

## MULTI-SCALE COMPLEX FLOW FIELDS AND NUMERICAL SIMULATION OF TURBULENT FLOW

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Multi-scale complex flows, such as turbulence, exist almost everywhere in the nature. Some achievements have been reached recently in the study of this kind of flows. With developments of computational technique the numerical simulations become one of the important tools for investigating the complex flow fields.

The complex flow fields, like turbulence, are characterized by the following properties: they are unstable and unsteady, they have multi-scale characters, and they are three dimensional. The nonlinear effect in the complex flow fields is a predominant feature. For correct simulation of such kind of problems the key point is capability of methods for capturing the multi-scale structures. We have successfully simulated the steady state flows with macroscopic spatial structures, like shocks, by using second-order accurate schemes. But for the unsteady, unstable field flows and flow with unsteady bifurcation, like turbulent flows, the multi-scale structures are changing in advancement of time, and usually the small structures are random and chaotic. The nonlinear effect is very complicated. All these physical phenomena should be captured well by numerical methods. Special attention should be paid on correct simulation of phase relation in the physical problems. Numerical dissipation may smooth out the small flow field structures, and the numerical dispersion may lead to wrong structures.

The flow fields with a range of scales are very complicated. In the paper we pay more attention on direct numerical simulation. There are three methods for improving the resolution. One of them is to refine the grid system, but the resource of computers is limited. The another is to construct a reasonable grid system with grid generation technique. With this method usually is difficult to use high order accurate scheme. In this paper we will discuss the third method, the method with high order accuracy.

The behavior of numerical solutions is analyzed. From Fourier analysis for the one dimensional model equation it can be seen that the Fourier components with lower wave numbers can be simulated very well even with the second order accurate scheme. In practical applications we have successfully solved large scale structure, like shock, with lower accurate TVD schemes. With Fourier analysis it also can be seen that with lower accurate schemes the high frequency components may smooth out or even have wrong traveling direction. This is not important if we are interested only in steady and stable large structures of flow fields. But it is important for solving the multi-scale problems. In the numerical solutions with low accurate schemes the high frequency components may go ahead, behind, or in opposite direction according to the corresponding physical waves. The behaviors of numerical solutions are also analyzed for the linearized two-dimensional Euler equations.

For multi-dimensional problems the influence of dispersion and dissipation errors exhibits anisotropic characters. The Fourier analysis shows that the resolution of numerical solution is getting better with increasing the order of accuracy of approximations. Three methods for improving the resolutions of solutions for solving the multi-scale problems. They are the method of increasing the order of accuracy of approximation, the method of accuracy balance between different Fourier components, and the method of group velocity control. The high order accurate schemes are used to solve physical problems.

In this lecture I will review the recent progress in understanding the role of anisotropy in the statistical description of turbulence. Until recently most of the analysis of experimental and simulation data was based on assuming that the statistical objects, the correlation functions and structure functions, possess isotropic and isotropic forms. In fact, most of the data that one encounters in experiments and simulations are anisotropic on the large scales, and then anisotropic decay it at all other scales with different rates. Characterizing the effects of anisotropy may lead to serious errors in the interpretation of data.

A useful approach to this issue is based on expanding the statistical objects in terms of the irreducible representations of the SO(3) symmetry group. It has been shown that correlation functions are characterized by one or several components in each sector of the symmetry group, and in general one has contributions from a number of sectors with nontrivial weights depending on the boundary conditions. It is important to learn how to extract information about each sector. Thus for example structure functions which appear not to scale in simple log-log plots exhibit clear scaling lines decomposed into their appropriate contributions from different sectors of the symmetry group.

An important theoretical issue is what are the values of the scaling exponents in the various sectors. The simple models like the Kolomogorov model of passive scalar and passive vector advection allow one to compute the scaling exponents explicitly, and demonstrate universality with a distinct strictly increasing spectrum as a function of the index of the sector and the order of the correlation function. For Navier-Stokes turbulent scaling exponents were measured in the first sector of the symmetry group. Details will be reported and discussed.

Finally, the role of the anisotropy in terms of understanding the role of nonperturbation with the scaling errors will be explained.