Development of an Oriented-Eddy Collision Model for Turbulence

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Abstract:

The exact governing equations of fluid dynamics are too computationally expensive to solve on a computer for practical applications. Hence, it is currently not possible to analytically describe the behavior of a turbulent flow -in particular its internal structures-, making turbulence one of the major remaining unsolved problems in Classical Physics. One solution to computationally predict the performance of engineering applications involving fluids is the formulation of alternative and computationally tractable equations. This work demonstrates the feasibility of modeling turbulence as a collection of interacting particles with intrinsic orientation. It also discusses current efforts regarding its accuracy and computational overhead in numerous turbulent flows. The goal of this thesis is to focus on numerical implementation as well as model evaluation and validation. The Oriented-Eddy Collision Model is tested for basic flow cases and incorporated inhomogeneity. The project is successful in demonstrating that with appropriate extensions, the model can be applied to a very wide variety of turbulent flows with high predictive accuracy.

Introduction:

In fluid dynamics, turbulence is a flow regime characterized by chaotic fluid variations such as energy and dissipation. Turbulent flows represent most flows encountered in engineering practice and therefore carry some importance. There are multiple applications of turbulent flows such as the dispersion of pollutants in the atmosphere, weather prediction, channel flow, internal combustions engines, gas turbines, external flow over airplanes, submarines.

It is currently not possible to analytically describe the behavior of a turbulent flow –in particular its internal structures-, making turbulence one of the major remaining unsolved problems in Classical Physics.

However, there are some known approaches to predicting turbulent flows. The first one involves the use of correlations such as the ones that give the friction factor as a function of the Reynolds number. This method is limited to extremely simple flows that are characterizable by just a few parameters.

The down-side of this approach is the lack of flexibility. Currently, the three main approaches that are extensively used by Computational Fluid Dynamics (CFD) users and researchers are the Reynolds-averaged Navier-Stokes (or RANS) equations, Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES).

RANS is a method based on equations obtained by averaging the equations of motion over ensembles. This is equivalent to time averaging in a statistically steady flow or spatial averaging over a coordinate in which the statistics do not vary. The RANS equations do not form a closed set and thus require the introduction of approximations of the Reynolds stresses.

RANS provides the engineer with only the average properties of a turbulent flow such as the average forces on a body, the degree of mixing between two incoming streams of fluids, or in chemical engineering the reacted amount of some substance. The RANS equations are very similar to the governing Navier-Stokes equations except for the unknown Reynolds stress tensor.
As of today, the most accurate approach to turbulence solution is Direct Numerical Simulations. DNS is very useful in extracting specific information such as the kinetic energy or the dissipation rate.

This approach solves the Navier-Stokes equations for all of the motions in a turbulent flow and therefore, does not involve any approximation or averaging other than numerical errors. However, the computational cost of DNS is very high and increases rapidly with higher Reynolds numbers. For the Reynolds numbers encountered in most industrial applications, the computational resources required by a DNS would exceed the capacity of the most powerful computer available in 100 years.

However, direct numerical simulation is a useful tool in fundamental research in turbulence. In addition, DNS is useful in the development of turbulence models for practical applications. Results obtained from DNS are extremely detailed, making DNS a very expensive and inappropriate tool for engineering design.

Finally, LES compromises between one point closure methods -like RANS- and direct solution methods such as DNS. This technique solves for the largest scale motions while modeling only the small scale motions. Because the large scale motions generally contain more energy than the small scale ones, this approach can capture much of the actual physics using first principles.

LES is three dimensional, time dependent and less expensive than DNS. DNS is useful in developing LES since it allows for both “a priori” (the input data for the model is taken from a DNS simulation) and "a posteriori" tests (the results produced by the model are compared to those obtained by DNS). In our research, DNS, LES and experimental results are used in developing the Oriented Eddy Collision (OEC) model for predicting turbulence.

CONCLUSIONS

This project has allowed us to demonstrate that oriented-eddy collisional (OEC) models are an interesting, accurate, and viable approach to turbulence modeling. We have demonstrated that:

- Models exist in the regime between LES and RANS that have very attractive cost and accuracy attributes for current day design.

- It is possible to increase the physics in turbulence models and reduce the number of tuned constants, while still having a cost effective model that can run on a PC.

- The structure (orientation) of turbulence is just as important as the magnitude of the fluctuations. Models that represent structure have huge advantages in capturing the turbulence physics.

- The model can be interpreted as a model for the evolution of the two-point correlation. Critical to this model – is decomposing the two-point correlation into self-similar ‘modes’. As with any turbulence model, a great deal of work remains to validate this model. In this project we have clearly demonstrated that the approach is extensible and can accurately predict a wide variety of quite different but fundamental turbulent flow situations.

Future work will complete the modeling of wall effects. In addition, we expect this model to predict transition very well, and this will be demonstrated. Finally, this model will be implemented in a 3D, unstructured, parallel, Navier-Stokes code so that more complex and practical flow situations can be tested.

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