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Basics

Two Main Categories of Hypersonics: Rocket based and airbreathing

Key Issue for Hypersonics: Beginning around Mach 5, flying objects encounter thermal and aerodynamic phenomena distinct from those encountered in supersonic and exoatmospheric flight. These phenomena

- Subsonic: $< \text{Mach } 1$ (commercial aircraft)
- Supersonic: Mach 1–5 (fighter jets, Concorde)

- Hypersonic: $> \text{Mach } 5$ (e.g., re-entry vehicles, hypersonic missiles)

Shock layer: region between shock and body surface

6-DOF stands for Six Degrees of Freedom — the six independent ways an object can move in 3D space.

The angle of attack is the angle between the oncoming airflow and the chord line of the wing (the straight line between the leading and trailing edges).

Camber: the convexity of the curve of an aerofoil from the leading edge to the trailing edge

The Coandă effect is the tendency of a fluid jet to attach itself to a nearby surface and flow along it, even when the surface curves away from the initial direction of the jet. Named after Romanian aerodynamicist Henri Coandă, who observed the phenomenon in 1910, this effect plays a crucial role in many fluid dynamics applications.

In laminar flow the fluid particles stay in the same “lamina,” whereas in turbulent flow a constant intermingling of the particles in neighboring laminas occurs, which can be easily visualized by adding dye particles to the flow.

Aeroelasticity is the study of the mutual interaction between the aerodynamic forces acting on a flexible body (like a wing or fuselage) and the body's elastic (structural) and inertial response. It determines how structures deform under airflow and how those deformations, in turn, affect the flow and resulting forces.

Theodore von Karman called the edge of space 100 km, which we now call The Karman Line

The Armstrong limit or Armstrong's line is a measure of altitude above which atmospheric pressure is sufficiently low that water boils at the normal temperature of the human body. This limit is approximately 18–19 km (11–12 mi; 59,000–62,000 ft) above sea level.

Aeroacoustics is the study of sound generation, propagation, and interaction in a fluid flow, especially airflow. It combines principles from aerodynamics and acoustics to understand how unsteady fluid motion produces noise.

Riblets are small, streamwise-aligned grooves etched or applied to a surface, typically resembling fine parallel ridges. They are engineered to interfere with the structure of turbulent flows in a way that reduces skin friction drag on aerodynamic surfaces.

Major Types of Hypersonics

Hypersonic Glide Vehicles (HGVs):

- Launched via a rocket, then glide through the atmosphere at hypersonic speeds.
- Maneuverable, which makes them harder to intercept (e.g., China's DF-ZF, Russia's Avangard).

Hypersonic Cruise Missiles:

- Powered throughout their flight by scramjets (supersonic combustion ramjets).
- Maintain sustained hypersonic speed within the atmosphere (e.g., U.S. HAWC program).

Spaceplanes / Reentry Vehicles:

- Vehicles that enter from space or orbit and re-enter Earth's atmosphere (e.g., future spaceplane concepts).

Scramjet

Scramjets (Supersonic Combustion Ramjets) are a revolutionary type of air-breathing jet engine specifically designed for hypersonic flight — speeds greater than Mach 5 (five times the speed of sound, or ~3,800 mph / 6,100 km/h). They are central to cutting-edge aerospace applications such as hypersonic missiles, spaceplanes, and high-speed reconnaissance vehicles.

- Scramjet stands for Supersonic Combustion Ramjet.
- It is an air-breathing jet engine that:
- Has no moving parts (like turbines or compressors)
- Compresses incoming air using the vehicle's high speed and specially shaped intake
- Combusts fuel in a supersonic airflow (unlike ramjets which combust at subsonic speeds)
- Expels hot gases out the nozzle to generate thrust

Ramjet

- A ramjet is a type of air-breathing jet engine that uses the engine's forward motion to compress incoming air, without any moving parts like compressors or turbines. It operates efficiently at supersonic speeds (Mach 3–6) and is commonly used in missiles, high-speed aircraft, and experimental propulsion systems.
- A ramjet has three main components:
- Inlet (Diffuser): Air enters at high speed and is compressed due to the vehicle's forward motion. This compression increases air pressure and temperature, slowing it to subsonic speed before combustion.
- Combustion Chamber: Fuel (usually a hydrocarbon like JP-7) is injected and mixed with the compressed air. The mixture is ignited, producing high-temperature, high-pressure gases.
- Nozzle :The hot gases expand through a converging-diverging nozzle, converting thermal energy into thrust. This propels the vehicle forward at very high speed.

Shock- Shock Interactions

The key physical processes in shock-shock interactions include:

- Shock Compression: Sudden increases in pressure, density, and temperature across shock waves.
- Triple Point Formation: Point where three shock waves meet, generating complex flow patterns.
- Mach Stem Development: Near-vertical shock between the incident and reflected shocks, leading to high thermal loads.
- Slip Lines: Shear layers where flow properties change discontinuously downstream of the triple point.

Shock/Shock Interactions can result in:

- Localized Heating: Extremely high heat transfer rates at the triple point and Mach stem regions, potentially causing thermal failure.
- Structural Loads: High-pressure forces that can lead to deformation or damage of vehicle surfaces.
- Design Challenges: Requires careful design of intakes, control surfaces, and thermal protection systems for hypersonic vehicles (missiles, re-entry vehicles, etc.).

Concepts

Static stability refers to the immediate response of an aircraft after it experiences a small disturbance, such as a gust of wind or a slight change in pitch or yaw. The question we ask is: “What happens right after the disturbance?” In other words, static stability determines whether the aircraft tends to correct itself, keep moving in the disturbed direction, or become even more unstable. There are three types of static stability: positive static stability, neutral static stability, and negative static stability.

While static stability tells us how an aircraft initially responds to a disturbance, dynamic stability describes what happens over time. Does the aircraft’s motion grow more stable or unstable as time passes? Dynamic stability is all about the aircraft’s long-term behavior following a disturbance. There are three main types of dynamic stability: positive dynamic stability, neutral dynamic stability, and negative dynamic stability.

Types of Drag

Type	Description
Parasite Drag	Due to friction and pressure differences; includes form and skin-friction drag
Induced Drag	Caused by lift generation (vortex formation at wingtips)

Wave Drag	From shock waves in transonic and supersonic flow
Base Drag	Caused by low-pressure wake at the rear of a blunt body
Viscous Drag	Internal friction within the boundary layer

Supersonic Pressure Disturbance

Type	Description
Shock waves	Thin regions across which pressure, temperature, and density increase suddenly.
Expansion fans (Prandtl-Meyer fans)	Smooth, continuous pressure decreases occurring when the flow turns around a convex corner.
Oblique shocks	Angled shocks formed when supersonic flow encounters a wedge or ramp.
Normal shocks	Perpendicular shocks, usually occurring inside supersonic inlets or nozzles.

Essential Formulas

For compressible flow, boundary layer thickness (δ) is proportional to Mach number squared; high altitude flight has low Reynolds number (Re)

$$\delta \propto \frac{M_{\infty}^2}{\sqrt{Re}}$$

Universal Gas Law

$$PV = nRT$$

P (Pressure): The force exerted per unit area by the gas on the walls of its container.

V (Volume): The amount of space occupied by the gas.

n (Number of moles): A unit of measurement for the amount of substance (a specific number of gas molecules).

R (Ideal gas constant): A constant that relates the energy scale to the temperature scale, and its value depends on the units used for pressure, volume, and temperature

Sometimes expressed as

$$pV = nk_B N_A T$$

or

$$Nk_B T$$

k_B is the Boltzmann constant, 1.380×10^{-23} J/K

N_A is the Avogadro constant, $6.02214078 \times 10^{23} \pm 0.00000018 \times 10^{23}$

T is the absolute temperature of the gas (Kelvin)

N is the number of particles (usually atoms or molecules) of the gas.

Newton Fluid Flow

Newton's model of fluid flow refers to his conceptualization of viscous behavior in fluids, leading to the definition of a Newtonian fluid. The mathematical expression of Newton's model is:

$$\tau = \mu \left(\frac{du}{dy} \right)$$

Where:

τ : Shear stress (Pa or N/m²),

μ : Dynamic viscosity of the fluid (Pa·s),

$\frac{du}{dy}$: Velocity gradient perpendicular to the direction of flow (s⁻¹).

Charles Law

Gas volume varies directly with temperature at a constant pressure

$$V_1/T_1 = V_2/T_2$$

Lift

$$L = \frac{1}{2} \rho V^2 C_L A$$

Where:

- ρ = air density
- V = velocity
- C_L = lift coefficient (depends on airfoil shape and angle of attack)
- A = reference area

Bernoulli's equation

Bernoulli's equation can provide insights into pressure changes:

$$P + \frac{1}{2}\rho v^2 + \rho gh = \text{constant}$$

P : Static pressure (Pa),

ρ : Density of the fluid (kg/m³),

v : Flow velocity (m/s),

g : Acceleration due to gravity (9.81 m/s²),

h : Elevation above a reference level (m).

In a streamline along the jet:

- Higher velocity near the wall = lower pressure, which draws the jet toward the surface.
- This helps explain the entrainment of ambient fluid and jet adherence qualitatively.

Reynolds Number

Helps predict boundary layer behavior (laminar vs. turbulent). At hypersonic speeds:

Re is high, leading to thin, high-shear layers.

Transition to turbulence affects heating significantly.

Whether flow is laminar or turbulent

$$Re = \frac{\rho v d}{\eta}$$

Where

Re – Reynold's number

ρ – density of fluid

v – velocity of fluid

d – diameter of tube and

η – viscosity of fluid

Reynold s number of 2000 - borderline

When

$Re < 2000$ – laminar

$Re > 2000$ – turbulent

- ✓ Viscosity is the important property of laminar flow
- ✓ Density is the important property of turbulent flow
- ✓ Reynold's number of 2000 delineates laminar from turbulent flow

Newton's Second Law

Translational Motion (for aircraft, spacecraft, missiles):

$$\vec{F} = m\vec{a}$$

Where:

F : net force vector (N)

m : mass (kg)

$\vec{a}$: acceleration vector (m/s²)

For forces in aerospace:

$$\vec{F} = \vec{T} + \vec{L} - \vec{D} - \vec{W}$$

T : thrust

L : lift

D : drag

W : weight

Euler's Buckling Load

When a long, slender column is subjected to axial compressive force, it may suddenly deflect sideways (buckle) at a certain load, rather than just compressing. This critical load is lower than the material's yield strength, making buckling a geometric and stability problem, not purely a strength issue.

Euler's Buckling Load is a classical solution in structural engineering and solid mechanics that predicts the critical axial load at which a slender column (or beam) will buckle. Buckling is a

form of instability that can cause structural failure, even if the material is still within its elastic range.

$$p_{cr} = \frac{\pi^2 EI}{(KL)^2}$$

Where:

P_{cr} : Critical (buckling) load (N)

E: Young's modulus of the material (Pa)

I: Minimum area moment of inertia of the column's cross-section (m^4)

L: Actual length of the column (m)

K: Effective length factor, depends on end conditions (dimensionless)

Taylor–Maccoll Equation (for Axisymmetric Conical Flow)

Derived for supersonic flow around a sharp cone, this equation relates:

Flow deflection angle (θ)

Mach number and pressure gradients

Velocity components (radial and angular)

$$\frac{d^2 V_\theta}{d\theta^2} + f(V_{r1} V_\theta, \theta, \gamma) = 0$$

Where:

V_r : radial velocity

V_θ : tangential velocity

γ : specific heat ratio

Prandtl-Meyer function

The Prandtl-Meyer function describes the expansion process of a supersonic flow around a convex corner. It's a fundamental concept in compressible flow and gas dynamics, especially relevant in hypersonic and supersonic aerodynamics. When supersonic flow turns around a convex corner, it accelerates and expands isentropically (no heat exchange or entropy change). The flow turns through a finite angle using a continuous fan of expansion waves, forming what's called a Prandtl-Meyer expansion fan. This contrasts with oblique shocks, which occur when flow turns into itself (concave corner), causing compression.

The function is shown here

$$\nu(M) = \sqrt{\frac{\gamma+1}{\gamma-1}} \cdot \tan^{-1} \left(\sqrt{\frac{\gamma-1}{\gamma+1}} (M^2 - 1) \right) - \tan^{-1} \left(\sqrt{M^2 - 1} \right)$$

Symbol Meaning

$\nu(M)$ Prandtl-Meyer angle (expansion function) in radians or degrees

M Mach number (must be > 1)

γ Ratio of specific heats (1.4 for air)

$\nu(M)$ gives the angle through which a supersonic flow must turn to reach Mach MM from sonic conditions ($M=1$).

The difference $\theta=\nu(M_2)-\nu(M_1)$ gives the turn angle needed to go from Mach M_1 to M_2 in an expansion.

Navier-Stokes Equation

The Navier-Stokes equations are a set of partial differential equations that describe the motion of fluids. They are fundamental in fluid dynamics and are used to model a wide range of phenomena, from weather patterns to blood flow. These equations express the conservation of mass and momentum, taking into account both pressure and viscous forces within the fluid

In 1845, Sir George Stokes derived the equation of motion of a viscous flow by adding Newtonian viscous terms, thereby the Navier-Stokes Equations were brought to their final form, which has been used to generate numerical solutions for fluid flow ever since

Momentum Equation (Navier-Stokes Equation)

$$\rho \left(\frac{\partial U}{\partial t} + U \cdot \nabla u \right) = -\nabla p + \mu \nabla^2 u + f$$

p: Pressure

μ : Dynamic viscosity

$\nabla^2 u$: Viscous (diffusion) term

f: External body forces (e.g., gravity)

This is essentially Newton's second law ($F = ma$) applied to a fluid element

Rankine-Hugoniot Equations (for Normal Shock)

1. Mass Conservation:

$$\rho_1 u_1 = \rho_2 u_2$$

2. Momentum Conservation:

$$P_1 + \rho_1 u_1^2 = P_2 + \rho_2 u_2^2$$

3. Energy Conservation:

$$h_1 + \frac{u_1^2}{2} = h_2 + \frac{u_2^2}{2}$$

or, using total enthalpy $h = e + \frac{P}{\rho}$

Continuum Flow

A continuum flow is one in which the fluid can be treated as a continuous medium, meaning the molecular nature of the gas is negligible. This is valid when the Knudsen number (Kn) is very small (typically < 0.01). The Knudsen number is defined as

$$k_n = \frac{\lambda}{L}$$

Where:

- λ = mean free path of gas molecules,
- L = characteristic length (like object diameter).
- In a hypersonic continuum flow, even though the velocity is extremely high, the density of the gas is sufficient for the continuum approximation to remain valid.

Conductive Heat Transfer

Heat absorbed at the surface travels inward through structural materials. Governed by Fourier's Law:

$$Q = -k \frac{dT}{dx}$$

Where

q: Heat flux (W/m²),

k: Thermal conductivity (W/m·K),

$\frac{dT}{dx}$: Temperature gradient