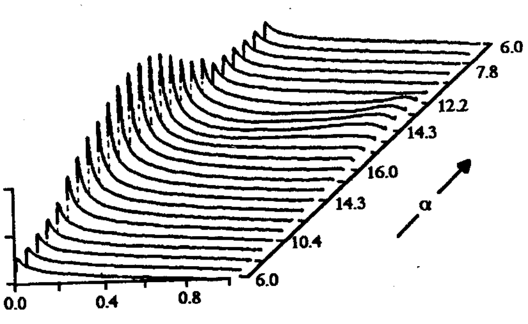

Fig. 8 Computed C_p—α sequence during light dynamic stall of the NACA0012 airfoil, $M_\infty = 0.3$, $\alpha(t) = \alpha_0 + 5\ \text{deg}\ \sin(2M_\infty kt)$, $\alpha_{0,\text{exp}} = 10$ deg, $\alpha_{0,\text{comp}} = 11$ deg, $k = 0.1$, $Re_\infty = 4 \times 10^6$, J-K model.

in Fig. 7. The change in σ in the downstroke is particularly interesting. It is seen that after the midchord, and around the trailing edge of the airfoil, strong nonequilibrium effects take place that alter the level of the maximum eddy viscosity. Probably this helps to set up the strength and location of the stall vortex more realistically. In Fig. 8, the C_p—α sequence of the motion is given that shows a vortex is released from the rear-half of the airfoil. Finally, the particle traces on the

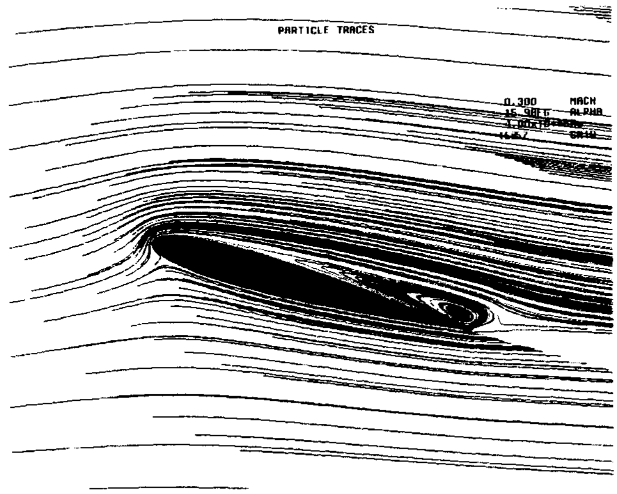

Fig. 9 Particle traces showing the location and size of the light stall vortex, $M_\infty = 0.3$, $\alpha(t) = \alpha_0 + 5\ \text{deg}\ \sin(2M_\infty kt)$, $\alpha_{0,\text{exp}} = 10$ deg, $\alpha_{0,\text{comp}} = 11$ deg, $k = 0.1$, $Re_\infty = 4 \times 10^6$, J-K model.

airfoil (15.9 deg downstroke), showing the stall vortex, are presented in Fig. 9. As seen, the interaction region is in the order of the airfoil thickness that is typical of the light stall.

Conclusion

An unsteady thin-layer Navier-Stokes program was developed that was capable of calculating the unsteady harmonic motion of an airfoil with a fixed grid on it. An assessment for the effect of equilibrium turbulence models was made for the light-stall regime of the NACA0012 airfoil. It was found that the equilibrium turbulence models were incapable of producing the light-stall vortex. Use of a nonequilibrium turbulence model with a mean angle-of-attck correction was necessary to obtain a light stall hysteresis loop similar to the experiment. The nonequilibrium state of the Reynolds shear stress seemed to set the strength of the shed vortex so that a more realistic lift-hysteresis-loop could be obtained.

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