AOE 3114 Compressible Aerodynamics

Primary Learning Objectives

The student will be able to:

1. Identify common situations in which compressibility becomes important in internal and external aerodynamics and explain, in those situations, the effects of compressibility and the physical processes behind them.
2. Explain the origins of and assumptions involved in the various mathematical equations and techniques of compressible aerodynamics.
3. State the fundamental concepts and terminology associated with the equations, charts, formulae and hardware of compressible aerodynamics.
4. Select and use appropriate compressible flow tables, charts and formulae in the solution of problems.
5. Solve simple problems involving…
    a. quasi one-dimensional isentropic flow with area variations
    b. normal shock waves
    c. unsteady one dimensional flow
    d. one dimensional flow with heat addition
    e. one dimensional flow with friction
    f. two-dimensional isentropic flow and oblique shocks
    g. conical flow
    h. linearized theory

    …with particular emphasis on applications involving

    a. nozzles (analysis and design)
    b. Pitot probes
    c. combustors
    d. airfoils
    e. 2D engine intakes

Detailed Learning Objectives

Fundamentals and Thermodynamics

1. Explain the physical meaning of the Mach number and its definition in terms of force magnitudes.
2. Explain why the pressure rises near the front of an aerodynamic body.
3. Sketch the flow past an airfoil as it develops with Mach number.
4. Define the various compressible flow regimes.
5. Use equation of state for a perfect gas, and where it comes from.

6. State the first and second laws of thermodynamics.
7. Define enthalpy, entropy, C_p and C_v.
8. State precisely what is meant by a thermally perfect gas and a calorically perfect gas, pressure work, heat, specific heats.
9. State the meaning of adiabatic, reversible and isentropic processes.
10. Identify based when a real world flow is isentropic or adiabatic, and when it is not, and why.
11. Identify where the relations p/ρ^γ = constant and $R = C_p - C_v$ come from and what assumptions they imply.
12. State the laws of continuity and momentum.
13. Explain what is meant by the Lagrangian and Eulerian perspectives.
14. State qualitatively the steps taken in deriving the fundamental equations of motion and why they are taken.
15. Explain the assumptions made.
16. Explain the role of the Reynolds transport theorem.
17. Explain the terms in the Eulerian forms of the equations of motion

Isentropic quasi 1D steady flow

1. State what is meant by 1D flow, and when this assumption is valid.
2. State the algebraic form of the governing equations that apply to 1D flow ($\rho uA=const.$, $h+u^2/2 = const.$ and $p+\rho u^2 = const.$) and state precisely the assumptions that each one implies.
3. Explain how the equation for the speed of sound ($a^2 = \gamma RT$) is obtained from these equations.
4. Explain the significance of the momentum equation in 1D isentropic flow.
5. Write down and use the various forms of the energy equation in terms of stagnation or critical properties (including A*), and when precisely these are valid.
6. Explain the physical meaning of the stagnation and critical quantities.
7. Explain how all flow properties vary as a function of streamtube or duct area in isentropic flow.
8. Calculate 1D isentropic flow using tables.

Normal shock waves

1. State the various properties of shock waves.
2. Explain what happens o the Mach number, all the flow variables, thermo variables, stagnation and critical properties across a normal shock. E
3. Explain why shocks cannot accelerate flows from subsonic to supersonic speed.
4. Calculate shocks using tables

Applications

1. Explain fully the operation of converging and converging-diverging nozzles (including typical pressure and Mach number distributions in them) and precisely what is meant by the design condition, overexpanded, underexpanded and choked flow, shock in nozzle etc..
2. State precisely what is meant by choked flow.
3. Compute the flow in a given nozzle simply from the nozzle geometry and back-pressure to chamber-pressure ratio.
4. Compute the range of back pressures that will produce a particular flow regime.
5. Compute flow through a converging diverging nozzle with a shock present.
6. Explain why supersonic wind tunnels have two throats.
7. Compute the chamber pressure required to start the tunnel, as distinct from that to run it.
8. Explain the restrictions on the area of the second throat.
9. Compute pitot-tube and similar flows.

Unsteady 1D flow

1. Explain how the flow pattern in a shock tube develops after the diaphragm is ruptured.
2. Explain/draw the pressure distribution along the tube.
3. Explain the motion of the shock (including reflection), expansion wave (both leading and trailing edges) and the contact surface accurately on an x-t diagram and interpret the slopes of these features.
4. Sketch accurately a particle path on the x-t diagram.
5. Explain what the contact surface is and what is constant across it.
6. Explain the generation of mass motion velocity in an expansion wave and through the passage of an unsteady shock, and how the mass motion velocity generated by these waves may be connected
7. Prove, beginning with the equation for speed of sound ($a^2 = \gamma RT$), why unsteady compression waves coalesce into shocks.
8. Analyze unsteady normal shocks using steady normal shock relations/tables by using a moving frame of reference.
9. Handle stagnation properties the moving and stationary frames of reference.
10. Explain what happens when a moving shock reflects, and why it reflects.
11. Prove, beginning with the equation for speed of sound ($a^2 = \gamma RT$), why unsteady expansion waves tend to spread out.
12. Explain the origins of, and and use the, expression $2a/(\gamma -1) + u = const.$.
13. Use it along with $p = \rho RT$ and $p/\rho o^{\gamma} = const.$ to calculate the mass motion velocity and other changes produced by an expansion wave.
14. Compute the complete 1-D flow produced from the collapse of a known pressure difference (i.e. given p_1/p_4, T_1, T_4 and γ_1 and γ_4).

Steady flow with heat addition (H) and friction (F)

1. State the assumptions made in analyzing these flows (H,F).
2. Derive $T_{02} = T_{01} + q/C_p$ beginning with the raw energy equation written for 1D flow (H).
3. Explain where the equation $dp + rho\ udu = -4tau_w dx/D$ comes from, and what tau_w and D represent (F).
4. Explain what is meant by sonic conditions in a given context (H) (F) and particularly the significance of the sonic length L^*.(F)
5. Explain the distinction between these and sonic (critical) properties in 1D isentropic flow in variable area ducts.
6. Explain we use sonic conditions to relate flow conditions at two points (H) (T).
7. Use tables (Anderson A.3, A.4 and NACA TR1135) to analyze heat addition and friction flow problems.
8. Interpret fuel to air ratio in connection with heat addition problems (H).
9. Explain what is meant by choked flow in these contexts, and what happens to a choked flow when you add more heat or more length of friction.
10. Explain qualitatively what the effects of heat addition or friction are on flow properties.
11. Identify, interpret, explain and use the Raleigh curve (H) and the Fanno curve (F) to explain the physical behavior of a flow.

Steady 2-D compressible flow.

1. Identify when isentropic compression and expansion turns occur, sketch the waves they produce and explain what they do to the flow.
2. Explain the definition of Mach angle and its physical significance to point disturbances in supersonic flow and to isentropic compression and expansion turns.
3. Explain where the Prandtl-Meyer function comes from and use it (along with isentropic tables) to compute the flow changes produced by isentropic compression and expansion turns (when they occur in isolation, or after oblique shocks).
4. Compute such turns also from pressure or other ratios, and compute the trailing and leading edge angles of compression and expansion turns.
5. Explain when oblique shocks occur and what they do.

6. Explain the distinction between these and isentropic compression waves.
7. Be able to write down and use the geometric relationships $M_{1n} = M_1 sin\ beta$ and $M_{2n} = M_1 sin(beta - delta)$.
8. Explain the functional form of the *M-beta-delta* relationship and be able to use its chart to compute wave angles and thus, along with normal shock tables, calculate the effects of an oblique shock on a flow for both explicit and implied turns.
9. Explain what is meant by the 'weak-shock solution' and the 'strong-shock solution' and know which to use.
10. Determine when an oblique shock will detach, and the details of the kind of flow that that produces.
11. Explain qualitatively what an oblique shock does to the various flow properties.
12. Calculate oblique shock reflections.
13. Explain what Mach reflection is and when it occurs.
14. Compute under and over-expanded jets up to the first expansion-wave reflection, including the angle(s) of the contact surface.
15. Explain what the contact surface is and what its properties are.
16. Compute (using charts) the conditions at which a 'Mach disc' is produced in an overexpanded flow (i.e. when the first oblique shock undergoes Mach reflection)

Applications

1. Explain the assumptions of shock expansion theory for airfoils.
2. Write down and use the definitions of lift, drag and pressure coefficient for supersonic flow.
3. Formulate expressions for the lift and drag of a geometric airfoil in terms of the pressures acting on its faces, and compute those pressures.
4. Explain what supersonic thin airfoil theory is, its underlying assumptions and its results.
5. Determine the camber and thickness distribution of an airfoil given its surface coordinates.
6. Use all the above expressions to compute the characteristics of a given airfoil.

Conical flow

1. Describe the supersonic flow past a cone, including the difference between the shock turning angle and the cone angle, the isentropic compression and non-uniform flow downstream of the shock, and the uniformity of cone surface conditions.
2. Explain that the shock is of constant strength and that flow properties are constant along rays emanating from the apex.
3. Use the relevant charts and tables to calculate these flows.
4. Explain where (on the chart) shock detachment occurs on these charts and that there is no strong-shock solution for external flow.

Differential forms of the equations of motion

1. Explain the physical interpretations of div and curl when applied to the velocity vector, of grad when applied to the pressure.
2. Explain the generic approach to deriving differential equations of motion from their integral form.
3. Explain what the substantial derivative is (physically and mathematically).
4. Given the equations of motion, be able to explain what the various terms mean.
5. Explain what Crocco's theorem relates (in words) and what it says about constant entropy and/or irrotational flow in 2D.

Linearized theory/Transonic flow

1. Explain the assumptions of small disturbance theory and the restrictions they impose (including Mach number ranges).
2. Write down and use the linearized form of the pressure coefficient.
3. Explain what the affine transformation is, and what it does.

4. Explain the Prandtl-Glauert rule, its range of application, and be able to apply it.
5. Explain the meaning of critical pressure coefficient, critical Mach number, and what their physical significance is for flow over an airfoil.
6. Be able to compute these from the approapriate relations.
7. Explain drag divergence, why it occurs and what are the principle source(s) of drag in transonic flow.
8. Sketch a supercritical airfoil, explain why it is designed as it is, what its operation is and the form of its surface pressure distribution, when compared with a conventional foil.
9. Explain the role of sweep in reducing drag at transonic speed.
10. Explain why wing-body interactions tend to increase drag at transonic speed. Be able to explain the area rule.

AOE 3114 Course Learning Objectives Analysis (College of Engineering)

a. An ability to apply knowledge of mathematics, science, and engineering
b. An ability to design and construct experiments, as well as to analyze and interpret data
c. An ability to design a system, component, or process to meet desired needs
d. An ability to function in multidisciplinary teams
e. An ability to identify, formulate, and solve engineering problems
f. An understanding of professional and ethical responsibility
g. An ability to communicate effectively
h. The broad education necessary to understand the impact of engineering solutions in a global and social context
i. A recognition of the need for, and the ability to engage in life-long learning
j. A knowledge of contemporary issues
k. An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice

Degree to which criteria are addressed in the course:

0 (or blank) – none 1 – low 2 – moderate 3 – high

1	Identify common situations in which compressibility becomes important in internal and external aerodynamics and explain, in those situations, the effects of compressibility and the physical processes behind them.	a 2	b	c	d	e 3	f	g	h	i	j	k 3
How will it be measured? Through performance of students in homeworks and tests. Through in-class feedback and student evaluations.												

2	Explain the origins of and assumptions involved in the various mathematical equations and techniques of compressible aerodynamics.	a 3	b	c	d	e 3	f	g	h	i	j	K 3
	How will it be measured? Through performance of students in homeworks and tests. Through in-class feedback and student evaluations.											
3	State the fundamental concepts and terminology associated with the equations, charts, formulae and hardware of compressible aerodynamics.	a 3	b	C	d	E 3	f	g	h	i	j	K 3
	How will it be measured? Through performance of students in homeworks and tests. Through in-class feedback and student evaluations.											
4	Select and use appropriate compressible flow tables, charts and formulae in the solution of problems.	a 3	b	c	d	e 3	f	g	h	i	j	k 3
	How will it be measured? Through performance of students in homeworks and tests. Through in-class feedback and student evaluations.											
5	Solve simple problems involving… i. quasi one-dimensional isentropic flow with area variations j. normal shock waves k. unsteady one dimensional flow l. one dimensional flow with heat addition m. one dimensional flow with friction n. two-dimensional isentropic flow and oblique shocks o. conical flow p. linearized theory …with particular emphasis on applications involving f. nozzles (analysis and design) g. Pitot probes h. combustors i. airfoils j. 2D engine intakes	a 3	b	c 2	d	e 3	f	g	h	i	j	k 3
	How will it be measured? Through performance of students in homeworks and tests. Through in-class feedback and student evaluations.											

ABET a-k Outcomes Ranking and Mapping Matrix

ABET a-k Outcomes	Coverage (0-3)	Application to this course	Corresponding objectives
a. An ability to apply knowledge of mathematics, science, and engineering.	3	This course involves the student in solving numerous problems requiring them to apply knowledge learnt inside and outside class, as well as in previous classes.	1,2,3,4,5
b. An ability to design and conduct experiments, as well as to analyze and interpret data.			
c. An ability to design a system, component, or process to meet desired needs.	1	Students perform homework problems involving the design of single component, hardware, particularly nozzles.	5
d. An ability to function on multi-disciplinary teams.			
e. An ability to identify, formulate, and solve engineering problems.	3	Students are evaluated based on their performance on both analysis and single-component design type problems.	1,2,3,4,5
f. An understanding of professional and ethical responsibility.			
g. An ability to communicate effectively.			
h. The broad education necessary to understand the impact of engineering			

solutions in a global and societal context.			
i. A recognition of the need for, and ability to engage in life-long learning.			
j. A knowledge of contemporary issues.			
k. An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.	2	Students use formulae, tables and web based software tools that will be available to them as professionals	1,2,3,4,5