MANE 4960/6960 Compressible Flows

Dr. Ozgur Tumuklu

Spring 2024

1 Course Information

Course Title .... Compressible Flows
Course Number .... MANE 4960 & 6960
Credit Hours 3
Semester/ Year .... Spring 2024
Meeting Days .... Tuesday + Friday: 10:00 - 11:20 am

Room Location .... Darrin Communications Center, Room 232

Course Website .... https://lms.rpi.edu
Announcements, supplementary course materials, and discussion will be posted on this website.
Prerequisites .... MANE 2720 Fluid Mechanics
Advanced Standing .... Engineering.

Instructor .... Prof. Ozgur Tumuklu

Office: Jonnson Engineering Center (JEC) 2044

Email: tumuko@rpi.edu
Phone 518.276.7547
Web: https://mane.rpi.edu/people/faculty/ozgur-tumuklu

Office Hours:[1]
Tuesday: 09:00 am - 10:00 am
Friday: 4:00 pm - 5:00 pm
By Appointment

Textbook .... *Modern Compressible Flow: With Historical Perspective*
John Anderson
4th. ed., ISBN10: 1260471446 | ISBN13: 9781260471441

Supplementary Book .... *Introduction to Compressible Fluid Flow*
Patrick H. Oosthuizen and William E. Carscallen
2nd. ed., CRC Press, 2014

Important Dates .... Feb. 27: First Exam
March 4-8: Spring Break

[1] Office hours are subject to change. Changes will be announced in class and LMS.

Apri 23: Second Exam
April 24: Last Day of Class
April 29- May 3: Final Exams
Additional Registrar Dates and Deadlines (linked)

Instructor/course feedback and evaluations will be utilized throughout the semester.

2 Course Outline

Course Description

This course is tailored as a technical elective for senior and graduate students, offering a comprehensive exploration of compressible flow principles. Throughout the duration of the course, an extensive range of unique concepts and their real-world applications are thoroughly examined. This will include a detailed analysis of fundamental elements such as the speed of sound and Mach number, isentropic quasi 1-D flow in variable area ducts, converging nozzles, choking phenomena, converging-diverging nozzles, moving shocks, blast waves, shock tubes, Rayleigh flow, Fanno flow, normal and oblique shocks, expansion fans, and other relevant topics that will be revealed, time permitting. Moreover, our focus will extend to the intricate development of potential flow theory under minor disturbances across subsonic, transonic, supersonic, and hypersonic nonequilibrium flow regimes, with a specific emphasis on its application within the realm of aerothermodynamics. The practical implications of the material will be elucidated within the framework of the professor's ongoing research, contemporary advancements, and historical context.

Course Objectives

The course will focus on the following information:

1. Understand the fundamental characteristics of compressible flows.
2. Derive and comprehend the equations governing compressible fluid dynamics.
3. Explore the conservation laws and thermodynamic principles relevant to compressible fluids.
4. Analyze the behavior of shock waves, expansion waves, and rarefaction waves.
5. Investigate the formation and properties of normal and oblique shocks.
6. Analyze the performance of nozzles and diffusers in compressible flows.
7. Understand the impact of heat and friction on compressible shock dominated flows.
8. Predict the wave structures over various flows with different Mach number.
9. Apply the method of characteristics to study expansion waves.
10. Comprehend shock motion and reflections in shock tubes.
11. Calculate lift and drag coefficients of vehicles in supersonic flows.
12. Understand the real gas effects for hypersonic flows.

Student Learning Outcomes

Students who successfully complete this course will have the ability to demonstrate: (i) proficiency in identifying, formulating, and solving problems within the field of aerospace engineering, (ii) a solid understanding of fluid mechanics and thermodynamics, and (iii) a comprehensive knowledge of flow physics.

Course Topics

During this course, we will:

1. Define the concept of compressibility and Mach number and identify the impact of these concepts on flow field.
2. Categorize flow fields based on attributes such as incompressible or compressible characteristics, steady or unsteady inviscid or viscous behavior, laminar or turbulent flow, and internal or external flows.
3. Differentiate between subsonic, transonic, supersonic, and hypersonic flow regimes.
4. Understand the basic principles and equations governing compressible flows, including the conservation of mass, momentum, and energy.
5. Apply the equation of state for compressible fluids, such as the ideal gas law, to analyze compressible flow behavior.
6. Analyze isentropic flow processes and calculate key parameters such as Mach number, pressure, and temperature ratios.
7. Understand the formation and properties of shock waves in compressible flows.
8. Correlate steady and moving shock wave concepts.
9. Analyze properties of shock waves, such as pressure, temperature, and velocity changes across the shock front.
10. Apply Rankine-Hugoniot relations to relate pre-shock and post-shock conditions.
11. Explain why entropy is important for flow discontinuities.
12. Apply the conservation equations for mass, momentum, and energy to analyze one-dimensional, steady, adiabatic compressible flow in ducts.
13. Understand the significance of Fanno flow in practical engineering applications, particularly in the context of ducts and pipes.
14. Apply the conservation equations for mass, momentum, and energy to analyze fluid flow with heat transfer, considering both internal and external heat transfer processes.
15. Demonstrate a comprehensive understanding of the mechanisms and conditions leading to the formation of oblique shock waves.
16. Apply the appropriate relationships, such as the oblique shock wave equations, to determine post-shock conditions.
17. Develop a comprehensive understanding of Prandtl-Meyer expansion waves, including their formation and characteristics in compressible fluid flows.
18. Analyze the properties of Prandtl-Meyer expansion waves, including changes in Mach number, pressure, and temperature across the expansion fan.
19. Apply the method of characteristics to determine the spatial characteristics of expansion waves.
20. Estimate flow field parameters in shock tube.
21. Develop a thorough understanding of the principles underlying linearized compressible flows, including the assumptions and mathematical models involved in linearization.

22. Develop a comprehensive understanding of the fundamental principles governing hypersonic flows, including shock waves, boundary layers, and rarefied gas effects.
23. Apply the Navier-Stokes equations for continuum flows and the Boltzmann equation for rarefied gas flows to analyze hypersonic and nonequilibrium conditions.

Outline (Tentative)*

The reading assignments from the textbook for each chapter are given in square brackets [ ].

(a) **Chapter 1: Overview of Fluid Mechanics and Thermodynamic Principles** [Secs: 1.2-1.4, 2.1-2.7, 3.3]
  - Definition of the Compressibility
  - Governing Equations
    - Reynolds' Transport Theorem
    - Conservation of mass
    - Momentum Equation of Inertial Control Volumes
    - First Law of Thermodynamics
    - Second Law of Thermodynamics
  - Thermodynamic of Ideal Gases
    - Equation of State
    - Entropy and Isentropic Processes
    - Speed of Sound and Mach Number
    - Static and Stagnation Properties
  - Classification of Fluid Motions
    - Subsonic to Hypervelocity Flows
    - Viscous and Inviscid Flows
    - Rarefied and Continuum Flows

(b) **Chapter 2: One-Dimensional Wave Motion; Shock and Expansion Waves** [3.6-3.7, 7.1-7.3]
  - Introduction
  - Normal Shock Relations
  - Hugoniot Equation
  - Strong and Weak Waves
  - Unsteady Wave Motion
  - Shock Motion and Reflections from Wall

(c) **Chapter 3: Governing Equations for General 1-D Flow** [5.1-5.5]
  - Introduction
  - Analysis with Quasi 1-D Flow Assumption

(d) **Chapter 4: Isentropic Flow with Area Change**
  - Isentropic Flow with Area Change
  - Area-Velocity Relation
  - Converging Nozzle
  - Nozzle and Diffuser

(e) **Chapter 5: Flow with Friction (Fanno Flow) and Flow with Heat Transfer (Rayleigh Flow)** [3.8-3.9]

- Introduction
- Fanno Line
- Converging Nozzle Feeding a Constant-Area Duct with Friction
- Rayleigh Line
- Converging Nozzle Feeding a Constant-Area Heated Duct

(f) **Chapter 6: Oblique Shock Waves**[4.1-4.13, 5.6]

- Steady, 2D Mach Waves
- Oblique Shock Waves Analysis
- Wave Reflections from a Plane Wall
- Conical Shock Waves

(g) **Chapter 7: Prandtl-Meyer Expansion Waves**[4.14-4.15, 5.6]

- Introduction
- Estimation of Maximum Turning Angle
- Reflections of Waves from Walls
- Supersonic Inlets
- Converging-Diverging Nozzles

(h) **Chapter 8: Multi-dimensional and Linearized Compressible Flows**[6.1-6.4,7.6-7.8, 8.1-8.3, 9.1-9.7]

- Linear Momentum Equation
- Speed of Sound Equation
- MOC Analysis for 1D Expansion Waves
- Shock Tube
- Compressible Potential Equation
- Linearization of the Governing Equations for Compressible Flows

(i) **Chapter 9: Introduction to Hypersonic Flows and Nonequilibrium Flows**[15.1-15.3, 16.1-16.3]

- Characteristics of High Temperature Flows
- Shock, Boundary, and Entropy Layers of Hypersonic Flows
- Properties of High-Temperature Gases and Internal Energy Modes

* *The majority of this course plan is built on input and materials provided by Professor Emeritus Craig Dutton from UIUC.*

3 Course Calendar

The following table shows a tentative plan for the course. It may be subject to slight changes during the semester. Please refer to the course objectives to find the corresponding **learning outcomes**. Chapter numbers have been assigned for reading assignments accordingly.

Week #	Course Topic	Reading Assignments from Course Book	Homework Assignment
1-2	1-6	Chapter 1	1
3-4	6-11	Chapter 2	2
5	12	Chapter 3	
6	8-12	Chapter 4	3
7	13-14	Chapter 5	4
Exam 1 : February 27, 2024 on Chapters 1-5.			
8	15-16	Chapter 6	5
9	17-19	Chapter 7	6
10-12	20-21	Chapter 8	7
13	22-23	Chapter 9	8
Exam 2 : April 23, 2024 on Chapters 6-9.			

4 Grading Policy

- **MANE 4960**
  Homework (Eight evenly weighted assignments): 25%
  Quizzes: 15%
  Two exams at 30% each: 60%
  Project* (25%)
  * *Undergraduate students may voluntarily submit a project. Upon submission, the overall grade will be calculated based on the MANE 6960 policy as follows:*
- **MANE 6960**
  Homework (Eight evenly weighted assignments): 20%
  Quizzes: 10%
  Two exams at 25% each: 50%
  Project: 20%

Extension or special accommodation requests submitted less than 48 hours before the due date will only be considered in cases of emergencies such as illness or family situations. The final decision on granting special accommodations rests entirely with the instructor based on the specific circumstances.

More information for RPI policy for Institutional Research and Assessment can be found in this link.

5 Absence Policy

Details of the excused absence policy can be found on the Student Success website (link). If you know you will have an excused absence in advance (funeral, wedding, Rensselaer-sanctioned event, etc.), inform your instructor as early as possible. In the case of illness, no medical excuse is required for absences of up to one week, but you should contact your instructor as soon as possible. Students are responsible for the missed content, and video recordings of lectures will not be provided. In the case of an excused absence on the day of a scheduled midterm exam, students will be eligible for a makeup exam, which will differ from the regular exam, although the content covered will be the same. The timing of makeup exams will be coordinated between the instructors and all affected students. A written make-up exam will not be offered after the cumulative final exam due to time constraints. As needed, the instructor may modify the grading policy or require an oral make-up exam..

6 Academic Integrity

Student-teacher relationships are built on trust. For example, students must trust that teachers made appropriate decisions about the structure and content of the courses they teach, and teachers must trust that the assignments the students that students turn in are their own. Acts which violate this trust undermine the educational process. The Rensselaer Handbook of Student Rights and Responsibilities defines various forms of Academic Dishonesty and you should make yourself familiar with these. In this class, all assignments that are turned in for grade must represent the student's own work. In cases where help was received, or teamwork was allowed, a notation on the assignment should indicate your collaboration.

Submission of any assignment that is in violation of this policy will result in the penalty of a grade of zero for this assignment. If you have any questions concerning this policy before submitting an assignment, please ask the professor for clarification. If you have any question concerning this policy before submitting an assignment, please ask for clarification.

All students are expected to be familiar with and abide by the policies and procedures, including those on academic integrity, contained in the current version of the Rensselaer Handbook of Student Rights and Responsibilities (link). Any individual assignments you submit in this course should be entirely your own work. Copying homework or projects will not be tolerated. You are encouraged to first do your assignments by yourself and then discuss solutions with others. Cheating or plagiarism will result in punitive measures. Violations of academic integrity may also be reported to the appropriate Dean (Dean of Students for undergraduate students or the Dean of Graduate Education for graduate students, respectively).

7 Disability Services

Rensselaer Polytechnic Institute strives to make all learning experiences as accessible as possible. If you anticipate or experience academic barriers based on a disability, please let me know immediately so that we can discuss your options. To establish reasonable accommodations, please register with The Office of Disability Services for Students. After registration, make arrangements with the Director of Disability Services as soon as possible to discuss your accommodations so that they may be implemented in a timely fashion. DSS contact information: dss@rpi.edu; +1-518-276-8197; 4226 Academy Hall.

8 Support Services

PInfo - contains various resource links for students, academic resources, support services, and safety emergency preparedness.

Academic Assistance	ALAC—Advising and Learning Assistance Center	518.276.6269	webpage link
Student Health and Wellness	Counseling Center Student Health Center	518.276.6479 518.276.6287	webpage link webpage link
Student Support Services	Class Deans, Undergraduate Dean, Graduate Experience Dean, Student Success Dean, First Year Experience	518.276.8022	webpage link
DOTCIO (IT Services)	Help Desk, Submit a ticket to IT Services and Support Center	518.276.7777	webpage link