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Comparative Numerical Study of Two Turbulence Models for Airfoil Static and Dynamic Stall

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Introduction

WHILE of fundamental interest because of the complex fluid mechanisms involved, both static and dynamic airfoil stall are also important in a variety of applications including high angle-of-attack aerodynamics, maneuvering aircraft, control surface motions, helicopter rotors, wind turbines, and turbomachinery. Moreover, a critical need exists for turbulence models which provide efficient and accurate simulation of such flows for practical numerical computations. The objective of the present work is to examine the adequacy of two turbulence models for the calculation of both static and dynamic airfoil stall flowfields by comparison with each other as well as with experimental data. For this purpose, the commonly used Baldwin-Lomax[1] algebraic model and the two-equation k-ϵ formulation of Launder and Sharma,[2] as generalized by Gerolymos,[3] were selected. The two-equation model requires no predefined turbulence length scales or wall functions, and because it includes low-Reynolds-number terms, both k and ϵ vanish at solid surfaces. Thus the formulation is attractive for the computation of flowfields about complex three-dimensional configurations, or for applications on unstructured meshes.

Results

Experimental conditions of the investigation by Lorber and Carta[4] were chosen to be simulated numerically. This selection was prompted by the comprehensive set of data that are available at high Reynolds number for both steady and unsteady flows. Two Mach numbers were considered, $M_\infty = 0.2$ and $M_\infty = 0.4$, with corresponding chord Reynolds numbers of 2×10^6 and 4×10^6. The wind-tunnel model consisted of a Sikorsky SSC-A09 supercritical section with a 43.9-cm chord.

The governing equations were taken to be the unsteady compressible two-dimensional Navier-Stokes equations written in mass-averaged variables and expressed in nondimensional strong-conservation form. Steady and unsteady solutions to these equations were obtained by an approximately factored Beam-Warming[5] finite difference algorithm. Complete details of the calculations including the governing equations, boundary conditions, numerical method, generation of the (303×131) mesh, and grid resolution study may be found in Ref. 6.

At $M_\infty = 0.2$, 17 cases were considered for angles of attack between 0 and 30 deg. Aerodynamic force coefficients for these cases appear in Fig. 1 where the computations employing both the k-ϵ and Baldwin-Lomax models are compared to the experimental data. Above an angle of attack of 20 deg, no steady solutions were obtainable with the Baldwin-Lomax model. Although the k-ϵ equations fail to predict the abrupt onset of stall that is evident experimentally, they do produce a more favorable comparison with drag and moment than the algebraic model.

Eleven steady solutions employing the k-ϵ equations for $0 \leq \alpha \leq 20$ deg at $M_\infty = 0.4$ were generated numerically. Once again, with the Baldwin-Lomax model no steady results could be obtained for $\alpha > 9$ deg. Aerodynamic force coefficients for these cases are shown in Fig. 2. The computations generally compare more favorably with the data than was true for $M_\infty = 0.2$. It is also noted that

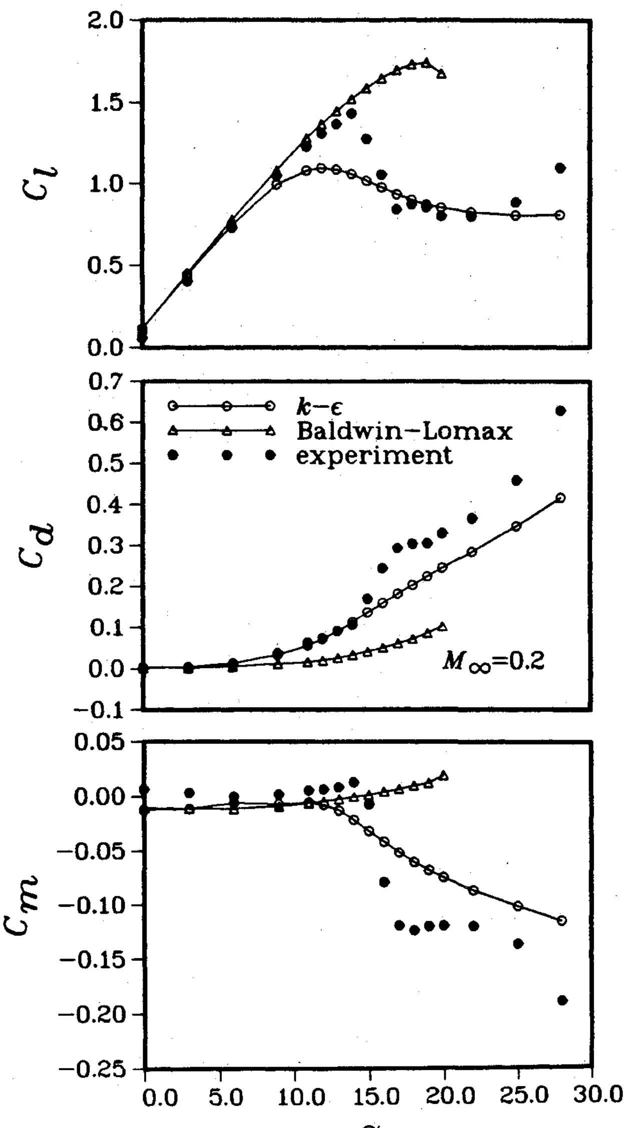

Fig. 1 Steady aerodynamic force coefficients for $M_\infty = 0.2$.

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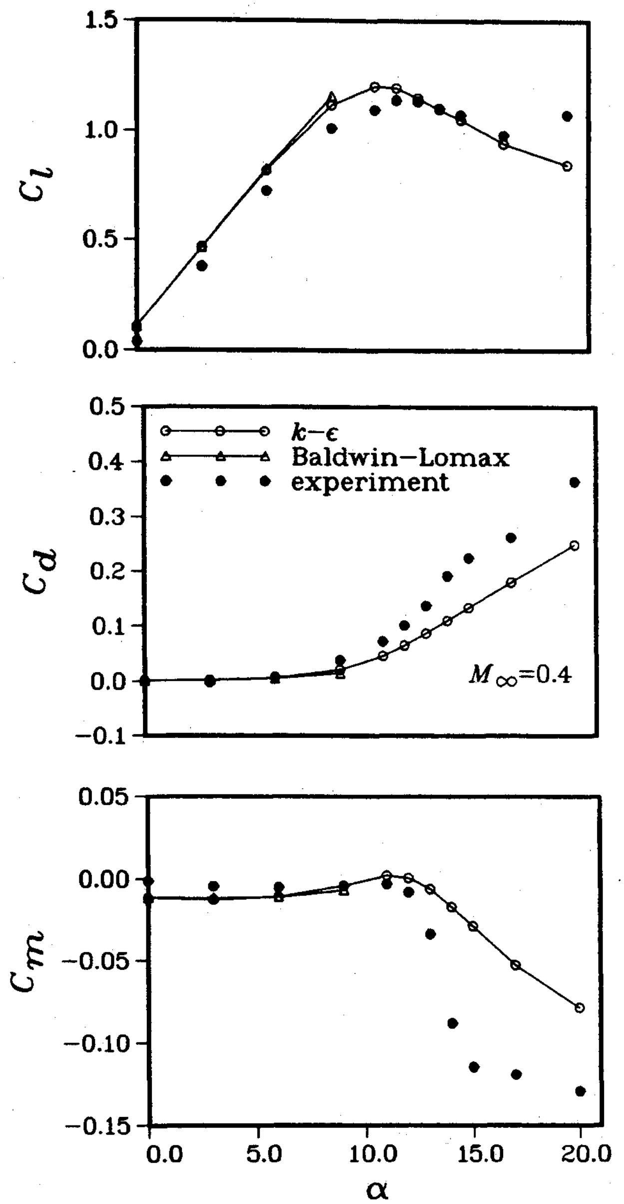

Fig. 2 Steady aerodynamic force coefficients for $M_\infty = 0.4$.

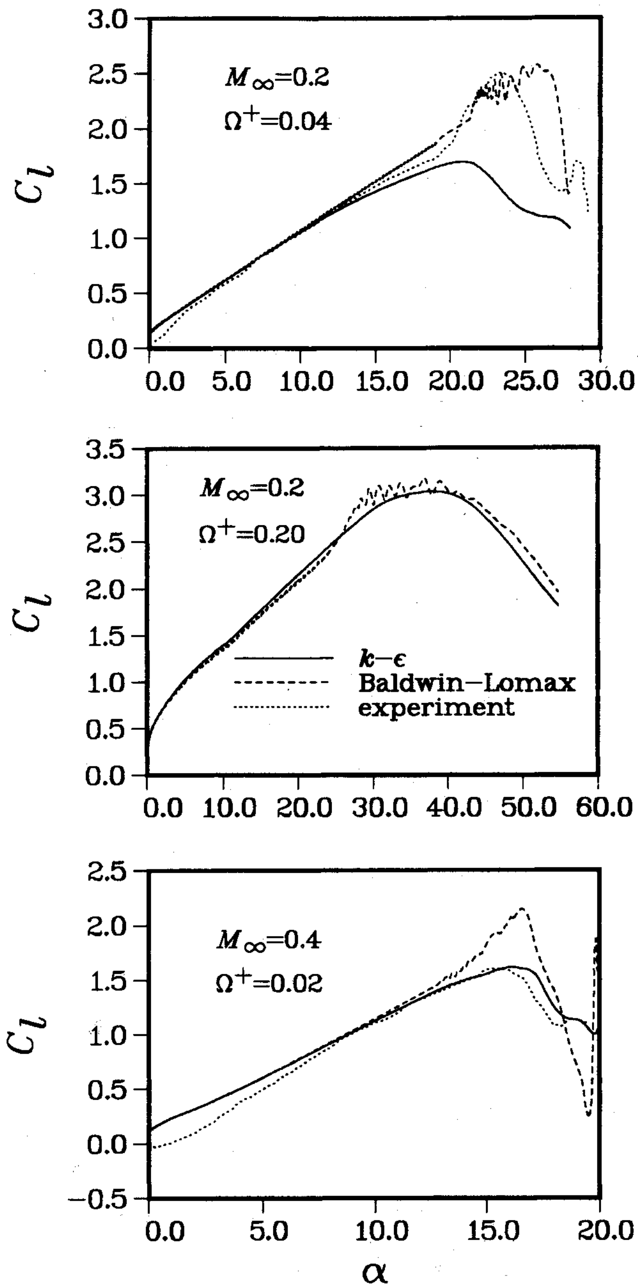

Fig. 3 Unsteady lift coefficient histories.

the computed maximum lift is slightly greater than the corresponding experimental level, which is opposite of the behavior for M_∞ = 0.2.

Unsteady flow at $M_\infty = 0.2$ for the subject airfoil being pitched about the 1/4 chord location at the nondimensional rate of $\Omega^+ = 0.04$ was computed for $0 \leq \alpha \leq 30$ deg. Comparison between the calculated and measured instantaneous lift coefficients is made in Fig. 3. Maximum level of the lift is reasonably well predicted by the algebraic turbulence model, but the evolution of the stall vortex appears to be somewhat delayed. In the case of the k-ϵ equations, the solution developed excessive viscous diffusion and thus no vortex was produced. Instead, the flowfield gradually evolved into a massively separated state without a high peak value in the lift coefficient. Such behavior is identical to that observed by Visbal[7] for calculation of a NACA 0015 airfoil being pitched at a rate of $\Omega^+ = 0.02$ using the Baldwin-Lomax model.

Because the k-ϵ equations were found to be overly diffusive for $\Omega^+ = 0.04$, it was felt that at a higher pitch rate its performance might improve. To investigate this possibility, pitch-up solutions were generated for $M_\infty = 0.2$ and $\Omega^+ = 0.20$. Figure 3 compares the calculated instantaneous lift coefficients for the k-ϵ and Baldwin-Lomax models for this example. It is evident that the solutions are in close agreement, but there are no experimental data available for validation purposes ($\Omega^+ = 0.04$ is the highest pitch rate considered experimentally).

With $M_\infty = 0.4$, pitch-up motions were computed for $0 \leq \alpha \leq 20$ deg at $\Omega^+ = 0.02$. This was the highest experimental pitch rate at this Mach number. Figure 3 shows force coefficient histories. The k-ϵ solution is seen to compare reasonably well with the data, whereas the algebraic result overpredicts the peak level of C_l. For $\alpha < 10$ deg, the lift histories of the computations agree with each other, but differ from the experiment. This may be due to variations in the initial airfoil motion, even though the experimentally prescribed angle-of-attack history[4] was utilized by the numerical simulations.

Conclusions

For steady flows at $M_\infty = 0.2$, the algebraic model produced an inordinate amount of leading-edge suction at high α, thereby delaying stall to an angle of attack greater than that observed physically. Even though the k-ϵ equations underpredicted the stall angle and the peak lift, comparison with experiment was qualitatively favorable. At $M_\infty = 0.4$, the steady k-ϵ solutions agreed reasonably well with the data.

In the case of pitch-up motion with $M_\infty = 0.2$ and $\Omega^+ = 0.04$, the algebraic model was in correspondence with experimental measurements. Because of excessive viscous diffusion, the k-ϵ equations generated no leading-edge vortex and therefore compared poorly with the data. For a higher pitch rate, however, the k-ϵ solution agreed with the algebraic result. When $M_\infty = 0.4$, the k-ϵ model compared more favorably with the experiment than did the algebraic formulation.

Both the k-ϵ and Baldwin-Lomax solutions were fully turbulent from the airfoil leading edge. No attempt was made to simulate transition. This was unlike the experiment in which the transition location developed naturally and moved forward toward the leading edge as the angle of attack increased.

Neither model was entirely successful in predictive capability. Generally, the algebraic model produced less diffusion than was seen physically, whereas the k-ϵ equations produced more. These results clearly indicate that even for this restricted class of flows, the accuracy of simulation was highly case dependent and therefore evidences a need for turbulence models which better represent the fluid physics.

Acknowledgment

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Intensified Array Camera Imaging of Solid Surface Combustion Aboard the NASA Learjet

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Introduction

FLAME spread over a paper surface in reduced gravity has received extensive study in drop tower facilities and has recently been observed in experiments aboard the Shuttle.[1–4] A common feature of flames produced in a reduced-gravity environment at the investigated oxygen concentrations is a low-level blue luminosity which makes it difficult to record the flame shape and position on cine film. Thus, there is a need to improve the visualization system for these experimental studies.

Most reduced-gravity work on solid surface combustion has been performed at the NASA Lewis drop towers, which offer 2.2 or 5 s of microgravity, but have high g-level impacts measured from 30 to 100 g and more. The power for all equipment is usually supplied by batteries onboard the experimental package. Aircraft flying Keplerian trajectories offer a longer test time, 10 to 15 s, of reduced gravity and eliminate the shock loadings, but the g levels are not as low as in the drop towers. Residual g levels of ± 0.01–$0.02\ g$ are common and effects on flame behavior due to the g jitter also may be seen, but have not been quantified. Aircraft offer a more hospitable environment than the drop tower for the use of sensitive, delicate, and expensive instrumentation with regards to shock impact, power availability, and operator interaction.

This Note summarizes the results of six experiments conducted aboard the NASA Lewis Learjet. These flights were undertaken primarily to demonstrate the use of a commercial, intensified array camera to detect a flame from a solid surface combustion experiment in reduced gravity. The intensified array camera is able to detect light levels several orders of magnitude less than that detected by film or other nonintensified cameras. The remainder of the Note contains a description of the experimental apparatus and camera, the images obtained during the flights, and a brief comparison of the flame spread rates to previous drop tower measurements.

Experimental Approach

The combustion apparatus is described in more detail elsewhere.[4] The combustion chamber is an engineering model of the solid surface combustion experiment first flown aboard STS-41 in October 1990. The paper samples are 100 mm $\times$ 30 mm. Two types of paper are used: ashless filter paper of thickness 0.19 mm and laboratory wipers of thickness 0.076 mm. For each flight, one sample is loaded into a metal holder and placed in the 39-l chamber. The vertical orientation of the paper corresponds to the z direction. The x-, y-, and z-axis outputs from an accelerometer mounted

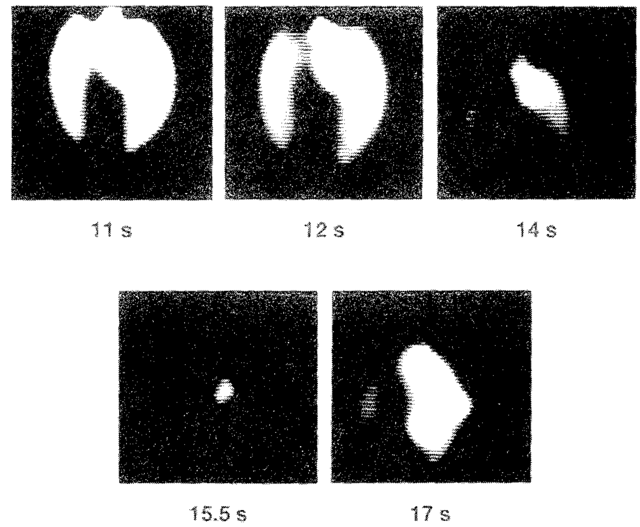

Fig. 1 Series of flame images for ashless filter paper burning in 21% oxygen.

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