INVESTIGATION OF RELAXATION EDDY VISCOSITY MODEL FOR COHERENT STRUCTURE DYNAMICS USING TOMOGRAPHIC PIV

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Summary We experimentally determine remaining stresses and rates of strain in the eddy viscosity model (EVM) for coherent structure (CS) dynamics equation of wall turbulence using tomographic PIV. In order to introduce EVM to simulate remaining stresses, the topology of remaining stresses and rates of strain are compared and the spatial relaxation effects between them are found to be distinct. A remaining stress-relaxation-strain EVM need be developed for the closure of the CS dynamics equation.

INTRODUCTION

Wall turbulence created when fluids flow past surfaces, causes drag on airplanes and ships, and influences how atmospheric pollutants are transported near Earth's surface. The Coherent structure (CS) in wall turbulence plays important roles on creating Reynolds stress and transporting energy. In order to discuss the CS dynamics in wall turbulence, a decomposition is required that can distinguish between the time-averaged base flow $\bar{f}(\boldsymbol{x})$, the unsteady components $f'(\boldsymbol{x},t)$ and the CS components $\tilde{f}(\boldsymbol{x},t)$. The selected mean for decomposing the flow is to use the triple decomposition of Reynolds[1], where $f(\boldsymbol{x},t)=\bar{f}(\boldsymbol{x})+\tilde{f}(\boldsymbol{x},t)+f'(\boldsymbol{x},t)$ and $\tilde{f}(\boldsymbol{x},t)=\langle f(\boldsymbol{x},t)\rangle-\bar{f}(\boldsymbol{x})$. The evolution equations for $\tilde{f}(\boldsymbol{x},t)$ are derived from the Navier–Stokes equations. The continuity and momentum equations of CS are given by

$$\frac{\partial \tilde{u}_i}{\partial t}+\bar{u}_j\frac{\partial \tilde{u}_i}{\partial x_j}+\tilde{u}_j\frac{\partial \bar{u}_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial \tilde{p}}{\partial x_i}+\nu\frac{\partial}{\partial x_j}\frac{\partial}{\partial x_j}\tilde{u}_i-\frac{\partial}{\partial x_j}\left(\left\langle \tilde{u}_i\tilde{u}_j\right\rangle-\overline{\tilde{u}_i\tilde{u}_j}\right)-\frac{\partial \tau_{ij}^R}{\partial x_j} \tag{1}$$

and

$$\frac{\partial \tilde{u}_i}{\partial x_i}=0 \tag{2}$$

Where, $\tau_{ij}^R=\left\langle u_i'u_j'\right\rangle-\overline{u_i'u_j'}=\widetilde{u_i'u_j'}$, namely the important remaining stresses. τ_{ij}^R is truly unknown in that its amplitude and structure have not been determined experimentally. Assuming that the background turbulence evolves on much shorter time and length scales than the structures, it seems plausible that a Newtonian stress-strain relation like that for the molecular stresses will provide the basis for a model. A closure model for remaining stress terms appearing in the CS dynamics equation had been proposed by Poje[2], who suggested that

$$\tau_{ij}^R-\frac{1}{3}\delta_{ij}\tau_{kk}^R=\nu_T S_{ij} \tag{3}$$

Where, $S_{ij}=\frac{\partial \widetilde{u_i}}{\partial x_j}+\frac{\partial \widetilde{u_j}}{\partial x_i}$. From a closure prospective, the isotropic eddy viscosity formulation imposes several severe and possibly unphysical restrictions on the behavior of the stresses. The scalar viscosity coefficient ensures that the principle axes of the stress tensor are aligned with the principle axes of rates of strain tensor or, the stresses are phase locked with the rates of strain. The phenomenon of eddy viscosity coefficient including relaxation effects is more remarkable in many periodic turbulent flows such as turbine flows. Jia[3] verified viscosity coefficient ν_T to be a plural in equation (3) using hot-wire technology. In this paper, the measured topology of stresses and rates of strain across the turbulence boundary layer (TBL) was investigated by the tomographic PIV (TPIV) technology.

EXPERIMENTAL PROCEDURES AND DATA ANALYSE MATHODS

The experiments have been performed in the water tunnel where a TBL flow has been established along a vertical mounted flat acrylic glass plate at a free stream velocity of 0.449 m/s corresponding to Reθ~ 2460 based on momentum thickness at the measurement volume. A high-repetition rate TPIV system has been applied by making use of a diode pumped double cavity Nd:YLF high repetition rate laser with a pulse energy of 25 mJ at 1 kHz and six CMOS cameras in 1024 x 1024 pixels full frame modus. A volume of about 63 x 68 x 15 mm³ in x-, y- and z direction (x- streamwise,

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y- spanwise and z- wall normal) centered 2090 mm downstream of the leading edge has been illuminated at 1 kHz frequency. The particle image volume is analyzed by local 3D cross-correlation with an iterative multi-grid volume deformation scheme reaching a final 32^3 voxels interrogation box size. With a given magnification of 85.9 µm/voxel the final 32^3 voxels corresponds to a spatial resolution of ~ 2.75 x 2.75 x 2.75 mm³ and with 75 % overlap a series of instantaneous three-dimensional velocity vector volumes over a grid of 92 x 99 x 22 measurement points located every 0.687 mm ~ 15 WU in all directions in space for each time step of 2 ms increment have been achieved.
The concept of spatial locally averaged velocity structure function is introduced to perform the multi-scale decompositions of longitudinal velocity component. The CS burst processes are deduced by the index of zero-crossing of spatial locally averaged streamwise velocity structure function. The topological of remaining stresses and rates of strain for CS bursting are obtained by spatial phase average technology.

RESULTS AND DISCUSSION

Figure 1 shows topology of rates of strain and stresses in CS bursting in TBL. It can be seen that the spatial topology of remaining stresses is different from that of rates of strain. Normal remaining stresses ($\tau_{11}^R, \tau_{22}^R, \tau_{33}^R$) show stream streak structures, rates of strain (S_{11}, S_{22}, S_{33}) present stream-spanwise quasi-periodic structures, while shear remaining stresses ($\tau_{12}^R, \tau_{13}^R, \tau_{23}^R$) are more similar to rates of strain (S_{12}, S_{13}, S_{23}). However, spatial phases of remaining stresses are different from those of CS rates of strain significantly. It is concluded that there is non-synchronization between remaining stresses and CS rates of strain in space. The reason is that in the near wall turbulence the turbulence characteristics and rates of strain change relatively fast, as a consequence, the local CS rates of strain characterize the history of the mean distortion to which the turbulence has not been subjected, and the remaining stress balance is dominated by non-local transport processes. The nonlocal stress-strain effects are accounted for by a closure model that simulates the history of the mean distortion to which the turbulence has been subjected. The EVM with the spatio-temporal relaxation effect between remaining stresses and rates-of-strain would need to be developed for accurately predicting the wall turbulence.

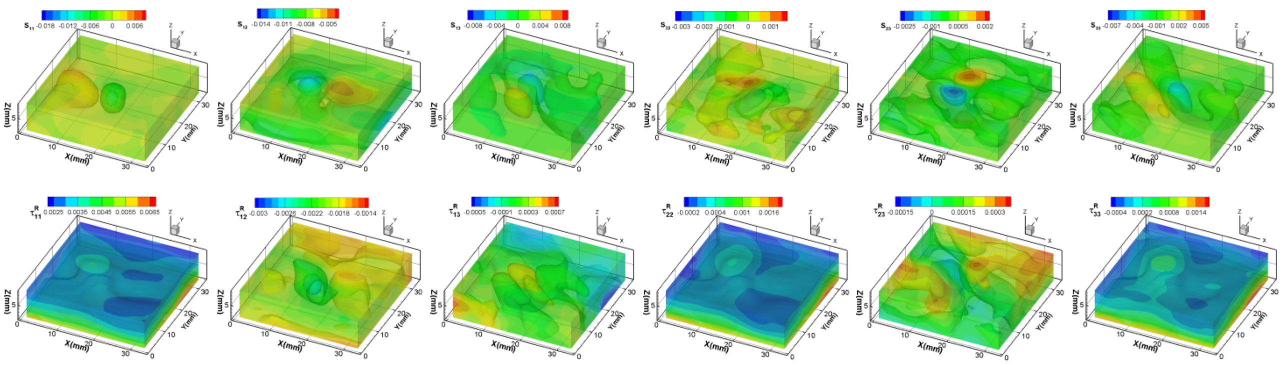

Figure 1 Topology of CS rates of strain (top) and remaining stresses (bottom) in CS bursting

CONCLUSIONS

It is found that the spatial phases of remaining stresses are not synchronized with those of rates of strain, therefore, the hypothesis of EVM for CS dynamics equation should be unreasonable through scalar eddy viscosity coefficient. The reason is that the macro relaxation spatio-temporal scale of the momentum exchange between CSs should be no longer negligible in TBL, and remaining stresses tensor are related with the accumulated rates of strain tensor. Spatio-temporal relaxation effect should be taken consideration in simulating CS dynamics of wall turbulence through EVM. So the turbulent-viscosity hypothesis - introduced by Boussinesq - is not used to elucidate the physical mechanism of non-equilibrium phenomenon in the wall turbulence due to this non-synchronization of the spatial phase of remaining stresses and rates of strain. The present proposed relaxation EVM with temp-spatial phase information may reveal the physical evolution mechanism of the remaining stresses in the CS dynamics. It may become a promising model to enclose the CS dynamics equation and forecast the widespread industrial non-equilibrium turbulence more accurately.

References

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