Conclusions

A technique for state-space modeling of full potential flow aerodynamic forces on a plate has been presented. This technique employs the singular value decomposition of a block Hankel matrix constructed from the aerodynamic matrix valued impulse response resulting in a system that has common global poles. These common poles result in a system of much lower order than previous techniques having similar accuracy. Comparison between the SVD realization and numerically computed results demonstrates the accuracy of this approach. Several advantages of using full-potential flow aerodynamics were also discussed, including validity over all Mach numbers and frequencies and the ability to be used with modern and optimal control theories.

Acknowledgments

This work was supported in part by the U.S. Air Force Office of Scientific Research (Contract Monitor, Jim Chang C.I.P.I.) and National Science Foundation Graduate Traineeship EE-92-56573.

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Modeling Influences of Inlet Swirl Profiles on Dump Combustor Flows

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Introduction

A CONFINED jet exiting into a sudden expansion, in which reverse flow occurs immediately downstream of the sudden expansion, is encountered in many practical combustion systems. Because of its importance, numerous numerical studies have been made by various researchers to study the effects of swirl in a variety of combustor geometries.[1–4] The studies demonstrate the superiority of stress closures over the k-ϵ model in the prediction of swirling flows, though the merits of alternative stress model variants differ at different swirl levels and swirler types.

Although cubic[2] and quadratic[3] pressure-strain models have been applied to further explore the effects of nonlinear pressure-strain models on predicting free swirling flows, the majority of the confined swirling flow predictions are limited to the linear models. The present research aims at investigating the capability of variants of Reynolds stress turbulence models, linear or quadratic pressure-strain models, on sudden-expanding-pipe geometry swirling flows. Flows with forced and free vortex swirl profiles at the inlet and swirl number of 0.4 form the basis of the investigations.

Turbulence Models

In the present application, turbulence is described either by the k-ϵ model or by Reynolds stress closures. The focal point of a Reynolds stress model is the pressure-strain term ϕ_{ij}, which identifies pressure/strain interaction and consists of three model components representing, respectively, return to isotropy ϕ_{ij1}, isotropization of mean-strain and turbulence correlation ϕ_{ij2}, and redistributive effects arising from wall reflection of pressure fluctuations ϕ_{ijw}.

Four variants of the linear form of the pressure-strain models were investigated. The first stress model closure variant (IPGL) adopted here is that of Gibson and Launder.[5] A variant (IPCM) of the preceding closure, proposed by Fu et al.,[2] includes the convection tensor C_{ij} in ϕ_{ij2} to arrive at the coordinate invariant, objective model form. The second variant (IPGY), proposed by Gibson and Younis,[1] modifies the coefficients C_1 and C_2 in the IPGL model by taking the values as 3.0 and 0.3, respectively. A third variant (LRR) adopted is that proposed by Launder et al.[6] Instead of the linear pressure-strain model, a variant (SSG) proposed by Speziale et al.[7] employs quadratic form of the pressure-strain process. This model does not include explicitly wall reflection terms.

Computational Model

The present numerical procedure[4] solves discretized versions of all equations on a staggered finite volume arrangement, incorporating the SIMPLE pressure-correction algorithm[8] and the QUICK scheme for convective fluxes.[9] The geometry of the dump combustor is a sudden-expanding pipe and the expansion ratio based on the ratio of the radii is 1.5. The step height H is defined as the difference of the radii of the sudden-expanding pipe. The coordinates X and R are denoted as the axial and radial directions, respectively; $X/H = 0$ represents the location of the expansion, and $R/H = 0$

Received Nov. 27, 1995; presented as Paper 96-0568 at the AIAA 34th Aerospace Sciences Meeting, Reno, NV, Jan. 15–18, 1996; revision received July 23, 1996; accepted for publication Aug. 29, 1996.

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and 3 correspond to the centerline and the pipe wall regions, respectively. The swirl number, which is defined as the ratio of the axial flux of swirl momentum and the axial flux of axial momentum multiplied by the inlet pipe radius, is 0.4. The inlet Reynolds number is 1.25×10^5 based on the inlet pipe diameter, and the inlet mean and turbulence quantities were taken from the experiment.[10] At the wall, a two layer wall function was adopted. The numerical meshes, of sizes 90 × 60 and 120 × 90, are nonuniform in both the X and R directions. Initial tests on the influences of the convection schemes revealed that the differences between the second-order QUICK and the first-order hybrid scheme were negligibly small and the two grids generated the same results.

Results and Discussions

Influences of the turbulence models on the predicted flowfield can be best exemplified by observing the centerline axial velocity development (Fig. 1). The distinct difference between the forced and free vortex cases is that the latter case experienced vortex breakdown due to the centerline adverse pressure gradients induced by the decay of free vortex type swirl. Measurements indicate that the free vortex flow develops much faster than the forced vortex one. This is possibly due to the fact that the reverse flow region, resulting from the vortex breakdown and hence intense shear, was present along the centerline in the former case. It is apparent that IPCM performs best in the forced vortex case and agrees well with the measurements. In contrast, all of the other models, especially the SSG, IPGL, and LRR, showed a slower rate of axial velocity recovery compared with the measurements. As for the free vortex case, the k-ϵ predictions exhibited an excessive rate of flow recovery, due to the diffusive nature of the model. From Fig. 1, it is difficult to tell with certainty which stress model is superior to the other on the free vortex case. Relatively speaking, IPCM's result is better; however, the models' behavior is in line with the previous observations made on the forced vortex case; i.e., the IPCM model results returned a faster rate of flow recovery than the SSG, IPGL, and LRR models did.

Detail flow developments can be examined by reference to the mean and turbulence results (Fig. 2) at selected axial location

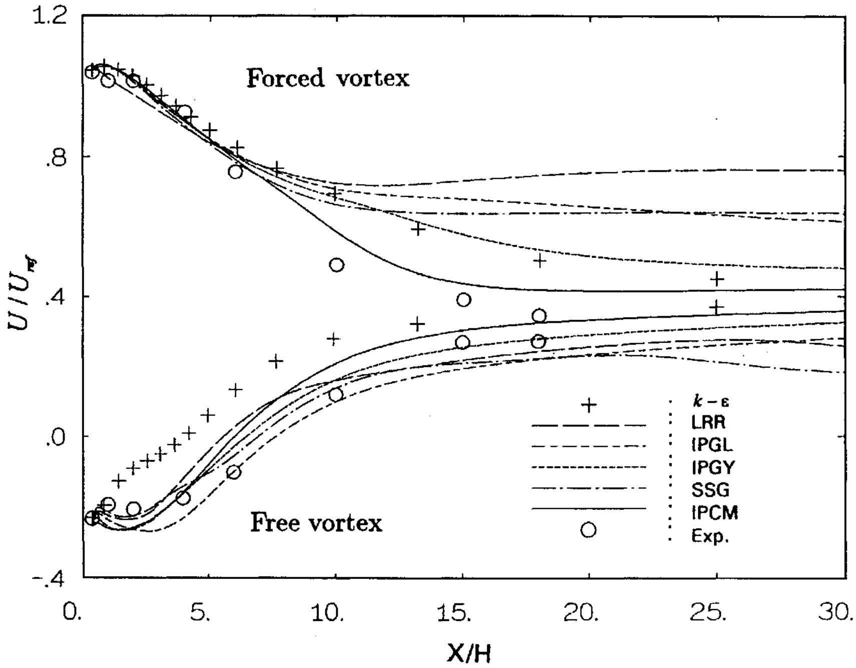

Fig. 1 Centerline axial velocity distributions.

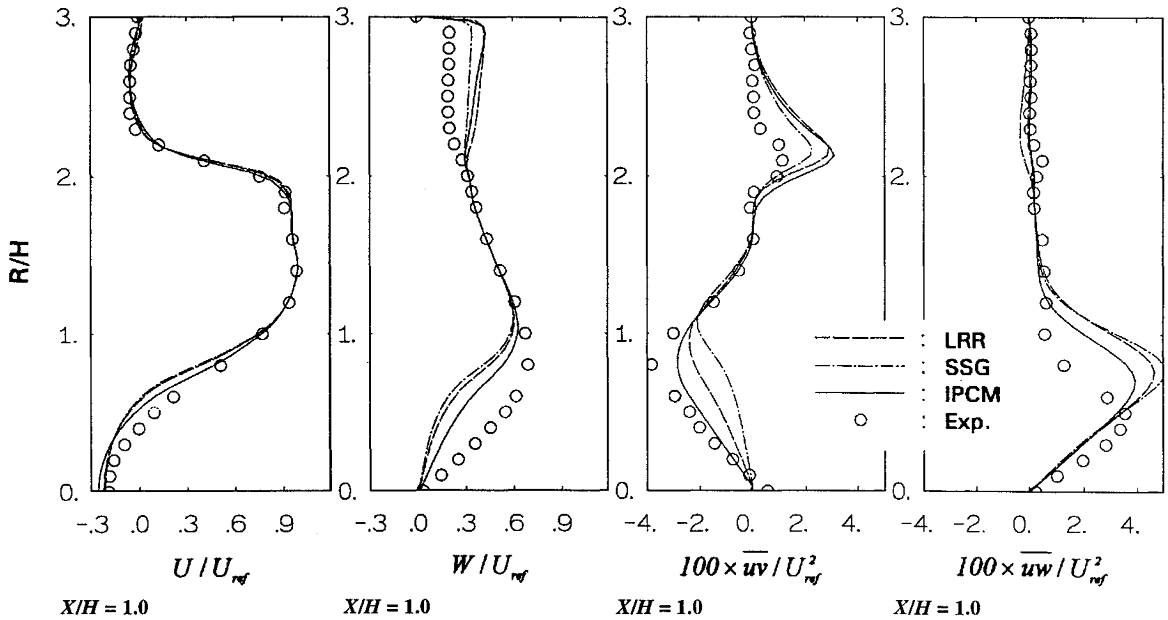

Fig. 2 Comparisons of predictions and measurements at X/H = 1, free vortex case.

$X/H = 1$. Because of space limitations, only predicted results by LRR, IPCM, and SSG on the free vortex case are presented here. By examining the distributions of $\overline{uv}$, one can observe that a higher level of shear stress was predicted by the IPCM model compared with LRR and SSG. This phenomenon is consistent with the previously observed centerline axial velocity development, indicating IPCM has a faster rate of flow recovery. The cause of this behavior can be traced back to the formulation of the modeled form of the pressure-strain process. The pressure-strain term of $\overline{uv}$ of the SSG model can be expressed in terms of that of IPCM and is as

$$(\phi_{\overline{uv}})_{\mathrm{SSG}} = (\phi_{\overline{uv}})_{\mathrm{IPCM}} + \underbrace{\epsilon\left(0.2 - 1.8\frac{P_k}{\epsilon}\right)b_{12}}_{A} + \underbrace{4.2\epsilon[(b_{11}+b_{22})b_{12}+b_{13}b_{23}]}_{B} - \underbrace{0.65\sqrt{b_{kl}b_{kl}}\,k\frac{\partial U}{\partial R}}_{C} + \underbrace{k(0.425b_{11} - 0.375b_{22})\frac{\partial U}{\partial R}}_{D} + \underbrace{kb_{13}\left(0.425\frac{\partial W}{\partial R} + 1.575\frac{W}{R}\right)}_{E} \tag{1}$$

where $b_{ij} = \overline{u_i u_j}/\overline{u_k u_k} - 1/3\delta_{ij}$ and the wall reflection terms of IPCM have been neglected. Terms B and C and the production related part of term A do not exist in the linear pressure-strain models.

Attention is now directed to the shear layer at $R/H = 0.8$ of the free vortex case, shown in Fig. 2. It is clear that the major terms A, D, and E act as extra sink terms, relative to the IPCM model, for the modeled $\overline{uv}$ equation adopting the SSG model. Across the nonequilibrium shear layer where the production term P_k is much higher than the turbulence dissipation rate ϵ, this makes the effect of term A even more pronounced. At $R/H = 2.2$, the lower level of $\overline{uv}$ predicted by the SSG model is consistent with what was observed at $R/H = 0.8$, albeit the SSG result is now closer to measurements. This conforms to preliminary computations of nonswirling sudden-expanding pipe flow, in which case SSG results were not only lower than the IPCM results but also closer to measurements. The lack of wall reflection terms in the SSG did not contribute to the predicted depressed level of $\overline{uv}$, for the terms, if present, would further reduce the level of shear stress near the wall. Comparing the level of predicted $\overline{uv}$ by the SSG model at $R/H = 0.8$ and 2.2, one can observe that at $R/H = 0.8$, the predicted level of shear stress is excessively depressed. This may be attributed to the fact that the influence of term E, which is related to swirl and $\overline{uw}$, is active only at $R/H = 0.8$. A better level of $\overline{uw}$ is also predicted by the IPCM model, and this can also be attributed to the pressure-strain modeling. The LRR model predicted the wrong sign of the stress $\overline{uw}$ around the region $R/H = 2.2$, where IPCM returned the best results.

Conclusion

Computations of turbulent swirling flows inside a dump combustor model were performed by the k-ϵ model and variants of the Reynolds stress transport model with linear (IPGY, IPGL, and IPCM) and quadratic (SSG) forms of the pressure-strain models. Comparisons of predictions with measurements indicated that IPCM performed best, in terms of mean and turbulence results. The slower axial flow recovery predicted by SSG and LRR was attributed to the lower level of $\overline{uv}$ predicted by the models, and this could be traced back to the modeled form of the pressure-strain term, after examining the formulations of the pressure-strain models.

Acknowledgments

This research work was supported by the National Science Council of Taiwan under Grant NSC-82-0401-E-007-251. The computational facilities were provided by the National Centre for High-Performance Computing of Taiwan, which the authors gratefully acknowledge.

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Prediction of Aerodynamic Flows with a New Explicit Algebraic Stress Model

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I. Introduction

COMPUTATIONAL fluid dynamics (CFD) has become an increasingly powerful tool in the aerodynamic design of aerospace vehicles as a result of improvements in numerical algorithms and computer capacity. Major future gains in efficiency are expected to come about as massively parallel supercomputer technology matures. However, some critical pacing items limit the effectiveness of CFD in engineering applications. Chief among these items is turbulence modeling. Numerous turbulence models of varying degrees of complexity, which can be classified as ranging from eddy-viscosity models to full Reynolds stress closures, have been proposed (see Refs. 1 and 2 for reviews).

Received Feb. 26, 1996; revision received June 16, 1996; accepted for publication Aug. 21, 1996; also published in *AIAA Journal on Disc*, Volume 2, Number 1. This paper is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

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