

**GEORGIA  
TECH**



## **MODEL ROCKET AERODYNAMICS**

## SOME TERMINOLOGY

Free stream – the flow far away from a moving body

Mach number – fraction of the local speed of sound

$v_\infty$  – free stream velocity (m/s)

$M_\infty$  – free stream Mach number

$\rho$  – air density ( $\text{kg}/\text{m}^3$ )

$q$  – dynamic pressure (Pa)

$C_D$  – drag coefficient

$S$  – planform area ( $\text{m}^2$ )

$\mu$  – kinematic viscosity ( $\text{kg}/\text{m}\cdot\text{s}$ )

Re – Reynolds number

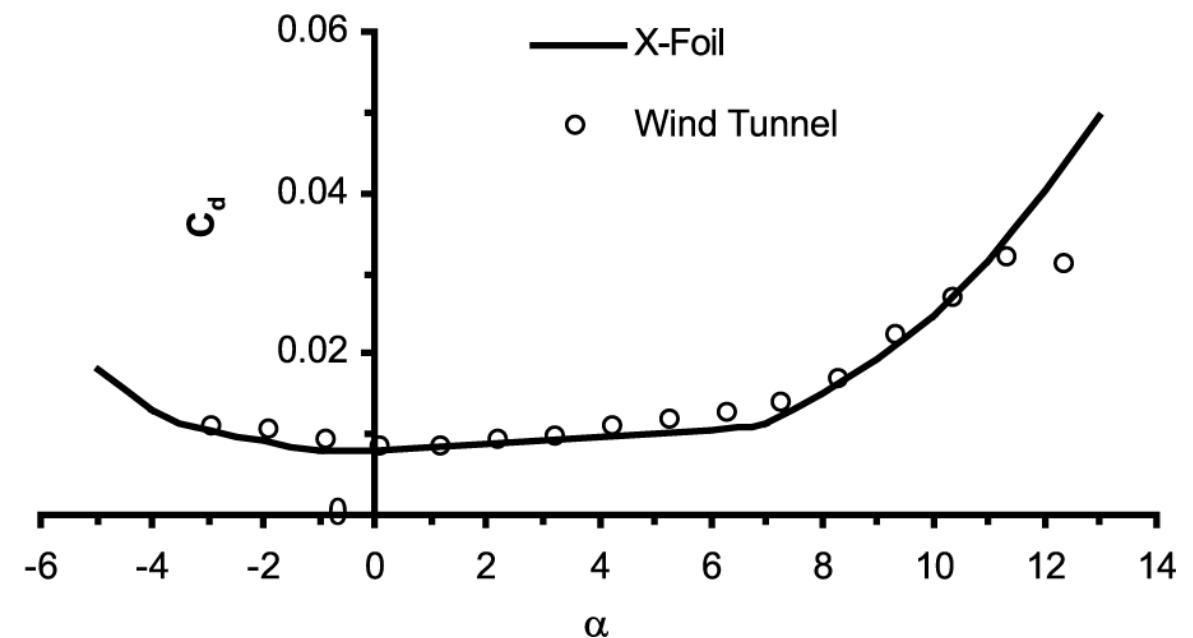
$A$  – frontal area ( $\text{m}^2$ )

Boundary layer – thin region around a body where flow speeds up to free stream

Angle of attack – orientation of a body with respect to the free stream

# AERODYNAMIC DRAG

- Drag coefficient determined analytically or experimentally
- Dynamic pressure required to find drag force  
 $q = \frac{1}{2} \rho v^2$
- Drag force changes with  $q$ , but  $C_D$  doesn't  
 $D = q C_D A$  or  $D = q C_D S$

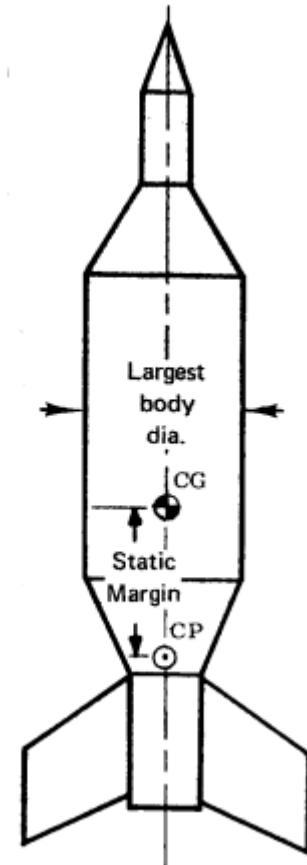


# TYPES OF DRAG

Type	Cause
Skin friction drag	Kinematic viscosity of air
Pressure drag	Body geometry
Base drag	Exhaust and wake
Induced drag	Lift coefficient, aspect ratio, and efficiency
Wave drag	Supersonic speeds

# AERODYNAMICS & STABILITY

- Center of pressure – the point through which the sum of all aerodynamic forces act
- For stable rockets, CP should be aft of CG
- Location can be approximated by the geometric centroid of the body
- More accurately predicted by Barrowman equations or other aerodynamic methods



# THE BARROWMAN EQUATIONS

## Assumptions

- Small angle of attack
- Flight speed lower than the speed of sound
- Smooth air flow over the body
- Large length-to-diameter ratio
- No discontinuities in the rocket body
- Axial symmetry
- Thin flat plate fins

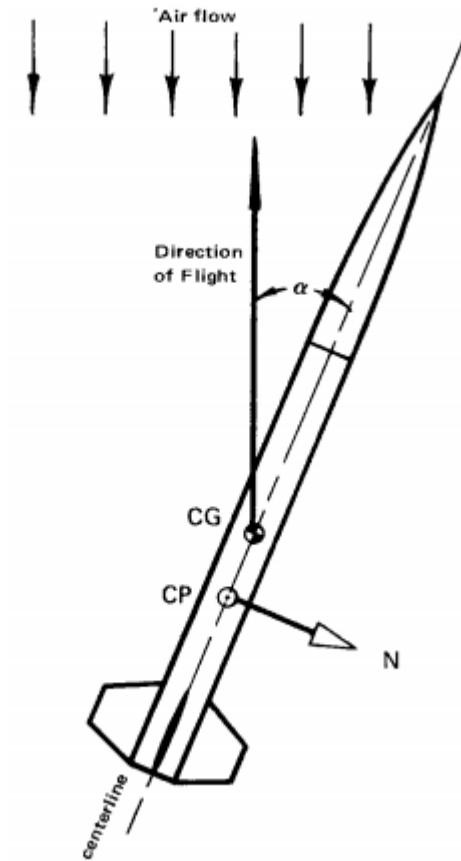
## The Equations

- Normal force coefficient  $C_{N,\alpha}$  varies from with component geometry
- Each rocket component  $i$  has its own center of pressure at  $x_i$  from the nosecone tip
- Total CP distance is a weighted average of component CP distances

$$x_{CP} = \frac{\sum C_{N,\alpha} x_i}{\sum C_{N,\alpha}}$$

# WHY STABILITY MATTERS

- Unstable rockets – BAD
  - Can spiral out of control under slight disturbances
- Stable rockets – GOOD
  - Trajectory not perturbed by wind
- Over-stable rockets – OKAY
  - Tend to weathercock, or fly into the wind
  - Not terrible, but can lead to horizontal flight on windy days
- No active control in model rocketry



# AERODYNAMIC FLIGHT REGIMES



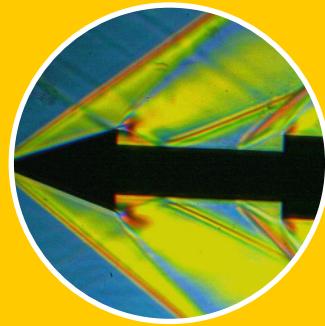
Low speed



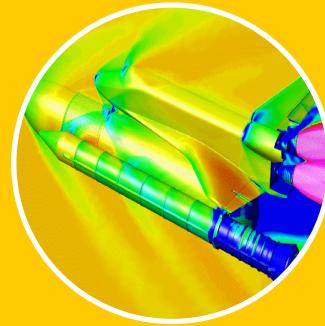
Compressible



Transonic



Supersonic



Hypersonic

←  
**Mach**

**0.3**

**0.7**

**1.2**

**5**

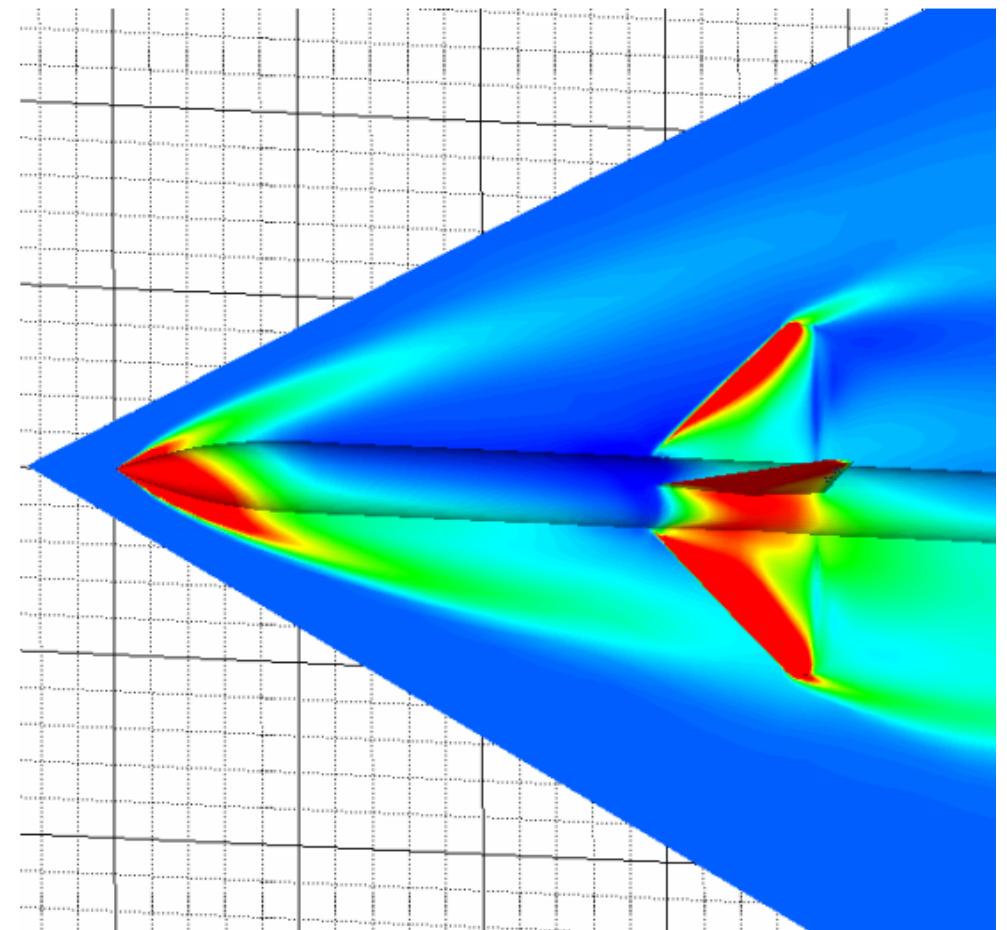
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## LOW-SPEED FLIGHT

- Aerodynamic forces are minimal, thus light construction is possible and preferred
- Lightweight materials like balsa are sufficient
- Simple building techniques like wall-mounted fins are possible without compromising the integrity of the rocket
- Generally only applies to low power rockets because of small thrust and short flight durations

# HIGH-SPEED FLIGHT

- As speed increases, so do drag forces
- Drag forces tend to want to rip apart rockets, so heavy-duty construction is required
- Use thick materials, reinforced structures, and heavy epoxy fillets
- Asymmetry leads to moments on the rocket



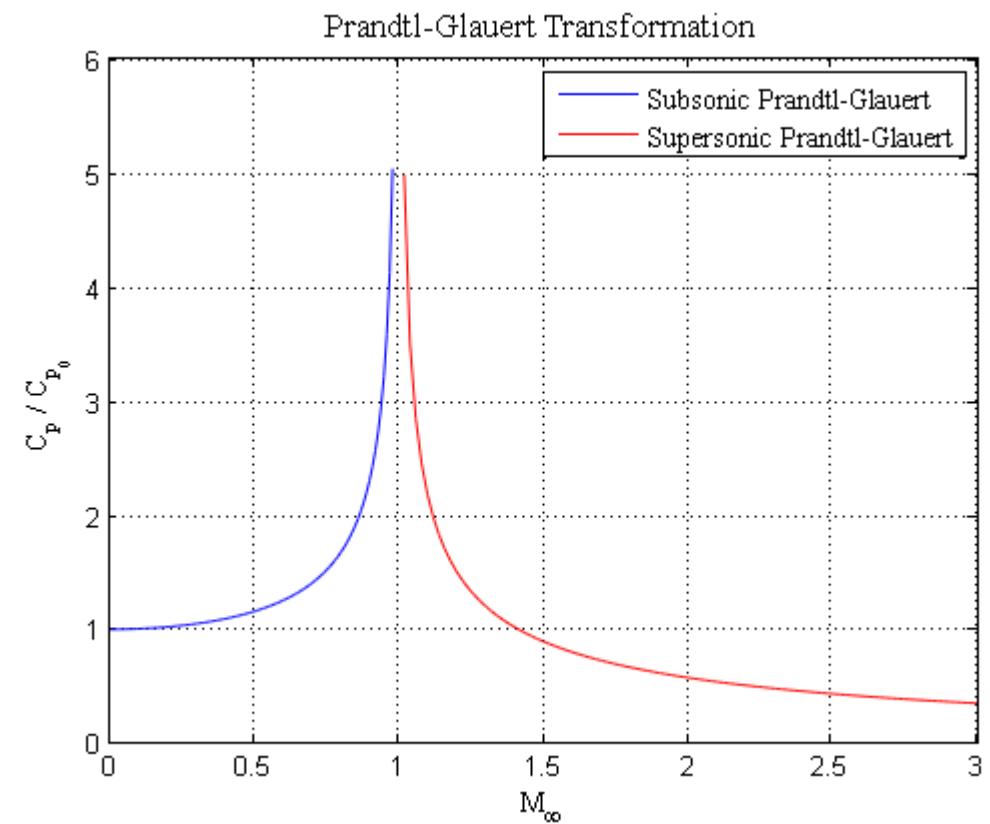
# SUPersonic FLIGHT

- Extreme forces near Mach 1 necessitate hefty construction and strong materials
- Supersonic rockets typically built using phenolic, fiberglass, or carbon fiber
- Avoid extreme aspect ratios due to bending moments



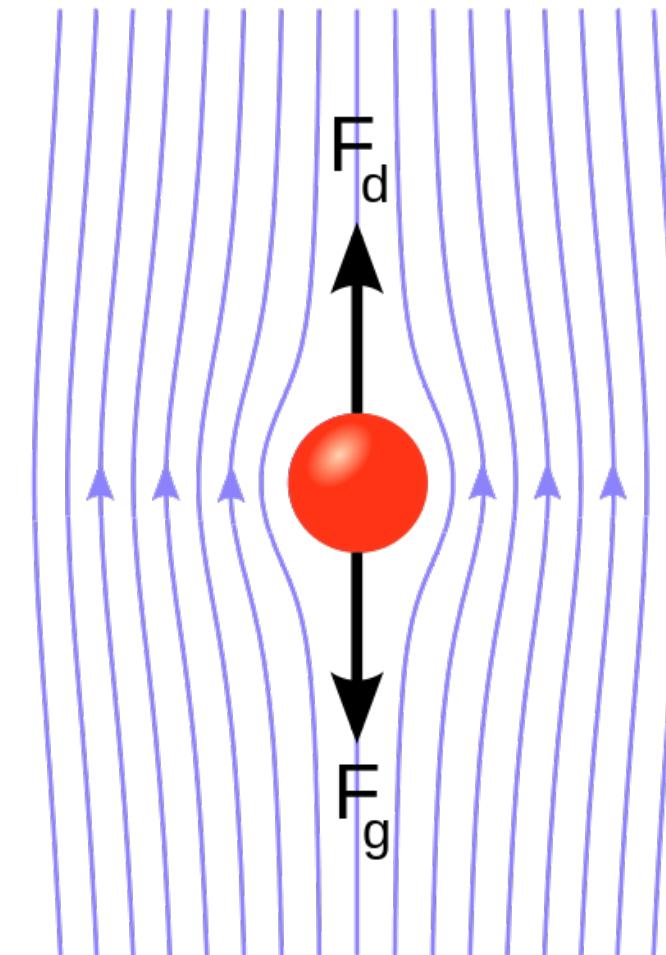
# DRAG IN COMPRESSIBLE FLOWS

- In subsonic flow  
 $C_D \approx C_{D,0} / \sqrt{1 - M_\infty^2}$
- In supersonic flow  
 $C_D \approx C_{D,0} / \sqrt{M_\infty^2 - 1}$
- Drag actually still increases in supersonic flow because of the dependence on  $v_\infty^2$ !



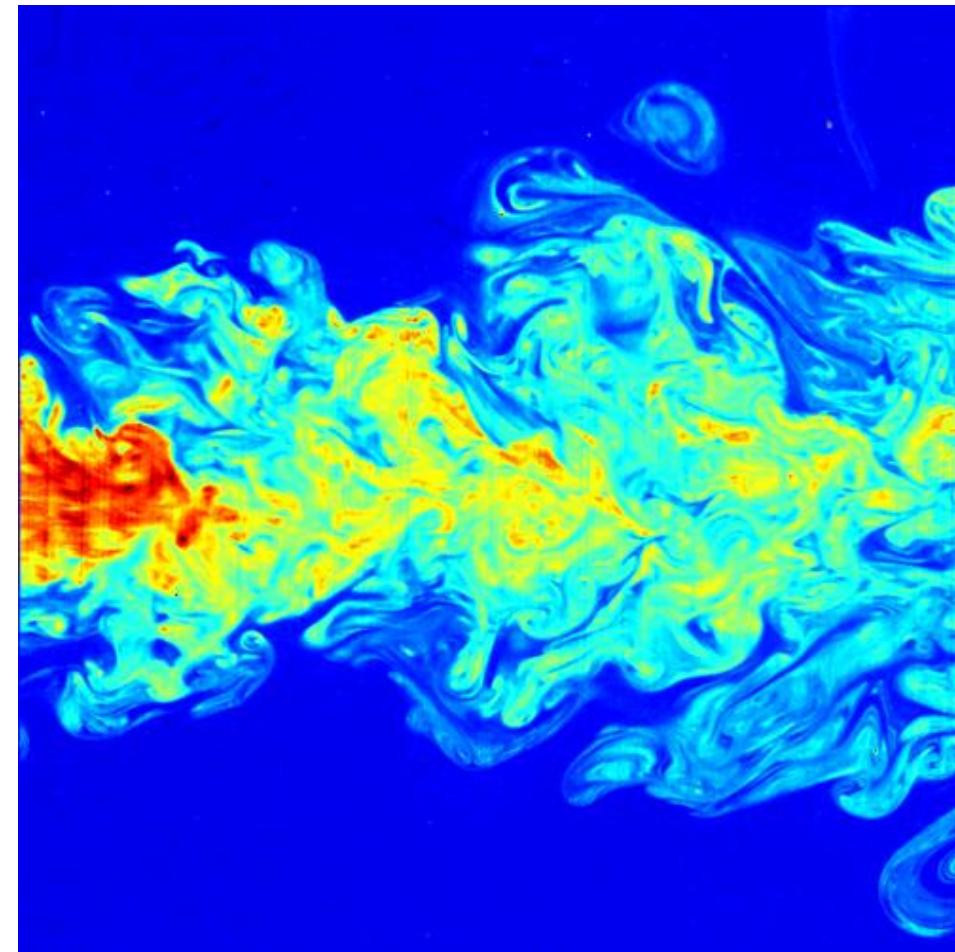
# AERODYNAMIC PHENOMENA – LAMINAR FLOW

- Streamlines relatively parallel and flow is orderly
- Ideal flow condition
- Relatively low drag coefficient compared to less orderly flows
- Occurs at Reynolds numbers less than 500,000



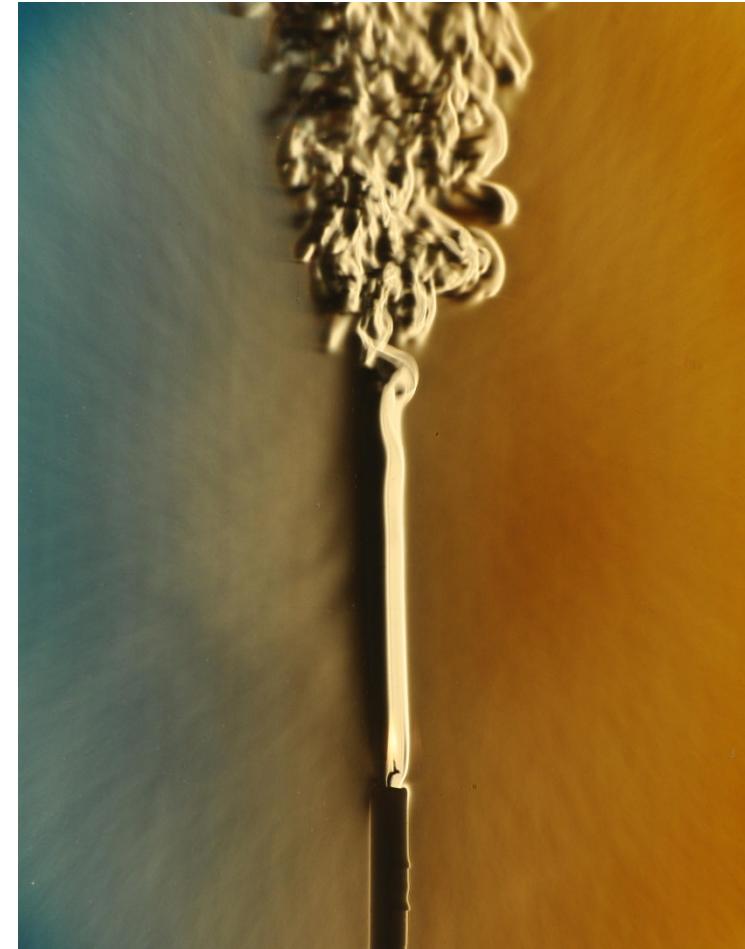
# AERODYNAMIC PHENOMENA – TURBULENT FLOW

- Flow exhibit disorderly and random patterns
- Occurs at Reynolds numbers around 500,000
- Characterized by higher drag coefficient than laminar flow
- Most flow around modern flight vehicles is turbulent



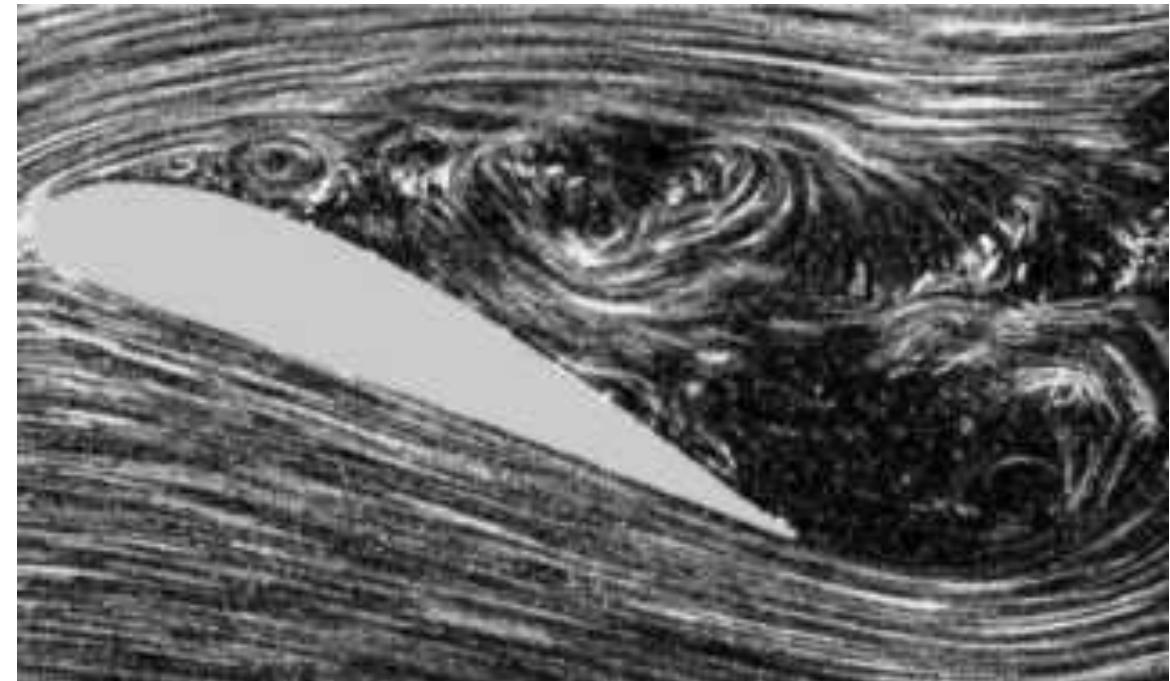
# AERODYNAMIC PHENOMENA – FLOW TRANSITION

- Because Reynolds number changes with position, the flow will change from laminar to turbulent
- Characterized by a region where laminar and turbulent flows mix
- Drag coefficient quickly rises in the transition region



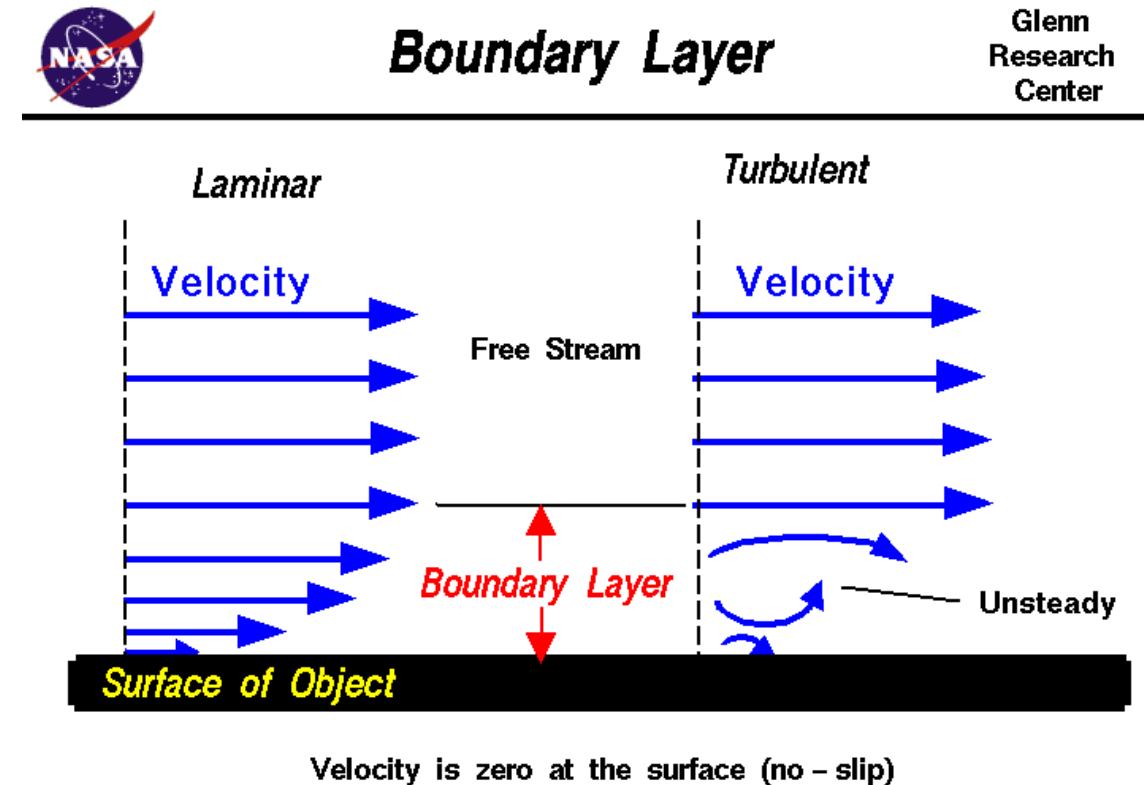
# AERODYNAMIC PHENOMENA – FLOW SEPARATION

- Airflow no longer follows the contour of an aerodynamic body
- Occurs when a large adverse pressure gradient exists
- Leads to a rapid increase in drag
- Fins area aft of separated flow is not effective



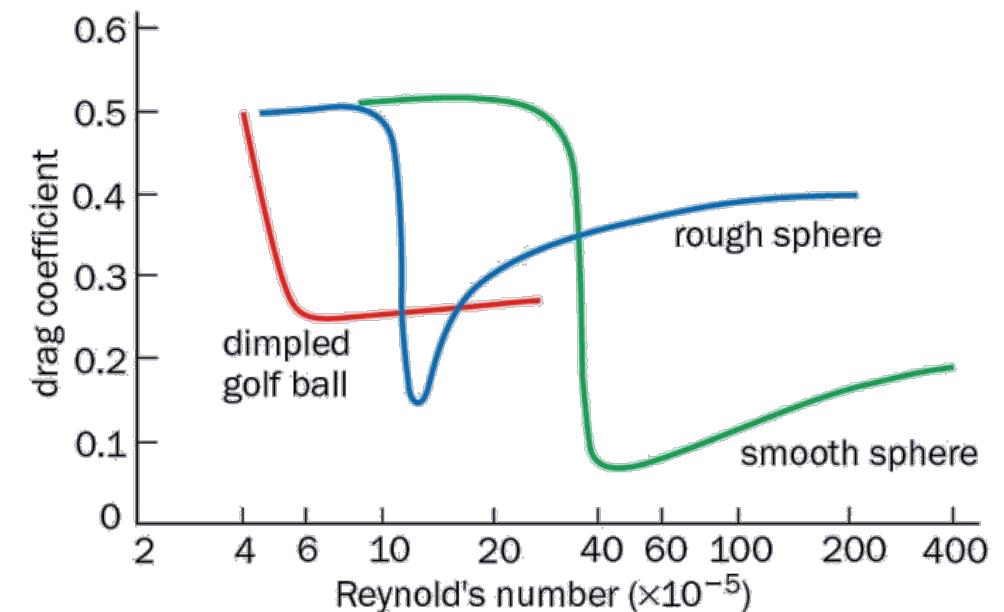
# LAMINAR VS. TURBULENT FLOWS

- Low energy layer exists near object (BL)
- Separation occurs when flow “runs out of forward energy”
- Turbulent flow continuously exchange energy between free stream and BL (i.e. higher drag, but suppressed separation)



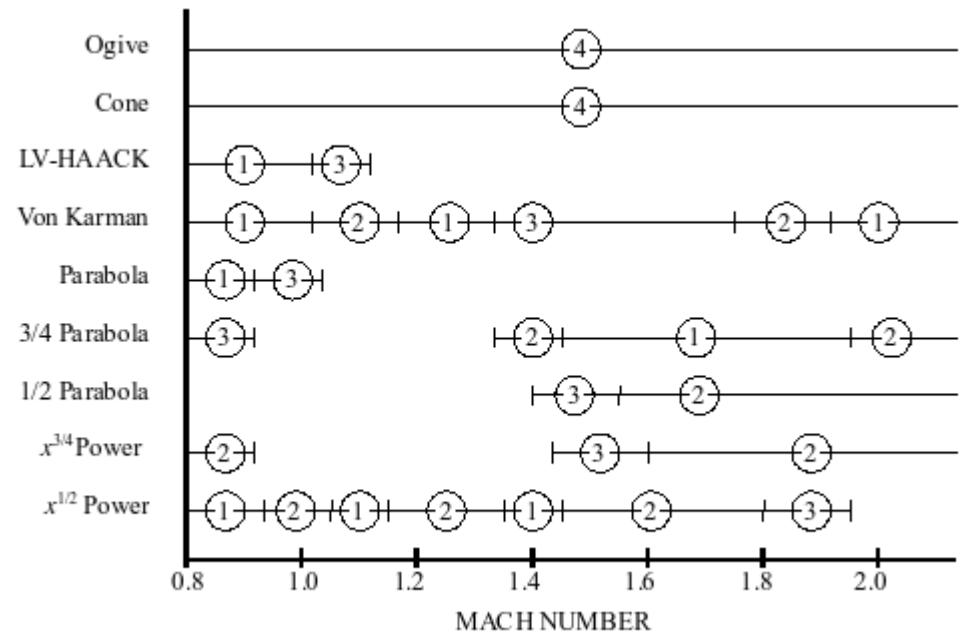
# DIMPLING

- Turbulent flow is draggy, but less draggy than separated flow (and safer)
- Laminar flow BL runs out of energy and separates
- Turbulent flow separates less readily than laminar
- Force transition to turbulent with dimples
- Effective only at low speeds (high speed flows usually turbulent even without dimple)



# NOSE CONE AERODYNAMICS

- Various geometries have different drag coefficients
- Minimum drag bodies like the von Karman ogive have best across-the-board performance
- Some shapes perform best in certain Mach regimes
- Model rocketry nose cones are generally ogives



## EFFECT OF ROCKET LENGTH

- Longer rockets lead to increases in skin friction drag
- Increased length-to-diameter ratio (fineness ratio) leads to a decrease in pressure drag per rocket volume
- Longer rockets are subject to extreme bending moments

# FIN AERODYNAMICS



## Rectangular cross section

- Simple to manufacture
- Relatively high drag coefficient for airfoils with similar thickness-to-chord ratios



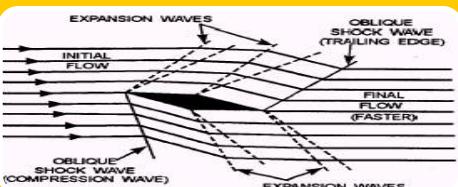
## Rounded cross section

- Not too difficult to manufacture
- Decent aerodynamic performance, but not the best



## Airfoil cross section

- Optimal fin cross section for subsonic rockets, but prone to high drag and shocks at supersonic speeds
- Should have a symmetric cross section

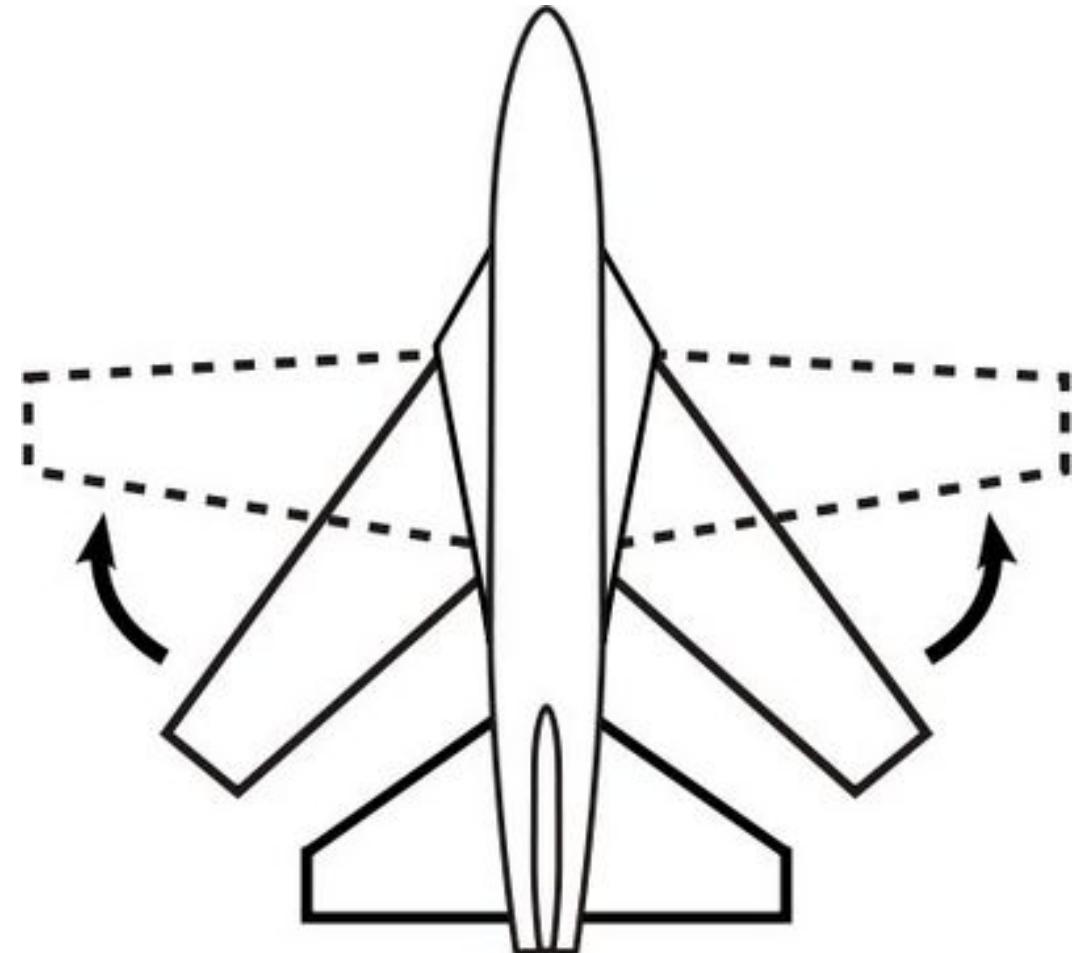


## Wedge cross section

- Good aerodynamic performance at supersonic speeds
- Decent aerodynamic performance at subsonic speeds

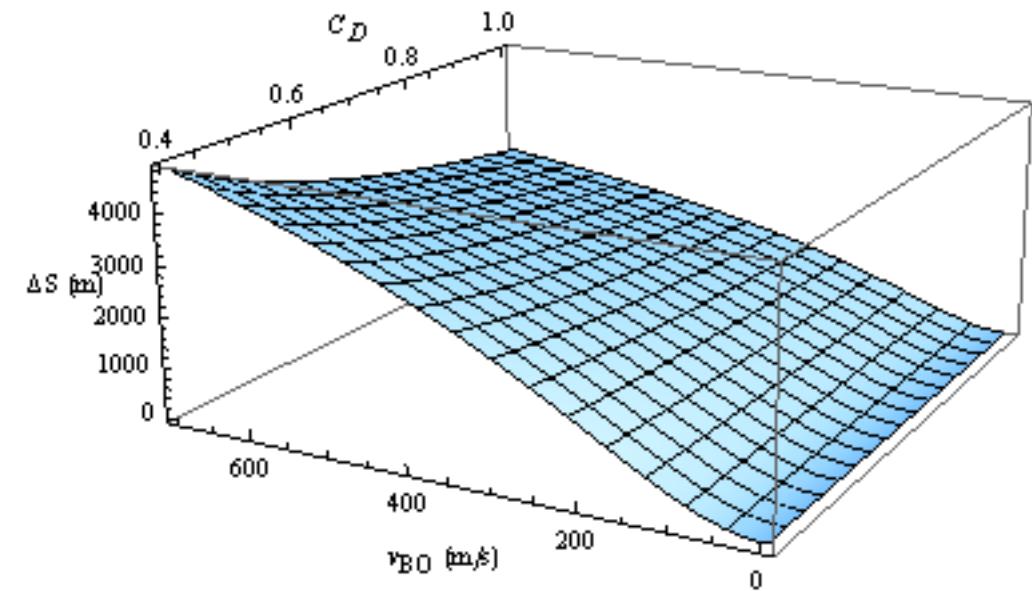
## FIN SWEEP

- Sweep reduces the apparent Mach number of flow over a fin by the cosine of the sweep angle
- Reduction in apparent Mach number reduces fin drag
- Sweep angle measured by the mean chord line
- Also brings CP aftward



# BALLISTICS

- Drag forces tend to slow down light, large objects more so than heavy, compact objects
- Ballistic coefficient is a ratio of inertial and aerodynamic forces  
 $\beta = m/C_D A$
- Higher  $\beta$  means higher apogees since rockets gain most altitude in coast



## FIN FAILURE MODES: STATIC

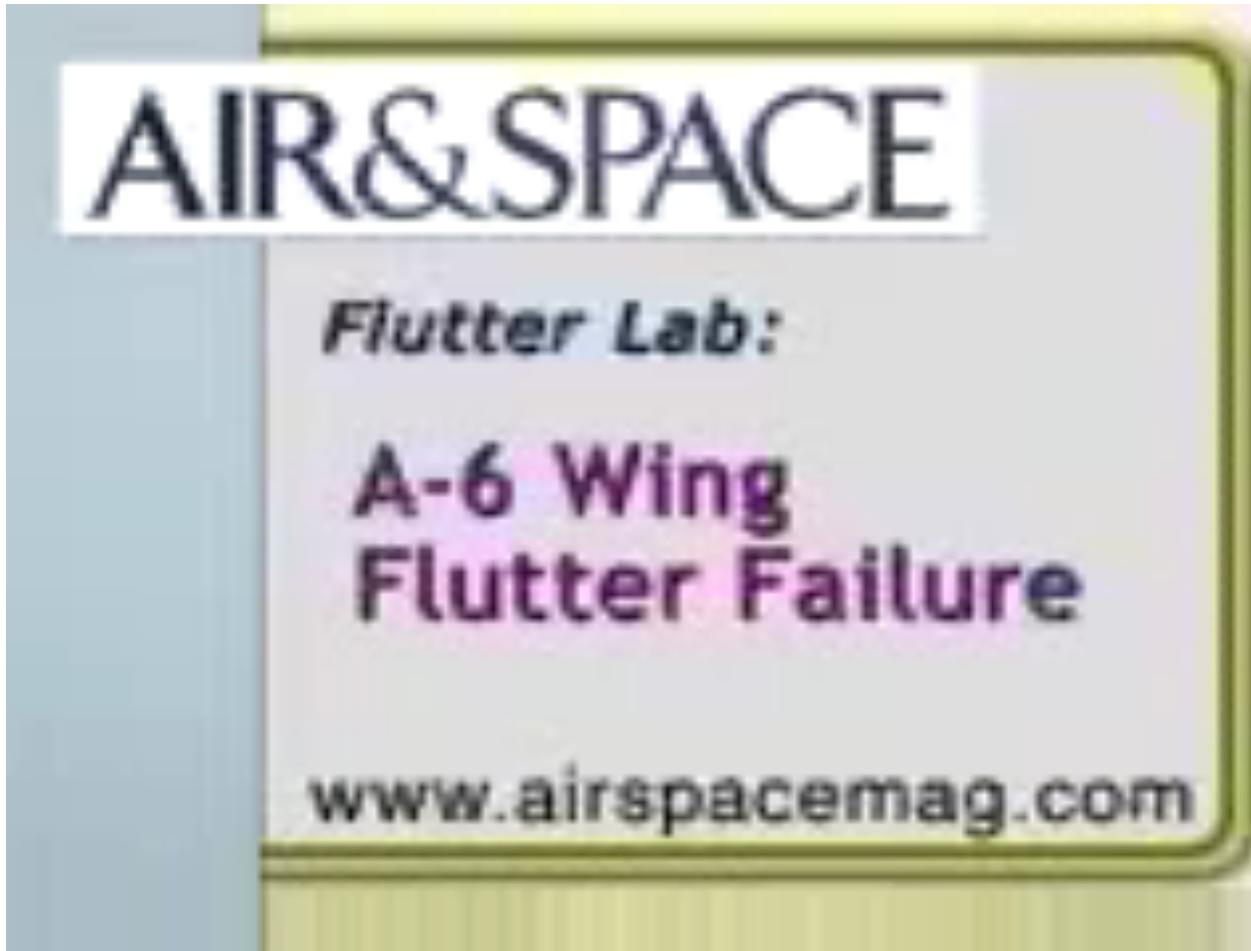
- Divergence: e.g. forward-swept fin deflect under load, resulting in more load, and even more deflection  
→ structural failure.
- Aft-swept fins will not diverge.



## FIN FAILURE MODES: DYNAMIC

- Flutter: elastic fins and aero forces hit a resonance point.  
Cause oscillations that rip fins off
- Buffeting: high-frequency vibrating loads caused by  
moving separation and shock wave
- Transonic Aeroelasticity: flow features/shock waves  
appear/move abruptly in transonic regime. Can cause  
sudden destruction of entire rocket

## FIN FAILURE MODES: DYNAMIC



## IMPLICATIONS ON MODEL ROCKETRY

- Aerodynamics is an crucial for performance in rocketry
- Geometric and material decisions must take aero forces into consideration to achieve a successful mission
- Much is intuitive (streamlined shapes, smooth contours), but advanced analysis can yield optimal designs
- Analysis can also yield back-of-the-envelope safety calculations for rocket flight (stability, ability to withstand drag and shocks, etc.)