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Test Code for the Assessment and Improvement of Reynolds Stress Models

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An existing two-dimensional, compressible flow, Navier-Stokes computer code, containing a full Reynolds stress turbulence model, has been adapted for use as a test bed for assessing and improving turbulence models based on turbulence simulation experiments. To date, the results of using the code in comparison with simulated channel flow and over an oscillating flat plate have shown that the turbulence model used in the code needs improvement for these flows. They also show that direct simulation of turbulent flows over a range of Reynolds numbers are needed to guide subsequent improvement of turbulence models.

1. Introduction

Various turbulence models are suggested in the literature to close the different terms in the Reynolds stress budget, each with its advocates and its critics. To properly assess these models, direct simulation of turbulent flows can be used to compute the terms in the Reynolds stress budget and directly compare the model expressions with the terms (see Mansour *et al.*, 1987). Direct comparison is not enough, however, because perfect agreement can rarely be achieved, and for a complete evaluation, the models should be used in an actual computation of the flow. A code previously developed by the authors (see. Vandromme *et al.*, 1983) has been modified to simulate the channel flow of Kim *et al.* (1987) and the oscillating flat plate of Spalart & Baldwin (1987). The code is based on a bidiagonal predictor-corrector time marching algorithm (MacCormack, 1981) that has been modified to solve the nonconservative equations that result from the introduction of Reynolds stress turbulence models. This algorithm has been used to calculate several complex compressible flows, including shock wave-boundary layer interactions (HaMinh *et al.*, 1985, and Viegas & Rubesin, 1983). Because the code is quite robust and can accept turbulence modeling changes conveniently, it was decided to adapt it to the low speed conditions of the existing turbulence simulations rather than to write a new code. For the selected cases of flow in a channel (Kim *et al.*, 1987) or over an oscillating infinitely long flat plate (Spalart & Baldwin, 1987), meshes having the

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dimensions of 5 (axial) and 50 (transverse) were employed. The small number of mesh points in the axial direction are adequate for these problems since there are no variations of dependent variables, except for pressure, in this direction. The code uses two mesh points at each of the upstream and downstream boundaries to define the conditions there. Computations with this mesh arrangement for the channel flow took about 1 minute of Cray cpu time for about 1000 iterations and about 10000 iterations to reach steady state. The code, when used to yield time-accurate oscillating plate solutions, took about an hour of cpu time to reach a steady periodic state.

2. Results and Discussion

To test the code's ability to handle low speed flows, both the channel and the oscillating plate were first run with laminar flow. The numerical results in both cases agreed quite well with the corresponding analytical solutions (Schlichting, 1960). When the same flow cases were run with the turbulence model developed by Vandromme *et al.* (1983), it was found that the numerical results did not agree with the statistical output from the simulations.

2.1 Channel Flow

The channel flow computations at Re=2800 gave results that differed considerably from the statistical quantities corresponding to the simulation of Kim *et al.*, (1987). For example, Fig. 1a shows a comparison of the distribution of the turbulent shear stress, normalized by the wall shear as a function of the distance from the surface in wall parameters. The solid symbols are the output from the simulation, whereas, the open symbols represent the computed results from the modeled equations. The difference between the results indicate that the current model in the code needs considerable improvement. When similar computations were performed for channel flows with higher Reynolds numbers, namely, Re=13000 and 50000, the stresses shown in Figs. 1b and 1c resulted. Here the solid symbols are the same as on Fig. 1a and are used as reference for the levels of the computed results, the open symbols. These figures indicate that the current model in the code shows a large sensitivity to the Reynolds number of the channel flow. If the LES calculations of Moin and Kim (1982) are examined, it is noted that the maximum Reynolds shear stress at Re=13800 found there is about 0.86. This is larger than the corresponding value of 0.7 in the complete simulation at Re=2800, and is in the same direction of increased normalized shear stress with higher channel Reynolds number exhibited by the turbulence model shown in Figs. 1a and 1b. There exist questions regarding the near wall treatments of the subgrid model in the LES, and this suggests that the process of improving the turbulence model to handle these Reynolds number effects could benefit from additional accurate channel flow simulations at Reynolds numbers higher than 2800.

Another aspect of the process of using the simulated results to improve statistical turbulence models becomes evident in Fig. 2. Here is shown the rate of dissipation

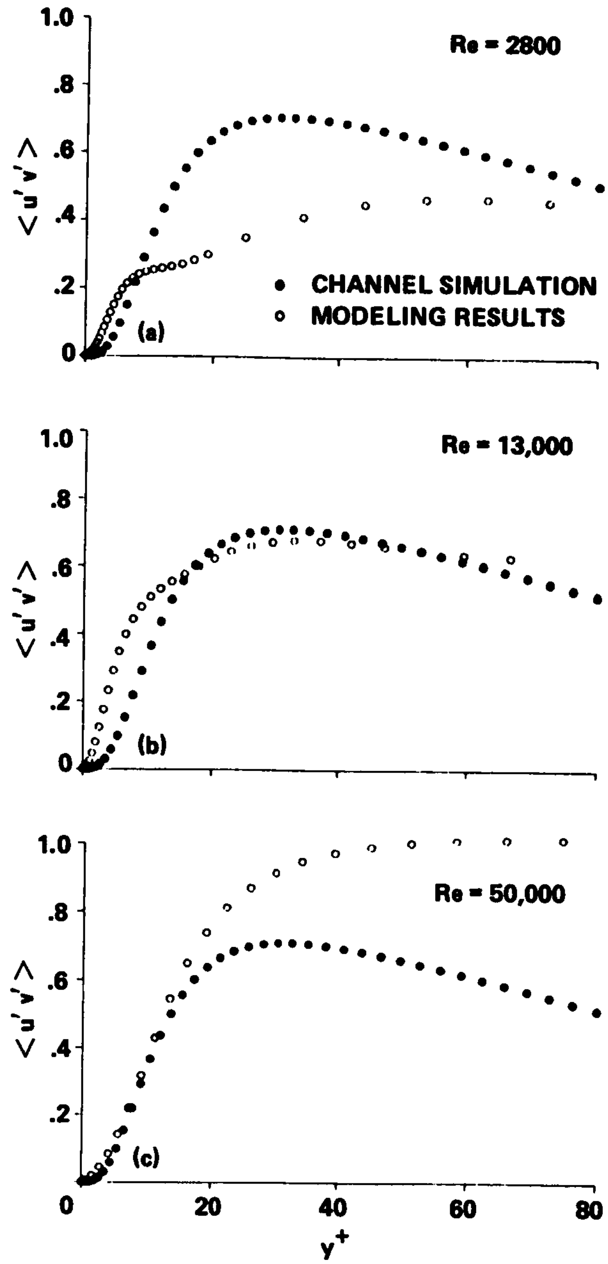

FIGURE 1. Dimensionless Reynolds shear stress in the near wall region of the channel. a) $Re = 2800$. b) $Re = 13000$. c) $Re = 50000$.

in the equation for the normal stress, $\overline{uu}$, expressed in dimensionless form. Again, the open and closed symbols represents the results of the model calculations and the simulations, respectively. The figure shows considerable difference between the two computations, and at first glance suggests difficulties with the particular model used for the turbulence dissipation rate. It was found (Mansour, Kim and Moin,

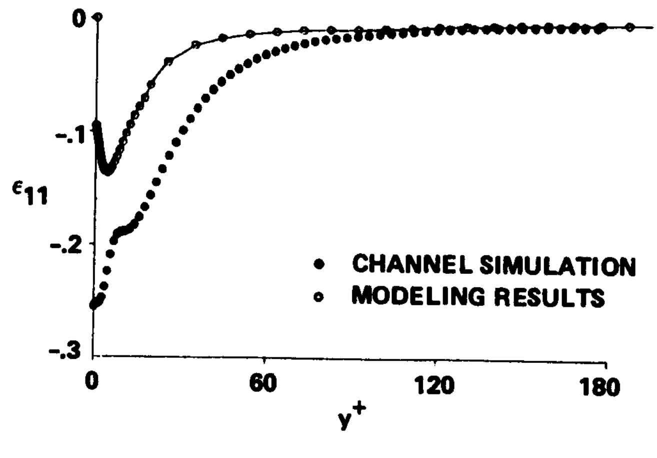

FIGURE 2. Distribution of dimensionless dissipation rate in $\overline{uu}$ equation.

1987), however, that the model used in the computations evaluated with the moments found from the simulations, rather than from the modeled computations, gave results quite close to those of the simulations. Thus the error of the modeled computations shown on this figure result from the errors of the Reynolds stresses used in the evaluation of the dissipation rather than the functional form of the dissipation model. This is an example of the highly interactive behavior of elements of turbulence models and indicates that model improvements must be made simultaneously in all elements of the model so that it improves in the aggregate. The wealth of information available in the simulations should facilitate this process in future studies.

2.2 Oscillating Flat Plate

Representative results of the comparison of the computation of the flow over an oscillating flat plate with the direct simulation of Spalart & Baldwin (1987) are shown in Fig. 3. Here are shown the time-dependent skin friction over a cycle of time for the model computations as well as the simulation. Although the computed results are periodic and show similar phase relationships as do the simulation, there are significant differences between the results which, again, indicate the weaknesses of the current turbulence model.

3. Future Directions

The authors plan to continue to use direct turbulence simulations to improve the Reynolds stress model used in the code. The directions this will take depends a great deal on the availability of simulations for a range of Reynolds numbers. The range in Reynolds number is needed to minimize the number of assumptions used

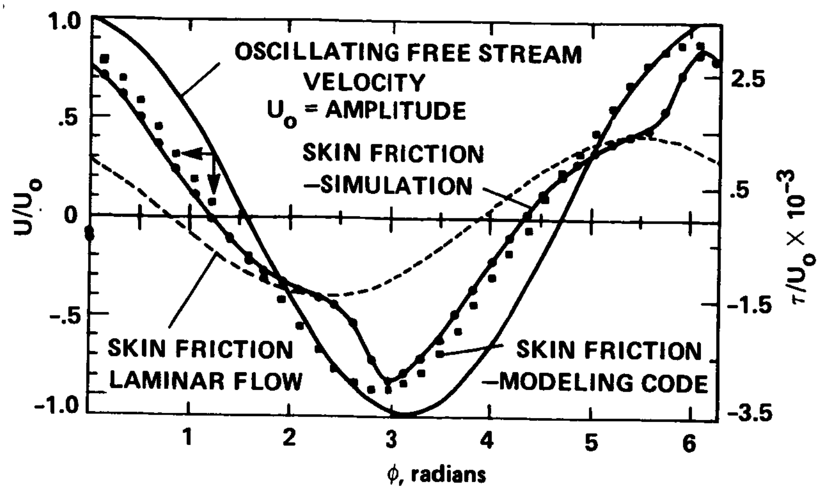

FIGURE 3. Skin friction as function of phase angle ϕ for an oscillating flat plate. Comparison of model results with simulation data.

regarding the functional form of of the various coefficients in the turbulence model. A test for the universality of these coefficients will be agreement with simulation data from a variety of flow fields.

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