Nose Cone & Fin Optimization

Tripoli Minnesota

Gary Stroick

January 2011

Purpose

Focus is on drag optimization to maximize rocket performance!

Agenda

- Definitions
- Mission Parameters
- Nose Cone Design
- Fin Design
- Summary
- Appendices
- References & Web Sites

Definitions[1]

- Drag Coefficient
  - Parasitic Drag
    - Form/Pressure/Profile Drag
      - Dependence upon the profile of the object
      - Base Drag
        - Due to Boundary Layer separation at base of airframe/fins
    - Skin Friction (Viscous) Drag
      - Friction of the fluid against the skin of the object
    - Interference Drag
      - Incremental drag above sum of all other drag components. Created at protrusion intersections.
  - Induced (Lift-Induced) Drag
    - Due to redirection of airflow
  - Wave (Compressibility) Drag
    - Due to shockwaves when moving near or above the speed of sound (typically leading & trailing edges)
  - Rotational Drag
    - Circumferential velocity from roll will thicken boundary layer and result in increased drag

Definitions[1]

- Wetted Area
  - Surface Area exposed to airflow
- Fineness (Aspect) Ratio
  - Nose Cone Length/Base Diameter
- Bluffness Ratio
  - Tip Diameter/Base Diameter
  - Hemispherical Blunting
  - Me’plat Diameter is a Flat Truncation (e.g., bullets and artillery shells)

Definitions[1]

- **Laminar Boundary Layer**
  - Fluid streams move in parallel (negligible transfer of momentum)
- **Turbulent Boundary Layer**
  - Fluid streams transverse with velocity variations around an average value
- **Boundary Layer Separation**
  - Boundary layer separates from object's surface creating an effective profile
- **Reynolds Number**
  - Dimensionless ratio of inertial / viscous forces
  - http://www.grc.nasa.gov/WWW/BGH/reynolds.html

Definitions[1]

- Aspect Ratio (AR)
  - Fin Span / Average Fin Cord
- Effective Aspect Ratio
  - Working AR due to Airflow Effects
- Taper Ratio
  - Tip Cord / Root Cord

Definitions

- **Thrust Profile**
  - **Thrust vs. Time Curve**
- **Velocity Definitions**
  - **Subsonic: < .8 Mach**
  - **Transonic: .8 to 1.2 Mach**
  - **Supersonic: 1.2 to 5 Mach**
  - **Hypersonic: > 5 Mach**

Mission Parameters

- Velocity
  - Coefficient of Drag
  - Thrust Profile
  - Total Mass
- Altitude
  - Coefficient of Drag
  - Thrust Profile
  - Total and Coasting Mass
- Mass
  - Material Volume and Strength
  - Payload
- Payload
  - Available Volume
  - Stability Impacts
- Stability (CP&CG - Discussed Last Year)

Nose Cone Design

- Mission Dependent Variables
  - Payload
  - Stability (CP, CG)
- Independent Variables
  - Atmospheric Density
  - Temperature
  - Wind Conditions
  - Surface Finish
  - Angle of Attack

Nose Cone Design

- **Assumptions**
  - **Zero Angle of Attack**
  - **Constant Surface Finish**
  - **No Roll**
  - **No Aerodynamic Heating Effects**

Nose Cone Solutions

Best in Class

Subsonic[1]

1. Elliptical

Transonic[4]

1. LD-Haack (Von Karman)
2. $X^{1/2}$ Power Series
3. LV-Haack (< Mach 1)

Supersonic[7]

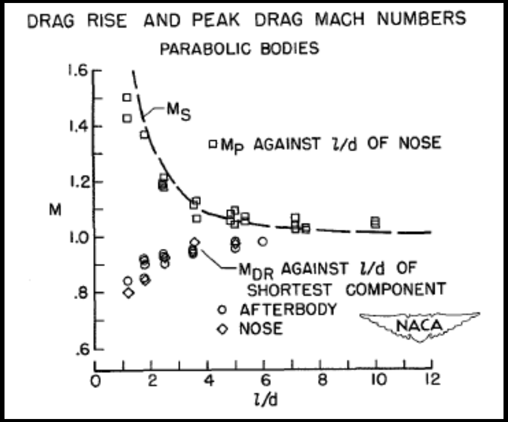
1. Eggers Minimum Drag
2. $X^{3/4}$ Power Series

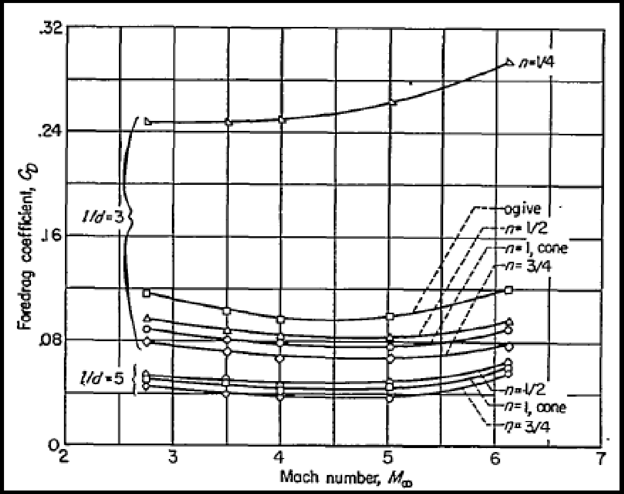
Hypersonic[8,9,10]

1. Love Minimum Drag
2. $X^{.6}$ Power Series

Fineness Ratio[6,7]

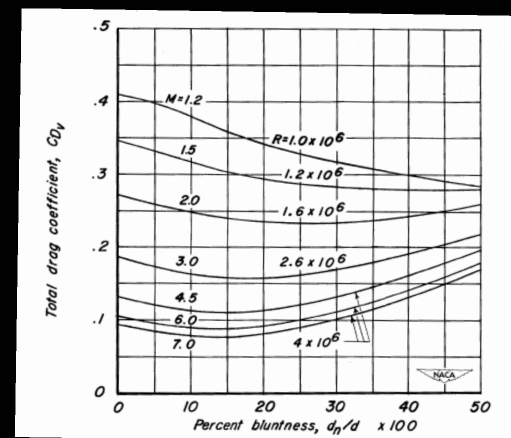
- Increasing Fineness Ratio
  - Decreases Wave Drag
  - Increases Skin Friction Drag
  - Optimum Ratio is approximately 5

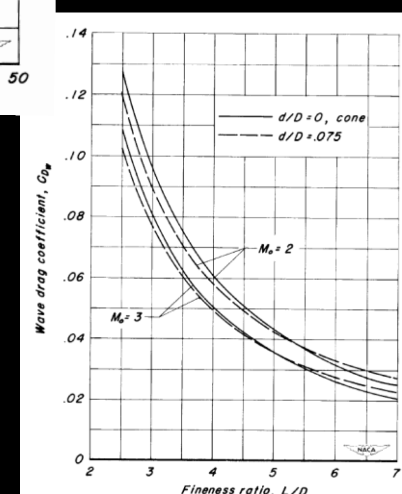




Bluntness Ratio[2,3,5]

- **Optimal ratio is .15**
  - **Provided length remains constant**
- **Applicability dependent upon fineness ratio and velocity**
  - **Fineness ratio ≤ 5**
  - **Below Hypersonic**

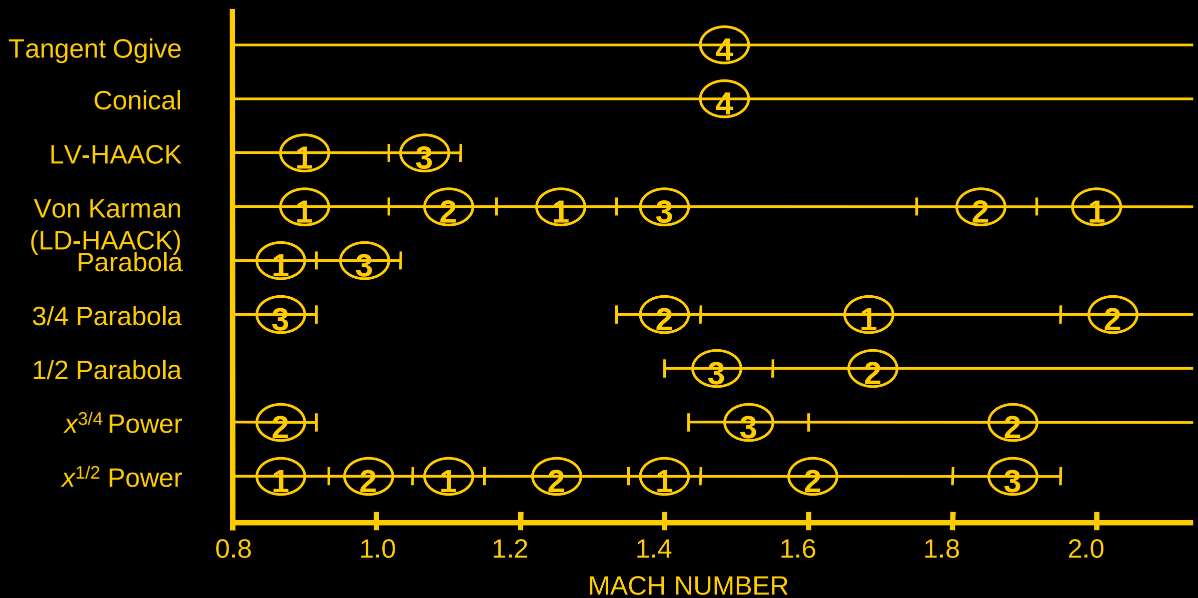




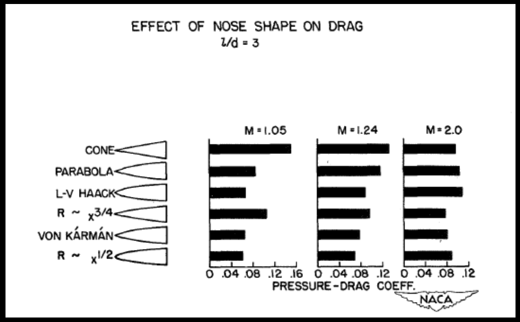
Coefficient of Drag (C_D) Subsonic[1]

- Primarily Skin Friction Drag
- Minimal Pressure Drag
- No Wave Drag
- No Interference Drag
- No Induced Drag
- Elliptical
  - Fineness Ratio of 2

Coefficient of Drag (C_D) Transonic[4]



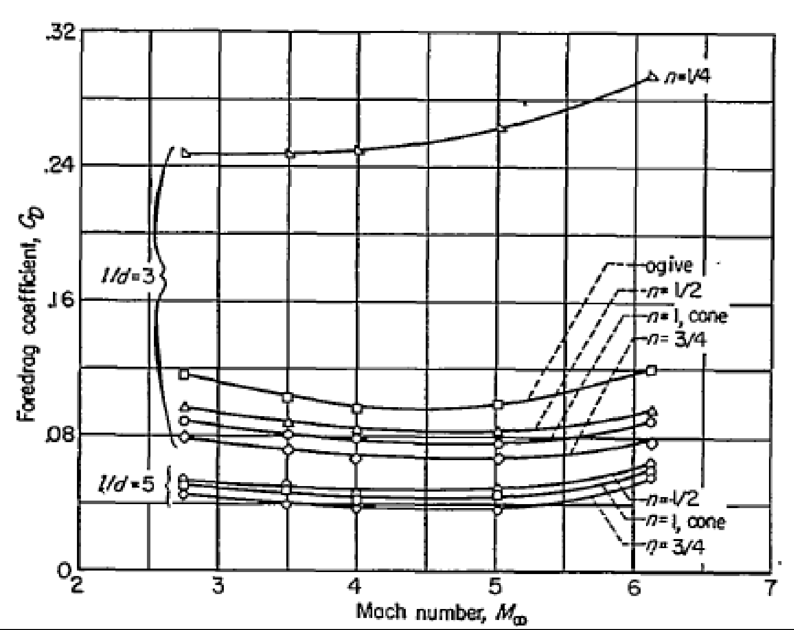
Comparison of drag characteristics of various nose shapes in the transonic-to-low Mach regions. Rankings are: superior (1), good (2), fair (3), inferior (4).



- **Wave Drag Increases Substantially**
- **Pressure Drag becomes Significant**
- **Fineness Ratio of 5 is Critical**

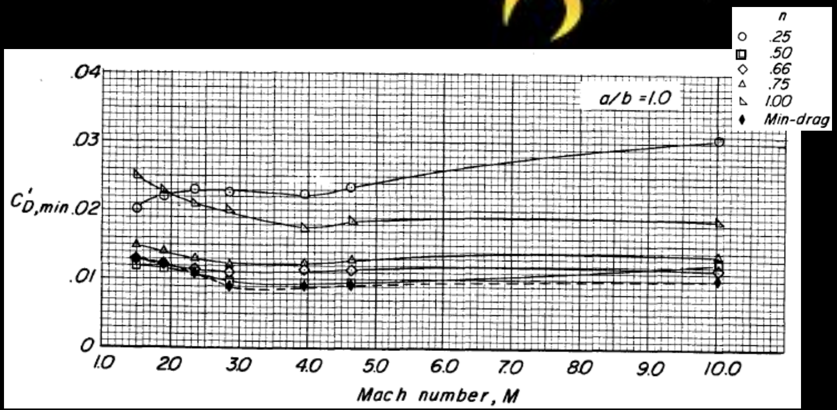
Coefficient of Drag (C_D) Supersonic[7]

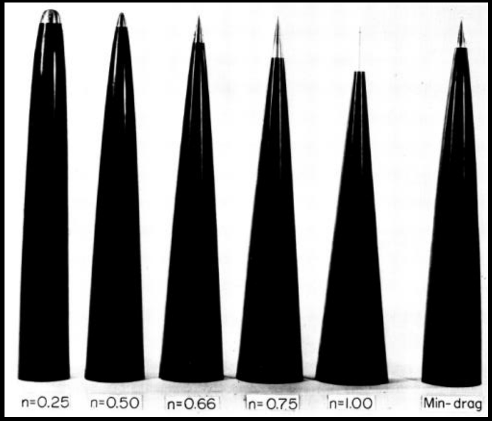
- **Pressure Drag Decreases**
- **Wave Drag Decreases**
- **Fineness Ratio of 5 is Critical**

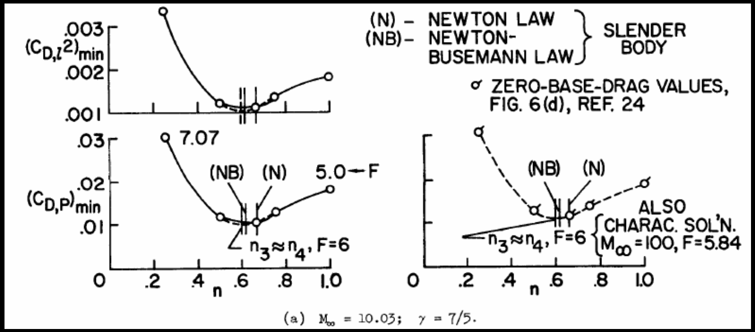


Coefficient of Drag (C_D) Hypersonic[8,9,10]

- **$X^{.6}$ Power Series**
  - **Fineness Ratio of 5 or 6**
- **Varies with Fineness Ratio**
- **No Blunting**







(a) M_∞ = 10.03; γ = 7/5.

Fin Design

- Mission Dependence
  - Stability (CP, CG, Roll, …)
- Independent Variables
  - Atmospheric Density
  - Temperature
  - Wind Conditions
  - Surface Finish (Assumed Constant)
  - Angle of Attack (Assumed Zero)

Fin Optimization

- Minimize Drag
- Maintain Structural Integrity
  - Minimize Divergence
  - Minimize Bending-Torsion Flutter
  - Minimize Mass
- Maximize Fin Joint Strength
- Maintain Passive Stability

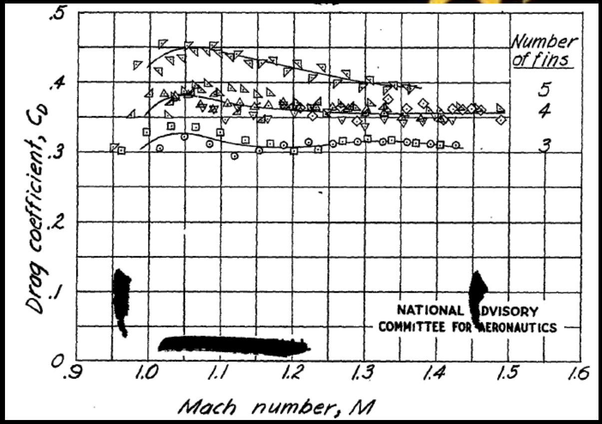
Fin Drag Optimization

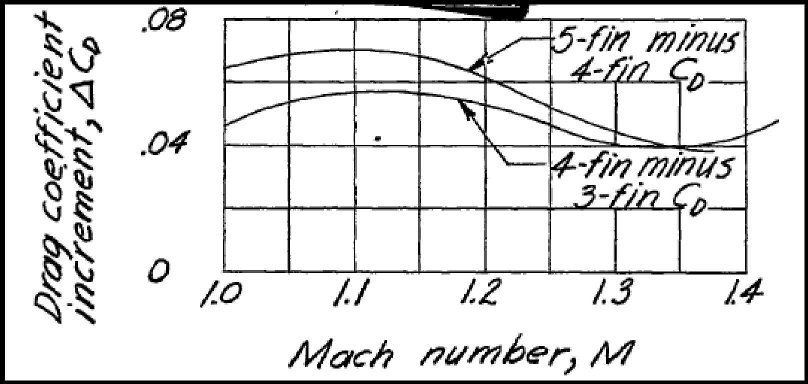
- No General Solution Unearthed
  - Computational Models Exist at Subsonic, Transonic, and Supersonic Speeds
- Solution Factors
  - Velocity
  - Density
  - Lift Requirements (Corrective Moment) at Angles of Attack
  - …
- Structural Strength

Fin Count[11]

- **Fin Count > 3**
  - **Skin Friction Drag Increases**
  - **Interference Drag Increases up to Mach 1.35**

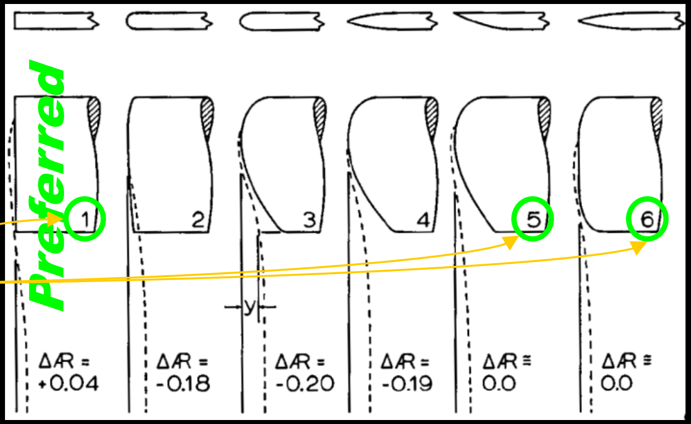
Fin Count → 3 but not always …





Fin Tip Vortices[1]

Desired

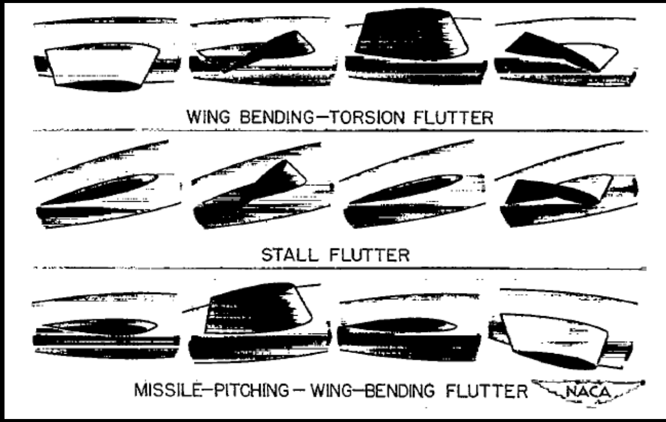


- Vortices alter Fin Effective Aspect Ratio
- Positive or Neutral Ratio Desired
  - Lower Angles of Attack for Given Lift (Increases Corrective and Damping Moments)
  - Lower Induced Drag for Given Lift
- Desire Zero or Positive Effective Aspect Ratio
- Ease of Manufacture
  - Implies Fins with a Tip Cord > 0
  - Square Edge Tips

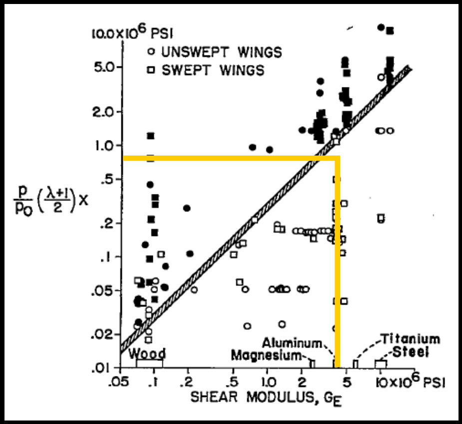
Fin Flutter[20]

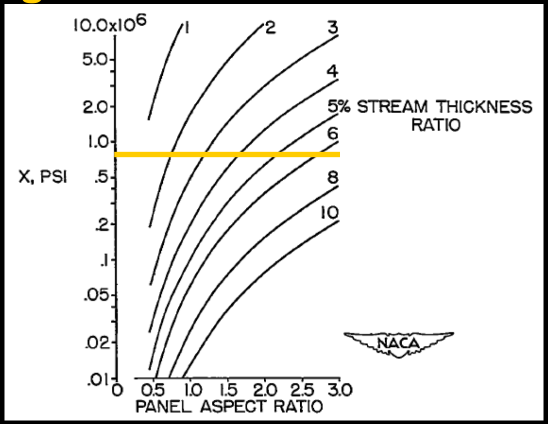
- **NASA Safety Factors**
  - **15% between vehicle & flutter velocity**
  - **32% between vehicle and flutter dynamic pressure**

Fin Flutter[16]



- **Stall Flutter not applicable**
- **Choose Shear Modulus for Material**
- **Apply Contingency when selecting Flutter criterion**
- **Criterion then used with Aspect Ratio to find Thickness Ratio**
- **Multiple Thickness Ratio & Cord to get Thickness**

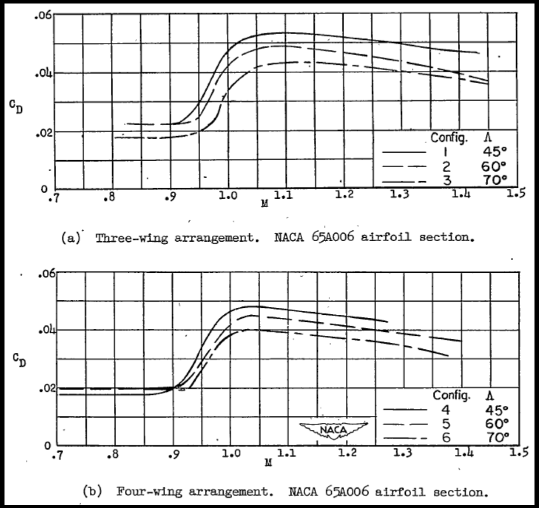


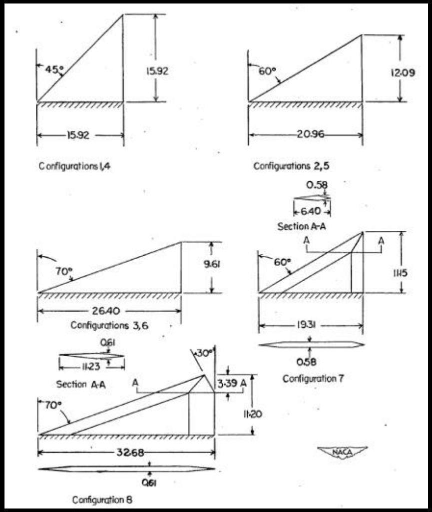


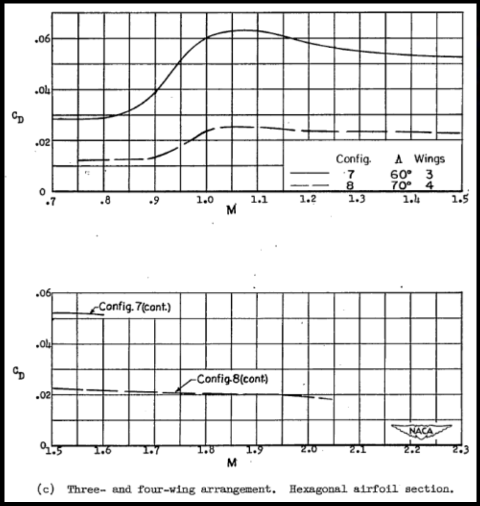
Fin Joint Drag[1,12]

- **Interference Drag**
  - **Minimized when fillet radius is between 4% and 8% of fin root cord**
  - **10” Root Cord → $^{1}/_{2}$” Radius**
  - **Consider Structural Strength**
- **Wing (Leading Edge) Fillets Increase Drag in the Transonic Region**

Sweep Angle[13]

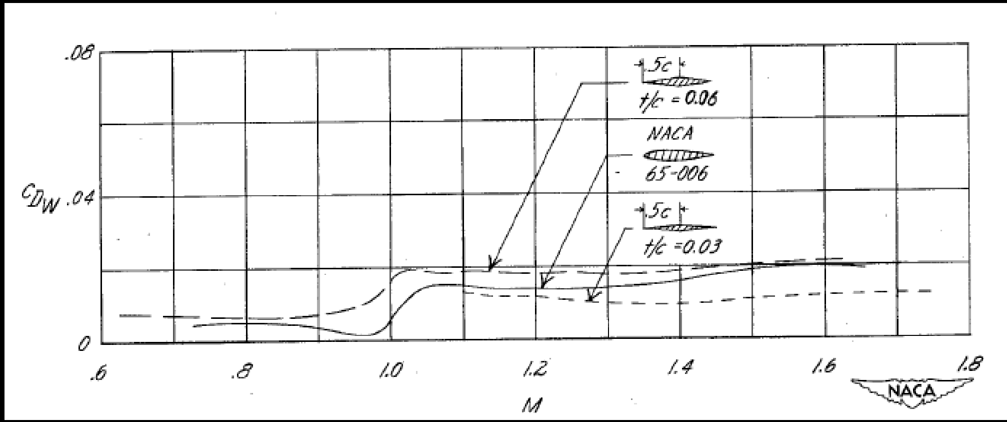






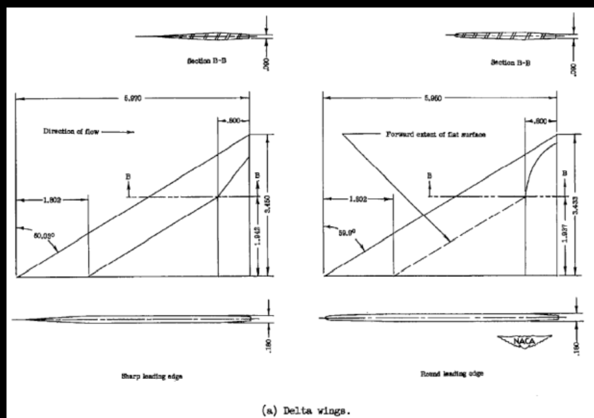
- **70° Sweep Angle Superior to Smaller Angles in Sub, Trans, & Supersonic Ranges**
  - **4 Fin Configuration Exception in Subsonic Region**

Fin Thickness[15,17,18]

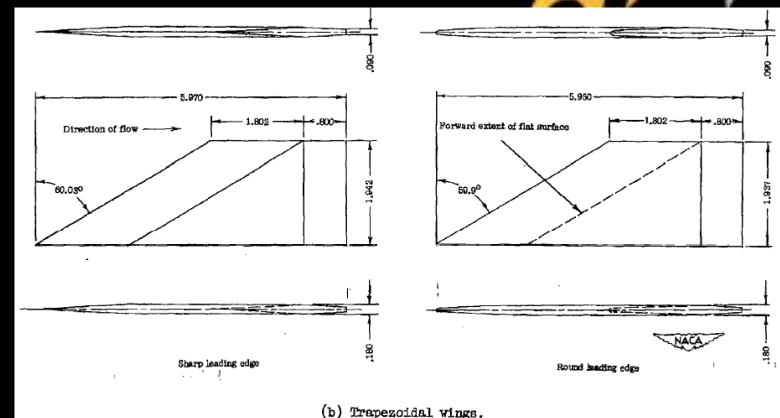


- Thinner Symmetrical Fins Result in Lower C_D in Sub, Trans, and Supersonic Regions

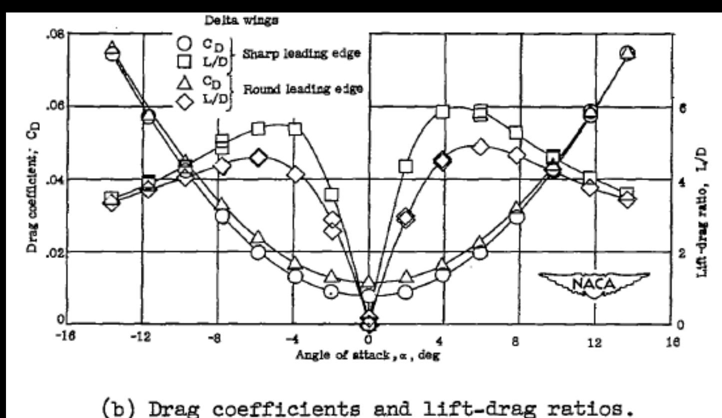
Leading Edge[14]



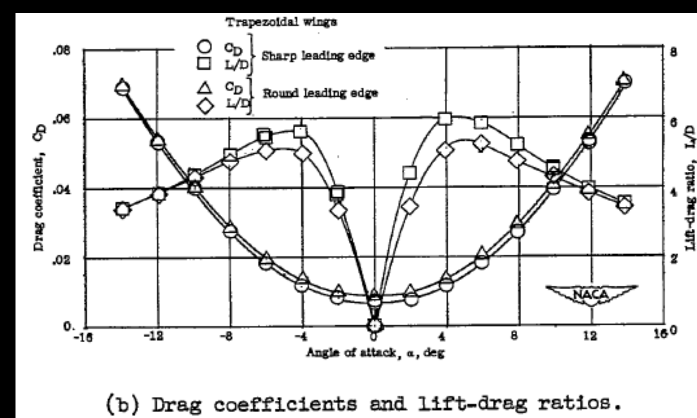
(a) Delta wings.



(b) Trapezoidal wings.

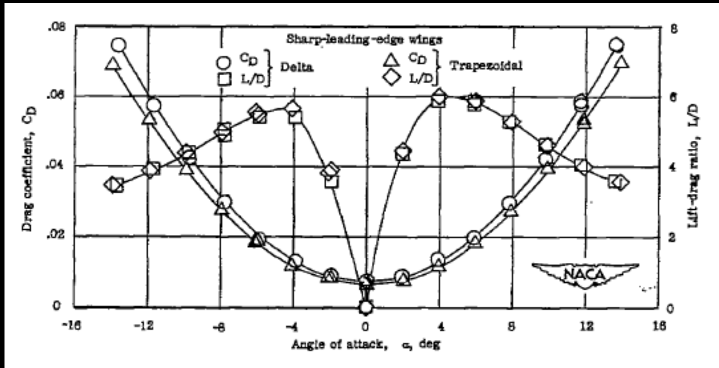


(b) Drag coefficients and lift-drag ratios.

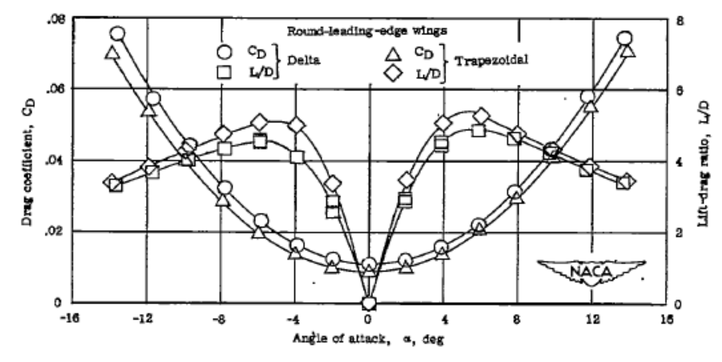


(b) Drag coefficients and lift-drag ratios.

Leading Edge[14]



(b) Drag coefficients and lift-drag ratios.



(b) Drag coefficients and lift-drag ratios.

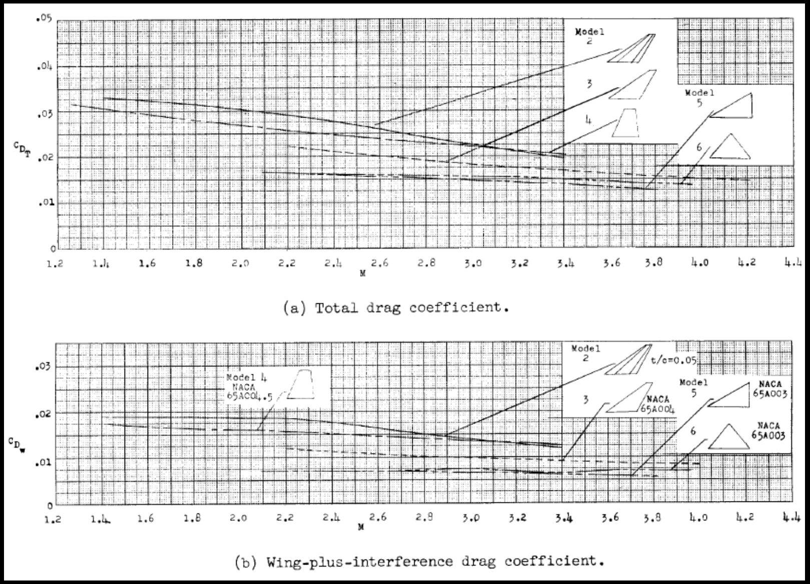
- **At Mach 4**
  - **Sharp Leading Edge has Lower C_D at all Angles of Attack**
  - **Trapezoidal (Clipped Delta) has Lower C_D than Delta**

Trailing Edge[21]

- Trailing-edge Thickness up to 0.7% Root Cord Reduces Transonic Drag
  - Does not Impact Subsonic Drag
- Trailing Edge Thickness > 0.7% Results in Increased Drag
- Varies with Airfoil Thickness and Optimum is < 0.7%
  - 10” Root Cord → $^{1}/_{16}$” Thick Trailing Edge

Fin Cross Section[13,19]

- **Sub, Trans, and Supersonic**
  - **Hexagonal Lower C_D than Double Wedge**
- **Supersonic**
  - **C_D NACA 65A003 < 65A004 < Hexagonal**



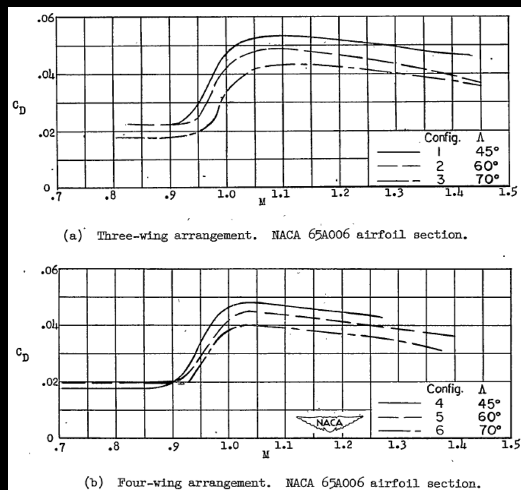
(a) Total drag coefficient.

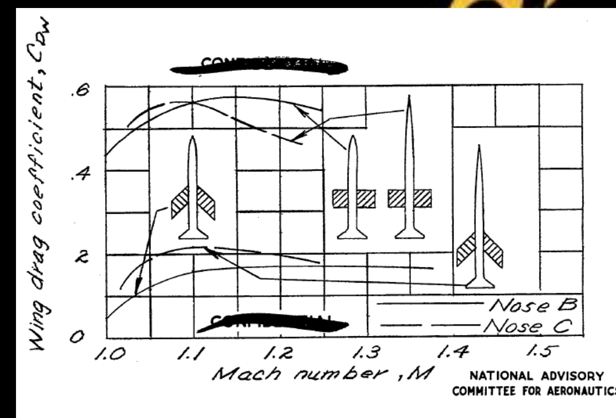
(b) Wing-plus-interference drag coefficient.

Shape[14,19]

- **Supersonic Data**
  - **Trapezoidal (Clipped Delta) Lower C_D than Delta**
  - **Delta and Diamond have Similar C_D**

Multi-Disciplinary Design Optimization (MDO)[x]





- **Optimizing Individual Components may not Result in an Optimum Design**
  - **Increasing Fin count from 3 to 4**
  - **Improving Nose Cone Fineness Ratio (3.5 vs. 7) may Result in Increased Fin Drag at Some Velocities**

Summary

- **Optimal Nose Cones**
  - Subsonic – Elliptical
  - Transonic – Von Karman (Blunted 15% of Base Diameter)
  - Supersonic - $X^{3/4}$ Power Series
  - Hypersonic – $X^{.6}$ Power Series
  - Fineness Ratio of 5
- **Fin Optimization**
  - Fin Count of 3
  - Fin Joints 4% to 8% of Root Cord
  - Thickness < 10% of Root Cord often between 3% & 6%
  - Trailing Edge Flat but < 0.7% of Root Cord in Thickness
  - Leading Edge may be Sharp
  - Sweep Angle between 45° and 70°
  - Flat Fin Tips
  - Hexagonal Cross Section
  - Clipped Delta Shape

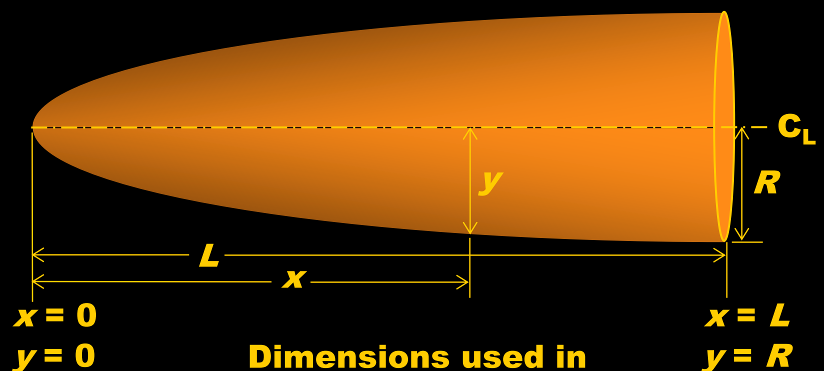
Appendices

Nose Cones

Nose Cone Geometries

- Conical
- Elliptical
- Ogive (Tangent)
- Parabolic
- Power Series
- Sears-Haack (Von Karman)

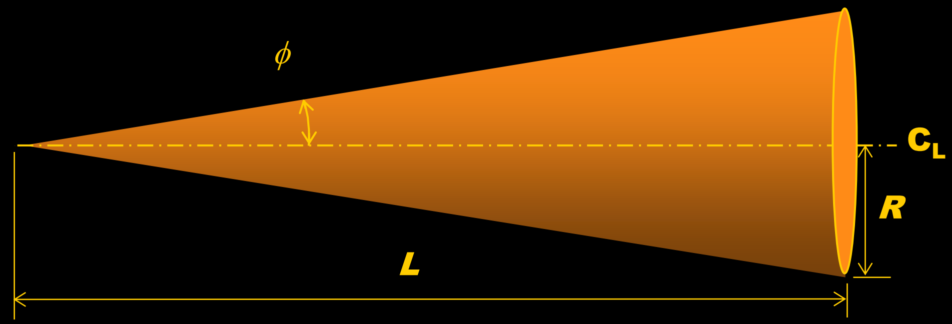
Nose Cone Parameters



Dimensions used in the equations

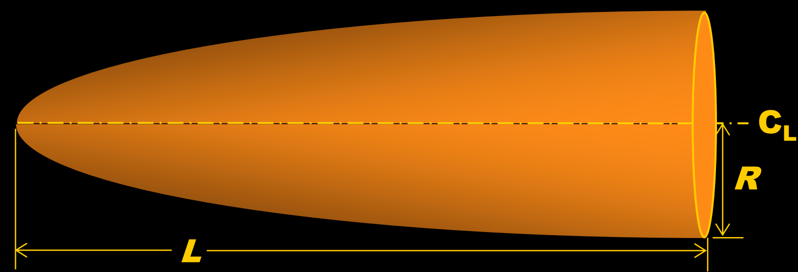
- *L* is the overall length of the nosecone
- *R* is the radius of the base of the nosecone
- *y* is the radius at any point *x*, as *x* varies from 0 at the tip of the nosecone to *L*
- The full body of revolution of the nosecone is formed by rotating the profile around the centerline (C_L)

Conical Nose Cones



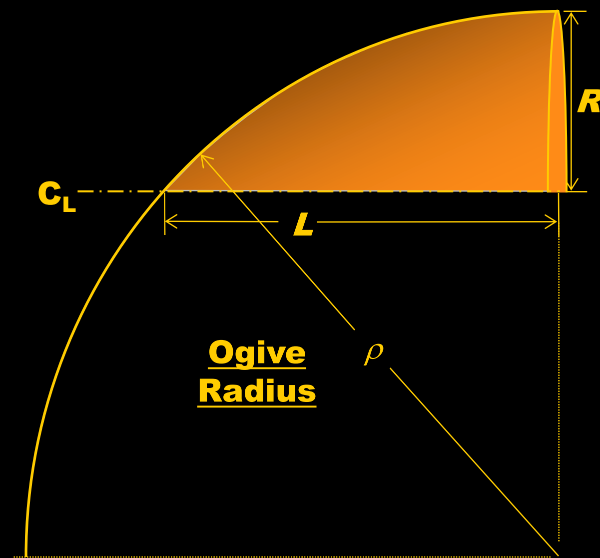
- The sides of a cone are straight lines, so the diameter equation is simply, $y = {}^{Rx}/_{L}$
- Cones are sometimes defined by their 'half angle', $\phi = \tan^{-1}({}^{R}/_{L})$ and $y = x \tan \phi$
- $C_p = {}^{L}/_{3}$
- $V = \pi R^2 L/3$
- $S = \pi R(R^2 + L^2)^{.5}$

Elliptical Nose Cones



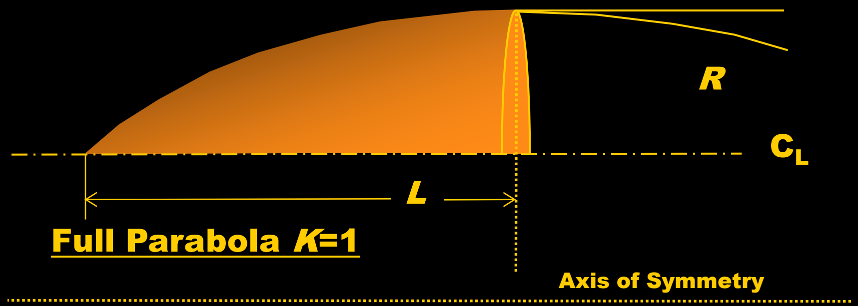
- The profile of this shape is one-half of an ellipse, with the major axis being the centerline and the minor axis being the base of the nosecone
- This shape is advantageous for subsonic flight due to its blunt nose and tangent base
- It is defined by: $y = R(1-{}^{x^2}/_{L^2})^{½}$
- $C_p={}^{3L}/_2$
- $V=2\pi R^2L/3$
- $S=\pi L^2+[\pi R^2/\sigma[\ln\{(1+\sigma)/(1-\sigma)\}]]/2$ where $\sigma=(L^2+R^2)/L$

Tangent Ogive Nose Cones



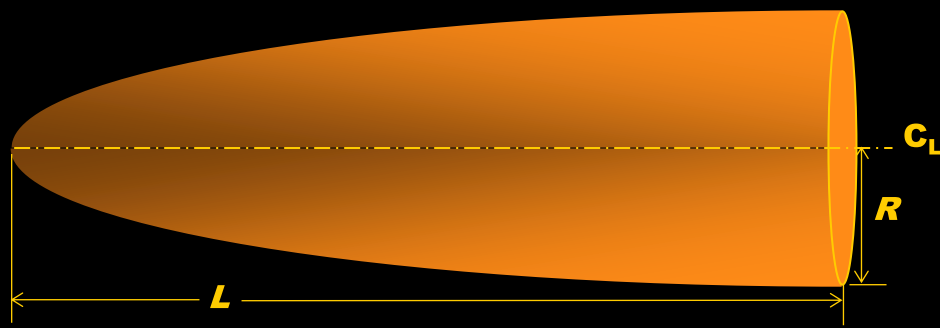
- This shape is formed by a circle segment where the base is on the circle radius and the airframe is tangent to the curve of the nosecone at its base
- The radius of the circle that forms the ogive is: $\rho = (R^2 + L^2)/2R$
- The radius *y* at any point *x*, as *x* varies from 0 to *L* is: $y = (\rho^2-(x-L)^2)^{½}+R- \rho$ where $L \leq \rho$
- $C_p=V/\pi R^2$
- $V=\pi[L\sigma^2 - L^3/\sigma – (\sigma^3 - R\sigma^2)\sin^{-1}(L/\sigma)]$ where $\sigma=(R^2 + L^2)/2R$
- S=?

Parabolic Nose Cones



- The Parabolic Series nose shape is generated by rotating a segment of a parabola around a line parallel to its axis of symmetry.
- $y=R\{(2[{}^{x}/_{L}]-K[{}^{x}/_{L}]^{2})/(2-K)\}$ for $0 \leq K \leq 1$
  - $K = 0$ for a CONE
  - $K = .5$ for a 1/2 PARABOLA
  - $K = .75$ for a 3/4 PARABOLA
  - $K = 1$ for a PARABOLA (base tangent to airframe)
- $C_p = {}^{L}/_{2}$
- $V = \pi R^2 L/2$
- $S = R^2/4L$

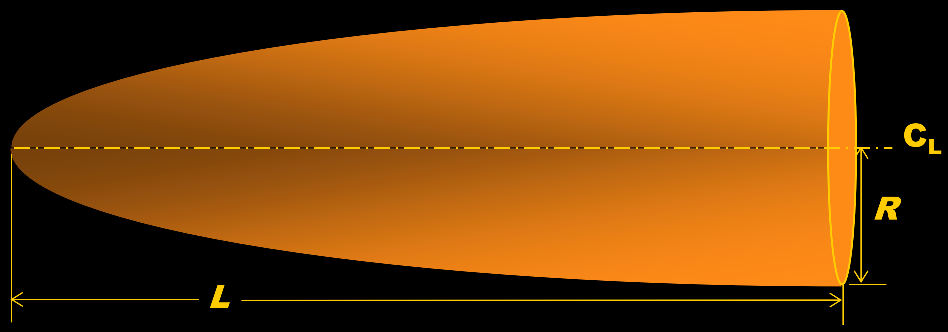
Power Series Nose Cones



Power Series

- The Power Series shape is characterized by its (usually) blunt tip, and by the fact that its base is not tangent to the body tube.
- The Power series nose shape is generated by rotating a parabola about its major axis. The base of the nosecone is parallel to the latus rectum of the parabola, and the factor *n* controls the 'bluntness' of the shape. As *n* decreases towards zero, the Power Series nose shape becomes increasingly blunt; at values of *n* above about .7, the tip becomes sharp.
- $y=R(^{x}/_{L})^{n}$ for $0 \le n \le 1$
  - *n* = 1 for a CONE
  - *n* = .75 for a ¾ POWER
  - *n* = .5 for a ½ POWER (PARABOLA)
  - *n* = 0 for a CYLINDER
- C_p=?
- V=?
- S=?

Sears-Haack Nose Cones



Sears-Haack

- **Not constructed from geometric figures**
- **Mathematically derived for drag minimization**
- **Not tangent to body at base**
- **Rounded not sharp nose tips**
- $y = R\{\theta - [\sin(2\theta)/2] + C\sin^3(\theta)\}^{1/2}/(\pi)^{1/2}$ **where** $0 \le C$ **and** $\theta = \cos^{-1}(1-2x/L)$
  - **C = 0 minimum drag for given Length and Volume (LV)**
  - **C = 1/3 minimum drag for given Length and Diameter (LD - Von Karman)**
- $C_p = {}^{L}/_{2}$ **Von Karman;** $C_p = .437L$ **LV-Haack**
- **V=?**
- **S=?**

Nose Cone References

1. Topics in Advanced Model Rocketry; Mandell, Gordon K.; Caporaso, George J.; Bengen, William P.; The MIT Press; 1973
2. Investigation of the Drag of Various Axially Symmetric Nose Shapes of Fineness Ratio 3 for Mach Numbers from 1.24 to 3.67; Perkins, Edward W.; Jorgensen, Leland H.; NACA Research Memorandum A52H28; 1952.
3. Investigation of the Drag of Various Axially Symmetric Nose Shapes of Fineness Ratio 3 for Mach Numbers from 1.24 to 7.4; Perkins, Edward W.; Jorgensen, Leland H.; Sommer, Simon C.; NACA Technical Report 1386; 1958.
4. Transonic Drag Measurements of Eight-Body Nose Shapes; Stoney, Jr., William, G.; NACA Research Memorandum L53K17; 1954.
5. The Effect of Bluntness on the Drag of Spherical-Tipped Truncated Cones of Fineness Ratio 3 at Mach Numbers 1.2 to 7.4; Sommer, Simon C.; Stark, James A.; NACA Research Memorandum A52B13; 1954.
6. Pressure Drag of Bodies at Mach Numbers up to 2.0; Nelson, Robert L.; Stoney, Jr., William, G.; NACA Research Memorandum L53I22c; 1953.
7. Bodies of Revolution having Minimum Drag at High Supersonic Airspeeds; Eggers Jr, A. J.; Resnikoff, Meyer M.; Dennis, David H.; NACA Technical Report 1306, 1957.
8. Hypersonic Aerodynamic Performance of Minimum-Wave-Drag Bodies; Spencer, Jr., Bernard; Fox Jr., Charles H.; NASA Technical Report R-250; 1966.
9. Longitudinal Aerodynamic Performance of a Series of Power-Law and Minimum-Wave-Drag Bodies at Mach 6 and Several Reynolds Numbers; Ashby Jr., George C.; NASA Technical Memorandum X-2713; 1974.
10. Performance and Dynamics of Aerospace Vehicles; Love, E. S.; NASA SP-258; 1971; pages 103-174.

Fin References

11. Effect of Number of Fins on the Drag of a Pointed Body of Revolution at Low Supersonic Velocities; Mastrocola, N; NACA Research Memorandum L7A08; 1947.
12. Transonic Drag Characteristics of a Wing-Body Combination Showing the Effect of a Large Wing Fillet; Cheatham, Donald C.; Kurbjun, Max C.; NACA Research Memorandum L8F08; 1948.
13. Damping in Roll of Models with 45°, 60°, and 70° Delta Wings Determined at High Subsonic, Transonic, and Supersonic Speeds with Rocket-Powered Models; Saunders Jr, E Claude; NACA Research Memorandum L52D22a; 1952.
14. Aerodynamic Characteristics of Two Delta Wings and Two Trapezoidal Wings at Mach 4.04; Dunning, Robert W.; Smith, Fred W.; NACA Research Memorandum L53D30A; 1953.
15. Results of a Flight Investigation to Determine the Zero-Lift Drag Characteristics of a 60° Delta Wing with NACA 65-006 Airfoil Section and Various Double-Wedge Sections at Mach Numbers from 0.7 to 1.6; Welsh, Clement J.; NACA Technical Note 3650; 1956.
16. Summary of Flutter Experiences as a Guide to the Preliminary Design of Lifting Surfaces on Missiles; Martin, Dennis J.; NACA Technical Note 4197; 1958.
17. The Characteristics of 78 Related Airfoil Sections from Tests in the Variable-Density Wind Tunnel; Jacobs, Eastman N.; Ward, Kenneth E.; Pinkerton, Robert N; NACA Technical Report 460; 1948.
18. Tests of 16 Related Airfoils at High Speeds; Stack, John; Von Doenhoff, Albert E.; NACA Technical Report 492; 1935.
19. Free-Flight Measurements of the Zero-Lift Drag of Several Wings at Mach Numbers from 1.4 to 3.8; Jackson, H. Herbert; NASA Technical Note D-395; 1960.
20. Aeroelastic Optimization of Sounding Rocket Fins; Simmons III, Joseph R.; Air Force Institute of Technology; 2009.
21. NASA Supercritical Airfoils; Harris, Charles D.; NASA Technical Paper 2969; 1990.

MDO References

1. Results of Flight Tests at Supersonic Speeds to Determine the Effect of Body Nose Fineness Ratio on Body and Wing Drag; Katz, Ellis R; NACA Research Memorandum L7B19; 1947.

Selected Websites

- http://exploration.grc.nasa.gov/education/rocket/guided.htm
- http://ntrs.nasa.gov/search.jsp
- http://www.apogeerockets.com/Peak-of-Flight_index.asp
- http://www.rocketmaterials.org/
- http://www.aerorocket.com/