bilities of both simulators were inadequate for testing purposes.

The simulation of the gun on the AH-1 included tracers, whereas the simulation of the gun on the AH-64 did not. According to the gunners, this made the simulated AH-1 gun much more effective.

Since neither simulator had an overhead visual system, one crew could fly over the other, then close and kill a blind target. These are artificial conditions. In most actual combat, the existence of surface-to-air missiles would prohibit ATAC at the altitudes practiced by these crews. Both an overhead visual system and the presence of realistic ground threats are mandatory for the realistic simulation of helicopter ATAC.

All four aviator participants stated that the training they received was very valuable. Simply networking two or more attack helicopter simulators together for the purpose of ATAC training will provide a substantial training benefit. However, the following factors should be considered as time and finances permit:

1) The simulators are already very close to full utilization. In order to provide all of our aviators with adequate networked training on our present simulator fleet, additional simulators would be required.

2) A wider field-of-view visual system would be of great benefit in helicopter ATAC simulation. An overhead visual scene is particularly important.

3) A better weapons-scoring system is required for most testing. The scoring available on the AH-64 CMS is marginal for test purposes. The scoring system available on the AH-1 FWS is very close to useless.

4) The crew in each simulator should be able to talk securely, i.e., without their conversation being overheard by the crew in the other simulator as was the case in this investigation.

5) Enough simulators should be connected to allow the use of air-to-air tactics, i.e., there should be a wingman.

6) The aviators in both simulators turned off the motion systems, but expressed a desire to have "g" seats to provide motion onset cues.

Recommendations

1) Provide a wider field-of-view visual system. An overhead visual is mandatory for realistic close range helicopter ATAC simulation.

2) Provide closed intracrew communications.

3) Network for at least a two-on-two contest.

4) Provide "g" seats for the crews. Allow the motion system to be turned off at the discretion of the aviators.

5) Delete any artificial pitch and roll constraints. Maneuver constraints should mirror the limitations of the aircraft. Exceeding those restraints should produce the expected results. A "g" load criterion would probably be most appropriate.

6) The visual should portray ordnance in flight accurately, including incoming rounds and tracers.

7) The following measures should be added to those already available on the AH-64 combat mission simulator: a) Time to first hit by each aircraft; b) Time to kill by each aircraft; c) If there is an advantaged aircraft, the number of times the advantaged aircraft is killed before his adversary is killed; d) Number and type of ordnance expended by each adversary at the time of each of the above criteria; e) Type of ordnance which resulted in each hit; f) Type of ordnance which resulted in each kill; g) Altitude difference between firing and target aircraft at time of hit or miss by missile, rocket, or gun burst (firing aircraft higher will be positive); h) Slant range between firing and target aircraft at time of hit or miss by missile, rocket, or gun burst; i) Difference between angular velocity of target aircraft and ordnance at time of hit or miss. (Gun fire will be considered in bursts. Greater target velocity will be positive.); and j) Difference between the angular acceleration of target aircraft and ordnance at time of hit or miss (Gun fire will be considered in bursts. Greater target acceleration will be positive.)

Evaluation of Three Turbulence Models in Static Air Loads and Dynamic Stall Predictions

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Introduction

THE flowfield surrounding modern rotorcraft and propeller configurations is highly complex and is dominated by three-dimensional effects, transonic flow, flow separation, and unsteadiness and can be properly modeled only through the numerical solution of the three-dimensional unsteady Navier-Stokes equations. Since full three-dimensional simulations are costly, historically researchers have used simpler three-dimensional analyses such as the lifting-line theory, which use a table look up of two-dimensional steady and unsteady airfoil characteristics. The airfoil tables needed may come from carefully performed experiments or from two-dimensional computer codes. To be useful, the two-dimensional computer codes should provide 1) reliable prediction of airfoil static load data and dynamic stall characteristics, 2) a method for evaluation of the flow-yaw effects on air-load characteristics, and 3) a suitable turbulence model for properly modeling separated flows.

In an effort to predict static and dynamic stall characteristics of airfoils, in this study, a two-dimensional compressible Navier-Stokes code has been developed. Three turbulence models have been implemented: 1) the Baldwin-Lomax algebraic model, 2) the Johnson-King ordinary differential equation (ODE) model, and 3) the two-equation k-ϵ model. This work summarizes the performance of these three turbulence models for a variety of steady and unsteady flow conditions. The effects of turbulence model on the predicted flow properties are also discussed. For a detailed description of the solution procedure, correction for flow-yaw effects, and several additional calculations, the reader is referred to Refs. 1 and 2.

Mathematical and Numerical Formulation

The compressible Navier-Stokes equations are parabolic in time and may be advanced in time using a suitable, stable, dissipative scheme. In the present work, a formulation similar to that described by Steger[3] was used. Standard second-order-accurate central differences were used to approximate the spatial derivatives and to compute the metrics of transformation. The nonlinear transport terms, which are unknown at a given time level $n+1$, were linearized about their values at a previ-

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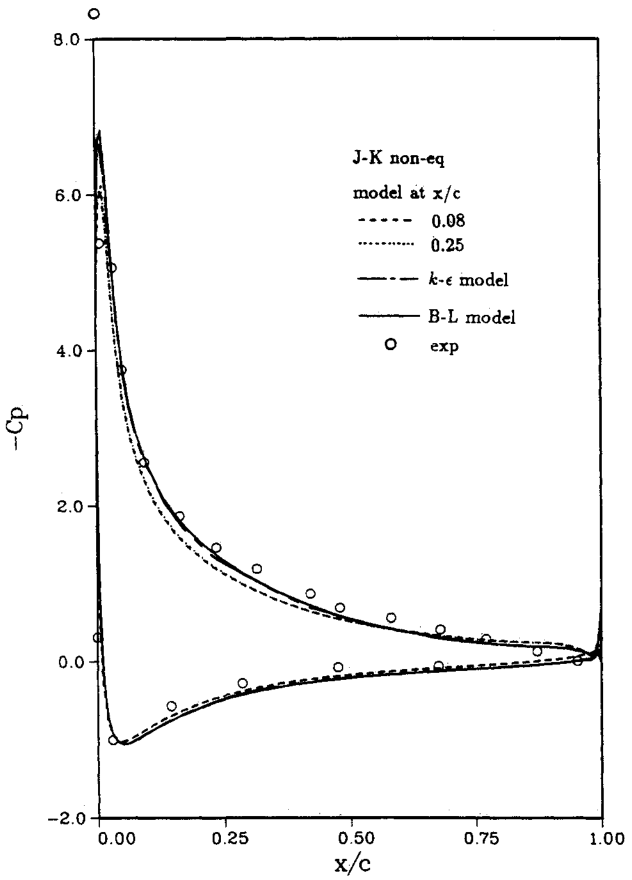

Fig. 1 Surface pressure distribution over an NACA 0012 airfoil at $M_\infty = 0.301$, $\alpha = 13.5$ deg, $Re = 3.9 \times 10^6$.

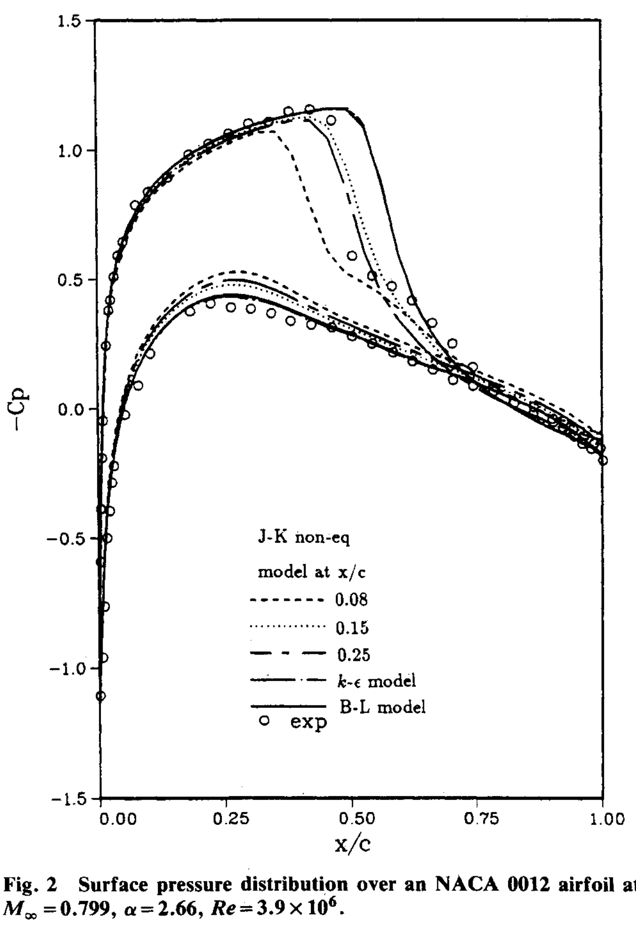

Fig. 2 Surface pressure distribution over an NACA 0012 airfoil at $M_\infty = 0.799$, $\alpha = 2.66$, $Re = 3.9 \times 10^6$.

ous time level n. The time derivative was approximated as a first-order-accurate, two-point, backward difference. This leads to a system of simultaneous equations for the flow vector $\mathbf{q}^{n+1}$. These equations were re-expressed as a pentadiagonal matrix system of simultaneous equations for the "delta" quantity $(\mathbf{q}^{n+1} - \mathbf{q}^n)$, where $\mathbf{q}$ is the flow-property vector. The pentadiagonal equation system was approximately factored into a product of tridiagonal matrices using the Beam-Warming approximate factorization scheme as discussed in Ref. 1. To control the growth of high-frequency spatial oscillations, a set of artificial dissipation terms were added to the discretized equations. These dissipation terms used a combination of second- and fourth-order differences of the flow properties in a manner discussed by Jameson et al.[4]

Turbulence Models

Three models for computing the eddy viscosity are considered in this work. These models are briefly described here.

Baldwin-Lomax Model

This model is patterned after the well-known Cebeci-Smith model[5] and has been extensively used by a number of researchers. It uses a two-layer formulation to model the eddy viscosity. In the inner layer, a classical mixing length model is used, and a van Driest damping function is used to drive the eddy viscosity to zero near the wall. In the outer layer, a function, which is the product of the distance from the solid wall and vorticity, was used to estimate the velocity scale. The location where function is maximum gives the length scale. Klebanoff's intermittency factor is used to drive the eddy viscosity to zero away from the viscous region.

Johnson-King One-Equation Model

The Baldwin-Lomax model is a equilibrium model in the sense that it assumes that the eddy viscosity instantaneously adjusts to the local-flow characteristics. The Baldwin-Lomax model thus does not take into account the upstream eddy viscosity or turbulent kinetic energy values. The Johnson-King model attempts to rectify this situation by solving an ODE for the maximum turbulent kinetic energy within the boundary layer at a given streamwise location.[6] This ODE may be thought of as a simplified form of the Reynolds stress equation. This ODE is solved as an initial value problem by marching along the flow direction and automatically brings into the account the upstream history of the flow.

Gorski k-ϵ Model

The third turbulence model considered in this work is the well known k-ϵ model, implemented with a set of wall-boundary conditions proposed by Gorski.[7] This model requires numerical solution of two partial differential equations for the instantaneous values of turbulent kinetic energy k and the dissipation rate ϵ at every point in the flowfield. Near solid walls, many of the conventional k-ϵ models fail and require special treatment. This model assumes the turbulent kinetic energy to vary as the square of the distance from the wall near the solid wall, and the dissipation rate is assumed to be constant in this region. This model does not make any assumptions regarding the behavior of the velocity profile (e.g., a logarithmic profile) near the solid wall and allows the mean-flow equations to be solved everywhere, including the viscous sublayer.

Results and Discussions

Steady Flow Studies

Over 50 steady and unsteady calculations have been carried out using the formulation just described. Here only a small subset of the results are presented.

First, results are presented for a turbulent attached flow past an airfoil. Figure 1 shows computed and experimental pressure distributions for the NACA 0012 airfoil at an at-

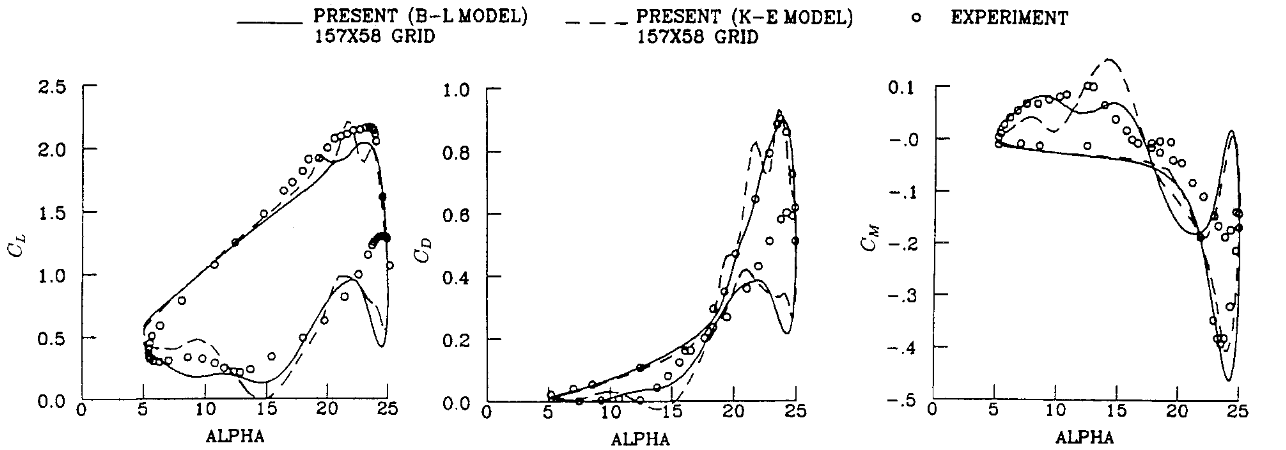

Fig. 3 Computed and measured loads for an NACA 0012 airfoil at deep dynamic stall condition, $M_\infty = 0.283$, $Re = 3.45 \times 10^6$, reduced frequency 0.151.

tached flow condition ($M_\infty = 0.301$, $\alpha = 13.5$ deg, and $Re = 3.9 \times 10^6$). The computed surface pressures using the three turbulence models are all in good agreement with experimental data.[8]

Transonic flow cases exhibiting mild and strong separation have been computed and compared with detailed turbulent flow measurements. In Fig. 2, the surface pressures are shown for an NACA 0012 airfoil at experimental conditions[9]: $M_\infty = 0.799$, $\alpha = 2.66$ deg, $Re = 3.9 \times 10^6$. It is seen that the Baldwin-Lomax and the k-ϵ models predict similar pressure distributions with a shock predicted stronger than the measurements. Some sensitivity was observed of the computed solutions on the x location where the Johnson-King ODE model was activated. The location $x/c = 0.15$ gives best agreement with measured surface pressures. The other two models perform poorly in this case.

A series of dynamic stall calculations have also been carried out for three airfoils using the Baldwin-Lomax and the k-ϵ model. In Fig. 3, the unsteady air loads on an NACA 0012 air foil pitching about a mean angle of 15 deg and amplitude of 10 deg at a reduced frequency of 0.15 are shown. The k-ϵ model predicts higher lift during the upstroke. During the downstroke, predictions using the k-ϵ model show trends similar to the Baldwin-Lomax model, except that a smaller second vortex shedding (around 24 deg) and much stronger third vortex shedding (around 15 deg) were detected. Results from both models only show a qualitative agreement with the experiment during the downstroke.

Concluding Remarks

A number of steady and unsteady flows of interest to fixed and rotary wing industries have been calculated using three turbulence models. Numerical results show that good prediction of static loads and dynamic stall hysteresis loops of rotor blade sections was feasible. Evaluation of three eddy viscosity models have been made. In attached flows, the three turbulence models considered gave good correlation with experimental data. For strongly separated flows, eddy viscosity models available, including the k-ϵ model, are not adequate. No clear trend could be found favoring the use of higher-order turbulence models in separated flows.

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