Rocket Design

Tripoli Minnesota

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Purpose

Focus is on designing aerodynamically stable rockets not drag optimization nor construction techniques!

Agenda

- Overview
- Airframes
- Fins
- Nose Cones
- Altimeter Bays
- Design Rules of Thumb
- Summary

Overview

- Mission
- Design Considerations
- Design Implications

Mission

- Certification (Level 1, 2, or 3)
- Altitude
- Velocity/Acceleration
- Payload (Liftoff Weight)
- Design Experiments
  - Recovery
  - Motors
  - Structural: Nose Cone, Fins, Transitions
  - Staging
  - Electronics: Cameras, Sensors, ...

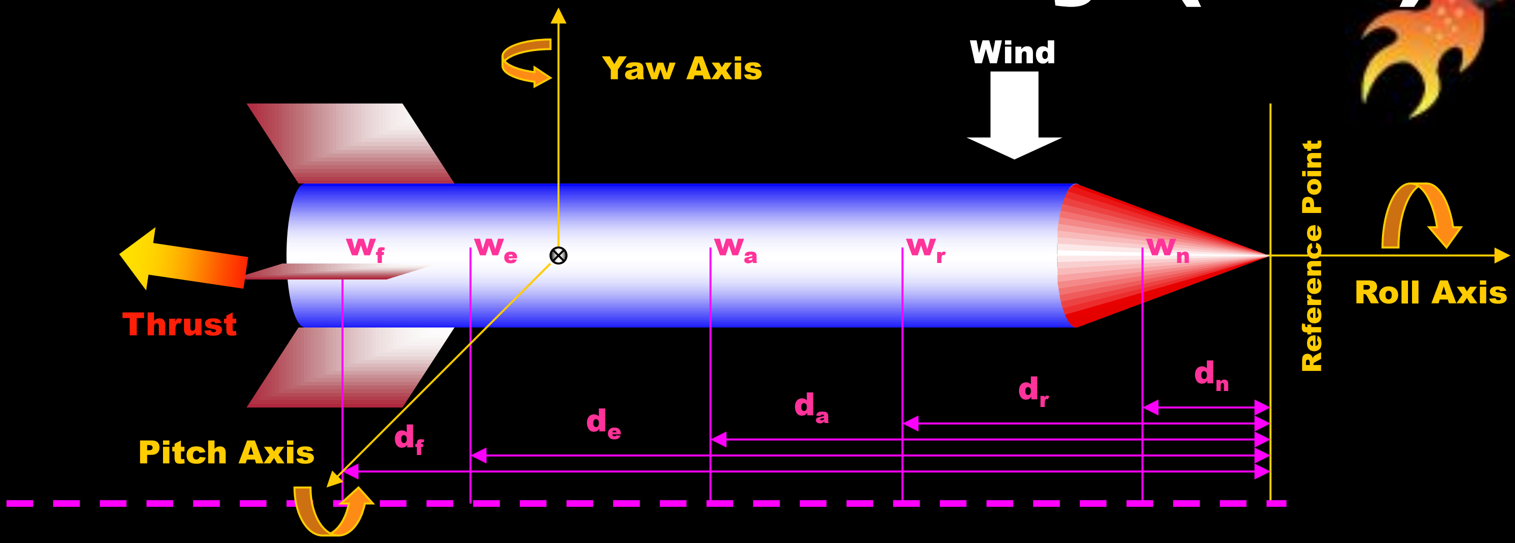
Design Considerations

- Aerodynamic Stability
  - Static
  - Dynamic
- Optimization
  - Drag: Pressure, Viscous (Surface Roughness, Interference, Base, Parasite) Angle of Attack, Rotation
  - Mass
- Flexibility
  - Motor Sizes
  - Airframe Configurations

Design Considerations

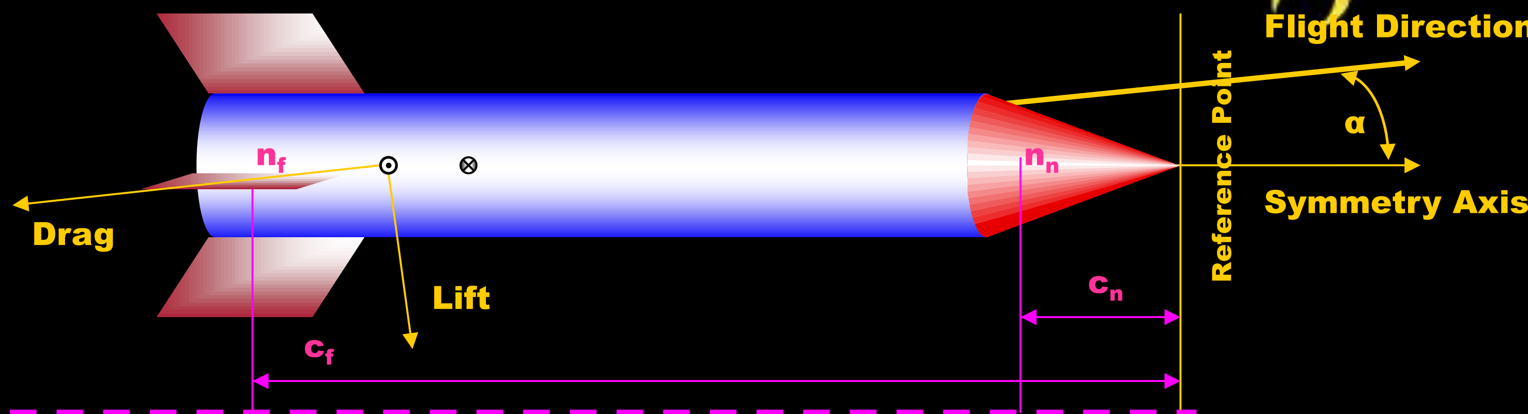
- Key Concepts
  - Center of Gravity
  - Center of Pressure
  - Damping Ratio
    - Corrective Moment
    - Damping Moment
    - Longitudinal Moment
  - Roll Stabilization

Design Considerations: Center of Gravity (CG)



- CG ia a single point through which all rotation occurs
- Sum of the product of weights and distance from a reference point
  $CG=(d_n w_n+d_r w_r+d_a w_a+d_e w_e+d_f w_f)/W$

Design Considerations: Center of Pressure (CP)



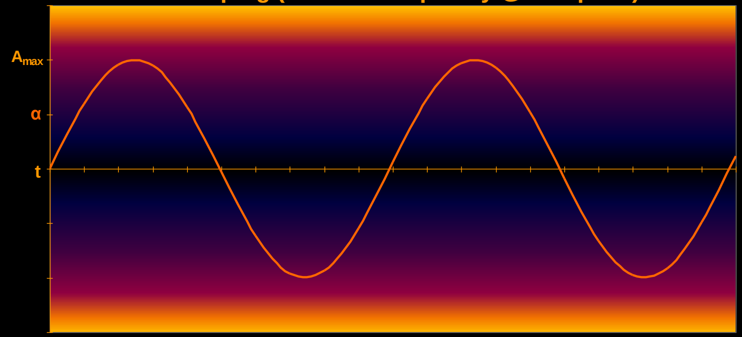
- **CP is a single point through which all aerodynamic forces act**
- **Barrowman's Method (Subsonic only)**
  - **Sum of the product of projected area, angle of attack, normal force, air density, airspeed, and distance from a reference point (simplification - requires integration)**
    $CP=(c_n n_n+c_f n_f)/N$
  - **Calibers = $(CP-CG)/d_{max}$**

Design Considerations: Damping Ratio (DR)

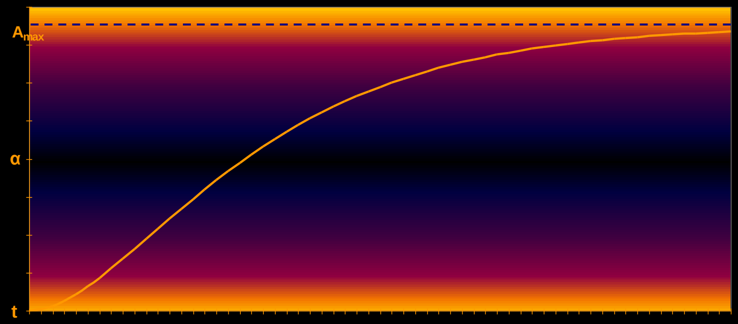
- **Applicable to both impulsive (wind gusts, thrust anomalies) and continuous (rail guides, fins) forces**
- **Over damping and significant under damping results in large flight deflections**
- **Optimum damping ratio is .7071**
  - **Under damping is preferred to over damping**

Design Considerations: Damping Ratio (cont)

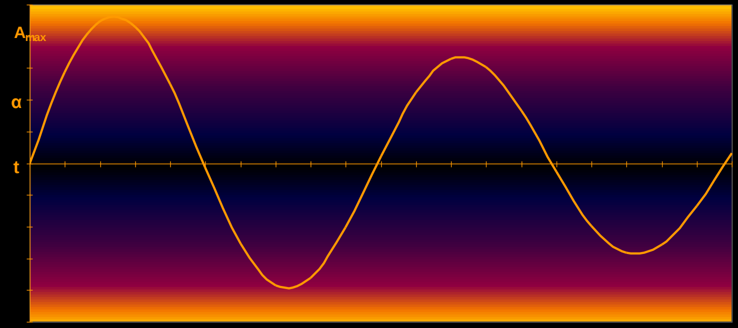
Zero Damping (Natural Frequency @ Airspeed)



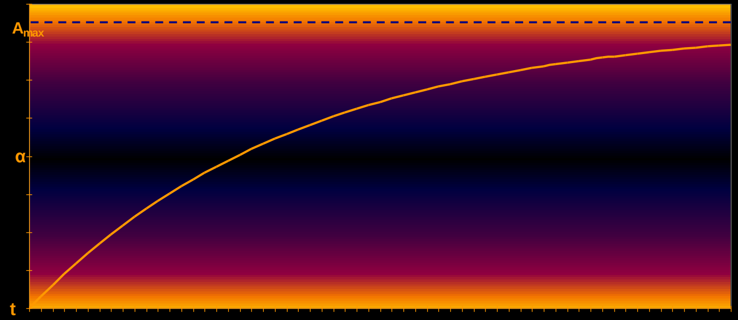
Critically Damped (ζ=1)



Underdamped Response



Overdamped Response



Design Considerations: Corrective Moment (CM)

- **An angular velocity which redirects nose to flight path in response to an angle of attack.**
- **$C_1 = {}^{\rho}/_{2} v^2 A_r N_\alpha (CP\text{-}CG)$ – subsonic only**
- **Variables:**
  - **Air Density (ρ) – decreasing**
  - **Velocity (v) – increases then decreases**
  - **Reference Area (A_r) – usually constant**
  - **Normal Force Coefficient (N_α) – increasing**
  - **CP – constant (unless supersonic)**
  - **CG – changes (usually forward)**

Design Considerations: Damping Moment (DM)

- **Response to corrective moment (minimizes overcorrection by slowing angular velocity).**
- **Comprised of two components:**
  - **Aerodynamic**
    - **Varies based on air density, velocity, reference area, and CG**
  - **Propulsive**
    - **Applicable only during motor thrust**
    - **Varies based on mass flux**

Design Considerations: Longitudinal Moment (LM)

- **Mass distribution along longitudinal axis**
- **Point mass assumptions appropriate for components distant from CG (underestimate)**
- **Large values of LM reduce sensitivity to impulsive forces and protect against over damping**

Design Considerations: Roll Stabilization

Negatives:

- Provides no benefit if statically unstable
- Damping ratio is still critical
  - Roll decreases damping effectiveness
  - Large slenderness ratio is critical
  - Rolling light, short stubby rockets can result in instability
  - Close roll rate and natural frequency values result in resonance
- Increases drag

Positives:

- Suppresses instability growth rate
- Reduces amplitude of initial disturbances
- Time average of disturbances
- Construction imperfections become sinusoidal

Requires High Angular Momentum!

Design Implications: Stability Margin

- Stable when CG in front of CP
- CG in front of CP by 1 or more calibers but less than 5 calibers
  - Increasing calibers increases CM and decreases DR
- CG can be moved by changing static weight distributions
- CP can be moved by
  - Alternative nose cone designs
    - Elliptical > Ogive > Parabola/Power Series/Von Karman > LV Haack > Conical
  - Fin size and placement
    - Move CP Back - Increase size and/or move back
    - Move CP Forward – Decrease size and/or move forward
  - Boat tail and transition length, radius differential, and placement

Design Implications: DM

Increase:

- Increase fin area
- Move fins away from CG
  - Applies to canards

→

- Increases damping ratio
- Taken to extremes:
  - Excessive drag reduces altitude
  - Construction errors may result in over damping

Decrease:

- All fin area aft of CG
- Fin area close to CG

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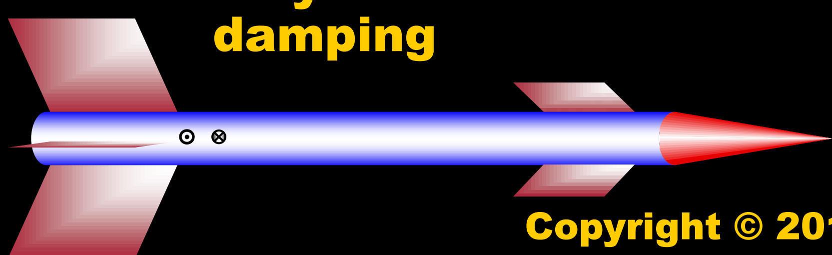
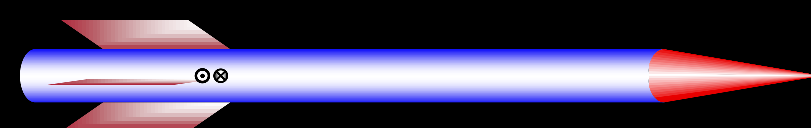
- Reduces corrective moment
- May reduce damping ratio

Taken to extremes:

  - Catastrophic resonance at low roll rates





Design Implications: CM

Increase:
- Increase fin area
- Move fins aft
- Increase Airspeed

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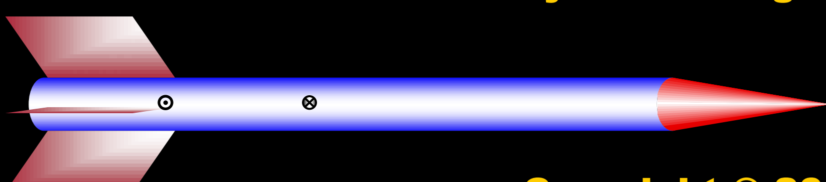
- Increases oscillation frequency
- May increase damping ratio
- Decreases disturbance recovery time
- Taken to extremes:
    - Step disturbances will cause severe weather cocking (turning into the wind)
    - Excessive speeds cause excessive aerodynamic drag



Decrease:
- Reduce CG/CP separation

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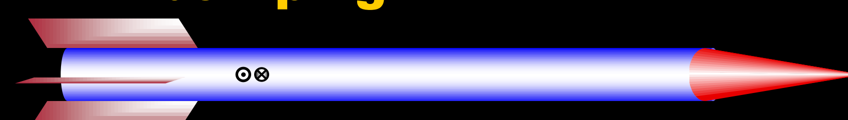
- Decreases oscillation frequency
- Decreases natural frequency
- Increases damping ratio

Taken to extremes:
- Catastrophic over damping



Design Implications: LM

Increase:

- Add weight fore and aft of CG
- Increase length

→

- Decreases damping ratio & natural frequency
- More difficult to deflect from flight path
- Taken to extremes:
  - Weight reduces altitude
  - Catastrophic resonance at low roll rates

Decrease:

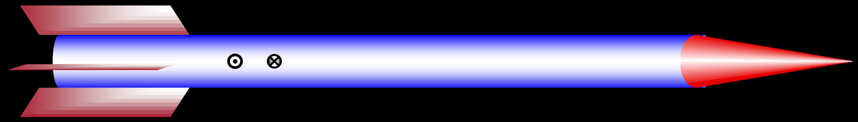
- Reduce weight fore and aft
- Reduce length

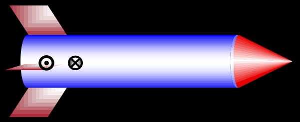
→

- Increases damping ratio & natural frequency
- Frequent disturbances and resulting angles of attack will increase drag & lower altitude
- More easily deflected from flight path

Taken to extremes:

- Weight reduces altitude (ballistically below optimum)
- Catastrophic over damping





Airframes

Type	Strength	Weight	RF	Aging Effects
Carbon Fiber	1	4	Opaque	Minimal
Aluminum	2	6	Opaque	None
Fiberglass	3	5	Transparent	Minimal
Blue Tube	4	3	Transparent	Unknown
Phenolic	5	1	Transparent	Brittle
Quantum Tube	6	2	Transparent	None

Fins

- Parallelograms are effective and easily produced shapes
- Roll stabilization
  - Canted
  - Airfoil
  - Spinnerons
- Location and size affect DM, CM, and stability margin
- Fin flutter and divergence undesirable
  - Avoid by using stiff materials, thicker fins, wider fillets, and/or thru the wall designs

Nose Cones

- Design Considerations:
  - CG adjustments by changing weight
  - Recovery harness assembly
    - Never use open ended eye bolts!
    - Never use plastic attachment points!
  - May include electronics or payload
  - Seriously consider shear pin retention
  - Types: Conical, Ogive, Parabolic, Elliptical, Power Series, & Sears-Haack (varying CP, CG, and drag coefficients)

Altimeter Bays

- Design Considerations
  - Space Availability
  - Survivability and Placement of Electronics
    - MAD use non-magnetic materials
  - Redundancy
  - Reusability
  - Ease of Use (Accessibility, Assembly, Disassembly)
  - Arming and Disarming
    - Switches in reachable location (avoid rod/rail)
  - Port Placement
    - Ports should be away from barometric sensors
  - Recovery System
    - Dual or single deployment
    - Split, aft, or forward deployment
    - Ejection method (BP, CO_2, Spring) and placement
    - Harness attachment points and assembly
      - Never use open ended eye bolts! Forged eyes or U bolts.
      - Sew together harness or use figure eight/bowline knots (weakest point)

Summary:
Design Rules of Thumb

- **Motor:**
  - **Thrust to weight ratio - 5:1**
  - **Minimum stable flight speed: 44 feet/sec**
    - **Calm – add 6 ft/sec for every 1 mph**
- **Airframe:**
  - **Length to diameter ratio – 10-20:1**
  - **Consider anti-zipper designs**
    - **Airframe reinforcement (AL bands, etc)**
    - **Recovery connections points (couplers in airframe, not altimeter bay, and extended outside airframe)**
- **Fins:**
  - **Number: ≥ 3**
  - **Fin Root to diameter – 2:1**
  - **Fin Span/Cord to diameter – 1:1**

Summary: Design Rules of Thumb

- **Recovery**
  - **Recovery Harness to length: 3+:1**
  - **Recovery Harness to weight: 50:1**
  - **Decent Rate: 15-20 feet/sec**
  - **Shear pin number: ≥ 3**
  - **Ejection Charge:**
    - **LBS*Length*.000516=BP grams**
      - **I use 100 lbs but can vary based on diameter**
    - **Don’t use black powder over 20,000 ft unless enclosed in airtight container**
    - **If using shear pins account for required shear pin shearing force**

Summary:
Design Rules of Thumb

- **Launch Guides**
  - **Rail Buttons**
    - **Number: ≥ 2**
    - **Location: CG (required) and Aft**
  - **Launch Lugs**
    - **Number: ≥ 1**
    - **Location: CG (required) and Aft**

Summary: Design Rules of Thumb

- Altimeter Bay
  - Port Number (P_n): ≥ 3
  - Port Diameter: $\pi r^2 l/(400 * P_n)$
- Vent Holes
  - Needed when friction retention is used
  - Unnecessary with shear pins (my opinion)
- Nose Cones
  - Optimum Fineness ratio: 5:1
  - Shoulder ratio to diameter: 1:1

What can happen?

References

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