PROGRESS IN MATHEMATICAL AND COMPUTATIONAL STUDIES ON SCIENCE AND ENGINEERING PROBLEMS

WORKSHOPS

理論科學研究中心
Center for Advanced Study in Theoretical Sciences

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Seminar Title: Time-accuracy in large-eddy simulation

Prof. Guowei He

Large-eddy simulation (LES) is emerging as a next-generation tool for computation fluid dynamics, in company with many new challenges. In LES of turbulent flows, large-scale eddies are directly solved from the filtered Navier-Stokes (NS) equations, while the effects of small-scale eddies on the large-scale ones have to be modeled using a so-called sub-grid scale (SGS) model. The important developments to achieve the goals are the filter approach, the SGS models and the energy conservative schemes. The recently increasing application of LES to predict non-equilibrium properties of turbulent flows requires that LES should correctly predict two-point, two-time correlations or space-time correlations. For example, turbulence-generated noise requires that a LES with a SGS model could accurately predicts space-time correlations, since the acoustic intensity radiated by turbulent flows depends on space-time correlations according to the Lighthill analogy. In turbulent two-phase flows, space-time correlations determine particle dispersions. Most of the currently existing SGS models are based on the energy budget equations. Therefore, they are able to correctly predict energy spectra at large scales, but they may not accurately predict other statistic quantities, such as space-time correlations. In the first lecture, I will present an introduction on large-eddy simulation, including the filter approach, the SGS models and the energy conservative scheme. These relevant concepts and methods are clearly explained in the fashion different from the Reynolds-Averaged NS method. In the second lecture, I will introduce our recent studies on time accuracy in LES. A new assessment quantity, space-time correlation, is introduced to evaluate the performance of the SGS models. It is found that a LES with the Smagorinsky SGS model may under-predict the correlation magnitudes and over-predict the decorrelation time scales (PoF 14 2186 2002). This may lead to an inaccurate prediction on sound power spectra. Based on those observations, we further develop a non-frozen flow model for the space-time correlations in turbulent shear flows (PRE 79 046319 2009). It is used to explain why the energy-based SGS model is not able to correctly predict space-time correlations. Finally, I will discuss possible SGS models to improve the LES prediction on space-time correlations. Those SGS models are especially useful to turbulence-generated noise and particle dispersion in turbulent flows.

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Seminar Title: Direct numerical simulation of two-dimensional wall-bounded turbulent flows from receptivity stage

Prof. Tapan K. Sengupta

Deterministic route to turbulence creation in 2D wall boundary layer is shown here by solving full Navier-Stokes equation by dispersion relation preserving (DRP) numerical methods for wall and free stream excitations. Results show that the transition by wall excitation is predominantly due to nonlinear growth of the Spatio-temporal wave front, even when Tollmien-Schlichting (TS) wave packets are created. The existence and linear mechanism of creating the Spatio- temporal wave front was established in Sengupta, et al. [Phys. Rev. Lett. 96, 224504 (2006)] via the solution of Orr-Sommerfeld equation. Effects of Spatio-temporal front(s) in the nonlinear phase of disturbance evolution have been documented by Sengupta et al. [Phys. Rev. Lett. 107, 154501 (2011) and Phys. Rev. E, 85, 026308 (2012)], where a flow is taken from the receptivity stage to a fully developed turbulent state by solving the Navier-Stokes equation. Details of the physical mechanism will be presented, along with the problem of forced excitation of flow over a natural laminar flow (NLF) airfoil for Re = 10.3 million. The wall excitation is monochromatic and time-harmonic, while free stream convecting vortical excitation is neither monochromatic, nor Spatio-temporal wave front is created, yet all cases show energy spectrum, which has been shown experimentally for atmospheric

dynamics in Nastrom, Gage & Jasperson [Nature 310, 36 (1984)]. Reproduction of the spectrum noted in atmospheric data (showing dominance of the spectrum over the spectrum) in lab scale indicates universality of this spectrum. Creation of universal features of 2D turbulence by a deterministic route has been established for the first time by solving the Navier-Stokes equation without any modelling or artifice. The case of 3D excitation field will also be shown to establish the role of Spatio-temporal front vis-à-vis TS wave packet. This is solved by compact schemes for velocity- vorticity formulation. All of these works have been made possible due to correct dispersion analysis of space-time discretization methods; developing optimized dispersion relation preserving methods and upwind multi-dimensional filters. This heralds a new beginning for DNS of actual transitional and inhomogeneous turbulent flows, which is distinctly different from solving homogeneous isotropic turbulence problem by pseudospectral methods.

Tutorial Title: Metrics of High Performance Computing: Dispersion Relation by Spectral Analysis

Prof. Tapan K. Sengupta

Over the last one decade, significant improvements have taken place which makes DNS possible, where some flows can be simulated from the onset of instability to fully developed turbulent stage. It is emphasized that this DNS is distinct from those practised by many in different disciplines, where governing equations are modified by many artifices. In this talk we explain how true DNS has been made possible by developing: (i) Spectral analysis tool for full domain; (ii) High accuracy compact difference scheme; (iii) A correct theory for error dynamics (replacing the celebrated von Neumann analysis) and (iv) Various upwind and adaptive multi-dimensional filters - all these have been developed at High Performance Computing Laboratory, IIT Kanpur slowly over the last decade. We will explain centrality of these concepts in developing the correct numerical dispersion relation and identify the major sources of errors. With the help of correct error propagation equation, one develops dispersion relation preserving (DRP) numerical methods for solving full Navier- Stokes equation. We will also discuss about various formulations of Navier-Stokes equation used for DNS of 2D and 3D flows. All the analysis tools developed are explained with the help of figures and animations showing various flow instabilities in internal and external flows, including DNS for 2D and 3D disturbance fields for turbulent flows. All these herald a beginning for DNS of transitional and turbulent flows.

Seminar Title: Revisit; Progress And Future Prospects of CFD in Aerospace - Wind Tunnel and Beyond –

Prof. Kozo Fujii

Based on the observation in the 30 years of CFD research, the present author pointed out both "evolutionary" and "revolutionary" efforts are required for CFD researchers for them to fully utilize CFD benefits and inherent power of CFD. In this talk, the speaker reflects back the 30 years of CFD research and three key issues for the future prospect of CFD will be addressed. The ISAS, the Institute of Space and Astronautical Science that the author belongs to, is the organization that actually develops spacecraft and rockets. All the needs for real developments motivate and require high level of research but at the same time, guarantee of the results. As examples of recent effort in the author's group, the project on the 10 PETAFLOPS "KEI" supercomputer in Kobe, JAPAN will be presented as well as recent study on rocket plume acoustics and Mars aircraft development.

Tutorial Title: Essence of Fluid dynamic Simulations

Prof. Kozo Fujii

Computational Fluid Dynamics (CFD) became one of the important tools for fluid dynamic analysis and design. However, CFD simulations still require large-scale computers for good estimation of flow structures and aerodynamic performance. Therefore, even with rapid progress of computers, we continue to develop more efficient and more accurate numerical algorithm. In this talk, reasons why CFD requires such high-end computers and highly accurate numerical algorithms are discussed as a background of CFD study and recent trend of CFD simulations. Flow unsteadiness is one of the key words and no-linearity and stiffness are the key characteristics of fluid dynamic equations. Numbers of application examples in aerospace and mechanical engineering will be used to show the key issues.

Seminar Title: Development of global geophysical fluid dynamic models by high-order multi-moment methods

Prof. Feng Xiao

Simultaneously using multiple discrete moments of a physical field, like cell integrated average, point value and derivatives, as the predicted variables or the constraints to derive the evolution equations for the predicted variables provides a new alternative framework to construct high order schemes. High order multi-moment methods have attractive properties for practical applications, such as algorithmic simplicity, flexibility and computational efficiency, hence are expected to be the suitable core numerics for new-generation models of global atmospheric and oceanic circulations. This talk will present some of our recent efforts toward the establishment of a new numerical model for atmospheric global circulations, using high-order multi-moment constrained finite volume (MCV) method. 1) In order to circumvent the polar problems in the conventional latitude-longitude grid, global shallow water models have been developed for spherical geometry on several popular spherical grids that have uniform grid spacing, including Yin-Yang composite grid, cubed sphere grid, icosahedral geodesic grid with both triangular and hexagonal tessellations. Widely used benchmark test problems were used to evaluate the numerical models, which verifies that the proposed numerical formulation works very well for different kinds of spherical grids and is promising for developing high-performance dynamic cores for global models. 2) Non-hydrostatic compressible dynamic core for atmosphere has been also developed by using the 3rd and 4th order MCV schemes. Two important features make MCV method particularly attractive as an accurate and practical numerical framework for atmospheric modelling. 1) Using nodal values as the predicted variables at solution points that can be flexibly located within the computational domain provides a great convenience in dealing with complex geometry and source terms including those from physical packages, and 2) High order schemes can be built by using constraints in terms of different moments, which makes the numerical model more robust and efficient (stable for larger CFL number). Numerical tests including the topographic effects have been conducted to evaluate the non-hydrostatic dynamic core as an accurate and practical framework for atmospheric models.

Tutorial Title: Construct high-order schemes using multi-moments or multi-moment constraints

Prof. Feng Xiao

Discrete quantities, such as cell integrated average, point value and derivatives, which are appellatively called moments in our context, reveal different respects of the physical field. Using more than two kinds of these quantities simultaneously as the predicted variables or the constraints to derive the evolution equations for the predicted variables leads to a class of schemes that are different from the conventional finite difference or finite volume methods. Rather than the Galerkin inner product procedure, the moments in a high order multi-moment finite volume (MV) or multi-moment constrained finite volume (MCV) scheme can be chosen through a more intuitive and physically motivated way, which allows greater flexibility in defining the computational variables and in deriving the corresponding prognostic equations to update the unknowns. Different moments are connected by local (cell-wise) reconstructions, and time marching is based on a set of equations which can be of different forms but consistent to the original governing equation(s). The moments can be either used directly as the prognostic variables as in an MV scheme, which can be interpreted as a modal type method, or used as the constraints to generate the equations to update other alternatively defined unknowns. A representative formulation of the latter is the nodal type MCV method, in which the unknowns are the point values defined at the solution points, and the prognostic equations to predict these unknowns are derived from the constraint conditions in terms of different moments. Multi-moment constraint concept also applies to the flux reconstruction formulation for conservation laws which provides a more general framework to accommodate many existing high order scheme, including discontinuous Galerkin method and spectral element method. Using multi-moment constraints to reconstruct the numerical flux function distinguishes the present methodology from other existing ones. High order multi-moment methods have attractive properties for practical applications, such as algorithmic simplicity, flexibility and computational efficiency, and have been applied to various problems in computational fluid dynamics. This talk will present the underlying idea of the methods, typical schemes and applications to fluid dynamics.