Computational Fluid Dynamics-2 (CFD-II)

Course Number: 33-31-085-31

Course Content:

1- Introductory Remarks
2- Numerical Grid Generation: A Review
3- Numerical Solution of 2D Ideal Flows (Inviscid, Incompressible, Irrotational)
4- Numerical Solution of 2D Full Potential Flows (Inviscid, Compressible, Irrotational)
5- Numerical Solution of Hyperbolic Equations
6- Numerical Solution of 1D Euler Equations (Inviscid, Compressible, Rotational)
7- Numerical Solution of 1D Navier-Stokes Equations (Viscous, Compressible, Rotational)
8- Numerical Solution of 2D Euler and Navies-Stokes Equations
9- Selected Advanced Topics

Course Description:

As opposed to the CFD-I course, in which the CFD algorithms are mostly discussed in a one-dimensional context, this graduate-level course is designed to introduce some new discretization tools and techniques appropriate for the solution of two-dimensional heat and fluid flow equations. Also, in contrast to CFD-I, in which the focus is on the numerical solution of incompressible flows, here attention turns to the compressible flow problems. Again, the Finite Volume Method (FVM) is the method of choice for the discretization of governing equations. A background finite element mesh is also used for further geometrical flexibility and for using the shape functions in interpolations (Element-Based FVM, or EBFVM).

The CFD-II course, broadly speaking, is mostly focused on the issues of multi-dimensional domain discretization (grid generation), discretization of the governing equations in 2D flow fields and the numerical treatment of phenomena associated with the compressibility effects. To discuss some fundamentally important discretization ideas regarding hyperbolic equations, one-dimensional wave equations are also discussed in some details.

Chapter 1 provides a brief introduction to the MATLAB programming environment. MATLAB is suggested for the implementation of the numerical schemes in this course. However, students are allowed to use other computer tools and languages if they prefer to do so. Various formulation methodologies and simplifications for the flow problems are also discussed in this Chapter in addition to a brief discussion regarding the historical advances in the field of CFD and some remaining issues.

Chapter 2 is dedicated to 2D grid generation. Both algebraic and differential (elliptic) methods for structured grid generation are discussed in depth. Brief remarks are also made regarding unstructured grid generation.

Chapter 3 is basically about the diffusion modeling in 2D domains via FVM (and in particular EBFVM). Numerical simulation of steady heat conduction and ideal flow fields are discussed in this Chapter.

Chapter 4 discusses the numerical solution of Full Potential Equation (FPE) in subsonic and transonic flow regimes. The similarities and differences between the incompressible and compressible potential flows are discussed here. Attention is drawn to the effect of the flow physics on the discretization scheme and it is shown how a smart computational molecule can be developed to cope with both subsonic and supersonic flow regions.

Chapter 5 is devoted to the wave equation. Here, linear and non-linear advection of signals in a fluid flow field are discussed. While, the focus is certainly on the advection modeling in a 1D context, the students have the opportunity to spend some time on the interplay between advection and diffusion in unsteady 1D test cases. The required theoretical background for the numerical solution of Euler and Navier-Stokes equations is provided here. Finite difference method is used throughout this Chapter.

Chapter 6 belongs to the numerical solution of a set of nonlinear coupled partial differential equations known as the Euler equations. This is certainly an important part of the course and both FDM and FVM are employed for the discretization.

Chapter 7 adds the viscosity to the mixture and discusses a 1D version of Navier-Stokes equations.

Chapter 8 takes aim at the discretization of 2D Euler and Navier-Stokes equations. The modeling of advection in a two-dimensional domain is the trophy here!

Chapter 9 is a regulatory Chapter. If time allows, selected topics such as convergence acceleration methods for the Euler solvers and grid adaptation concepts and techniques are discussed.

Course Resources:

A comprehensive list of CFD and grid generation reference books will be provided to the students. Sections from the following books have been consulted in the preparation of this course:

[1] Klaus A. Hoffmann, Steve T. Chiang, Computational Fluid Mechanics, volume1: EES 1989, 1993, 1998, 2000.

[2] Klaus A. Hoffmann, Steve T. Chiang, Computational Fluid Mechanics, volume2: EES 1989, 1993, 1998, 2000.

[3] Klaus A. Hoffmann, Steve T. Chiang, Computational Fluid Mechanics, volume3: EES 1989, 1993, 1998, 2000.

[4] J. H. Ferziger and M. Peric, Computational Methods for Fluid Dynamics, Springer (3rd ed) 2002.

[5] C. A. J. Fletcher, Computational Techniques for Fluid Dynamics-I, Springer, 1997.

[6] C. A. J. Fletcher, Computational Techniques for Fluid Dynamics-II, Springer, 1997.

[7] Patrick J, Roache, Fundamentals of Computational Fluid Dynamics, Hermosa publishers, 1998.

[8] Charles Hirsch, Numerical Computation of Internal & External Flows, Elsevier, volume 1, 1998, 2007.

[9] Charles Hirsch, Numerical Computation of Internal & External Flows, Elsevier, volume 2, 1998.

[10] J. Blazek, Computational Fluid Mechanics: Principles & Applications, Elsevier, 2001.

[11] J. C. Tannehill, D. A. Anderson, R. H. Pletcher, Computational Fluid Mechanics & Heat Transfer, Taylor & Francis, 1997.

[12] T. J. Chung, Computational Fluid Mechanics, Cambridge University Press, 2002.

[13] M. Farrashkhalvat and J. P. Miles, *Basic Structured Grid Generation*, Butterworth, Hienmann, 2003.

[14] Patrick Knupp and Stanly Steinberg, *Fundamentals of Grid Generation*, CRC, 1993.

[15] J. F. Thompson et. Al, *Numerical Grid Generation*, Elsevier Science, 1982.

[16] J. F. Thompson, Z.U. A. Warsi, and C.W. Mastin, *Numerical Grid Generation*, North Holland, 1985.

[17] J. F. Thompson, B. K. Soni, and N. P. Weatherill, Handbook of Grid Generation, CRC Press, Boca Raton, FL, 1999.

Also, many articles/papers are used and/or referred to during class discussions. A number of these papers are mentioned below:

1978- J. P. Van Doormal, G. D. Raithby, and B. H. McDonald, The Segregated Approach to Predicting Viscous Compressible Fluid Flows, J. Turbomachinery, vol. 109, pp. 268–277, 1978.

1980- P. D. Thomas and J. F. Middlecoff, Direct Control of the Grid Point Distribution in Meshes Generated by Elliptic Equations, AIAA J., vol. 18, pp. 652–656, 1980.

1987- G. E. Schneider and M. J. Raw, Control Volume Finite-Element Method for Heat Transfer and Fluid Flow using Colocated Variables—1. Computational Procedure, Numer. Heat Transfer B, vol. 11, pp. 363–390, 1987.

1994- S. M. H. Karimian and G. E. Schneider, Pressure-Based Computational Method for Compressible and Incompressible Flows, J. Thermophys. Heat Transfer, vol. 8, pp. 267–274, 1994.

1995 - S. P. Spekreijse, Elliptic Grid Generation Based on Laplace Equations and Algebraic Transformations, J. Comput. Phys., vol. 118, pp. 38–61, 1995.

1997- M. Darbandi and G. E. Schneider, Momentum Variable Procedure for Solving Compressible and Incompressible Flows, AIAA J., vol. 35, pp. 1801–1805, 1997.

1998- M. Darbandi and G. E. Schneider, Comparison of Pressure-Based Velocity and Momentum Procedures for Shock Tube Problem, Numer. Heat Transfer B, vol. 33, pp. 287–300, 1998.

2010- M. Rezvani and A. Ashrafizadeh, Numerical Simulation of the Inter-Equation Couplings in All-Speed Flows Via the Method of Proper Closure Equations, Numerical Heat Transfer, part A, 58(4), 313-332, 2010.

2012- A. Ashrafizadeh, M. Ebrahim and R. Jalalabadi, Alternative Methods for Generating Elliptic Grids in Finite Volume Applications, Finite Volume Method - Powerful Means of Engineering Design, PhD. Radostina Petrova (Ed.), ISBN: 978-953-51-0445-2, InTech, Available from: http://www.intechopen.com/books/finite-volume-method-powerful-means-of-engineering-design/alternative-methods-for-generating-elliptic-grids-in-finite-volume-applications

Course Evaluation:

CFD-II is a project-based course and there is no mid or final term examination. Students are expected to write codes to solve a number of heat and/or fluid flow problems and to submit professionally-written reports (usually between 3 to 5 term projects). In addition, students might be individually invited by the instructor to answer questions and to explain and run their codes. Depending on the number of students, seminars on some research projects may also be assigned to Ph.D. students or those who audit the course.

Sample Term Projects:

- Grid generation in 2D domains.
- Grid generation for external flow problems (e.g. around airfoils).
- Numerical solution of 2D heat conduction problems via EBFVM.
- Numerical solution of 2D ideal flow around airfoils.
- Numerical solution of 2D compressible potential flow around airfoils.
- Numerical solution of the flow in convergent-divergent channels (including shocks).
- Numerical solution of the flow in a shock-tube.
- Numerical solution of 2D inviscid (Euler) flow around airfoils.
- Numerical solution of a 2D supersonic flow over a bump.

Sample Research Topics:

- Numerical solution of advection-diffusion equations with linear/non-linear source terms.
- Use of error indicators in grid adaptation.
- Grid adaptation mechanisms.
- Convergence acceleration (including multigrid).
- Efficient use of data structures and unstructured grid generation methodologies.
- Numerical solution of sample flow problems via Finite Element Method (FEM).
- Numerical solution of sample flow problems using grid-less or over set grid methods.
- Transient and compressible versions of the SIMPLE family of methods.