ME 605 | Computational Fluid Dynamics

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L-T-P-C: 3-1.5-0-4
Lecture hours: P1,P2 slots, 5-6:20 pm on Wed and Fri (7/203)
Tutorial Hours: N2 slot, 5-6:20 pm on Thu (7/203)
Tutor: Mr. Malay Vyas
Teaching Assistant: Mr. Mutyala Pardha Sai

General description

This is a foundational postgraduate level course on Computational Fluid Dynamics. Third and fourth year undergraduate students would also find this course interesting and useful. In this course, students will learn and apply different computational methods to solve fluid flow and heat transfer problems. A project-based learning approach will be adopted in the course. All the projects will involve code development from scratch.

Course contents

1. **Introduction**
   - History, utility, and applications
   - Role of CFD in virtual prototyping
   - Components of a CFD simulation system

2. **Governing equations for fluid flow and heat transfer**
   - Governing transport equations: The continuity, momentum, and energy equations
   - Simplified model equations: 1D convection-diffusion equation, linear advection equation, diffusion equation, and wave equation

3. **Mathematical nature of governing equations**
   - Behavior of physical systems: Illustration using heat diffusion and wave propagation examples
   - Characteristics: Definition, derivation of characteristics for first order and second order PDEs
   - Classification of PDEs and system of PDEs based on characteristics: Elliptic, parabolic, and hyperbolic PDEs
   - Concepts of domain of dependence, domain of influence, and implications on initial and boundary conditions

4. **Computational solution of elliptic PDEs**
   - Introduction to finite difference method
   - Approximations to first derivative and second derivative using Taylor series and polynomial fitting methods. Concept of truncation error
   - Boundary conditions: Dirichlet and Neumann boundary conditions
   - Solution methods: Thomas algorithm, Iterative solution methods such as Gauss-Seidel method, Alternating Direction Implicit (ADI) method
   - Computational solution of important elliptic PDEs such as the steady-state heat diffusion equation.

5. **Computational solution of parabolic PDEs**
   - Euler explicit and implicit methods
   - Crank-Nicholson method
   - Time-splitting ADI method
   - Error and stability analysis
   - Computational solution of important parabolic PDEs such as the boundary layer equations, unsteady-state heat diffusion equation.

6. **Computational solution of hyperbolic PDEs**
   - Euler explicit and implicit methods
   - Upwind spatial discretization
   - Lax and leap-frog schemes
   - Lax-Wendroff method
   - MacCormack method
   - Error and stability analysis
   - Computational solution of important hyperbolic PDEs such as the unsteady Euler equations

7. **Computational solution of Navier-Stokes equations**
   - Introduction to finite volume method: Approximation of surface and volume integrals, interpolation and differentiation practices
   - Special features of Navier-Stokes equations
   - Co-located vs staggered arrangements
   - Calculation of pressure – The Pressure Poisson equation
   - Rhie-Chow Interpolation based algorithms
   - The family of SIMPLE algorithms.
   - Computational solution of important fluid flow problems such as the lid-driven cavity flow, pipe flow, Couette flow problems.

Learning objectives

Upon completion of this course, students should be able to:

1. demonstrate a strong understanding of different numerical methods commonly used to solve fluid flow and heat transfer problems
2. make a judicious choice of suitable numerical methods for a particular problem.
3. write and develop CFD codes from scratch independently to solve fluid flow and heat transfer problems

Texts and references

1. Computational Methods for Fluid Dynamics by Ferziger and Peric
2. Numerical Methods for Partial Differential Equations: Finite Difference and Finite Volume Methods by Sandip Mazumder
3. Computational Fluid Dynamics: The basics with applications by John D. Anderson
4. Numerical Computation of Internal and External Flows by Charles Hirsch
5. Computational Fluid Mechanics and Heat Transfer by Tannehill, Anderson and Pletcher
6. Numerical Heat Transfer and Fluid Flow by S.V.Patankar

Grading

Projects – 100 % (There will be four projects in this course and each will be given a weightage of 25 %)

Project policy

Students can discuss while working on projects. However, each student must produce and submit his/her own independent project. Projects have to be submitted by the due date and time to avoid any late submission penalty. The late submission penalty is as follows:

a. For submissions past the due time on the due date, a penalty of 10 % will be applied.

b. For submission after midnight of the due date, a penalty of 25 % will be applied.

c. For submissions past 24 hours after the midnight of the due date, a penalty of 50 % will be applied and so forth.

Honor code

Students are expected to adhere to the IIT Gandhinagar honor code.

Course Schedule

Date	Day	Lecture Topics	Project
Aug 2	Fri	Introduction- History, utility, and applications, Role of CFD in virtual prototyping, Components of a CFD simulation system	
Aug 7	Wed	Governing transport equations: The continuity, momentum, and energy equations. Simplified model equations: 1D convection-diffusion equation, linear advection equation and diffusion equation. Behavior of physical systems: Illustration using heat diffusion and wave propagation examples.	
Aug 8	Thu	Characteristics: Definition, derivation of characteristics for first order PDEs. Implications on initial and boundary conditions	
Aug 9	Fri	Derivation of characteristics for second order PDEs. Classification of PDEs and system of PDEs based on characteristics: Elliptic, parabolic, and hyperbolic PDEs	
Aug 14	Wed	Examples of Elliptic, parabolic and Hyperbolic PDEs - Implications on initial and boundary conditions. Introduction to Numerical Methods – Finite differences and Desirable properties of numerical methods	
Aug 15	Thu	Holiday (Independence Day)	
Aug 16	Fri	Approximations to first derivative and second derivative using Taylor series. Concept of truncation error	
Aug 21	Wed	Polynomial fitting method. Boundary conditions: Dirichlet and Neumann boundary conditions	
Aug 22	Thu	Tutorial 1 – Linear solvers (LU decomposition method)	
Aug 23	Fri	Solution methods: Banded matrices, Thomas algorithm, Illustration using an example	
Aug 28	Wed	Multidimensional problems – Loss of tridiagonality (Illustration), Iterative solution methods such as Gauss-Seidel method. Convergence of iterative solvers, Point by point method, Line by line method	Project 1
Aug 29	Thu	Tutorial 2 – 1D convection-diffusion equation	
Aug 30	Fri	ADI method, Treatment of source terms. Computational solution of Parabolic PDEs: Explicit Euler method, stability analysis	
Sep 4	Wed	Implicit Euler method and stability analysis	
Sep 5	Thu	Tutorial 3 – 1D unsteady heat conduction equation	
Sep 6	Fri	Crank Nicholson method, Time splitting ADI method, Computational solution of Hyperbolic PDEs: Explicit Euler method – stability analysis	
Sep 11	Wed	Implicit Euler method, Upwind vs downwind spatial discretization	
Sep 12	Thu	Tutorial 4 – 1D wave equation (including Lax and Leapfrog schemes)	Project 2
Sep 13	Fri	Lax-Wendroff and McCormack schemes	
Sep 18	Wed	Euler equations, characteristics, Eigen values, MOC boundary	

		conditions	
Sep 19	Thu	Tutorial 5 – Quasi 1-D flow in Nozzles	
Sep 20	Fri	Introduction to finite volume method: Approximation of volume integral; Evaluation of diffusive fluxes	
Sep 25	Wed	Evaluation of convective fluxes: upwind & linear interpolation schemes.	
Sep 26	Thu	Tutorial 6 – Project 3 discussion	Project 3
Sep 27-Oct 13 (Exam 1/Recess)			
Oct 16	Wed	Demonstration of conservatives of finite volume method, boundary conditions: Finite difference vs Finite volume methods	
Oct 17	Thu	Navier-Stokes equations – discretization of continuity and momentum equations	
Oct 18	Fri	Rhie-Chow Interpolation and pressure-velocity split problem	
Oct 23	Wed	SIMPLE algorithm	
Oct 24	Thu	Tutorial 8 - Project 4 discussion	Project 4
Oct 25	Fri	SIMPLE algorithm	
Oct 30	Wed	SIMPLER, SIMPLEC, and PISO algorithms	
Oct 31	Thu	Holiday (Deepavali)	
Nov 1	Fri	Advanced Topics – CFD methods for compressible flows	
Nov 6	Wed	Advanced Topics – CFD methods for compressible flows	
Nov 7	Thu	Tutorial 9 - Project 4 discussion	
Nov 8	Fri	Advanced Topics – CFD methods for compressible flows	
Nov 13	Wed	Advanced Topics - CFD methods for compressible flows	
Nov 14	Thu	Tutorial 10 - Project 4 discussion	
Nov 15	Fri	Holiday (Guru Nanak's Birthday)	
Nov 20	Wed	Advanced Topics - TVD schemes	
Nov 21	Thu	Tutorial 11 - Project 4 discussion	
Nov 22	Fri	Advanced Topics - TVD schemes	