LONGITUDINAL VORTEX PAIR IMBEDDED IN A TURBULENT BOUNDARY LAYER: COMPARATIVE PERFORMANCES OF SEVERAL TURBULENCE MODELS*

Xiong Guohua (熊国华)
(Department of Mechanical Engineering, University of Kentucky, Lexington, KY 40506, USA)

Zhang Guanghua (张扬华)
(Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China)

ABSTRACT: Four turbulence models, namely, the basic and nonlinear stress-transport models and the basic and anisotropic k-ε models, have been tested in the case of interaction between a longitudinal vortex pair and a flat-plate boundary layer. The results of their predictions were compared with Mehta and Bradshaw’s measurements. In this paper, part of the results involving those of the nonlinear stress-transport model and anisotropic k-ε model are presented and discussed.

KEY WORDS: longitudinal vortices, boundary-layer flow, turbulence modelling, numerical calculation

1 INTRODUCTION

The interaction between a turbulent boundary layer and longitudinal vortices generated by laterally skewing the flow upstream is often encountered in engineering practice. In the cases of a single vortex and a vortex pair with ‘common flow’ upwards imbedded in a flat-plate boundary layer, Shabaka et al.[1] and Mehta and Bradshaw[2] have presented detailed experimental results including those of the mean-flow fields and statistical turbulence behaviours. Their results demonstrated that the turbulence is strongly reorganized by distortion and rotation of the mean flow. Such flows, that are simple in geometry but intricate in turbulence behaviour, have posed challenging problems in turbulence modelling.

One of the previous attempts to predict such flows with current turbulence models is that of Liandrat et al.[3]. Comparison between their predictions and experiments showed that the models based on eddy-viscosity hypothesis are entirely not capable of reproducing the Reynolds-stress distribution, although they provide a qualitative description of the mean-flow feature. Even with a simplified stress-transport model[3], predictions of turbulence quantities still deviate obviously from the experiments. For instance, the spanwise components of the shear stress $\overline{uu}, \overline{vw}$ and hence the distortion of the mean flow are much underpredicted. In view of this, in 1987 Bradshaw and Cutler[4] concluded: “Present-day...
turbulence models are not capable of qualitatively representing the effects of imbedded longitudinal vortices”.

Since that time, there has been a significant progress in developing second-moment closures that retain more physics of turbulence and satisfy more physical and mathematical constraints. Computational results have shown that using a well-founded nonlinear model of the pressure-strain correlation, instead of its basic form, will greatly improve the predictions of strongly swirling flows as illustrated by Fu\cite{5}, and 3D boundary-layer flows as illustrated by Zhang and Zhao\cite{6}. In the meantime, anisotropic two-equation turbulence models have been developed via continuum-mechanics methods as well as statistical methods. Including the higher-order terms of mean-velocity derivatives in the Reynolds-stress representation, such kind of models accounts for the effects of mean vorticity and anisotropy of the normal Reynolds stress. A rather successful example of such models has been presented by Myong and Kybayashi\cite{7}, who used an anisotropic low-Reynolds-number $k$-$\varepsilon$ model to predict the developing turbulent flow in a square duct reproducing the secondary motions in crossflow planes.

The motivation of our work is to examine the abilities of a nonlinear second-moment closure and an anisotropic $k$-$\varepsilon$ model in predicting a vortex/boundary layer interaction flow. The flow considered in this paper is the vortex pair/boundary layer flow described in Ref.\cite{2}, that is a more severe test case for turbulence modelling compared with the single vortex/boundary layer flow of Ref.\cite{1}.

2 MATHEMATICAL FORMULATION OF THE PROBLEM

The measurements of Ref.\cite{2} were made in the floor boundary layer of a wind tunnel in which a pair of longitudinal vortices were generated by two half-delta wings mounted in the settling chamber. Since such flow conditions are rather difficult to be reproduced in mathematical forms, a simpler flow model shown in Fig.1 is considered to simulate the flow measured in Ref.\cite{2}.

The flow is assumed incompressible and statistically steady. As the streamwise pressure-gradient term and the streamwise diffusion terms can be neglected in the present case, the mean-flow continuity and momentum equations read as follows