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Final Technical Report
Structure-Based Turbulence Model
AFOSR-95-1-0145
Award period 2/1/95-1/31/98

30 OCT 2000

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Objectives and approach

Turbulence modeling is the limiting factor in the ability of aerospace engineers to predict turbulent flows of importance in aircraft and propulsion system design. The objective of this program is to make a significant advance in the quality of aerospace engineering turbulence predictions through the development of a new type of turbulence model.

Current engineering models (*e.g.* k-ε models) relate the turbulent stresses to the local mean deformation *rate* through an eddy viscosity. Such models are valid in the limit of slow deformation rates, but do not do well in complex non-equilibrium flows where the turbulence is rapidly deformed by the mean motion. Rapid Distortion Theory (RDT) does describe the response of the stresses to rapid mean deformations. Under RDT the stresses are determined not by the instantaneous strain *rates* but instead by the total *amount* of mean deformation. RDT is a closed two-point theory, but engineering models require one-point formulation. Therefore, what is needed is a one-point model that matches eddy viscosity models for weak deformation rates and RDT for rapid deformations. This would require a good one-point RDT model, and building such a model might seem to be a formidable challenge.

However, a very effective one-point structure-based model for RDT of homogeneous turbulence was developed by Kassinos and Reynolds (1994), hereafter denoted by KR, under previous AFOSR support. This RDT model is now being used as the backbone for a general structure-based turbulence model of the type described.

The new *structure-based* model is based on substantially more physics than in existing models. The turbulent stresses, which are needed in the CFD codes that predict the mean flow, are related to parameters of the turbulence structure, which are then evolved using transport equations developed from the underlying Navier-Stokes equations. These structural parameters evolve differently under slow and rapid deformations, and by representing the stresses in terms of the structure both regimes are captured correctly.

Accomplishments

During the period of this award, the basic structure-based model for rapid distortions of homogeneous turbulence was extended to deal with slow distortions and inhomogeneities. A computer program was written to study the extended model in various one-dimensional flows, including channel flows with frame rotation and transpiration. The model was installed in NASA's INS2D code for generalized flow analysis. The rapid distortion versions of both codes were checked against the parent KR calculations. New insight into the structure of various inhomogeneous flows was obtained from calculations of our new structure tensors from the DNS database at NASA/Ames Research Center. This work has been submitted to the *Journal of Fluid mechanics.*

The Particle Representation Model (PRM) first described for rapid distortions of homoheneous turbulence in KR, was adopted by Prof. Stephen Pope (Cornell) in his pdf turbulence modeling, and allows his stochastic models to agree exactly with RDT when RDT applies. This represents a major advance in modeling of turbulence by stochastic simulations that will have impact in the design of practical combustors and propulsion systems. The advance enabled by this PRM can be credited directly to our AFOSR support. During this award period we extended our PRM to slow deformations using a stochastic model for non-linear interactions. This is proving to be a very simple and quick way to explore the combined effects of rapid distortion and non-linearity in complex turbulent flows.

Dr. Michael Rogers of NASA/Ames Research center worked with us to calculate the various structure tensors introduced by KR for his direct numerical simulations (DNS) of homogeneous shear flow, the time-developing mixing layer, and the time-developing wake. These results are useful in developing insight useful for model development. For example, the wake and mixing layer calculations show that the structure of the turbulence in these flows is remarkably homogeneous, which indicates that our model in which homogeneous turbulence is the basic backbone should do well in these flows. This work was incorporated in a paper that will appear in the Journal of Fluid mechanics.

During the award period we began to explore ways to simplify the structure-based modeling so that it could be used in repetitive engineering calculations. The idea is to use an algebraic version of the model that gives the turbulent streses in terms of the mean strain rate and mean and frame rotation rates as an alternative to the linear or non-linear stres-strain relationships used in conventional two equation modeling. The difference would be that the algebraic structure-based turbulence model (ASBM) would do a much better job of representing the streses in complex flows. Development of this concept into a working engineering model and codes will be the principal objective under subsequent awards.

The full details of the more recent structure-based modeling work will be reported in the PhD Dissertations of Carlos Langer and Scot Haire, which we expect to complete under subsequent AFOSR support. Partial details have and will appear in various conference proceedings

Personnel

- Prof. W.C. Reynolds, Principal Investigator
- Dr. S.C. Kassinos, Postdoctoral Investigator
- Mr. Scot Haire, PhD student (AFOSR-AASERT support)
- Mr. Carlos Langer, PhD student (Brazilian and AFOSR support)
- Dr. Michael Rogers, NASA/Ames (DNS database analysis)

Discoveries, inventions, patent disclosures

No patentable discoveries.

Honors and awards

- During the award period, Prof. W.C. Reynolds was elected to the American Academy of Arts and Science and was the 1995 W.R. Sears Distinguished Lecturer at Cornell University.
- Prior to the award period, Prof. W.C. Reynolds was elected to the National Academy of Engineering (1978), Fellow of the ASME, and Fellow of the APS, and received the Otto Laporte Award from the APS, the Fluids Engineering Award from the ASME, and the G. Edwin Burkes Award and a Centenary Award from the ASEE.

Publications

Reynolds, W.C. & Kassinos, S.C 1995 One-point modeling of rapidly deformed homogeneous turbulence. To appear in *Proc. Roy. Soc. A* in a special Osborne Reynolds Centenary Issue.

Papers on the KR work is being prepared for submission to *J. Fluid Mechanics*.

Reference

Kassinos, S.C. & Reynolds, W.C. 1994 A structure-based model for the rapid distortion of homogeneous turbulence. Report TF-61, Thermosciences Division, Department of Mechanical Engineering, Stanford University.