ASEN 5151: Fundamentals of Gas Dynamics

Spring 2022

Time:	Mon./Wed./Fri. 10:40 – 11:30 AM	**Location:**	AERO 111
Instructor:	Professor Robyn Macdonald	**Email:**	robyn.macdonald@colorado.edu
Teaching Assistant:	DeAnna Gilchrist	**Email:**	deanna.sewell@colorado.edu

Course Page: https://canvas.colorado.edu/

Office Hours: ?

Text: There is no required textbook for this course. Notes will be posted on the course website for each section of the course. Some useful references are listed below which are available digitally or in the course reserves at the Gemmill Library. At the beginning of the notes for each section is a list of sources from which the notes were compiled.

- Anderson, J. D., Jr., *Modern Compressible Flow with Historical Perspective,* Second Edition, McGraw-Hill, 1990. Available in course reserves.
- Liepmann, H. W. and Roshko, A., *Elements of Gasdynamics,* Dover Publications, 2001. Available online: https://tinyurl.com/yb5pux98
- Pletcher, R. H., Tannehill, J. C., and Anderson, D. A., *Computational Fluid Mechanics and Heat Transfer,* Third Edition, CRC Press, 2013. Available online: https://tinyurl.com/y2hjeflc
- Rathakrishnan, E., *Theoretical Aerodynamics,* Wiley, 2013. Available online: https://tinyurl.com/y6tt3sv6
- Shapiro, A. H., *The Dynamics and Thermodynamics of Compressible Fluid Flow,* Vol. I, Ronald Press, 1953. Available online: https://tinyurl.com/yxergkvo
- Zucrow, M. J. and Hoffman, J. D., *Gas Dynamics,* Vol. I, Wiley, 1976. Available in course reserves.
- Zucrow, M. J. and Hoffman, J. D., *Gas Dynamics,* Vol. II, Wiley, 1977. Pending purchase at the library.

Prerequisites: A first course in fluid mechanics or aerodynamics, including ASEN 3111. I will assume that you are familiar with typical topics from an introductory compressible flow course, including isentropic flow with area change, normal shock waves, oblique shock waves, Prandtl-Meyer flow, associated applications such as converging and converging-diverging nozzles, etc. I expect students to be proficient with programming in MATLAB which will be used for some assignments.

Grading Policy: Homework (50%), Exam 1 (25%), Exam 2 (25%).

Homework: Homework will be assigned periodically as the appropriate material is covered, and will include both handwritten problem solutions and computer solutions. The due date for each assignment will be announced when the assignment is made. All students will submit assignments through the course website. The late penalty for homework will be 10% per day, for up to 5 days. Beyond 5 days late, the assignment is worth 0%. You may receive help from a classmate or the instructor/TA on homework assignments, but the submitted assignment must be your own work. This includes both handwritten solutions, as well as programming assignments.

Class format: This class operates in two modalities: in-person and asynchronous remote. All lectures will be recorded via Classroom Capture and will be made available to all students.

Classroom Behavior: Both students and faculty are responsible for maintaining an appropriate learning environment in all instructional settings, whether in person, remote or online. Those who fail to adhere to such behavioral standards may be subject to discipline. Professional courtesy and sensitivity are especially important with respect to individuals and topics dealing with race, color, national origin, sex, pregnancy, age, disability, creed, religion, sexual orientation, gender identity, gender expression, veteran status, political affiliation or political philosophy. For more information, see the policies on classroom behavior and the Student Conduct & Conflict Resolution policies.

Requirements for COVID-19: As a matter of public health and safety, all members of the CU Boulder community and all visitors to campus must follow university, department and building requirements and all public health orders in place to reduce the risk of spreading infectious disease. Students who fail to adhere to these requirements will be asked to leave class, and students who do not leave class when asked or who refuse to comply with these requirements will be referred to Student Conduct and Conflict Resolution. For more information, see the policy on classroom behavior and the Student Code of Conduct. If you require accommodation because a disability prevents you from fulfilling these safety measures, please follow the steps in the "Accommodation for Disabilities" statement on this syllabus.

CU Boulder currently requires masks in classrooms and laboratories regardless of vaccination status. This requirement is a precaution to supplement CU Boulder's COVID-19 vaccine requirement. Exemptions include individuals who cannot medically tolerate a face covering, as well as those who are hearing-impaired or otherwise disabled or who are communicating with someone who is hearing-impaired or otherwise disabled and where the ability to see the mouth is essential to communication. If you qualify for a mask-related accommodation, please follow the steps in the "Accommodation for Disabilities" statement on this syllabus. In addition, vaccinated instructional faculty who are engaged in an indoor instructional activity and are separated by at least 6 feet from the nearest person are exempt from wearing masks if they so choose.

If you feel ill and think you might have COVID-19, if you have tested positive for COVID-19, or if you are unvaccinated or partially vaccinated and have been in close contact with someone who has COVID-19, you should stay home and follow the further guidance of the Public Health Office (contacttracing@colorado.edu). If you are fully vaccinated and have been in close contact with someone who has COVID-19, you do not need to stay home; rather, you should self-monitor for symptoms and follow the further guidance of the Public Health Office (contacttracing@colorado.edu).

If you are sick or quarantined and must miss an in-person assessment, please alert me of your absence via email but do not include specific information about your illness due to privacy laws. Because attendance is not required in this class, if you miss a class you do not need to inform me but can watch the lecture asynchronously on Canvas.

Accommodation for Disabilities: If you qualify for accommodations because of a disability, please submit your accommodation letter from Disability Services to your faculty member in a timely manner so that your needs can be addressed. Disability Services determines accommodations based on documented disabilities in the academic environment. Information on requesting accommodations is located on the Disability Services website. Contact Disability Services at 303-492-8671 or dsinfo@colorado.edu for further assistance. If you have a temporary medical condition, see Temporary Medical Conditions on the Disability Services website.

Preferred Student Names and Pronouns: CU Boulder recognizes that students' legal information doesn't always align with how they identify. Students may update their preferred names and pronouns via the student portal; those preferred names and pronouns are listed on instructors' class rosters. In the absence of such updates, the name that appears on the class roster is the student's legal name.

Honor Code: All students enrolled in a University of Colorado Boulder course are responsible for knowing and adhering to the Honor Code academic integrity policy. Violations of the Honor Code may include, but are not limited to: plagiarism, cheating, fabrication, lying, bribery, threat, unauthorized access to academic materials, clicker fraud, submitting the same or similar work in more than one course without permission from all course instructors involved, and aiding academic dishonesty. All incidents of academic misconduct will be reported to the Honor Code (honor@colorado.edu; 303-492-5550). Students found responsible for violating the academic integrity policy will be subject to nonacademic sanctions from the Honor Code as well as academic sanctions from the faculty member. Additional information regarding the Honor Code academic integrity policy can be found on the Honor Code website.

Sexual Misconduct, Discrimination, Harassment and/or Related Retaliation: CU Boulder is committed to fostering an inclusive and welcoming learning, working, and living environment. The university will not tolerate acts of sexual misconduct (harassment, exploitation, and assault), intimate partner violence (dating or domestic violence), stalking, or protected-class discrimination or harassment by or against members of our community. Individuals who believe they have been subject to misconduct or retaliatory actions for reporting a concern should contact the Office of Institutional Equity and Compliance (OIEC) at 303-492-2127 or email cureport@colorado.edu. Information about university policies, reporting options, and the support resources can be found on the OIEC website.

Please know that faculty and graduate instructors have a responsibility to inform OIEC when they are made aware of incidents of sexual misconduct, dating and domestic violence, stalking, discrimination, harassment and/or related retaliation, to ensure that individuals impacted receive information about their rights, support resources, and reporting options. To learn more about reporting and support options for a variety of concerns, visit Don't Ignore It.

Religious Holidays: Campus policy regarding religious observances requires that faculty make every effort to deal reasonably and fairly with all students who, because of religious obligations, have conflicts with scheduled exams, assignments or required attendance. In this class, let me know by email of the conflict, and I will work with you to accommodate.

See the campus policy regarding religious observances for full details.

Course Outline:

1. Review of Fluid Mechanic and Thermodynamic Principles
    I. Governing Equations for a Control Volume
        A. Reynolds' Transport Theorem
        B. Conservation of Mass (Continuity)
        C. Linear Momentum Equation (Newton's Second Law)
        D. First Law of Thermodynamics (Energy Equation)
        E. Second Law of Thermodynamics
    II. Thermodynamics of Ideal Gases
        A. Equation of State
        B. Energy/Specific Heat Relations
        C. Entropy Changes/Isentropic Processes
        D. Speed of Sound/Mach Number
        E. Static and Stagnation Properties
2. Generalized One-Dimensional Flow
    I. Introduction
    II. Analysis
    III. Table of Influence Coefficients
    IV. Solution Procedure for Generalized 1D Flow
    V. Qualitative Features of Generalized 1D Flows
        A. $dG < 0$
        B. $dG = 0$
        C. $dG > 0$
        D. $dG < 0$, $dG = 0$, $dG > 0$
        E. $dG > 0$, $dG = 0$, $dG < 0$
    VI. Numerical Solution Near the Critical Point, $M = 1$, $dG = 0$
    VII. Solution Technique for a Flow with a Sonic Point
3. Partial Differential Equations Governing Inviscid Compressible Flow
    I. Partial Differential Equations in Conservation Form
        A. Continuity Equation
        B. Linear Momentum Equation
        C. Energy Equation
        D. Second Law of Thermodynamics
    II. Partial Differential Equations in Nonconservation Form
        A. Continuity Equation
        B. Linear Momentum Equation
        C. Energy Equation
        D. Second Law of Thermodynamics
        E. Speed of Sound Equation
    III. Kelvin's Circulation Theorem
    IV. Crocco's Theorem

V. Compressible Potential Equation
   A. Mathematical Features of the Potential Equation
   B. Elliptic Equations
   C. Parabolic Equations
   D. Hyperbolic Equations
   E. Canonical (Characteristic Coordinate) Form of PDEs
   F. Classification of Systems of First-Order PDEs
   G. Boundary Conditions for the Compressible Potential Equation
VI. Compressible Stream Function
VII. Orthogonal Curvilinear Coordinates
   A. Metric Coefficients
   B. Vector Operators in Orthogonal Curvilinear Coordinates

4. Linearized Flows/Analytical Techniques

I. Linearization of the Governing Equations
   A. Perturbation Velocity Potential
   B. Classification of the Perturbation Potential Equation
   C. Linearized Boundary Condition at a Solid Surface
   D. Linearization of the Pressure Coefficient
II. Subsonic Flow Over a Wavy Wall
III. Supersonic Flow Over a Wavy Wall
IV. Summary: Features of Subsonic and Supersonic Flow Over a Wavy Wall

5. Supersonic Flow Over a Cone

I. Properties of Supersonic Flow Over a Cone
II. Analysis
III. Numerical Algorithm for Supersonic Flow Over a Cone
IV. Numerical Integration of the Coupled ODEs
   A. Predictor-Corrector
   B. Fourth-Order Runge-Kutta
V. Results and Physical Aspects of Supersonic Flow Over a Cone

6. Steady, Two-Dimensional Supersonic Flow

I. Definition of Characteristics
II. MOC Analysis for Steady 2D Planar or Axisymmetric Irrotational Supersonic Flow
III. Numerical Implementation of MOC for Steady 2D Planar or Axisymmetric Irrotational Supersonic Flow
   A. Interior Point Algorithm
   B. Domain of Dependence and Range of Influence
   C. Axis of Symmetry Point Algorithm
   D. Wall Point Algorithm
   E. Direct and Inverse Marching Methods
IV. Example: Design of Uniform Flow Supersonic Nozzles
V. Intersection of Characteristics of the Same Family

VI. MOC for Steady 2D Planar or Axisymmetric Rotational Supersonic Flow

7. Unsteady, One-Dimensional Flow

I. Governing Equations
II. MOC Analysis
III. Special Case: Planar Flow of an Ideal Gas
IV. Numerical Implementation of MOC for Unsteady 1D Homentropic Flow
   A. Interior Point Algorithm
   B. Solid Boundary Point Algorithm
   C. Inflow/Outflow Point Algorithms
V. Physical Features of Unsteady 1D Homentropic Flow
   A. Definitions
   B. Simple Compression and Expansion Waves
   C. Centered Waves
   D. Reflection of Compression and Expansion Waves
   E. Intersection of Continuous Waves
VI. Example: Shock Tube (Riemann Problem)
VII. MOC Analysis for Unsteady 1D Isentropic Flow