Compressible Flow Regimes

Basics of Compressible Flows – Lesson 4

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Intro

- In the previous lesson, we introduced the speed of sound and the non-dimensional Mach number which is the ratio of local flow velocity to the local speed of sound.
- In this lesson we will examine the different flow speed regimes and see how they differ in basic behavior and what type of flow features emerge as the speeds increase past the speed of sound.
- We will look at the analyses of these types of flows in later lessons, but for now it is instructive to understand from a physical perspective how the flow regimes differ.

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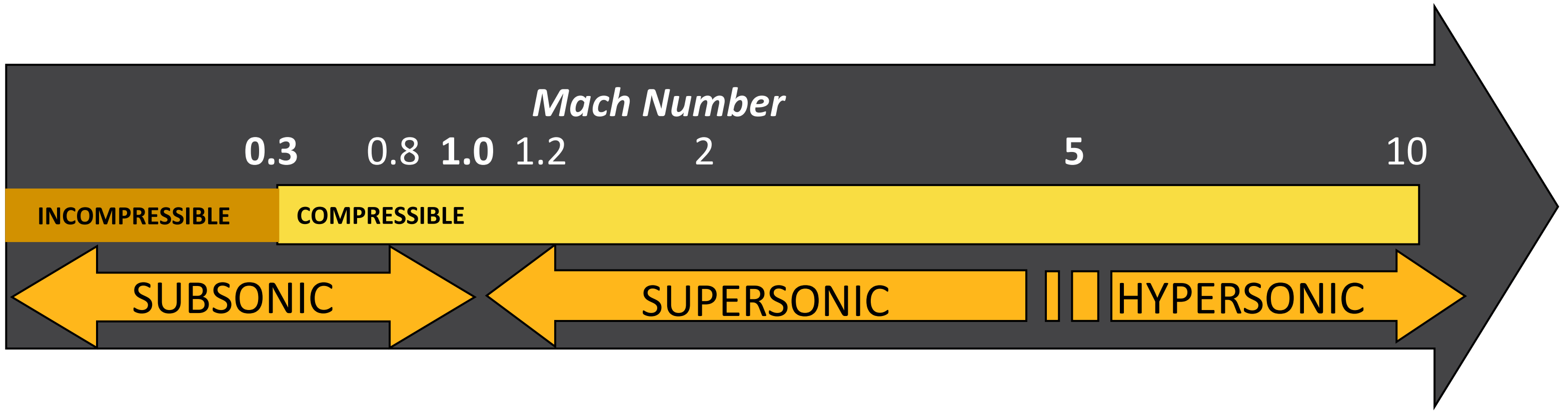
Flow Regimes

- While all gas flow regimes are compressible, we encounter compressibility effects when:
  - Flow velocities are high
  - Pressure and density changes are large
- Any flow can be considered incompressible if the Mach number is less than about 0.3.
  - Even gases can flow incompressibly
  - The incompressible assumption greatly simplifies the flow analysis!
- At Mach numbers greater than 0.3, compressibility effects start to become important.



$$M = \frac{V}{a}$$

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Incompressible Flow

- Low velocities
- Mach number < 0.3
- Density and pressure variations are small
- Can usually assume constant fluid properties if temperature variations are small
- Incompressible flows are typically considered as constant density flows

Cessna airplane in flight, cruise speed 140 mph (Mach ~ 0.2)

While the flow around the airplane fuselage and wings can be considered incompressible at $M = 0.2$, its propeller rotates at the tip speed equivalent to $M = 0.7$, and compressibility effects must be included in the propeller analysis.

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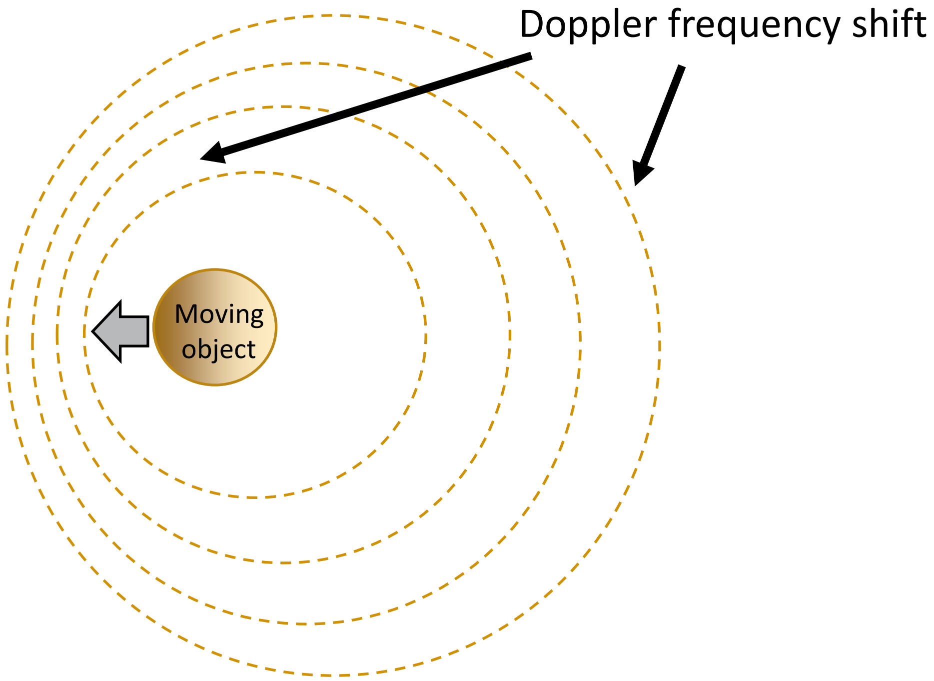
Compressible Subsonic Flow

- Higher velocities
- 0.3 < Mach number < 1.0
- Pressure waves propagate away from a moving object, but as the object starts moving the waves begin to build up near the front
  - Higher frequency pressure waves at the front versus the rear of the object. This is known as the Doppler Effect.
- Density and pressure variations are larger
- Temperature variations are often modest and hence we can assume a calorically perfect gas behavior



Commercial turboprop at cruise altitude, M ~ 0.5

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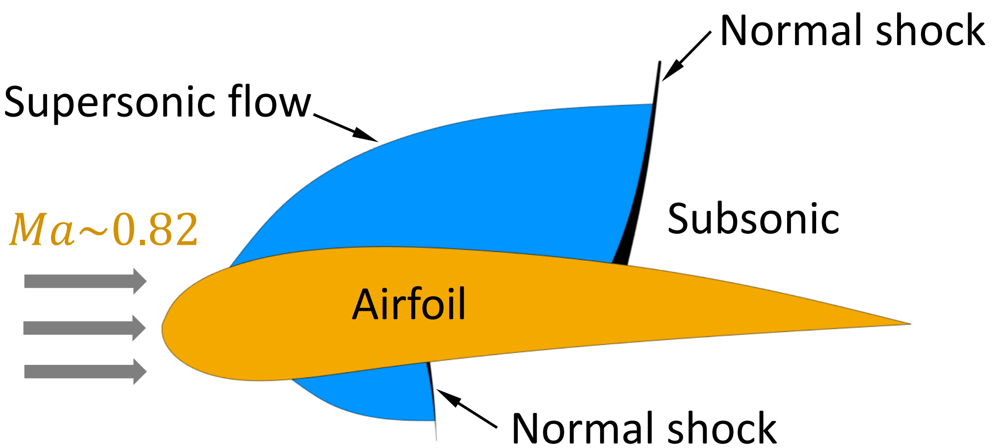
Transonic Flow

- High velocities
- Freestream Mach number ≈1
- Density and pressure variations are large
- Regions of subsonic and supersonic flow around the body
  - Normal shock forms on suction sides of wings
- Large increase of drag



Commercial jetliner at cruise altitude, M ~ 0.8

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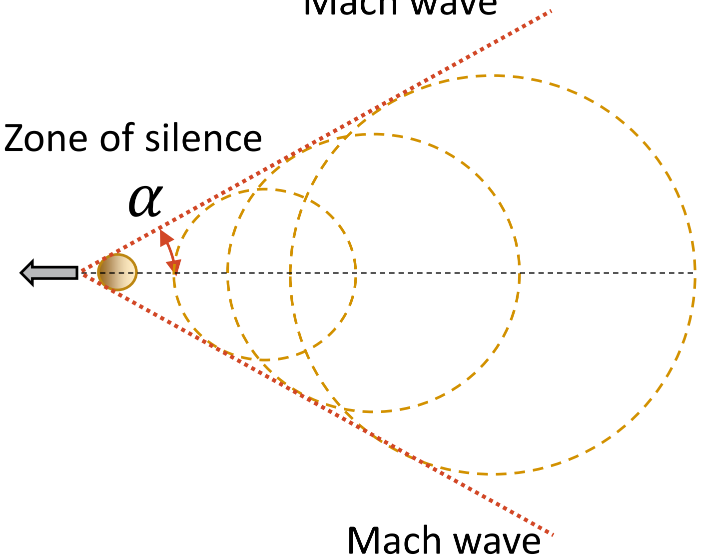
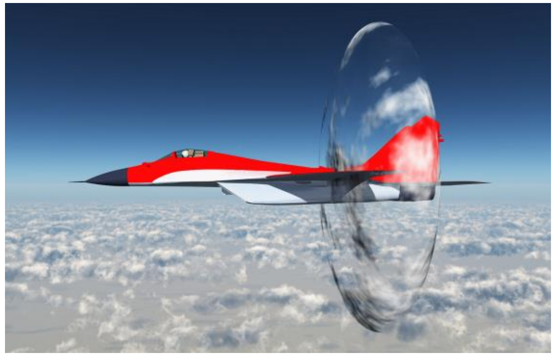
Supersonic Flow

- Very high velocities
- Mach number > 1.0
- Object is now moving faster than the sound waves. The pressure waves form a Mach Cone, where the cone angle α is related to the Mach number:

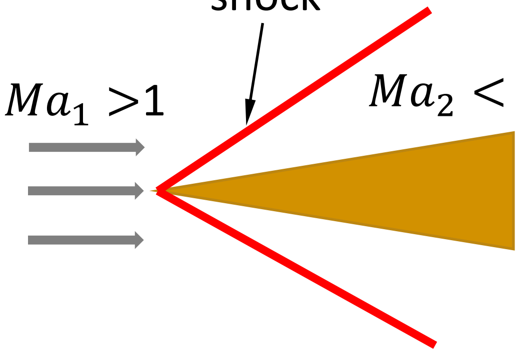


$$\alpha = \sin^{-1}(1/M)$$

- Outside of the Mach cone is the Zone of Silence – here no pressure waves from the objects will be detected
- If the object is not small a shock wave forms at the leading edge and oblique shocks propagate downstream.



Shock forming around a supersonic aircraft



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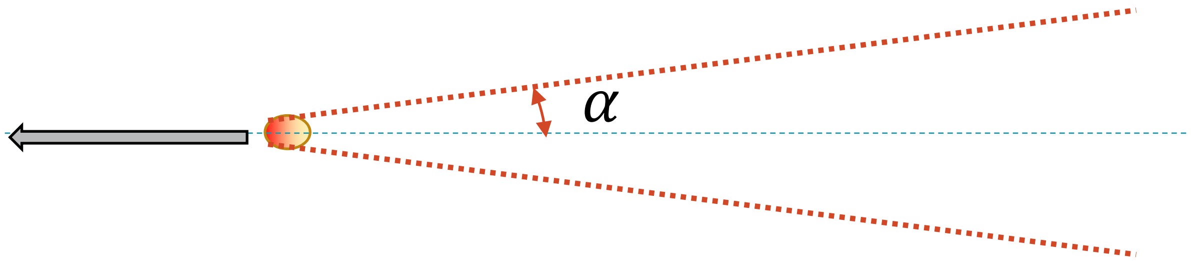
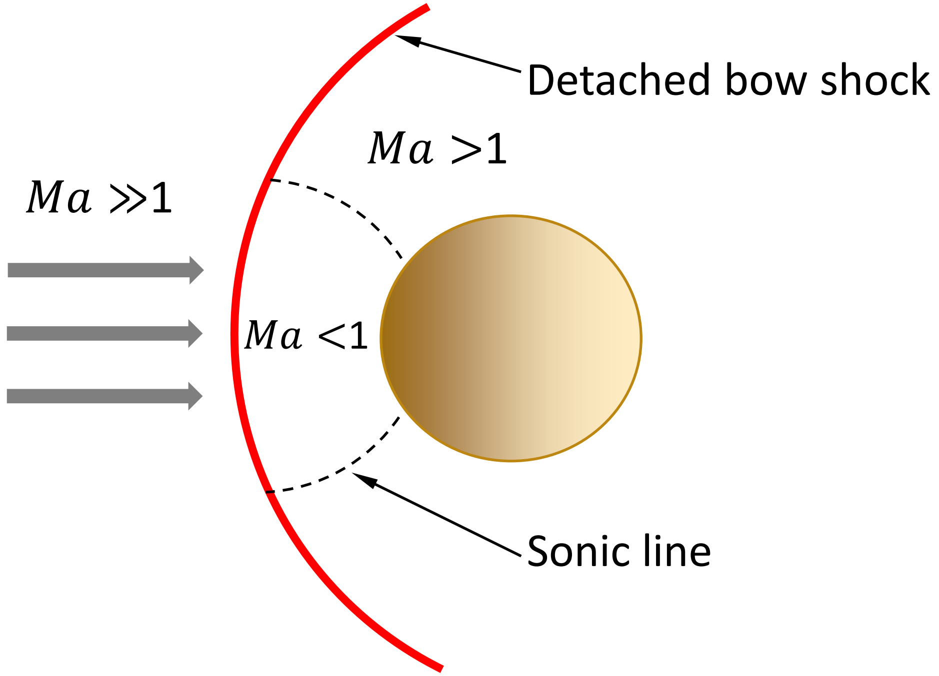
Hypersonic Flow

- Extremely high velocities
- Mach number ≫1.0 (generally greater than 5)
- Very shallow Mach angles
- Strong bow shock
- Very high temperatures at the stagnation point and in the boundary layer
- High temperatures lead to chemically reacting flow (dissociation and ionization) and very large property variations
- Plasma and communications blackout





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Summary

- In this lesson, we analyzed how the Mach number can be used to define different flow regimes.
- We discussed the main characteristics that distinguish these regimes and learned how to categorize and recognize them.

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