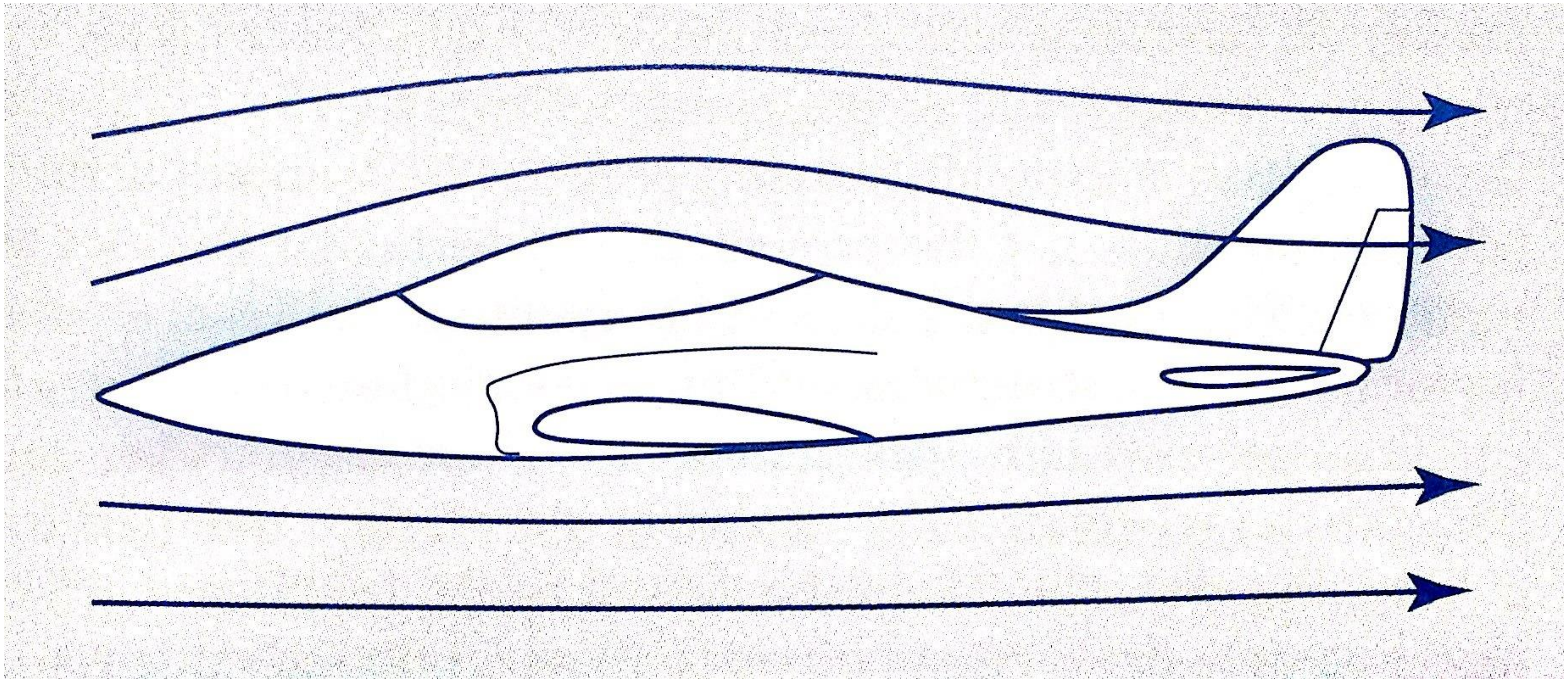
ME4932 Aircraft Performance & Design

Aerodynamics (Chapter 12)



Source: Aircraft Design by Daniel P. Raymer

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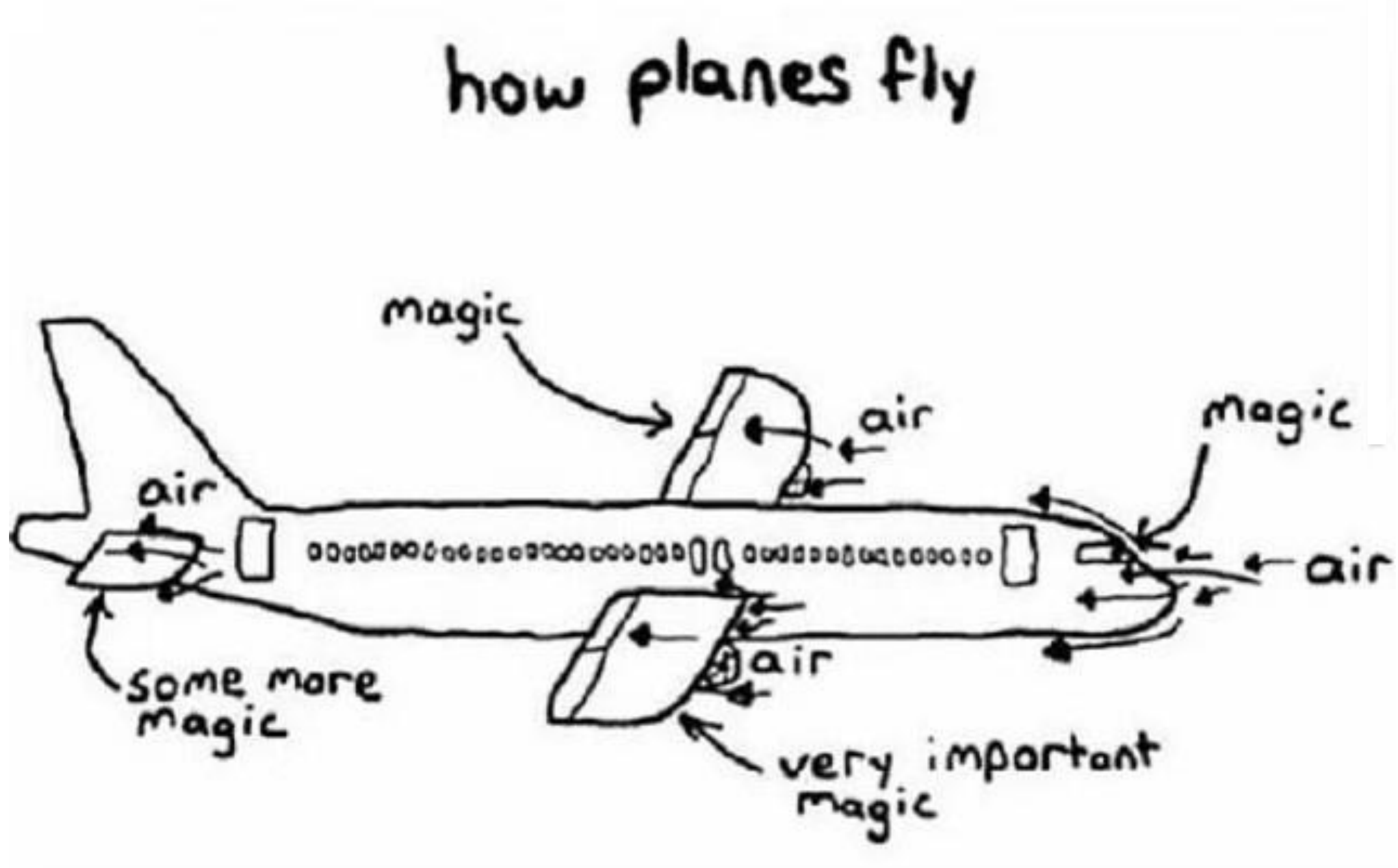
Aerodynamics (Chapter 12)



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Aerodynamics (Chapter 12)

- Only two forces!
- Shear (Tangential to aircraft surfaces)
    - Friction Drag
    - Laminar or Turbulent Boundary Layer
- Pressure (Perpendicular to aircraft)
    - Local changes in flow velocity cause pressure differences
    - When M>1 additional forces by shock waves
    - Form drag and lift

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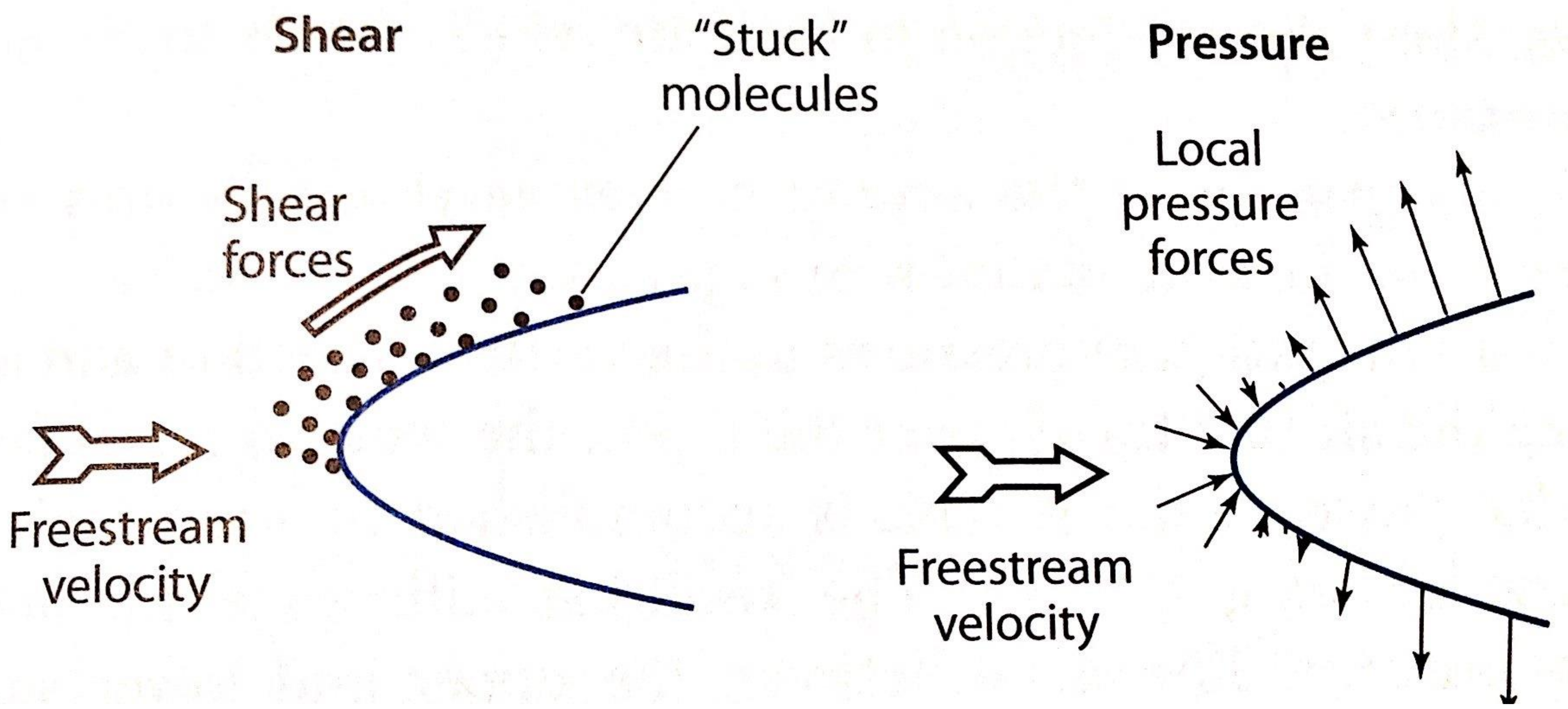

Parasite Drag = Skin Friction Drag + Form Drag + Wave Drag

Source: Aircraft Design by Daniel P. Raymer

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Drag-due-to-lift = Induced Drag + Profile Drag Change due to Flow Separation vs. AOA

Induced Drag = Drag Directly Caused by Lift

It is a 3-D effect. In a finite wing higher pressure air from bottom of wing wants to escape around wing tip, shedding vortices @ wing tips.

Profile Drag Change with AOA = It is a 2D effect. Due to INCREASED separation at higher AOA's

Trim Drag = Additional drag due to deflection of tail to balance moments.

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Perpendicular to Freestream:

$$L = C_L \overline{q} S$$

Parallel to Freestream:

$$D = C_D \overline{q} S$$

Dynamic Pressure:

$$\overline{q} = \frac{1}{2} \rho V_\infty^2$$

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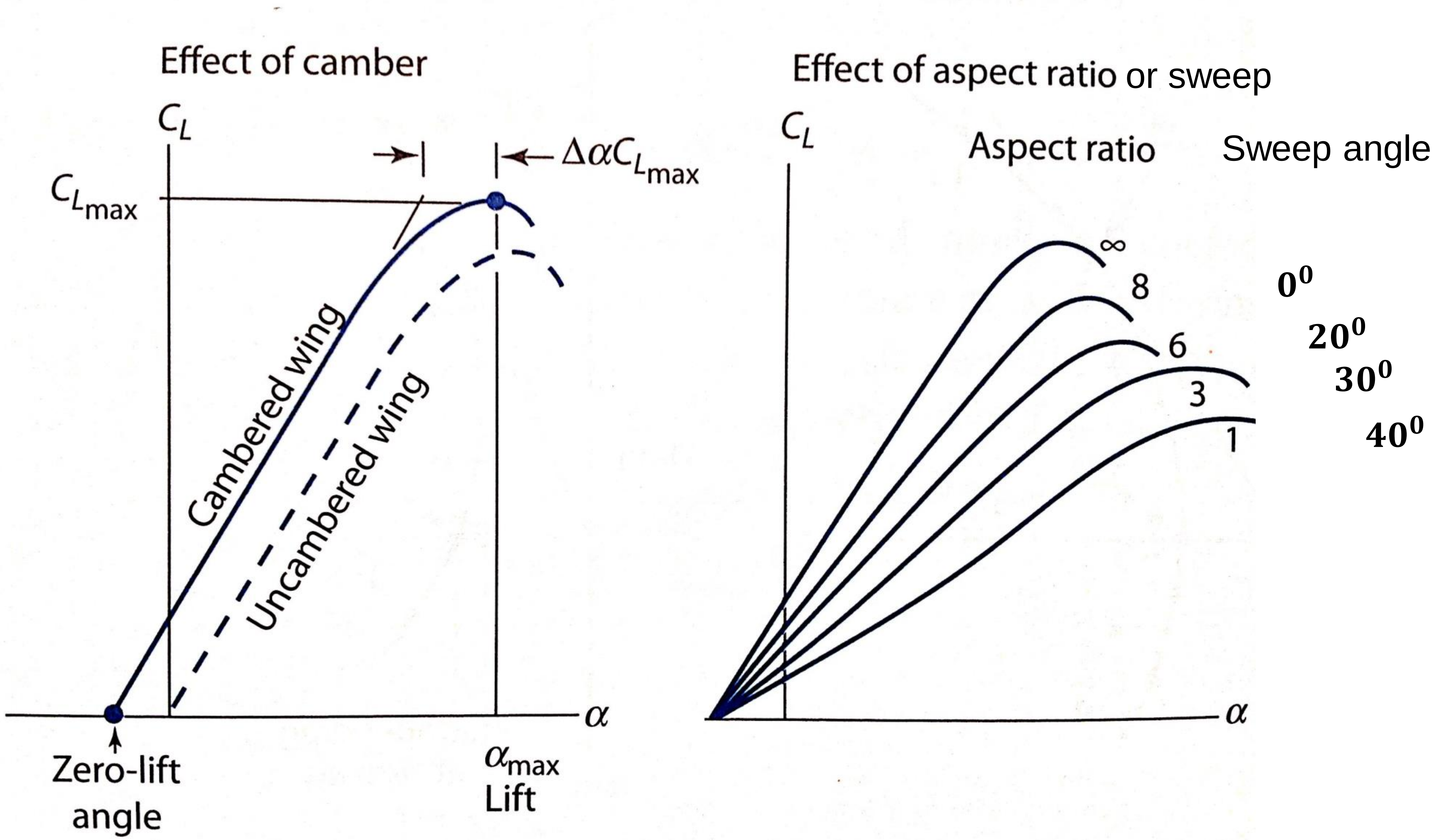

Airfoils have lift curve slopes of about 90-100% of 2xPi.
Zero-lift angle in degrees is roughly = % camber.
As AR decreases, slope decreases, but max AOA increases due to wing tip vortices
(Sweep has a similar effect)

Source: Aircraft Design by Daniel P. Raymer

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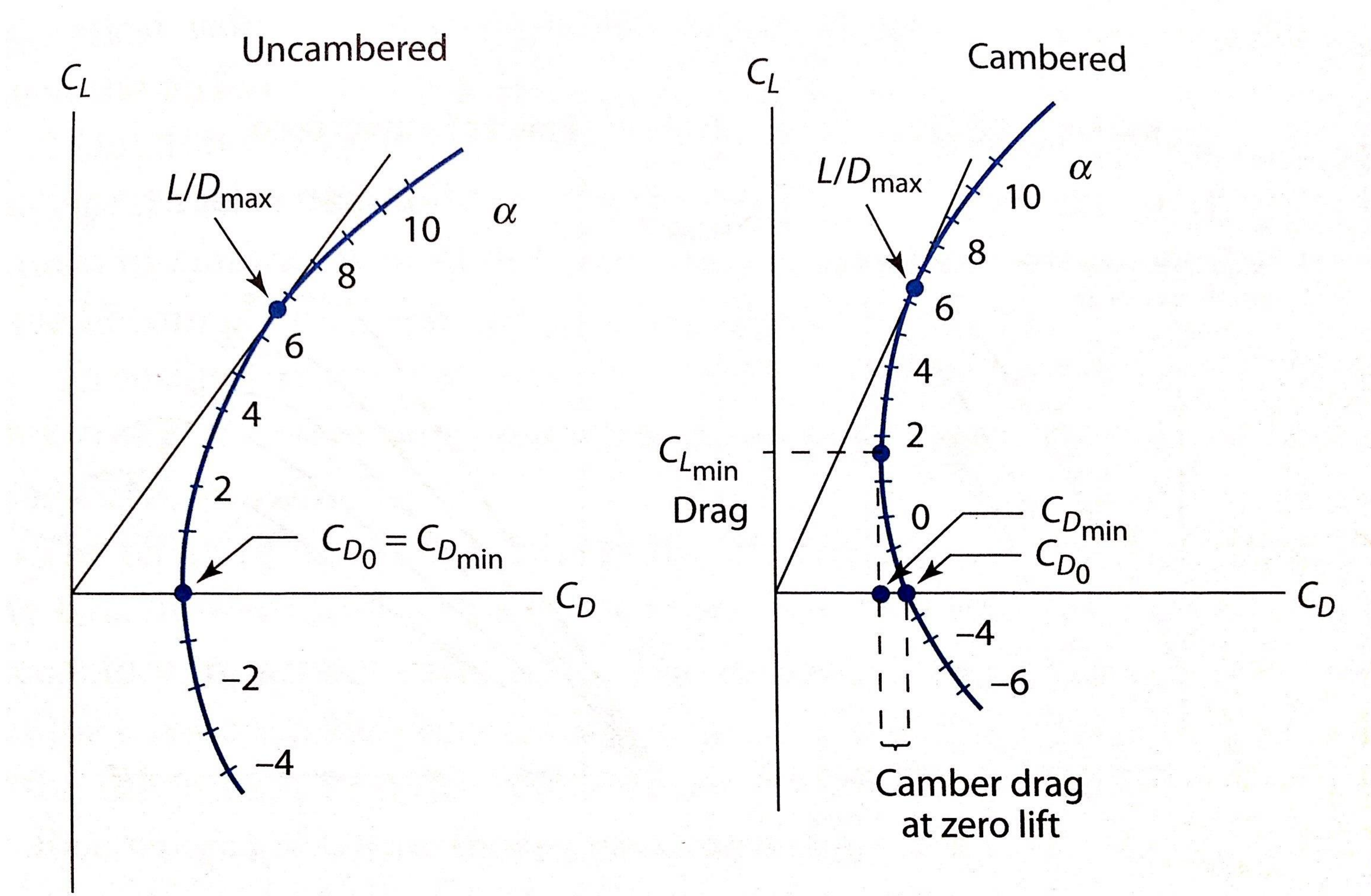

$$C_D = C_{D0} + KC_L^2$$

$$C_D = C_{D\,min} + K(C_L - C_{L_{mindrag}})^2$$

Source: Aircraft Design by Daniel P. Raymer

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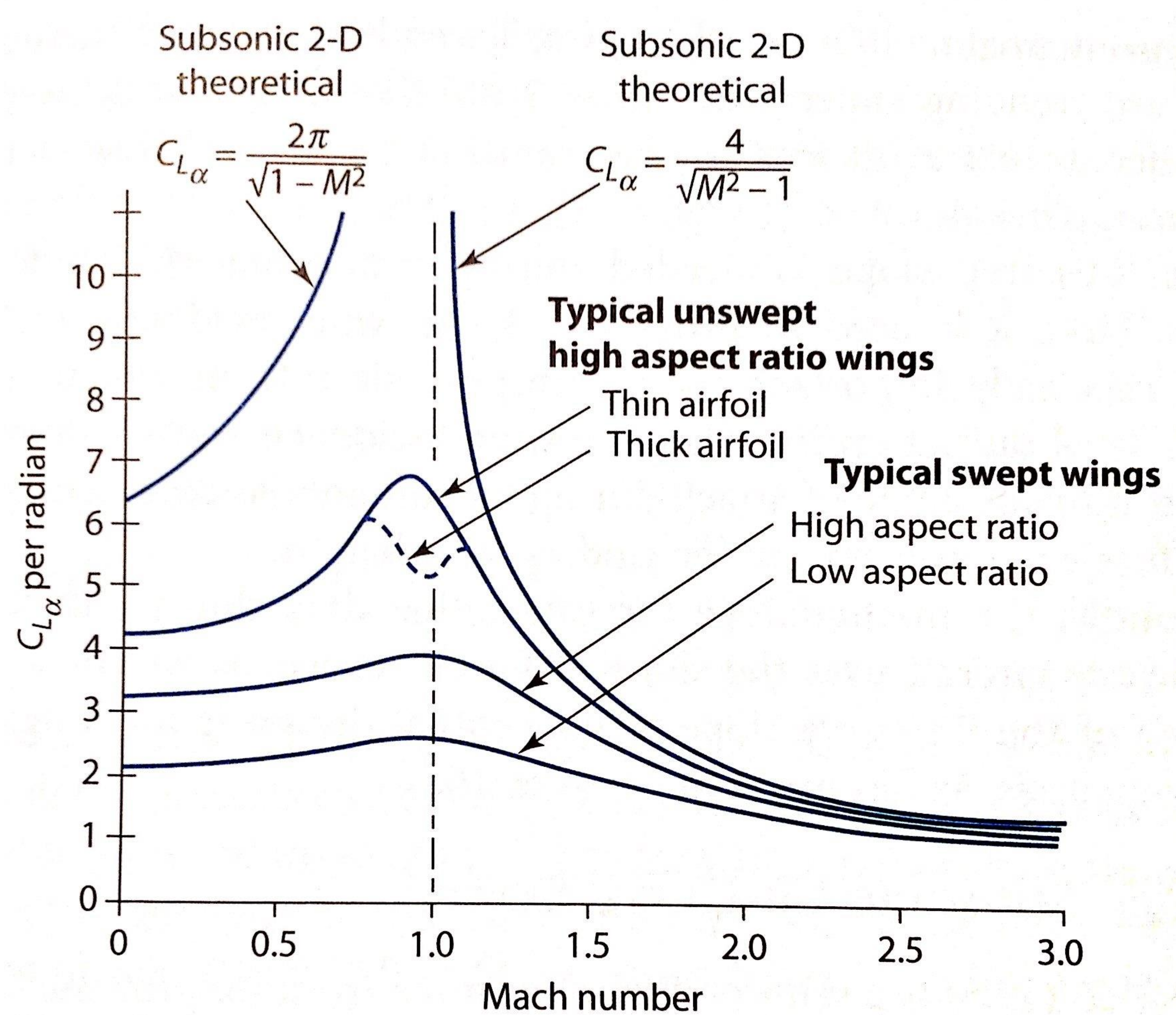

Effect of Mach Number, Sweep, and Aspect Ratio on Lift-Curve Slope

Source: Aircraft Design by Daniel P. Raymer

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Subsonic Lift Curve Slope (M<Drag Divergence):

$$C_{L\alpha} = \frac{2\pi A}{2 + \sqrt{4 + \frac{A^2\beta^2}{\eta^2}\left(1 + \frac{tan^2\Lambda_{maxt/c}}{\beta^2}\right)}}\left(\frac{S_{exp}}{S_{ref}}\right)(F)$$

$$\beta^2 = 1 - M^2$$

$$\eta = \frac{C_{l\alpha}}{\frac{2\pi}{\beta}}$$

$$F = 1.07(1 + d/b)^2$$

F = fuselage form factor
A = Aspect Ratio (should be corrected for endplates or winglets (eqns. 12.10-11)

Supersonic Lift Curve Slope :

$$C_{L\alpha} = \frac{4}{\beta}$$

(IDEAL) For fully supersonic leading edge i.e.
Mach cone > Sweep

For ALL supersonic Mach numbers, use DATCOM Charts (figures 12.7)

Transonic Lift Curve Slope :

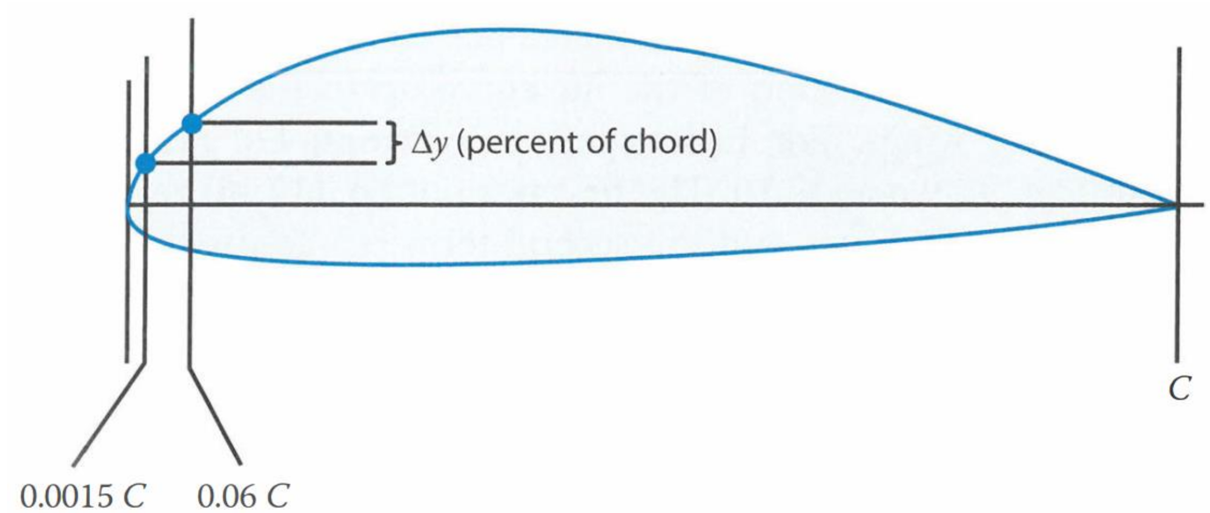
Just Fair a Curve Between Drag Divergence
and Supersonic

Maximum CLEAN Lift for **Moderate** Sweep Angles and **High** Aspect Ratios if Airfoil Aerodynamic Data is Available:

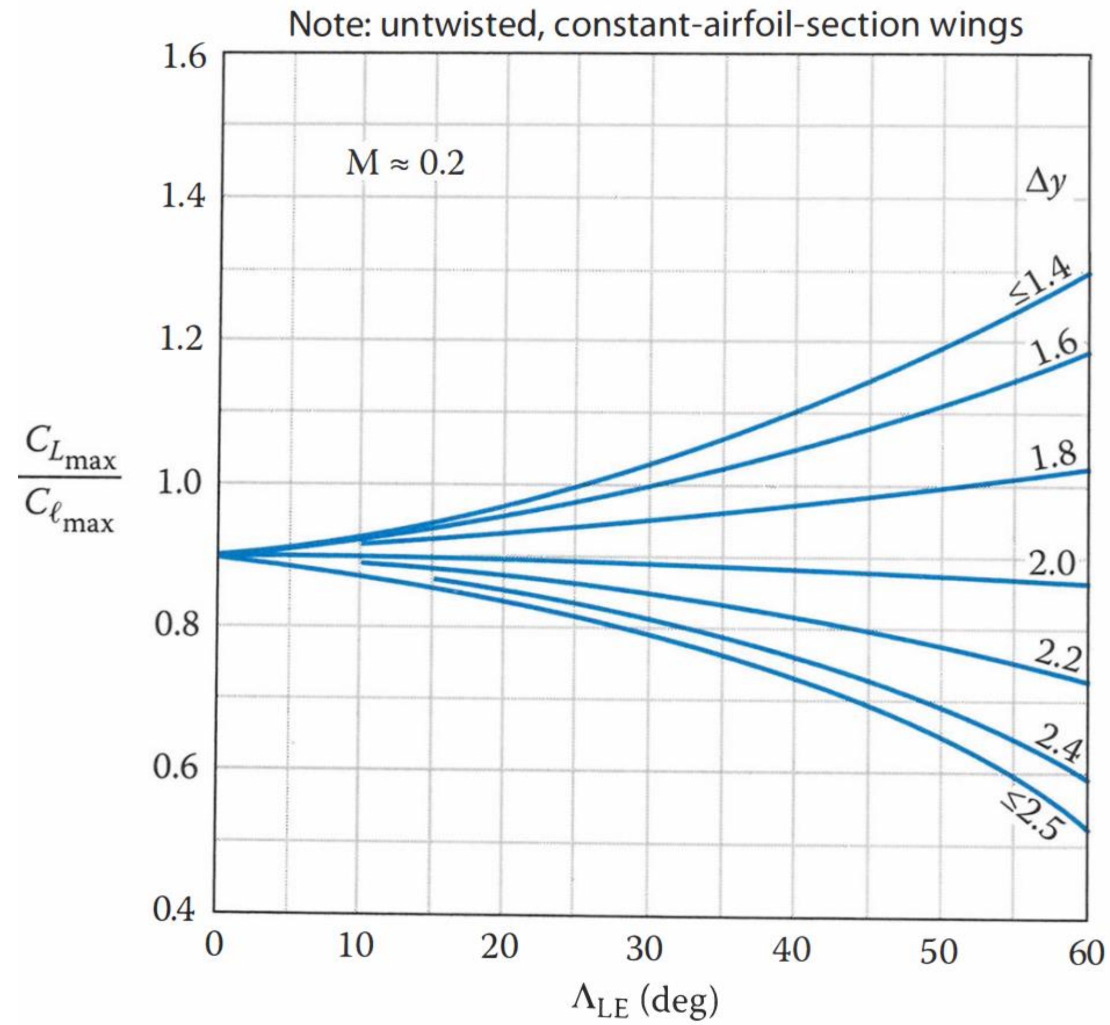
$$C_{L\,max} = 0.9 C_{l\,max} cos(\Lambda_{\frac{1}{4}chord})$$

For Very High Sweep Angles, Leading Edge Sharpness Becomes a First Order Effect Parameter. Use the tables and charts of pp. 418-421

Maximum CLEAN Lift for **All** Sweep Angles and **High** Aspect Ratio Subsonic Wings, Based on Leading-Edge Bluntness:



Airfoil Type	Δy
NACA 4 digit	$26\ t/c$
NACA 5 digit	$26\ t/c$
NACA 64 series	$21.3\ t/c$
NACA 65 series	$19.3\ t/c$
Biconvex	$11.8\ t/c$



High Aspect Ratio: $$C_{L\,max} = C_{\ell_{max}}\left(\frac{C_{L\,max}}{C_{\ell_{max}}}\right) + \Delta C_{L\,max}$$

Incompressible Compressible

Source: Aircraft Design by Daniel P. Raymer

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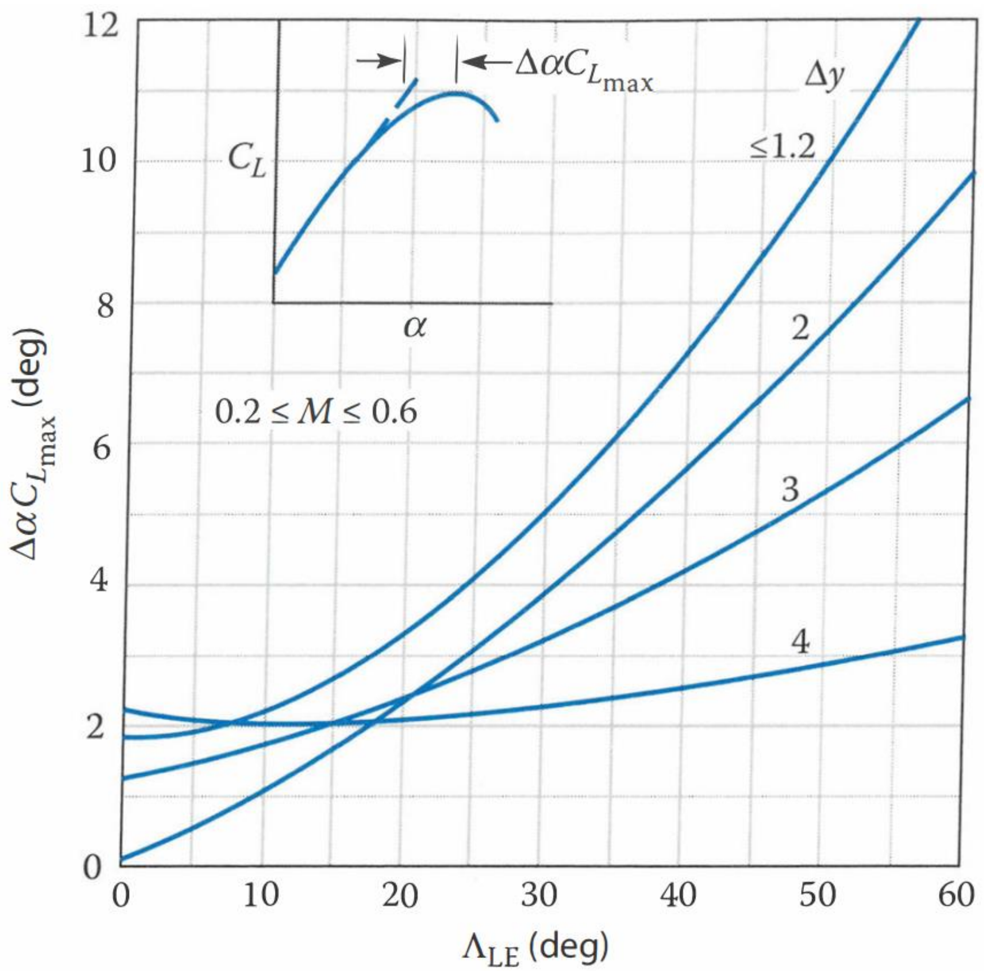
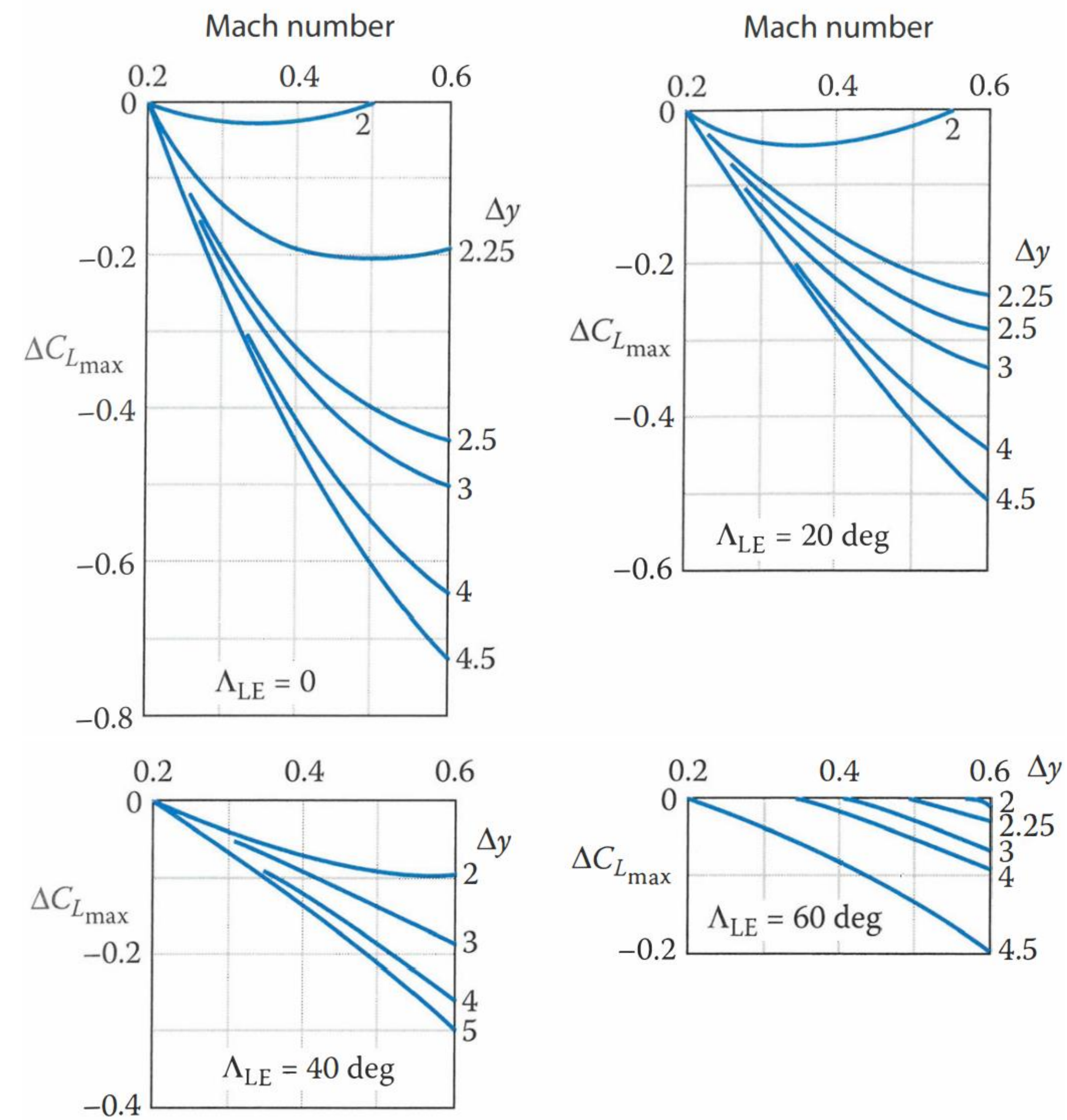
Maximum CLEAN Lift for **All** Sweep Angles and **High** Aspect Ratio Subsonic Wings, Based on Leading-Edge Bluntness :

$$C_{L\,max} = C_{\ell_{max}} \left(\frac{C_{L\,max}}{C_{\ell_{max}}} \right) + \Delta C_{L\,max}$$

$$\alpha_{C_{L\,max}} = \frac{C_{L\,max}}{C_{L_\alpha}} + \alpha_{0L} + \Delta\alpha_{C_{L\,max}}$$





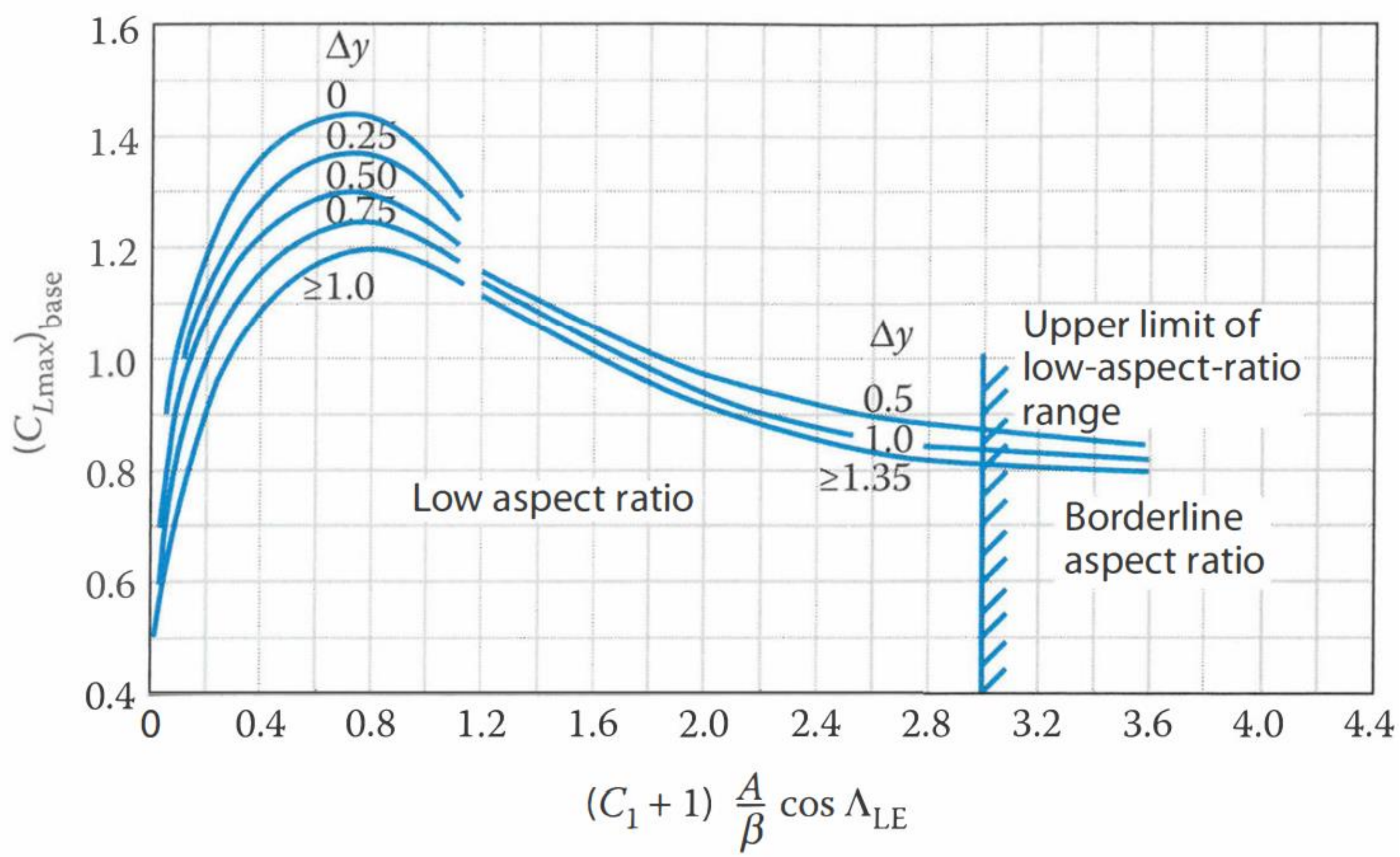
Source: Aircraft Design by Daniel P. Raymer

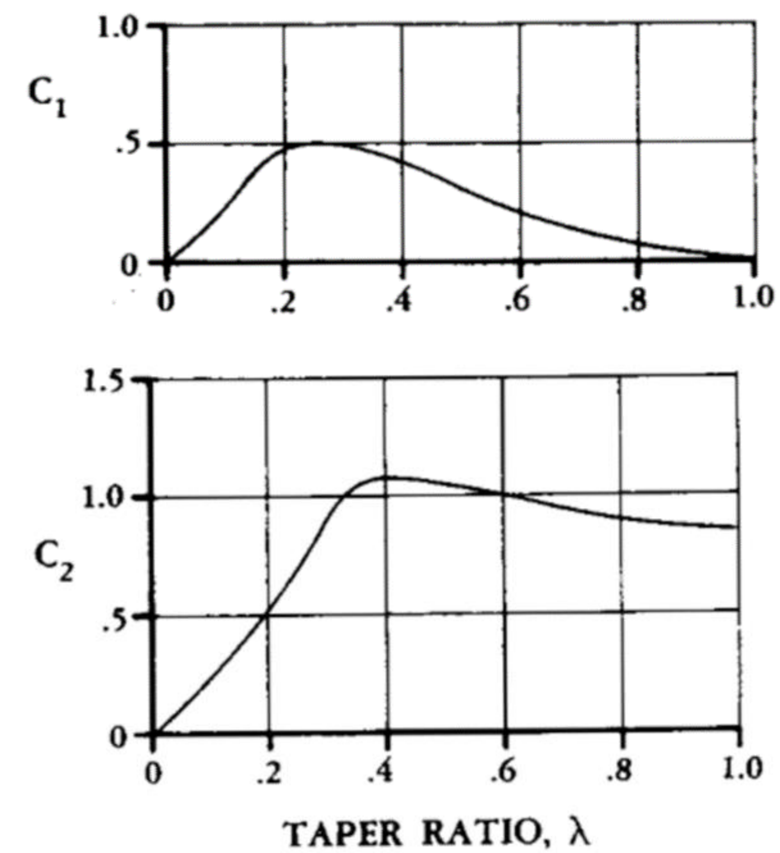
Maximum CLEAN Lift for **All** Sweep Angles and **Low** Aspect Ratios or Supersonic Wings:

Low Aspect Ratio if: $A \leq \dfrac{3}{(C_1 + 1)(\cos\Lambda_{LE})}$

$$C_{L_{max}} = (C_{L_{max}})_{base} + \Delta C_{L_{max}}$$

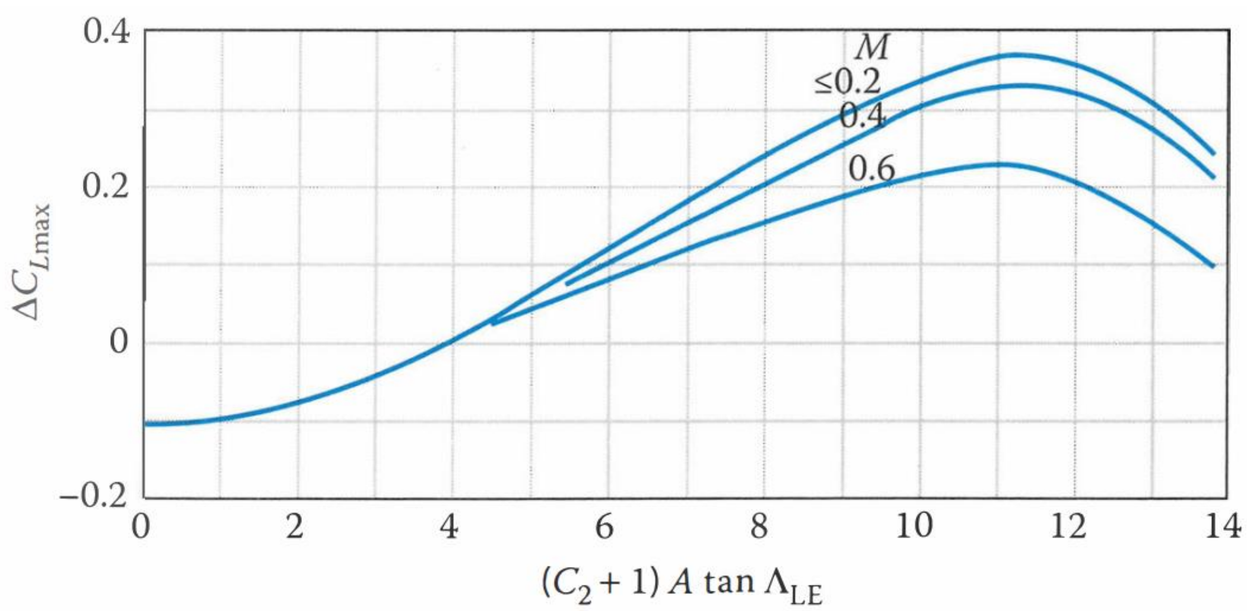
$$\alpha_{C_{L_{max}}} = (\alpha_{C_{L_{max}}})_{base} + \Delta\alpha_{C_{L_{max}}}$$





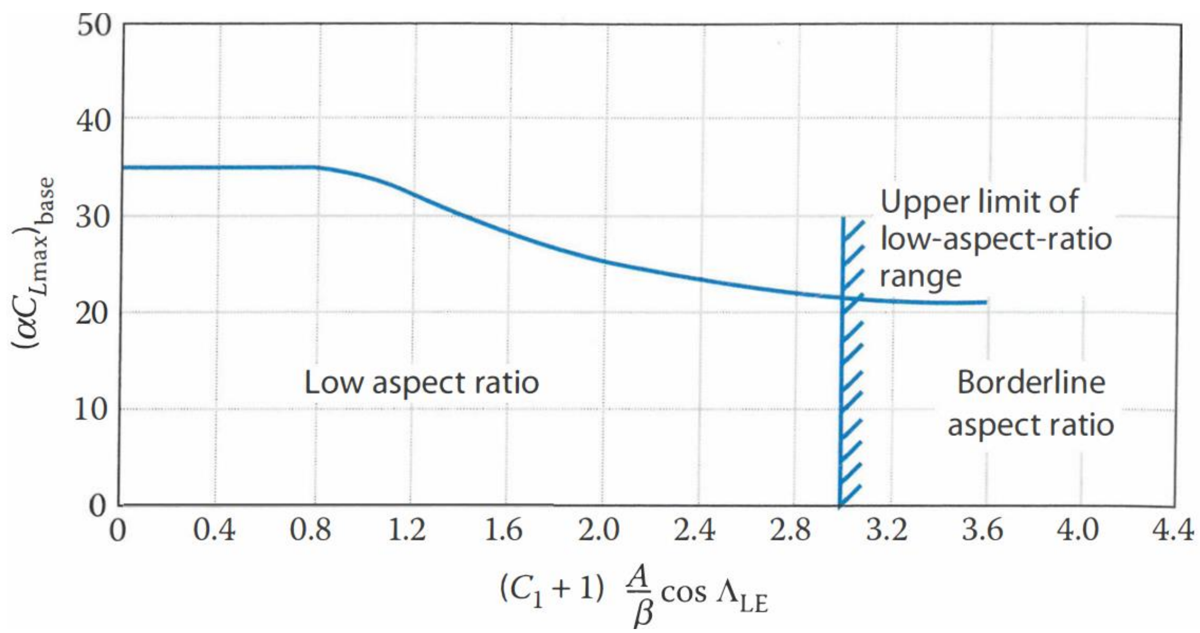
Source: Aircraft Design by Daniel P. Raymer

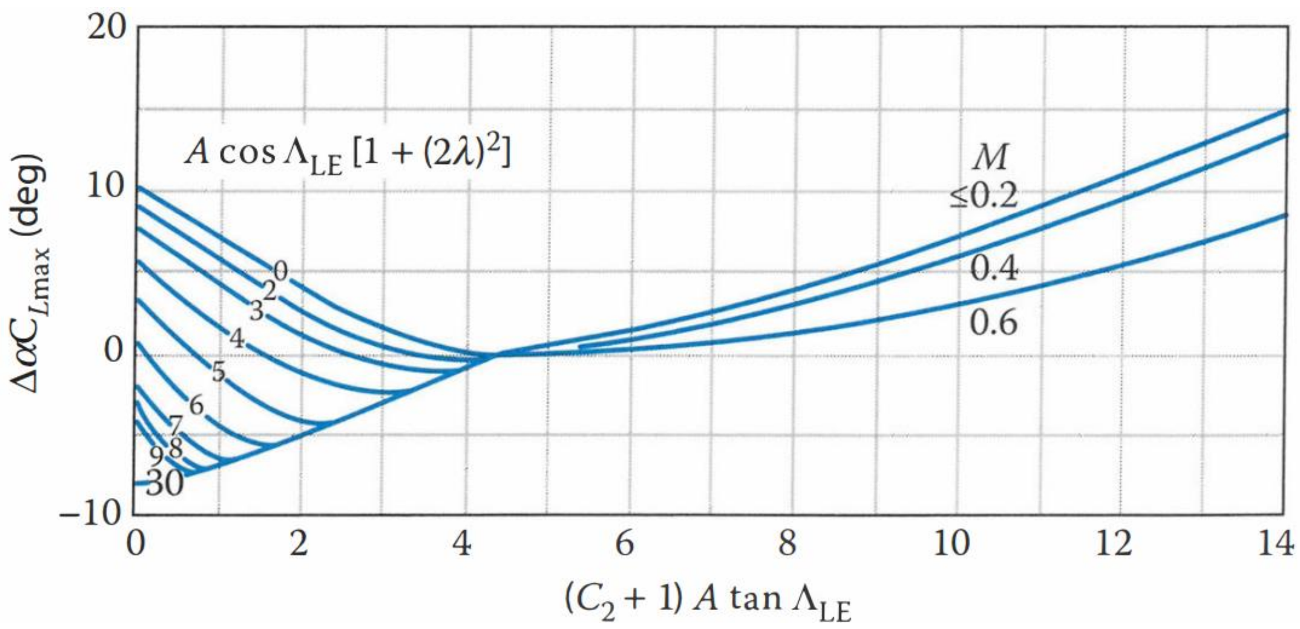
Maximum CLEAN Lift for **All** Sweep Angles and **Low** Aspect Ratios or **Supersonic** Wings:



$$C_{L_{max}} = (C_{L_{max}})_{base} + \Delta C_{L_{max}}$$

$$\alpha_{C_{L_{max}}} = (\alpha_{C_{L_{max}}})_{base} + \Delta\alpha_{C_{L_{max}}}$$





Source: Aircraft Design by Daniel P. Raymer

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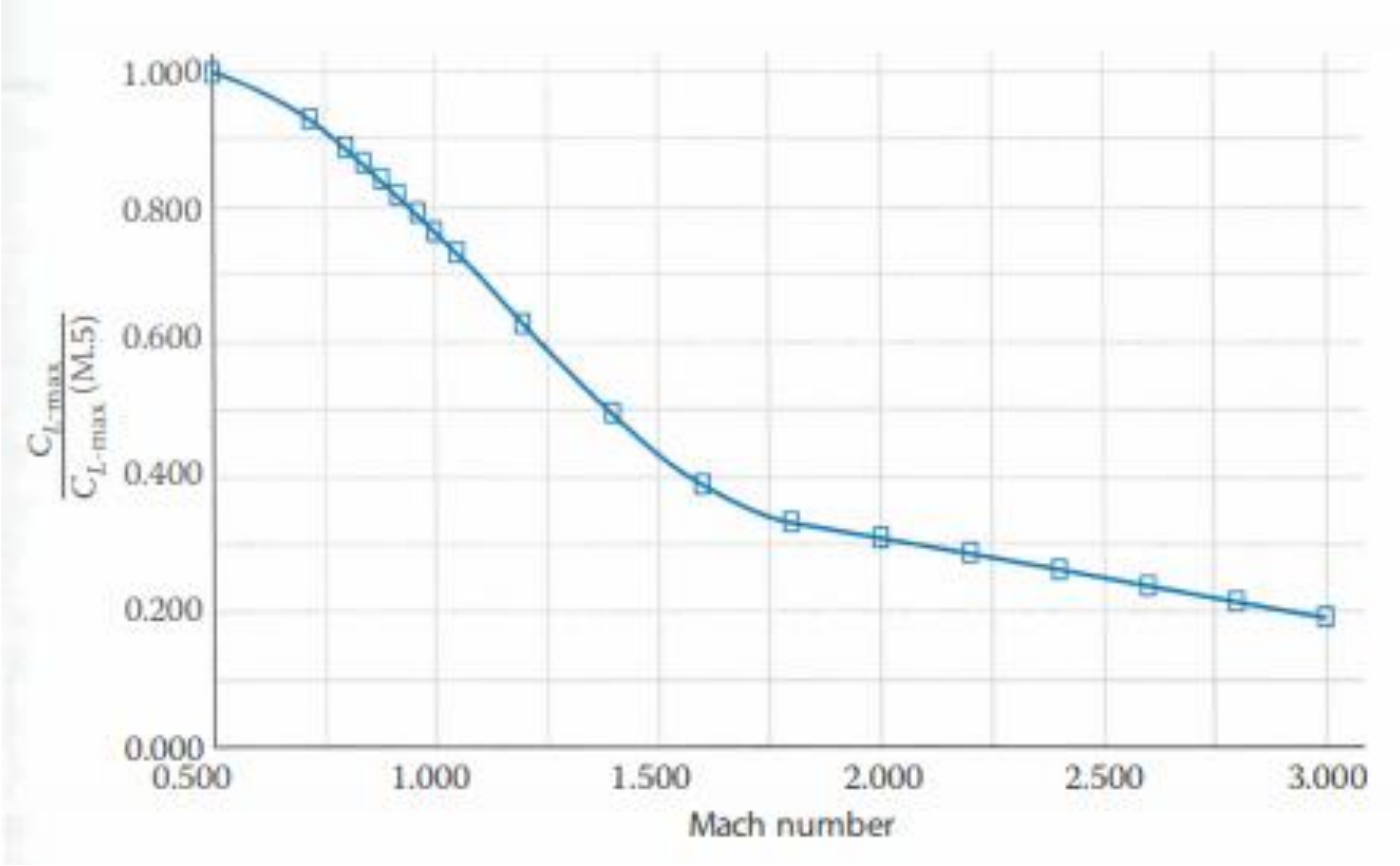
Maximum CLEAN Lift for **All** Sweep Angles and **Low** Aspect Ratios or Supersonic Wings:



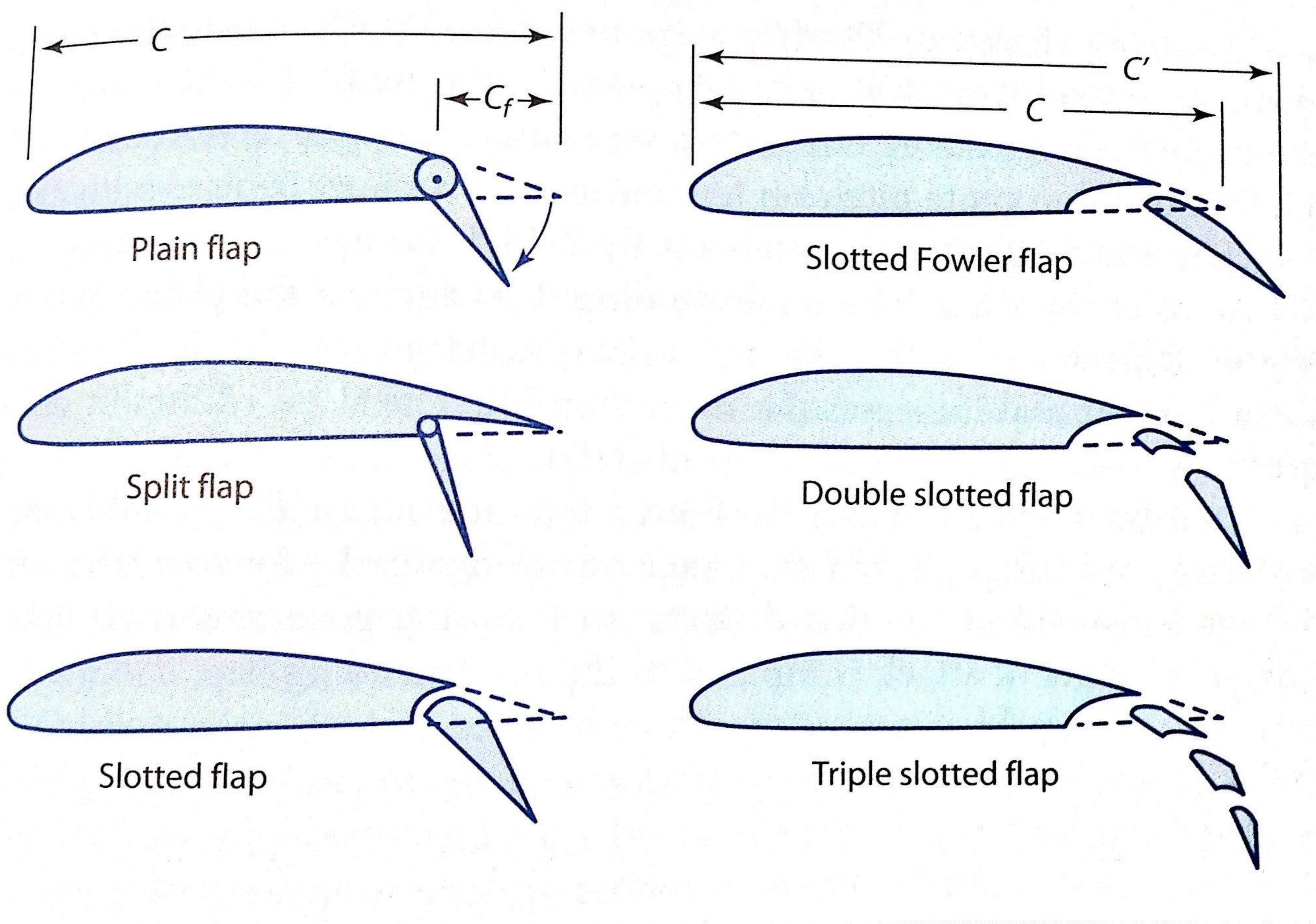
Source: Aircraft Design by Daniel P. Raymer

High-Lift Devices:

- Plain flap, 45 deg. optimum, works by increasing camber
- Split flap, more drag, when you want to increase glide slope
- Slotted flap, high pressure air energizes top, delaying separation
- Fowler flap; a slotted flap that increases wing area!

Flaps Do Not increase stall AOA, in fact they somewhat reduce it.

High-Lift Devices (continued):



Source: Aircraft Design by Daniel P. Raymer

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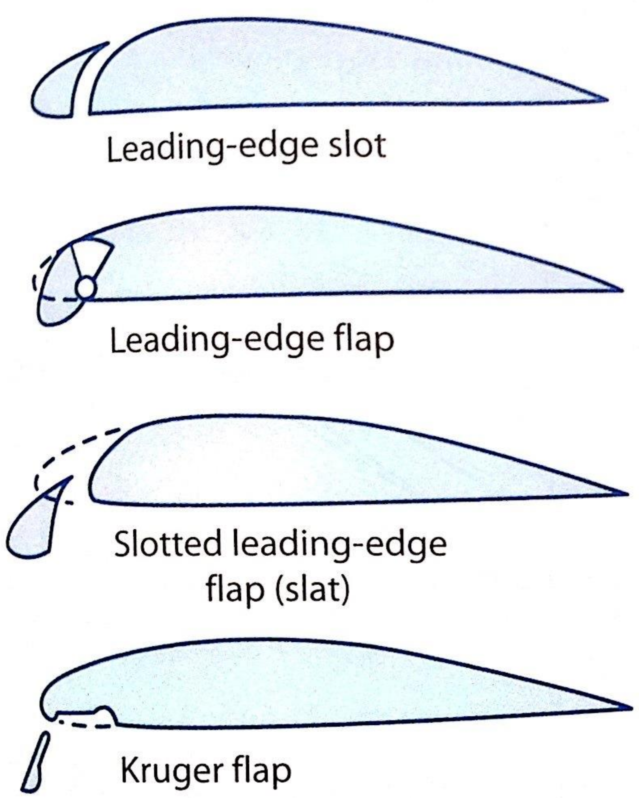
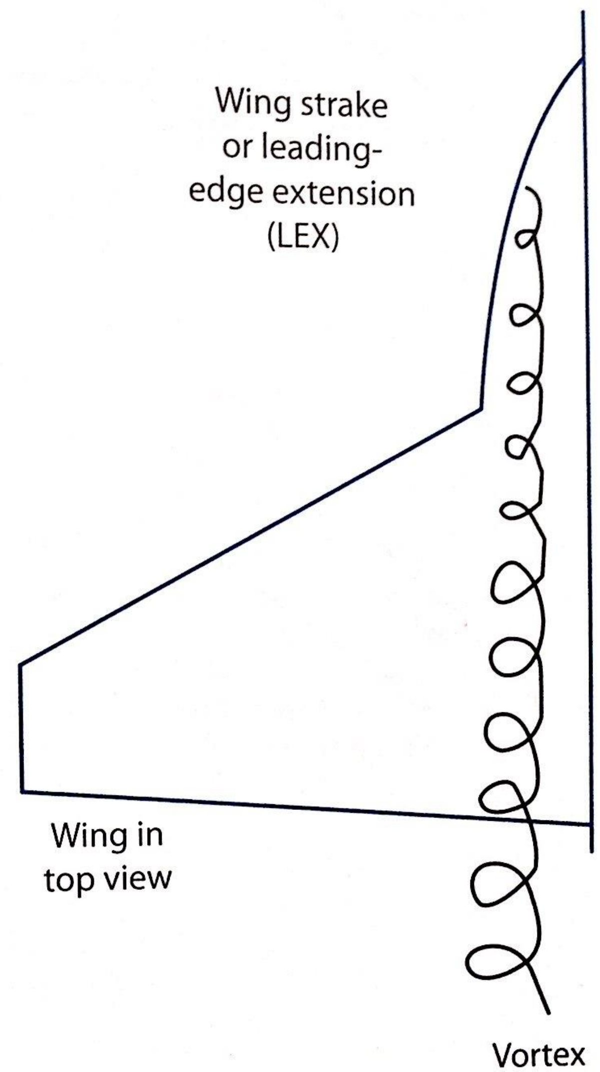
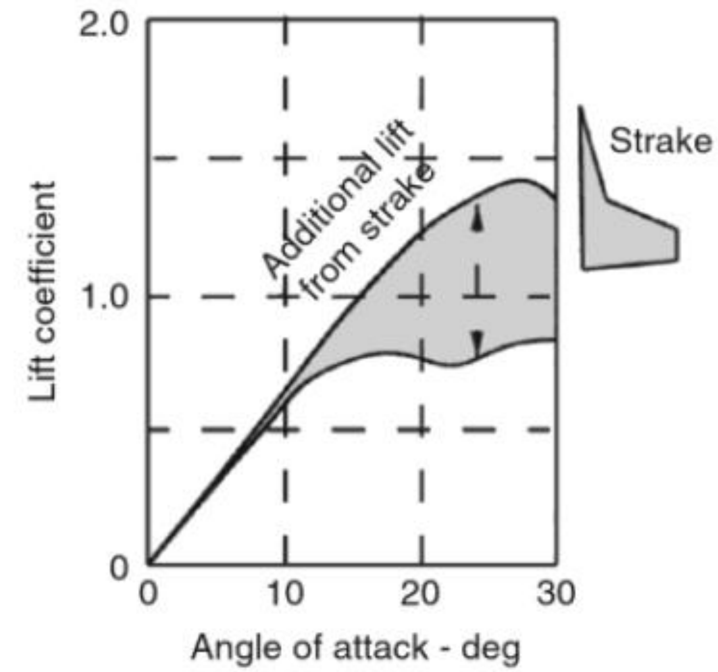
High-Lift Devices (continued):

- Leading Edge Slot, hole to energize the top of the wing,
- Leading Edge Flap, leading edge droops to increase camber
- Leading Edge Slat, energizes top of wing, increases camber and increases area!
- Kruger Flap, while the top of the wing remains smooth, uninterrupted, this device turns more streamlines travel towards the top and not the bottom of the wing
- Leading Edge Extension (LEX) is a fixed, always present feature that creates a strong vortex at AOA>20 degrees, it also increases area. Most effective for combat maneuvering.

High-Lift Devices (continued):



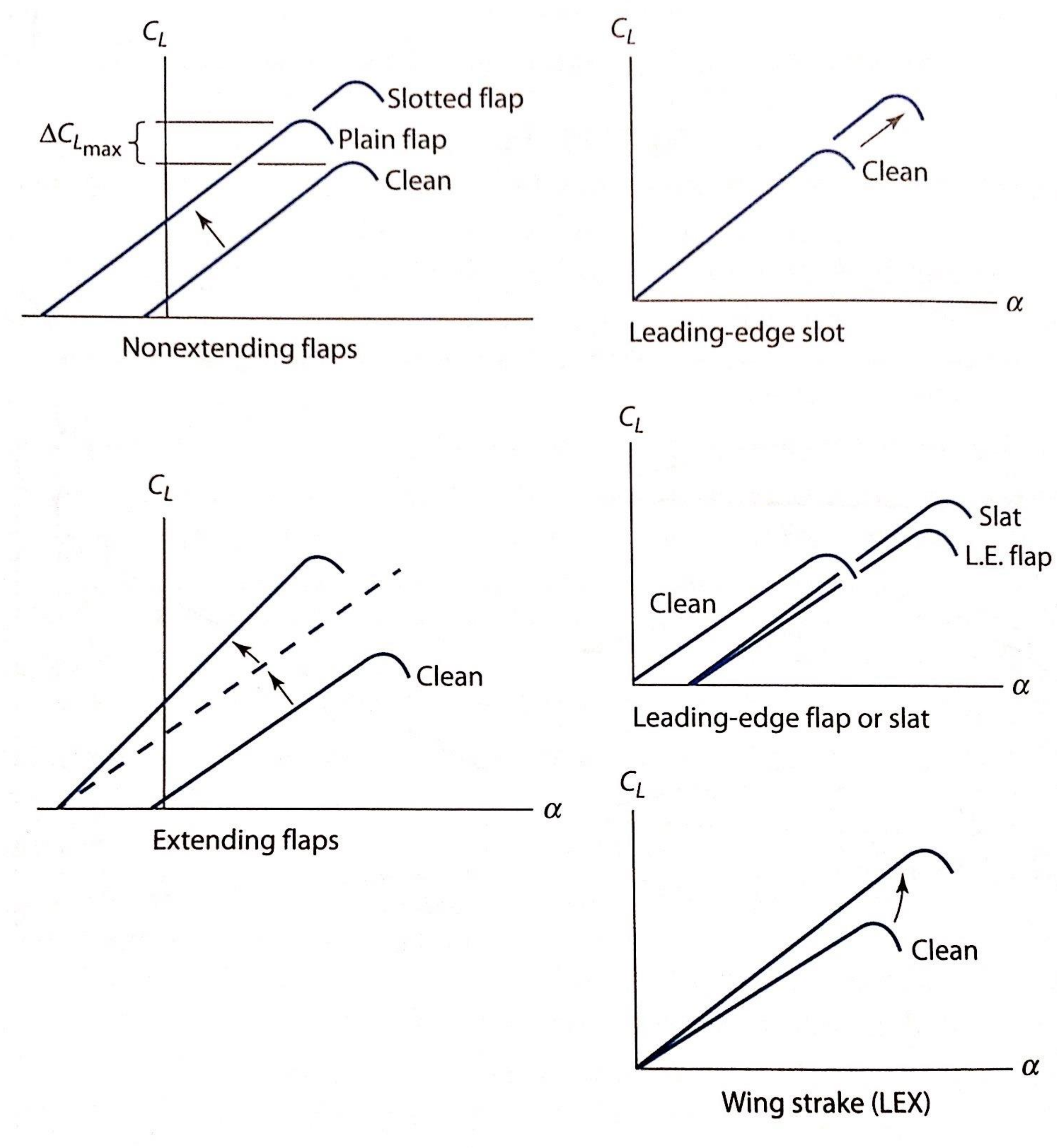




A wing designed for supersonic performance (low camber and t/c) suffers flow separation at a fairly low C_L. This is alleviated by the vortex lift of the LEX.

Source: Aircraft Design by Daniel P. Raymer

High-Lift Devices (continued):



Leading Edge Devices work well when combined with Trailing Edge Devices in order to obtain lift benefit at various AOA's and not just at the very high angles.

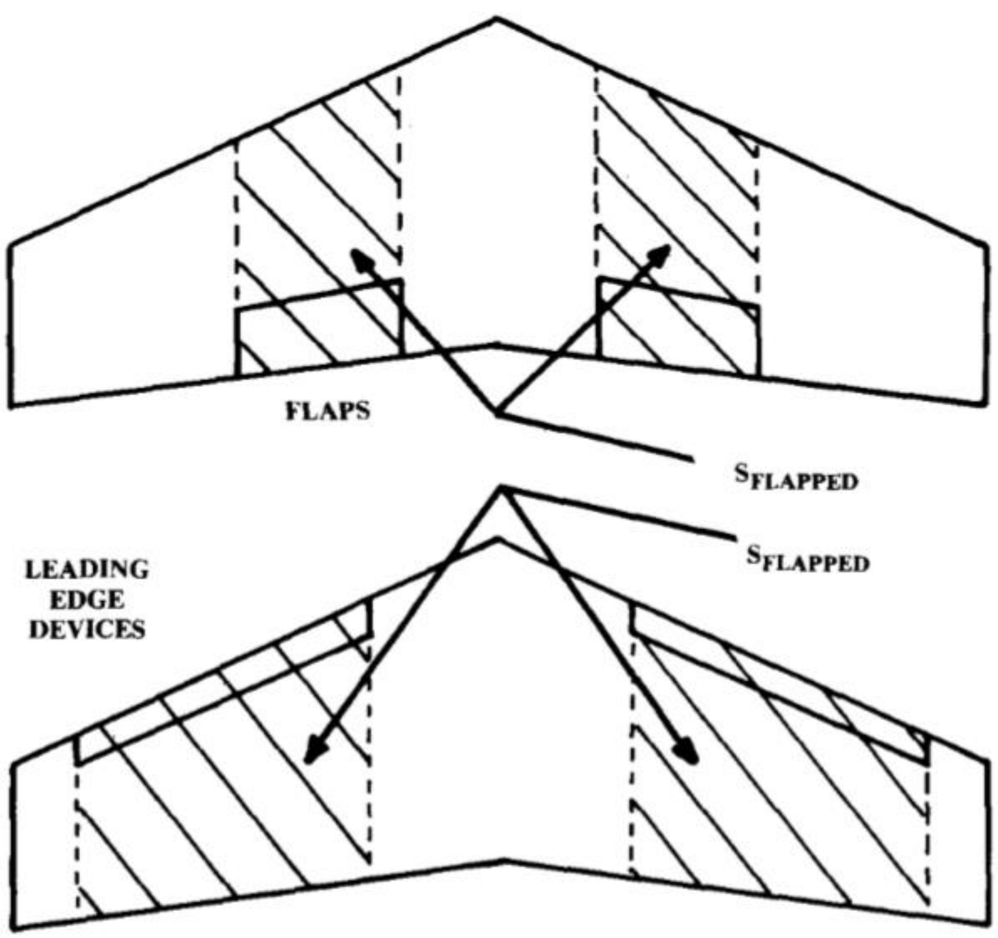
Source: Aircraft Design by Daniel P. Raymer

High-Lift Devices (continued):

High Lift Devices are used on most aircraft to achieve takeoff/landing performance without the cost of a **larger wing**. Combat aircraft use these to do the same for high AOA maneuver performance.

The increase in CLmax due to the use of these devices can be found on table 12.2 and must be corrected for device size and sweep angle.

High-Lift Devices (continued):



$$\Delta C_{L_{max}} = \Delta C_{\ell_{max}} \left(\frac{S_{flapped}}{S_{ref}} \right) \cos \Lambda_{H.L.}$$

$$\Delta \alpha_{OL} = (\Delta \alpha_{OL})_{airfoil} \left(\frac{S_{flapped}}{S_{ref}} \right) \cos \Lambda_{H.L.}$$

High-lift device	$\Delta C_{\ell_{max}}$
Flaps	
Plain and split	0.9
Slotted	1.3
Fowler	1.3 c′/c
Double slotted	1.6 c′/c
Triple slotted	1.9 c′/c
Leading edge devices	
Fixed slot	0.2
Leading edge flap	0.3
Kruger flap	0.3
Slat	0.4 c′/c

Change in CLmax should be 60-80% for takeoff. Change in zero-lift angle should be -10 and -15 deg. at takeoff and landing.

Source: Aircraft Design by Daniel P. Raymer

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Parasite (zero lift) Drag:

- Equivalent Skin-Friction Method
  - Very Simple
  - Based on existing aircraft
- Component Buildup Method
  - Analyzes each component of aircraft
  - Estimates friction contribution
  - Estimates form or pressure drag contribution

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Subsonic Parasite (zero lift) Drag :

Equivalent Skin-Friction Method

$$C_{D_0} = C_{f_e} \frac{S_{wet}}{S_{ref}}$$

It includes both friction and form effects. This method is good for initial analyses or to check more detailed methods. S_{wet} is the wetted area , the area of all external surfaces.

$C_{D0} = C_{fe}(S_{wet}/S_{ref})$	C_{fe}
Bomber	0.0030
Civil transport	0.0026
Military cargo (high upsweep fuselage)	0.0035
Air Force fighter	0.0035
Navy fighter	0.0040
Clean supersonic cruise aircraft	0.0025
Light aircraft—single engine	0.0055
Light aircraft—twin engine	0.0045
Prop seaplane	0.0065
Jet seaplane	0.0040

Source: Aircraft Design by Daniel P. Raymer

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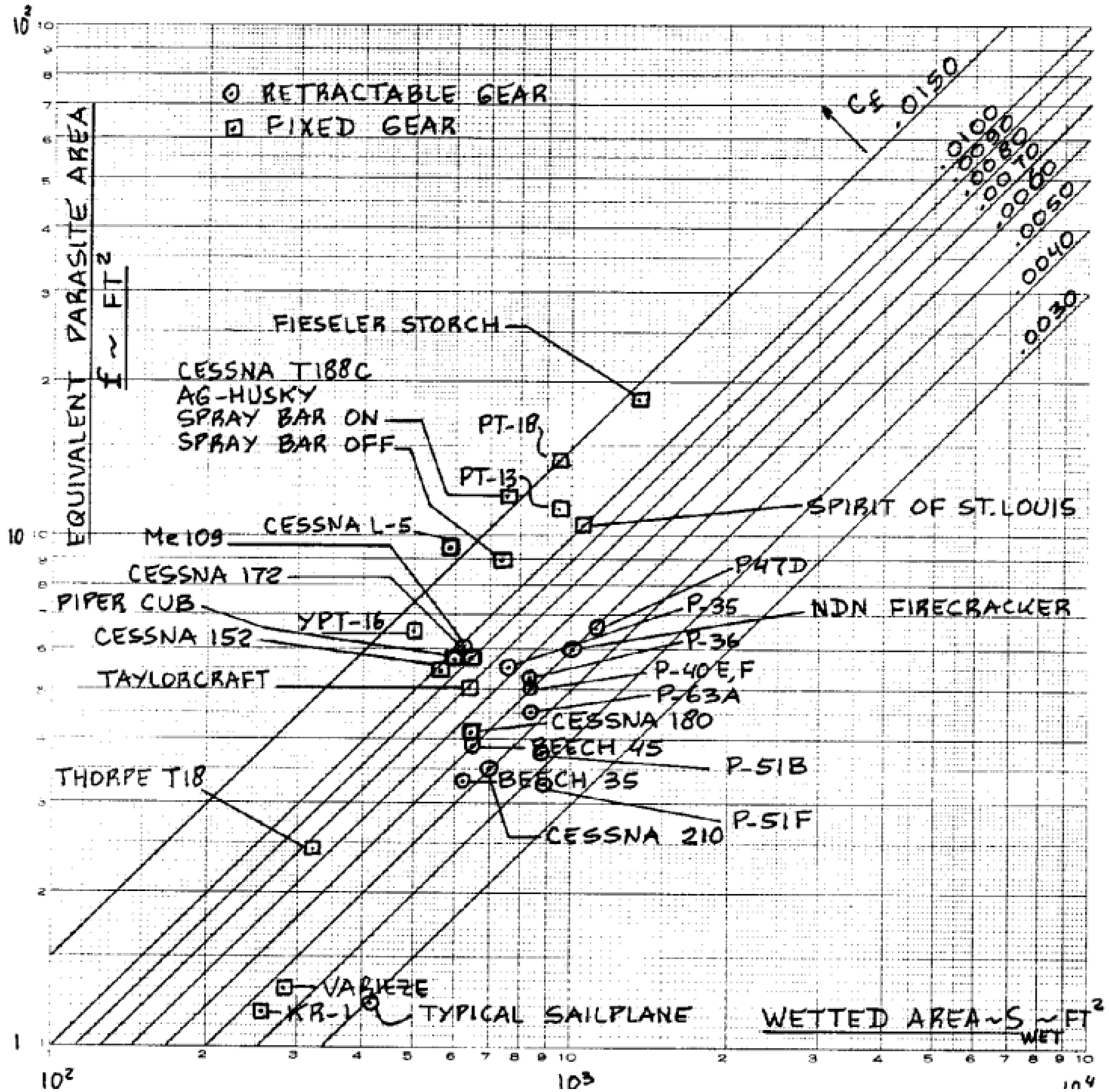
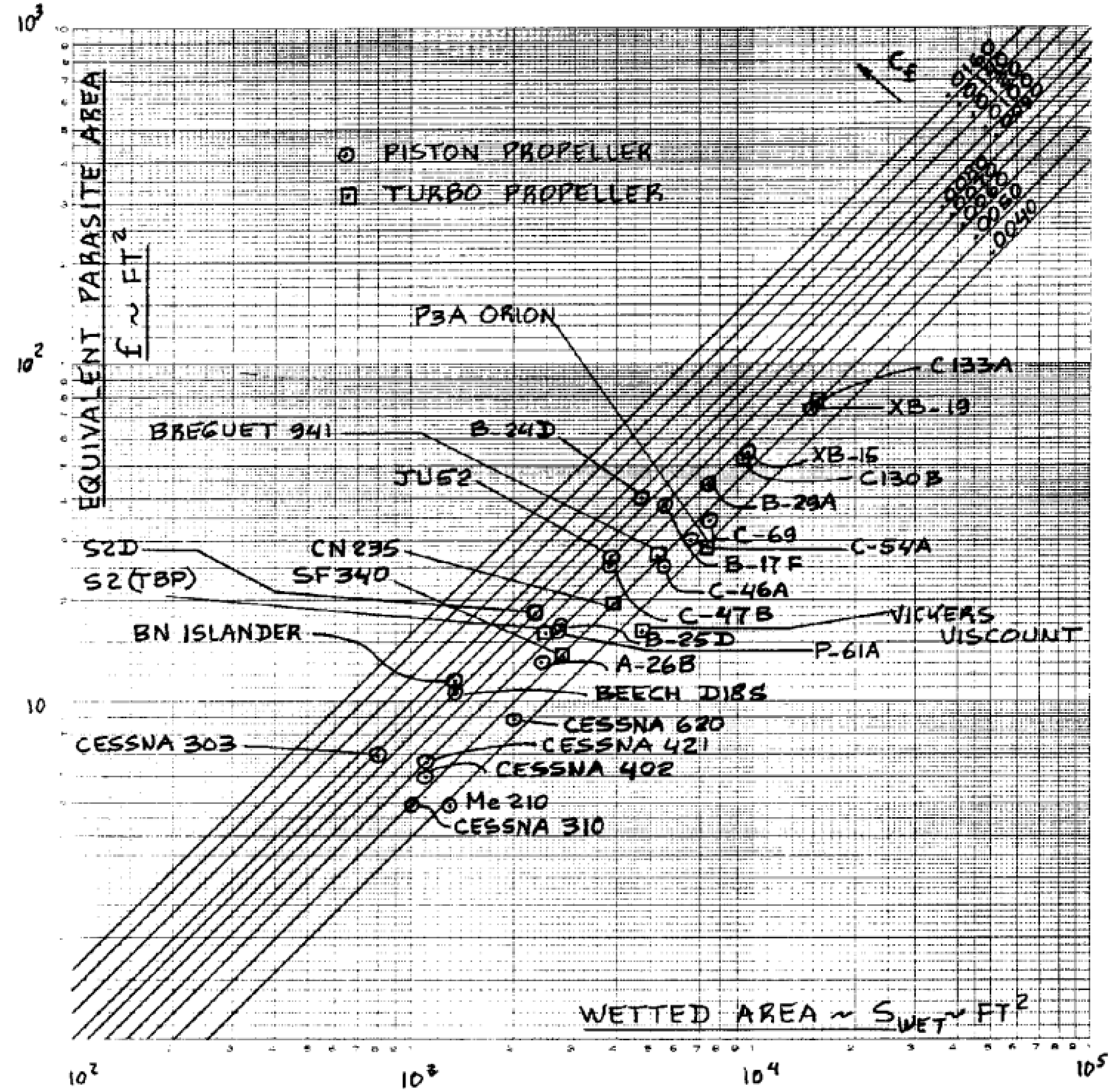
Subsonic Parasite (zero lift) Drag :

Single Engine Propeller Aircraft:



Subsonic Parasite (zero lift) Drag :

Multi-Engine Propeller Aircraft:



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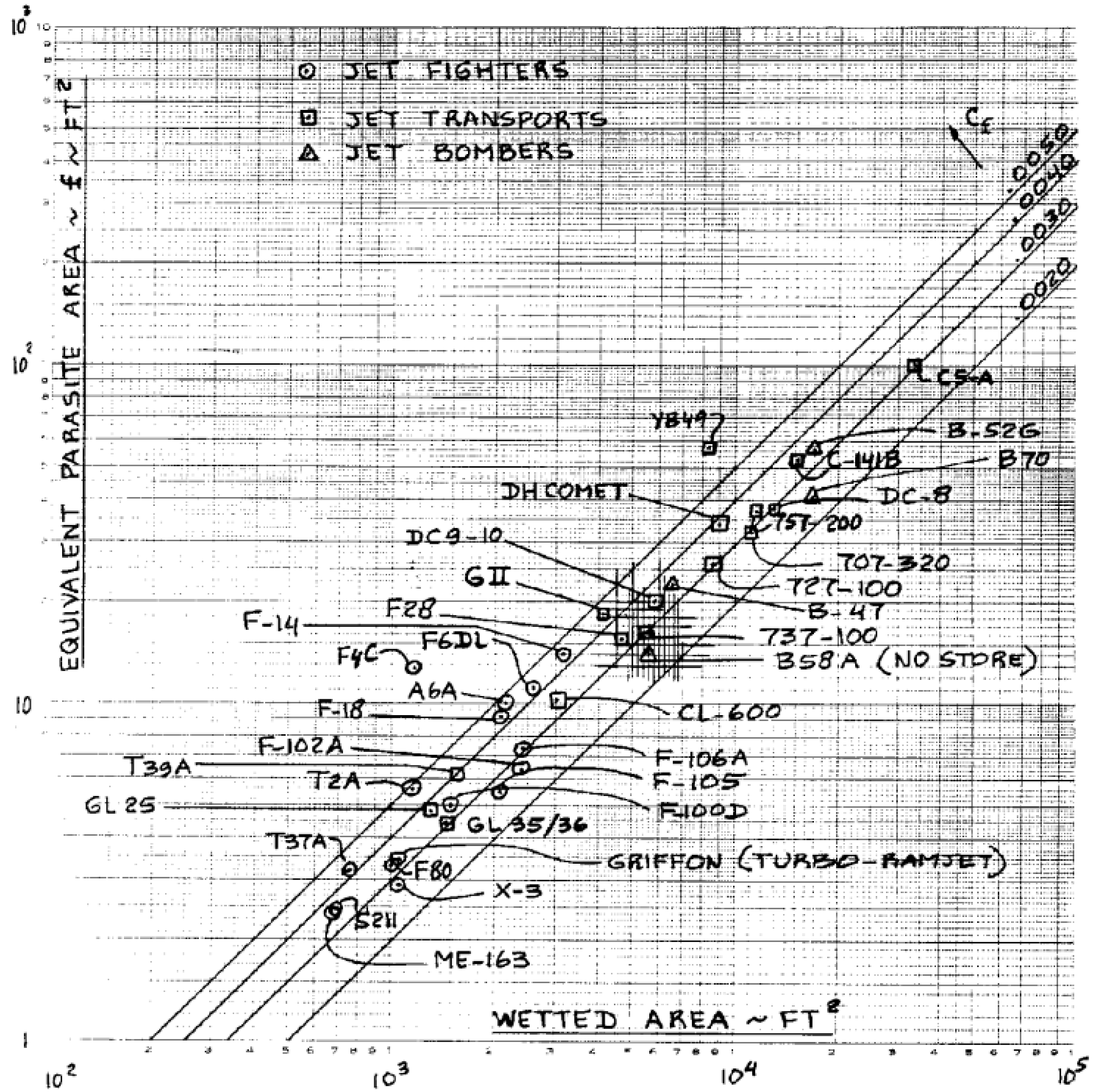
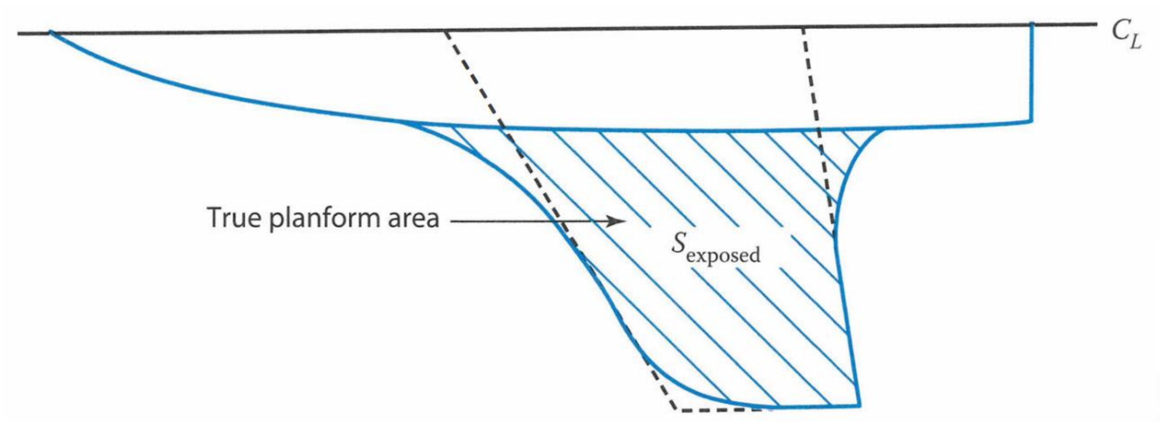
Subsonic Parasite (zero lift) Drag :

Jet Aircraft:



Subsonic Parasite (zero lift) Drag :

Estimation of Wetted Area

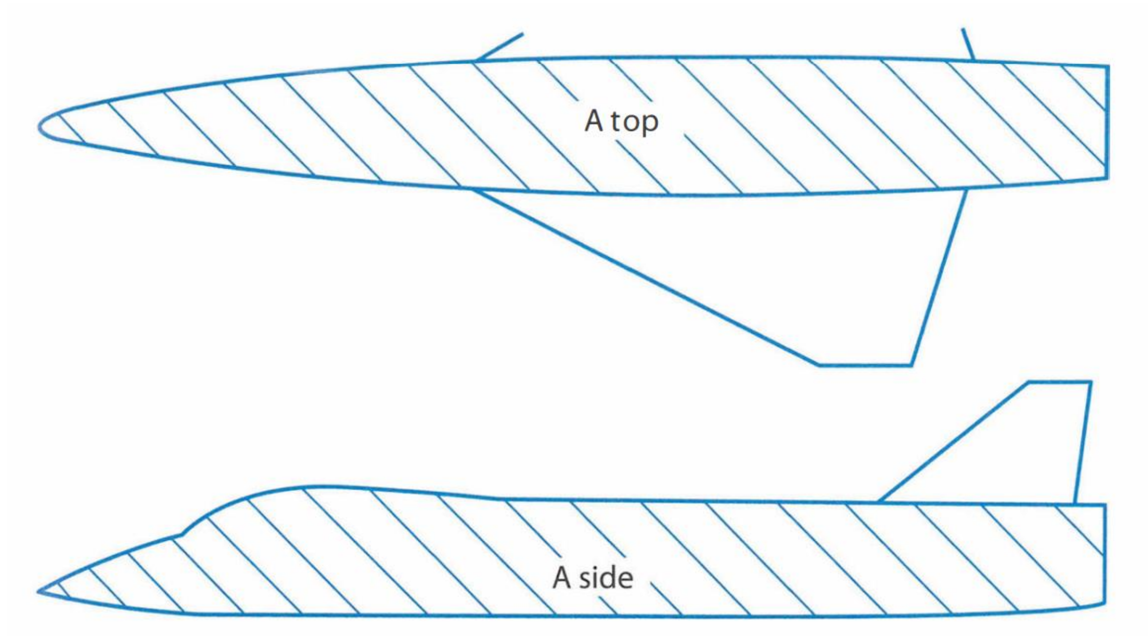


If $t/c < 0.05$,

$$S_{wet} = 2.003 S_{exposed}$$

If $t/c > 0.05$,

$$S_{wet} = S_{exposed}[1.977 + 0.52(t/c)]$$



$$S_{wet} \cong 3.4\left(\frac{A_{top} + A_{side}}{2}\right)$$

Source: Aircraft Design by Daniel P. Raymer

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Subsonic Parasite (zero lift) Drag :

Component Buildup Method

$$(C_{D_0})_{\text{subsonic}} = \frac{\Sigma(C_{f_c} FF_c Q_c S_{\text{wet}_c})}{S_{\text{ref}}} + C_{D_{\text{misc}}} + C_{D_{\text{L\&P}}}$$

- Cfc is the calculated component flat plate friction coefficient, based on Reynold's number.
- FFc, is a form factor to take into account the pressure distribution contribution to zero lift drag.
- Qc is an interference factor due to the interaction of the boundary layers of closely located components.
- The last two terms take into account special features of the specific aircraft and a 'reality' contribution due to less than perfect fabrication, etc.

Subsonic Parasite (zero lift) Drag :

Flat Plate Skin Friction Coefficient

- It is a function of Reynold's number and Actual surface conditions.
- Can be twice as large if flow is turbulent!
- Flow is certainly turbulent aft of surface discontinuities!
- Guess (table 12.4) % of flow that is laminar and obtain a weighted average.
- Take into account surface roughness (table 12.5) to decide to use Re or a cuttoff Re to calculate Cf

Subsonic Parasite (zero lift) Drag :

Flat Plate Skin Friction Coefficient

Laminar:

$$C_f = 1.328/\sqrt{R}$$

Turbulent:

$$C_f = \frac{0.455}{(\log_{10} R)^{2.58}(1 + 0.144M^2)^{0.65}}$$

For turbulent friction coefficient calculation, use the cutoff Reynolds if lower than actual Re.

Subsonic Parasite (zero lift) Drag :

Flat Plate Skin Friction Coefficient

Surface	k, ft	k, m
Camouflage paint on aluminum	3.33×10^{-5}	1.015×10^{-5}
Smooth paint	2.08×10^{-5}	0.634×10^{-5}
Production sheet metal	1.33×10^{-5}	0.405×10^{-5}
Polished sheet metal	0.50×10^{-5}	0.152×10^{-5}
Smooth molded composite	0.7×10^{-5}	0.052×10^{-5}

Transonic or Supersonic: $R_{\text{cutoff}} = 44.62(\ell/k)^{1.053} M^{1.16}$

Subsonic: $R_{\text{cutoff}} = 38.21(\ell/k)^{1.053}$

Source: Aircraft Design by Daniel P. Raymer

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Subsonic Parasite (zero lift) Drag :

Attainable Laminar Flow as a Percentage of Wetted Area	Fuselage, %	Wing and Tails, %
Subsonic		
General aviation—classic production metal	0	10
General aviation—smooth metal (no rivets or cracks)	10	35
General aviation—smooth molded composites	25	50
Sailplane—smooth molded composites	35	70
Helicopter—traditional design	0	0
Helicopter—smooth design	20	20
Civil jet—classic production metal	5	10
Civil jet—research goal (passive)	25	50
Civil jet—research goal (with active suction)	50	80
Military aircraft with camouflage	0	0
Supersonic		
Current	0	0
Research goal (with active suction)	20	40

- Unlikely past crack for movable surfaces like leading-edge flaps
- Unlikely near wing-mounted engines (~1 diameter each side)
- More difficult for wings with more sweep
- Reduces behind propeller (for area in propwash, multiply above by 0.8 and 0.9)
- These are for entire wetted area of wing, not just 2D airfoil
- These are a percentage of total wetted area, not the length from the nose

Source: Aircraft Design by Daniel P. Raymer

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Subsonic Parasite (zero lift) Drag :

- Component Form Factors
- To take into account drag due to separation
- FF a function of component geometry

Wing, tail, strut, and pylon:

$$FF = \left[1 + \frac{0.6}{(x/c)_m}\left(\frac{t}{c}\right) + 100\left(\frac{t}{c}\right)^4\right]\left[1.34M^{0.18}(\cos\Lambda_m)^{0.28}\right]$$

Fuselage and smooth canopy:

$$FF = \left(1 + \frac{60}{f^3} + \frac{f}{400}\right)$$

Nacelle and smooth external store:

$$FF = 1 + (0.35/f)$$

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Subsonic Parasite (zero lift) Drag :

- Component Interference Drag
- Because of Interference, drag of two components is usually larger than the sum of their individual drags because of the interaction of their boundary layer.
- Good area for wind tunnel/CFD work
- In Conceptual Design we just estimate, e.g for nacelles, external stores under wing, $1.3<Q<1.5$
- Q is less than 1.0 when components are in-line as the aft component is under lower dynamic pressure

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Subsonic Parasite (zero lift) Drag :

- Miscellaneous, Leakage, Protuberance Drags
- For non-smooth stores D/Q's , figs. 12.24-26
- Fuselage Aft Upsweep a function of angle
- Table 12.6 lists Cd's for a variety of exposed shapes.
- Gaps, discontinuities, product of fabrication or modifications of day-to-day operation will cause additional parasite drag. Table 12.8 lists estimated %'s of parasite drag.
- Stopped-propeller and windmilling engine drags a function of propeller disk or jet engine front area. (Eqns. 12.39-40)

Miscellaneous Component Drag :

	$C_{D_\pi} = \left[\frac{D/q}{\text{Frontal Area}}\right]$
Flat plate perpendicular to flow	1.28
Sphere alone—high R#	0.10
Sphere alone—low R#	0.3–0.5
Hollow sphere, open end forward	1.40
Hollow sphere, open end to rear	0.40
Bullet shape, blunt back	0.30
Exposed water—cooled radiator	1.00
Cowled water—cooled radiator	0.3–0.5
Air scoops	1.2–2.0
Control horn	0.3–0.8
Speed brake—fuselage mounted	1.00
Speed brake—wing mounted	1.60
Windshield smoothly faired into fuselage	0.07
Windshield—sharp edged, poorly faired	0.15
Open cockpit (ref. windscreen A-frontal)	0.50
Parachute or drogue chute	1.40
Regular wheel and tire	0.25
Second wheel and tire in tandem	0.15
Streamlined wheel and tire	0.18
Wheel and tire with fairing	0.13
Streamlined strut ($1/6 < t/c < 1/3$)	0.05
Round strut or wire (R# $> 3 \times 10^5$)	0.30
Round strut or wire (R# $< 3 \times 10^5$)	1.17
Flat spring gear leg	1.40
Fork, bogey, irregular fitting	1.0–1.4

Source: Aircraft Design by Daniel P. Raymer

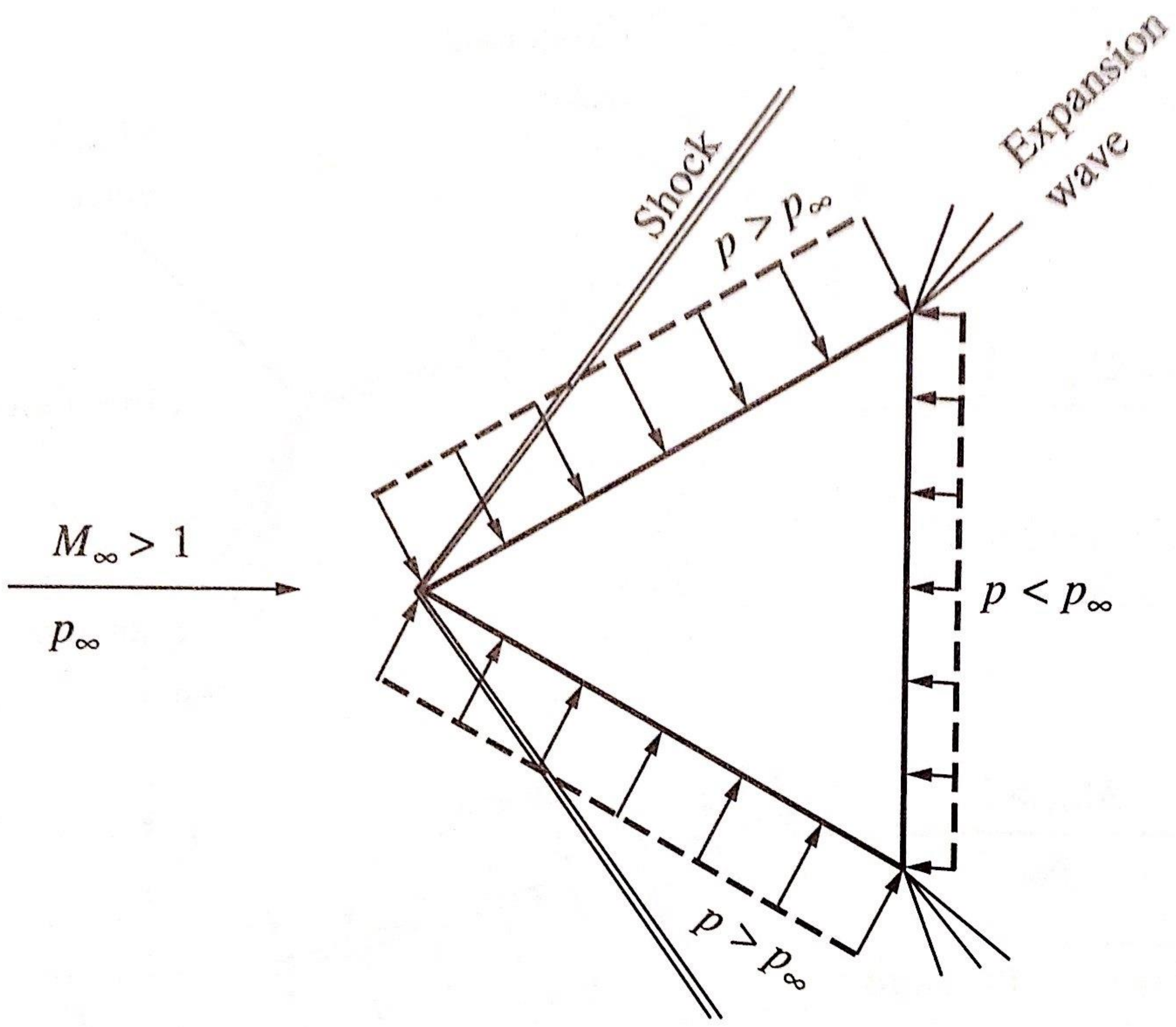
Supersonic Parasite (zero lift) Drag :

$$C_{D_{0\,rmsupersonic}} = \frac{\Sigma(C_{f_c} S_{\text{wet}_c})}{S_{\text{ref}}} + C_{D_{\text{misc}}} + C_{D_{L\&P}} + \boxed{C_{D_{\text{wave}}}}$$

- Skin friction component does not include form factors or interference; they are in CDwave.
- Wave drag often becomes the largest component!

Supersonic Wave (zero lift) Drag :

- Pressure increase across shock creates increased pressure along inclined surfaces.
- Pressure decrease across expansion waves create lower pressure at base.
- Both pressure differences are in the drag direction!



Source: Aircraft Performance and Design by John D. Anderson

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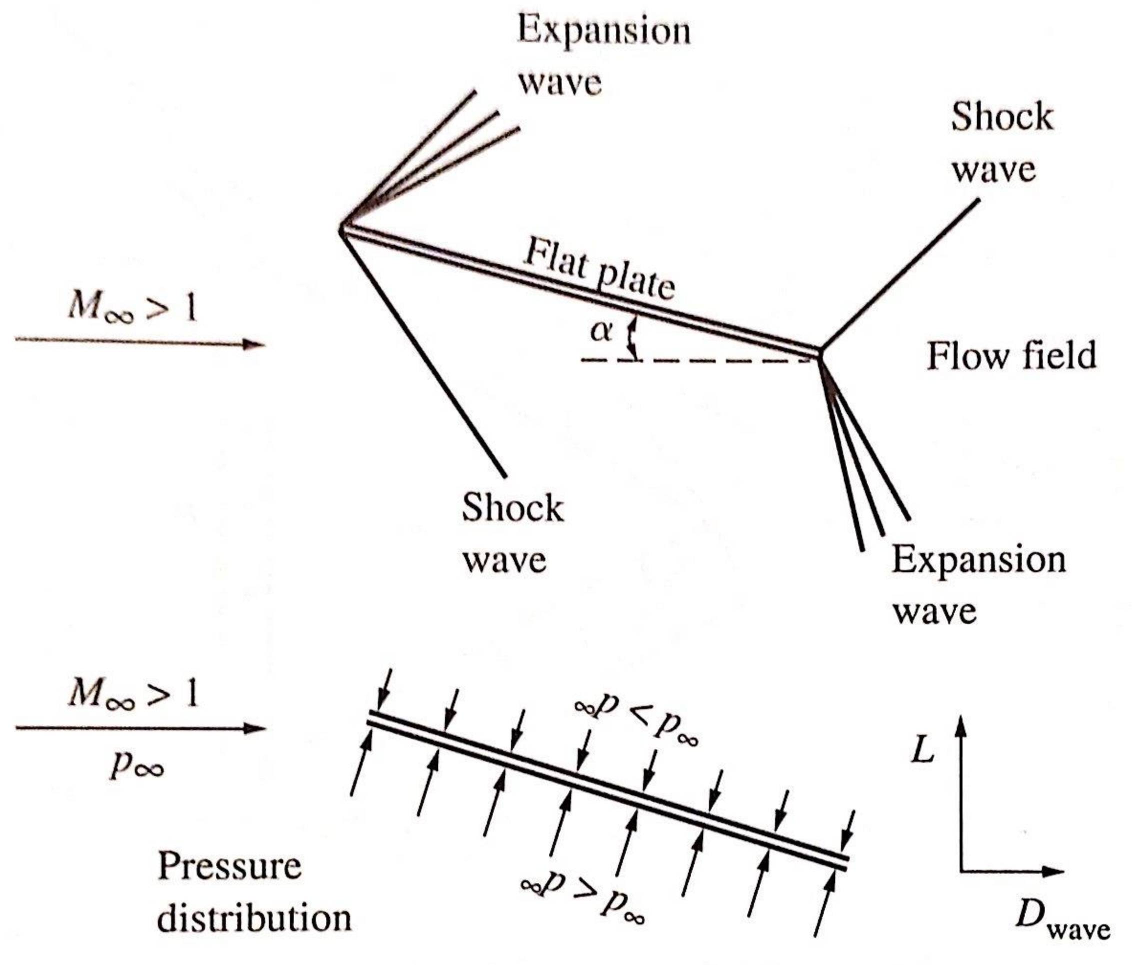
Supersonic Wave (drag due to lift) Drag :

- Pressure increase across shock creates increased pressure along bottom of plate.
- Pressure decrease across expansion waves create lower pressure at top.
- The resultant wave force, perpendicular to the plate can be resolved in the Lift and Drag direction, thus resulting in a wave drag due to lift effect!



Source: Aircraft Performance and Design by John D. Anderson

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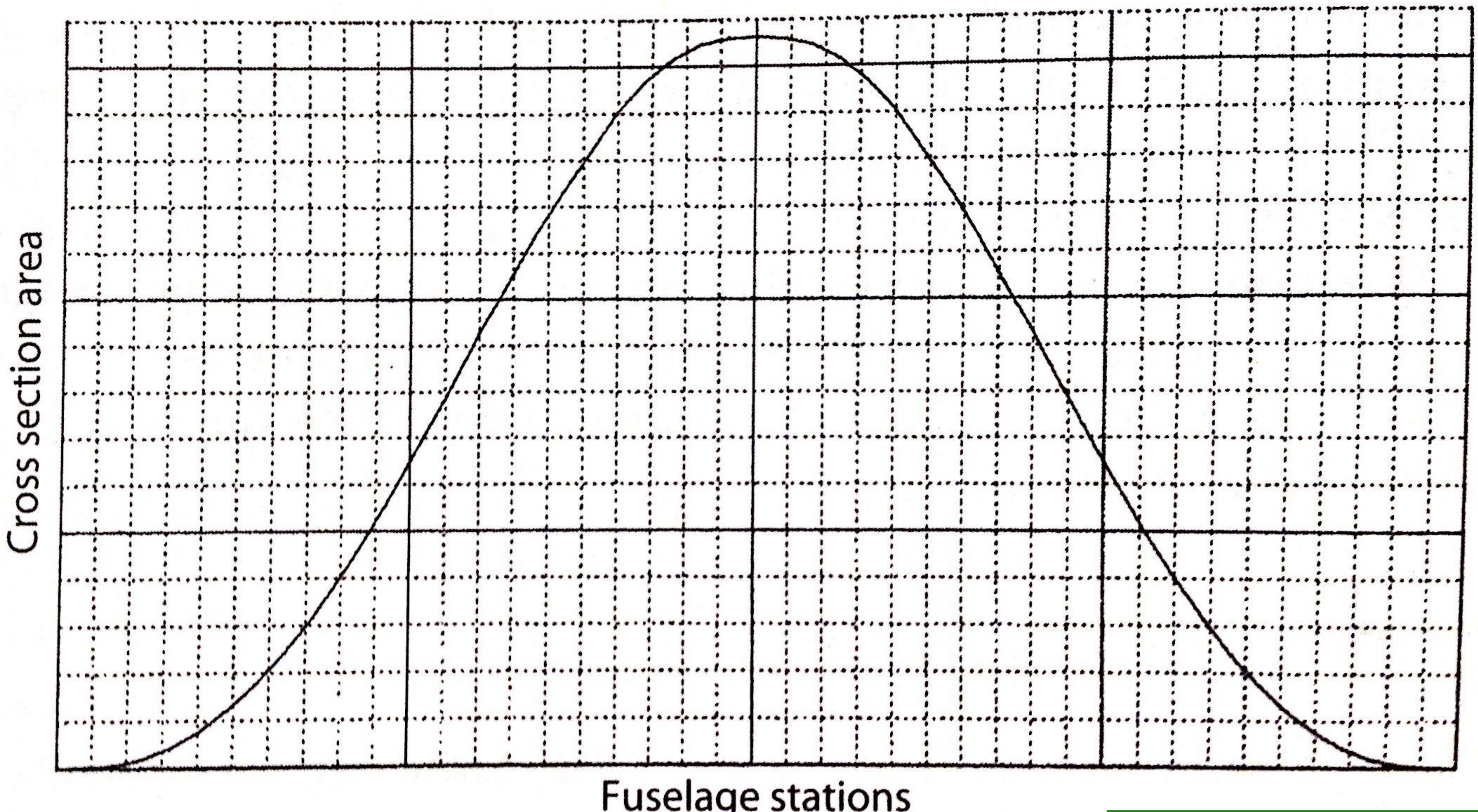
Supersonic Parasite (zero lift) Drag :

- Wave drag is a pressure drag due to shocks and is a result of the volume distribution from nose to tail.
- The minimum wave drag at M=1.0 is that of the sears-Haack body:

$$(D/q)_{\text{wave}} = \frac{9\pi}{2}\left(\frac{A_{\text{max}}}{\ell}\right)^2$$

- Typical aircraft will have TWICE the wave drag of the Sears-Haack body!
- To minimize wave drag, we look at a Mach number and we smooth the volume plot composed by taking x-section cuts at the Mach angle and at various roll angles.

Supersonic Wave Drag :



Source: Aircraft Design by Daniel P. Raymer

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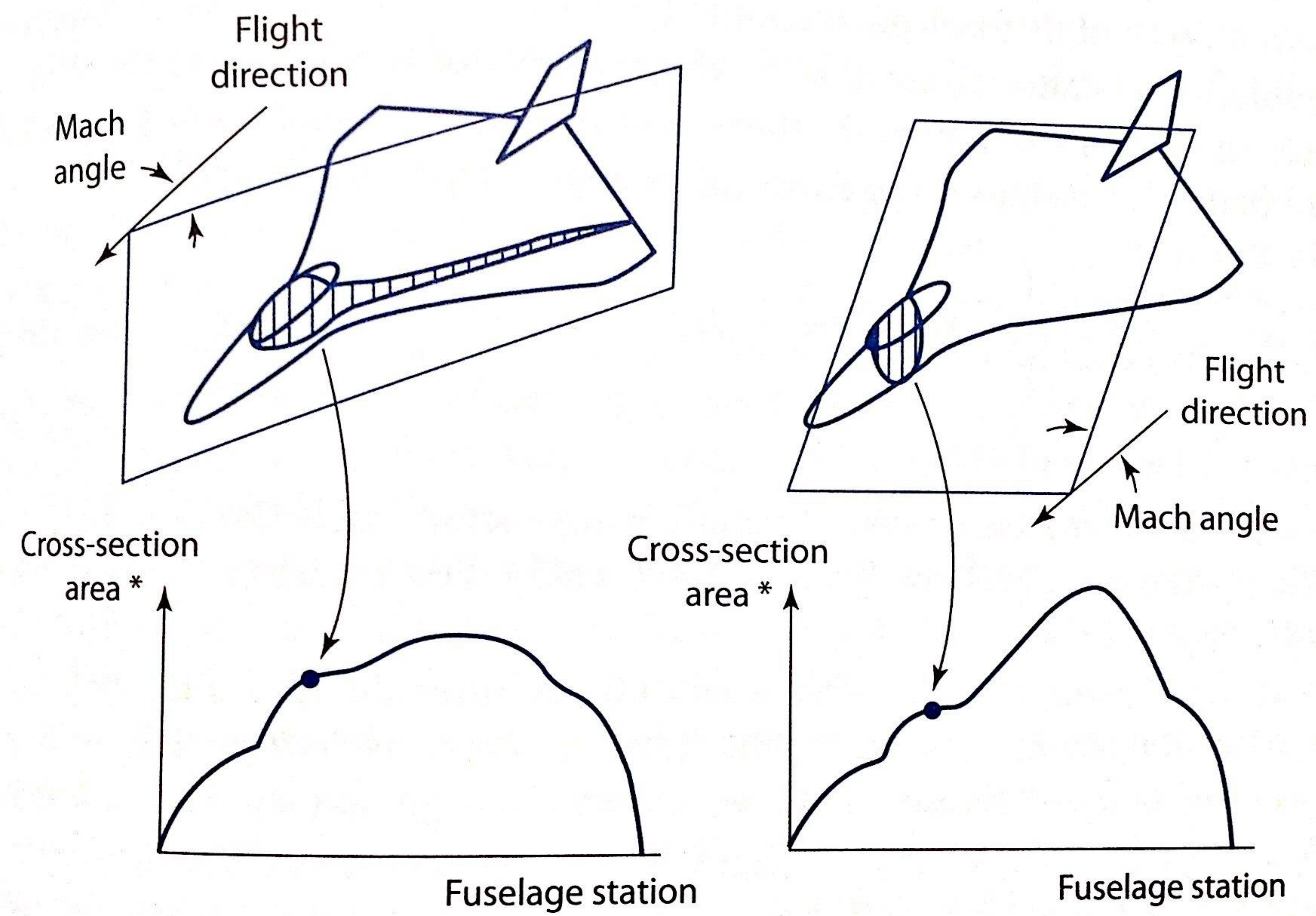
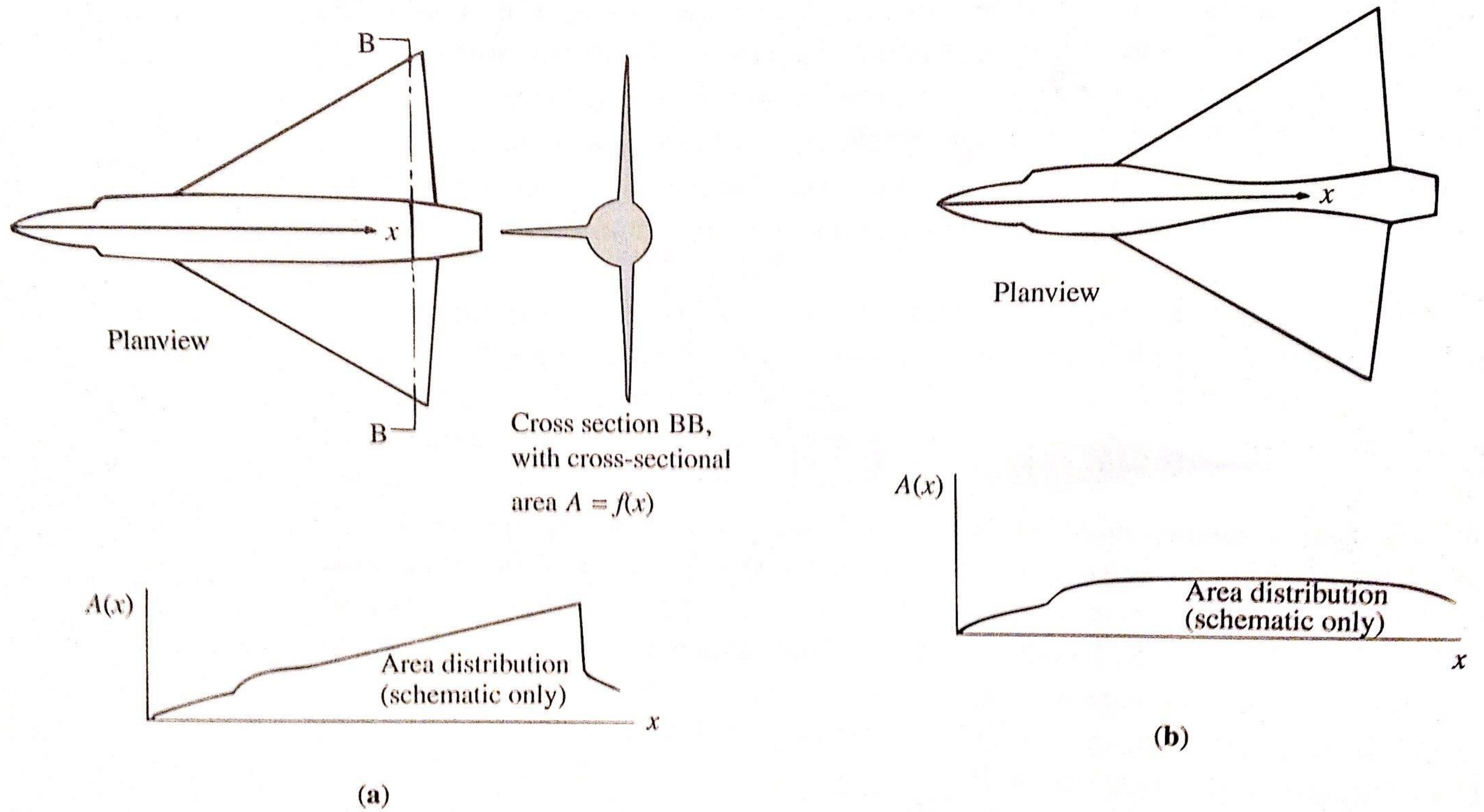
Supersonic Wave Drag :



* Projected forward onto a plane perpendicular to the flight direction

Source: Aircraft Design by Daniel P. Raymer

Supersonic Wave Drag :



Source: Aircraft Performance and Design by John D. Anderson

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Supersonic Parasite (zero lift) Drag :

$$(D/q)_{\text{wave}} = E_{\text{WD}}\left[1 - 0.386(M-1.2)^{0.57}\left(1 - \frac{\pi\Lambda_{\text{LE-deg}}^{0.77}}{100}\right)\right](D/q)_{\text{Sears-Haack}}$$

- Ewd is am empirical wave drag efficiency factor = actual wave drag / Sears-Haack
- 1.2 < Ewd < 2.2
- E.g F-15 Ewd = 2.9!

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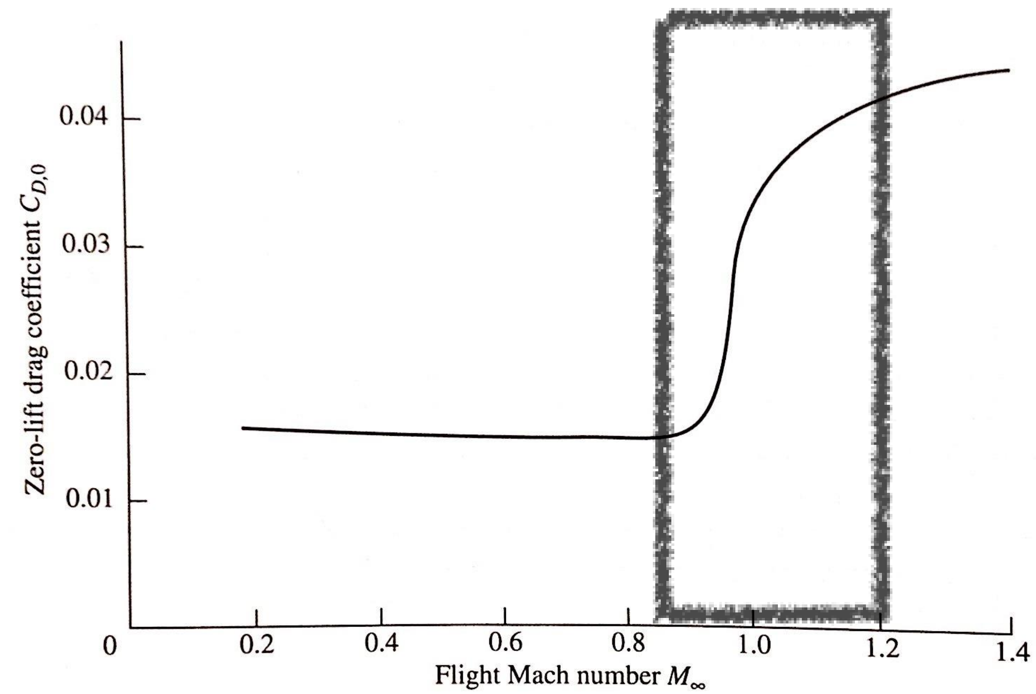
Transonic Parasite (zero lift) Drag :



- 0.8<M<1.2
- Both subsonic and supersonic flow around aircraft
- Drag rise is due to formation of shocks
- Mcr reached when first shocks occur on aircraft
- Mdd>Mcr; reached when drag is affected substantially

Source: Aircraft Performance and Design by John D. Anderson

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Transonic Parasite (zero lift) Drag :

- Approximate Method
- Calculate and plot Cd0 @ M=1.2 (point A).
- Plot Cd0 at 1.05M as the same value(point B).
- Plot Cd0 at M=1 at 50% of that value (point C).
- Draw Straight Line from 1.05M to 1.0M and almost to x-axis
- Smooth curve from Mcr(point D) to this straight line and through Mdd (point E).
- Draw a smooth curve from 1.05M to 1.2M.

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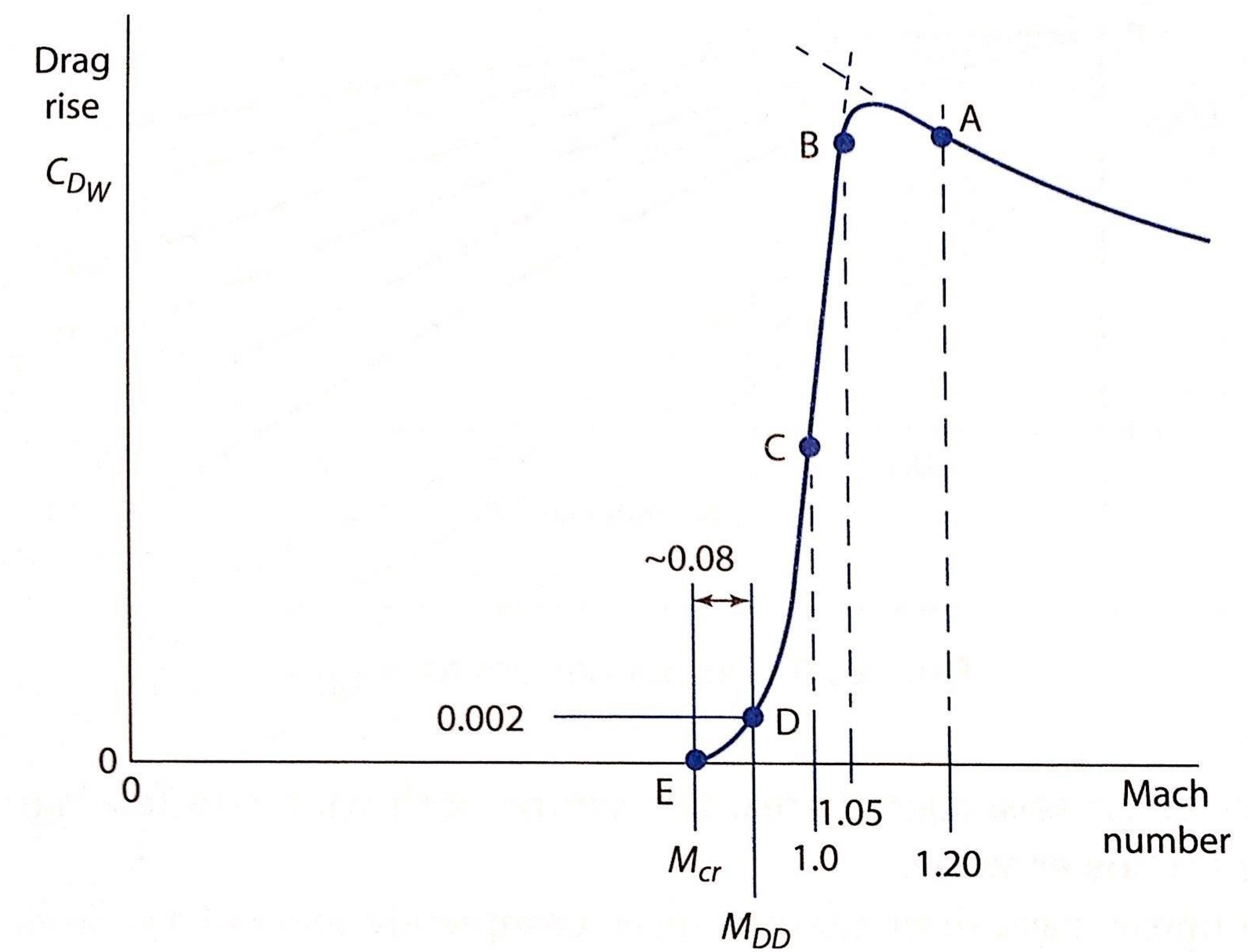
Transonic Parasite (zero lift) Drag :

- Approximate Method



By definition, Mdd is where drag increases by 0.002. Mdd = Mcr-0.08

Source: Aircraft Design by Daniel P. Raymer

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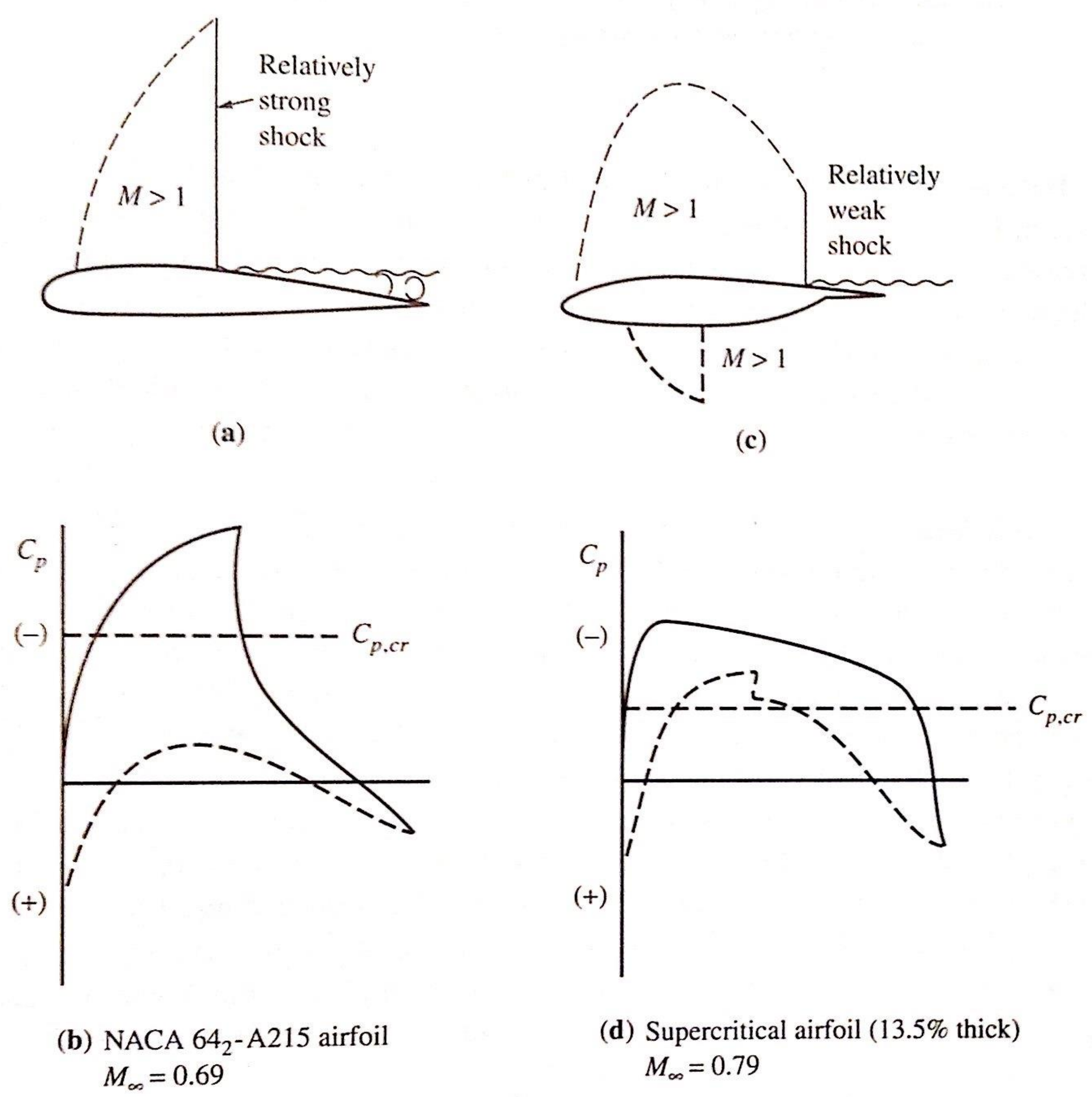
Transonic Parasite (zero lift) Drag :

- Shock Management



Source: Aircraft Performance and Design by John D. Anderson

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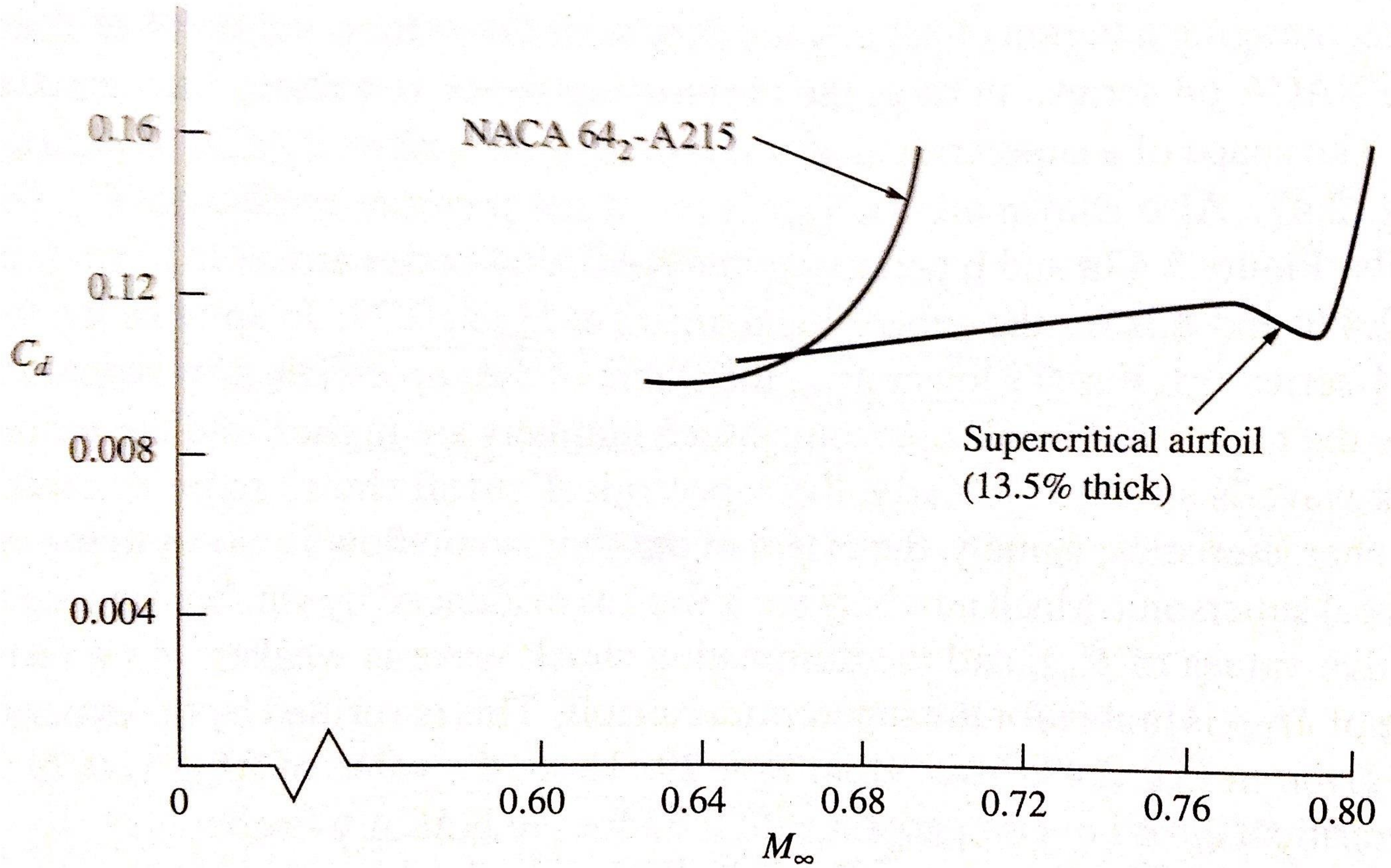
Transonic Parasite (zero lift) Drag :

- Shock Management



Source: Aircraft Performance and Design by John D. Anderson

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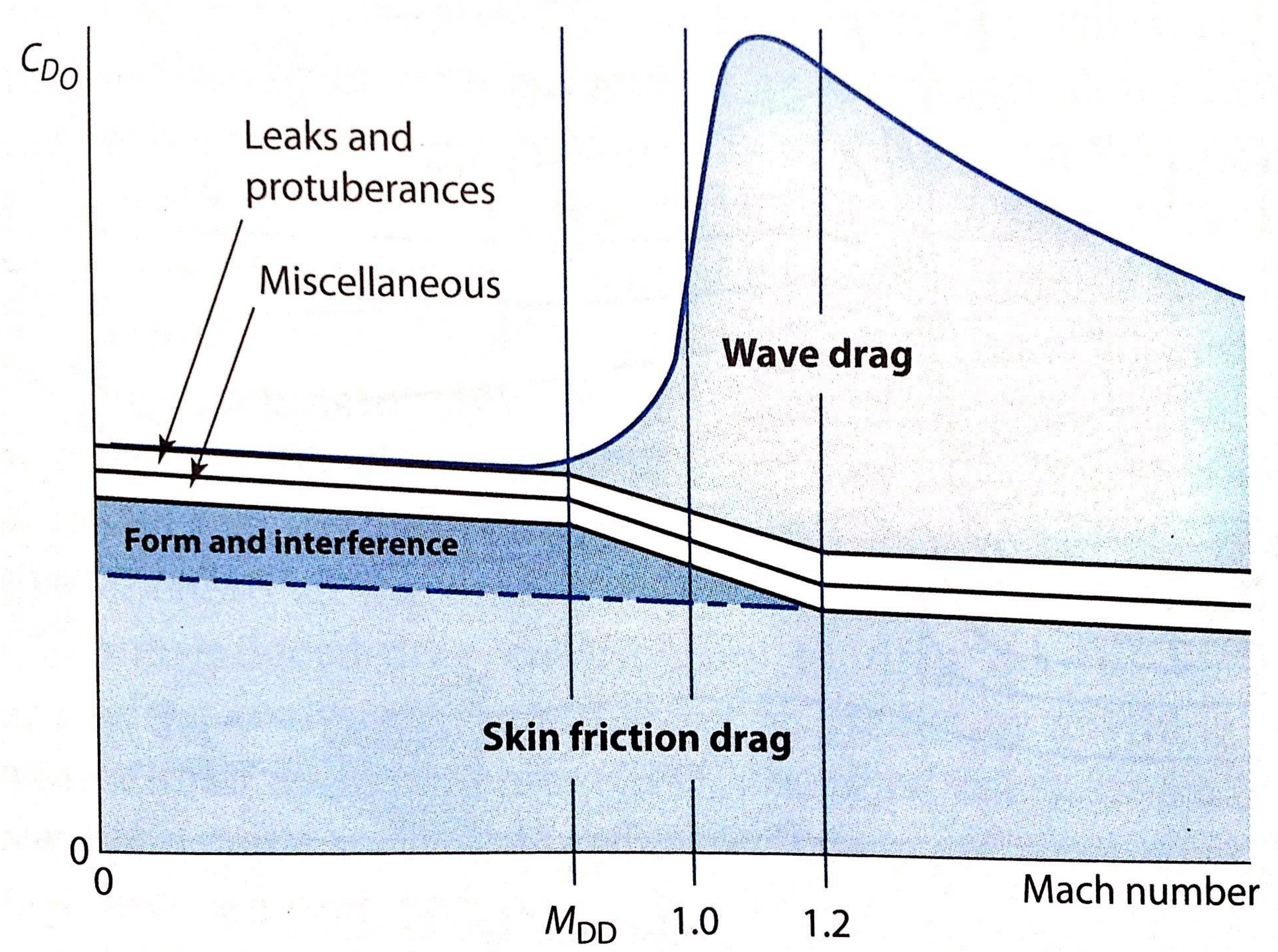
Completed Parasite Drag Buildup:



Source: Aircraft Design by Daniel P. Raymer

Drag due to Lift:

- Proportional to the square of CL, (twice the lift, 4 times the drag due to lift!)

- Includes induced drag due to a finite wing, plus change in form drag at AOA, including a laminar drag bucket and other separation phenomena.

- Two methods to account for it: Oswald's Span Efficiency, and Leading Edge Suction.

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Drag due to Lift, Oswald Span Efficiency Method:

$$C_{D_i} = \frac{C_L^2}{\pi A}$$

Classical wing theory / elliptical distribution

$$K = \frac{1}{\pi A e}$$

To account for non elliptical lift distribution and separation

Oswald Efficiency Factor:
0.7 < e < 0.85 (Subsonic)
0.3 < e < 0.5 (M= 1.2)

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Drag due to Lift, Oswald Span Efficiency Method:

Straight-wing aircraft:

$$e = 1.78(1 - 0.045A^{0.68}) - 0.64$$

Swept-wing aircraft:

$$e = 4.61(1 - 0.045A^{0.68})(\cos \Lambda_{LE})^{0.15} - 3.1 (\Lambda_{LE} > 30\,\mathrm{deg})$$

Supersonic speeds:

$$K = \frac{A(M^2 - 1)\cos \Lambda_{LE}}{(4A\sqrt{M^2 - 1}) - 2}$$

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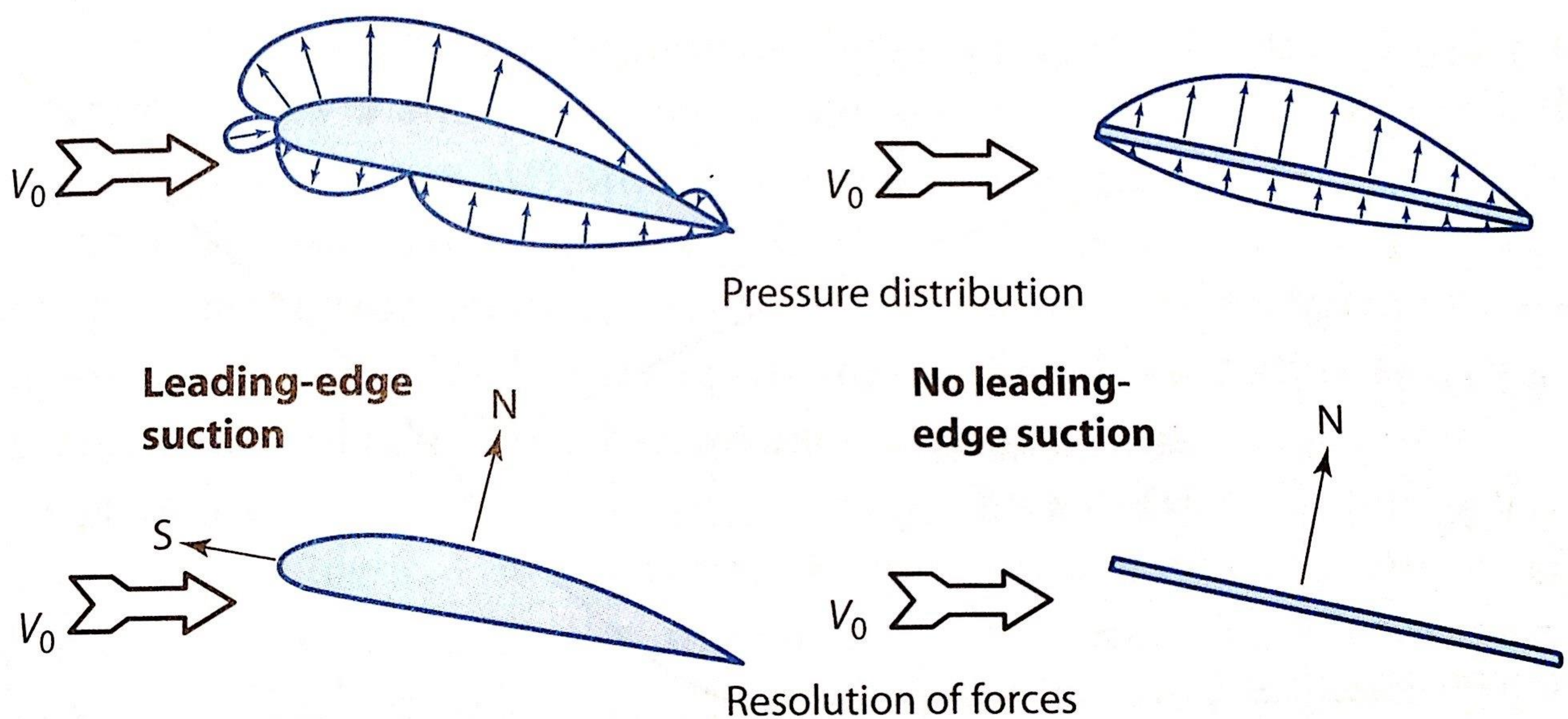
Drag due to Lift, Leading Edge Suction Method:

- Drag at AOA is strongly affected by viscous separation thus deviating from a parabolic drag polar, simply represented by a "K"

- An airfoil pressure distribution results in a "suction" resultant tangential to the chord, and a resultant normal to it. The suction component balances de form drag component that created D' Alembert's Paradox. A 100% suction would result in zero form drag.

- A flat plate would only have the normal component, or 0% suction. That would mean in completely separated flow and huge form rag with AOA!

Drag due to Lift, Leading Edge Suction Method:



100% Suction

$$K = \frac{1}{\pi A}$$

$$K = \frac{1}{C_{L_\alpha}}$$

0% Suction

Source: Aircraft Design by Daniel P. Raymer

Drag due to Lift, Leading Edge Suction Method:

- It uses empirical data that places K somewhere in between the one for 0% and 100 % suction.

$$K = SK_{100} + (1 - S)K_0$$

- S = f(Leading Edge Radius, Wing Sweep, Design CL, Actual CL) for subsonic flight.
- S is approximately 0.9 when wing is operating at design CL.
- As soon as the leading edge becomes supersonic, suction is zero so K is the inverse of the lift curve slope. This is a function of leading edge sweep.

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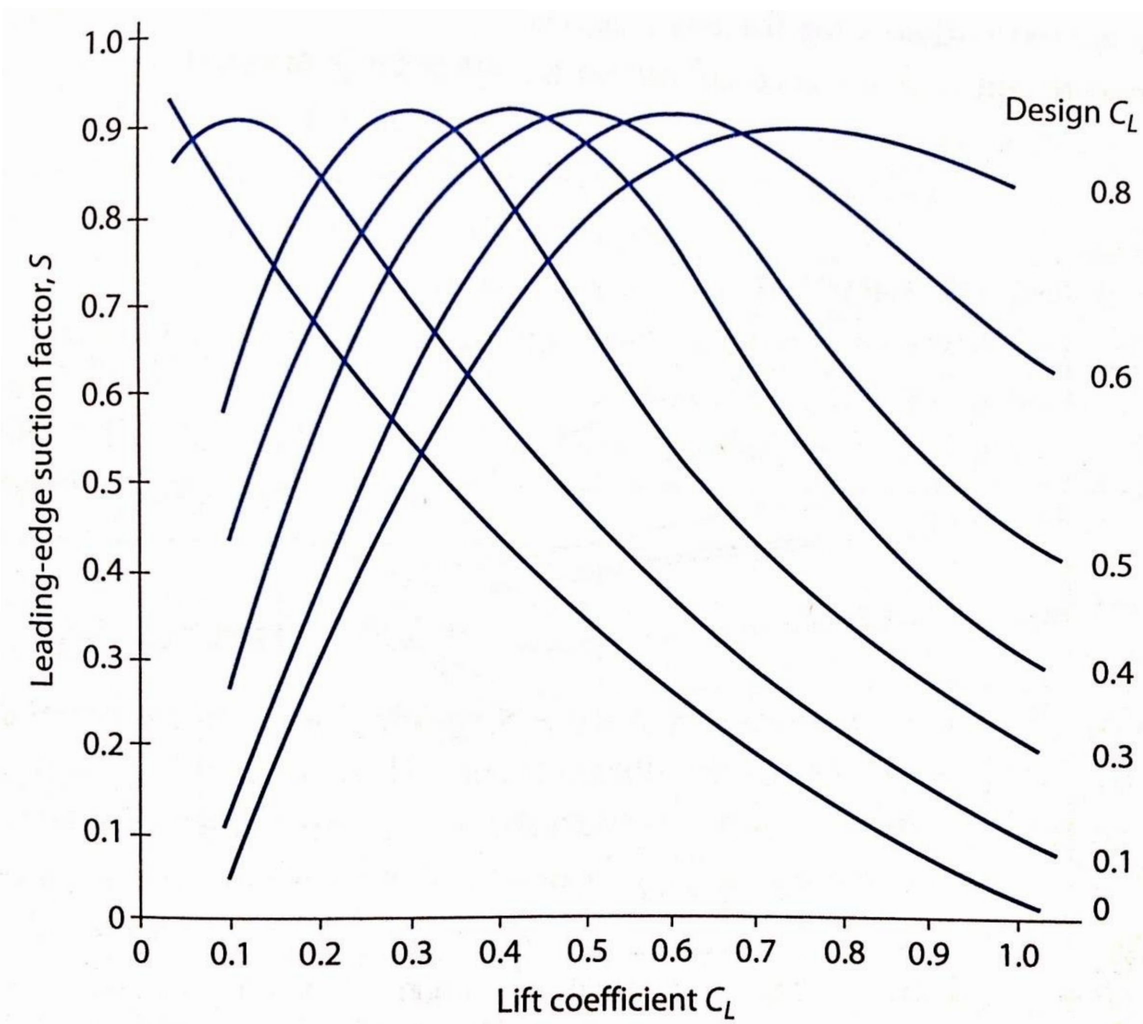
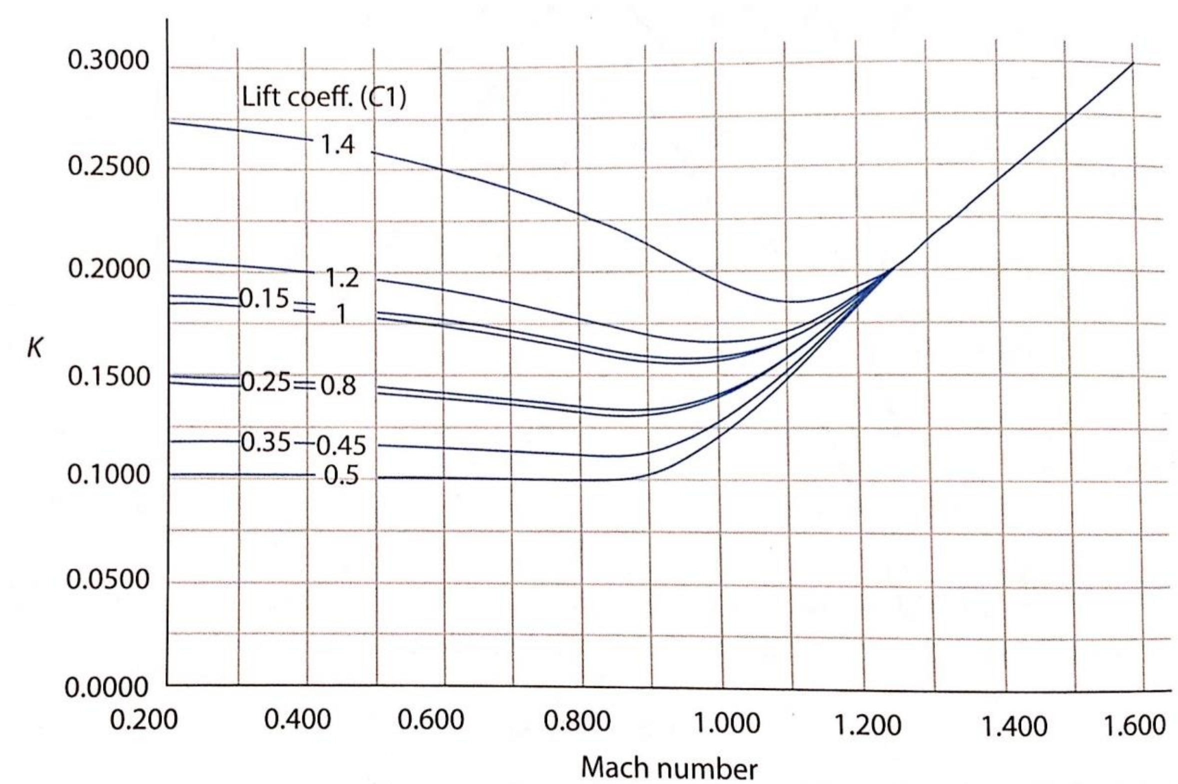
Drag due to Lift, Leading Edge Suction Method:

Leading Edge Suction Schedule for a Supersonic Wing



Resulting K's



Source: Aircraft Design by Daniel P. Raymer

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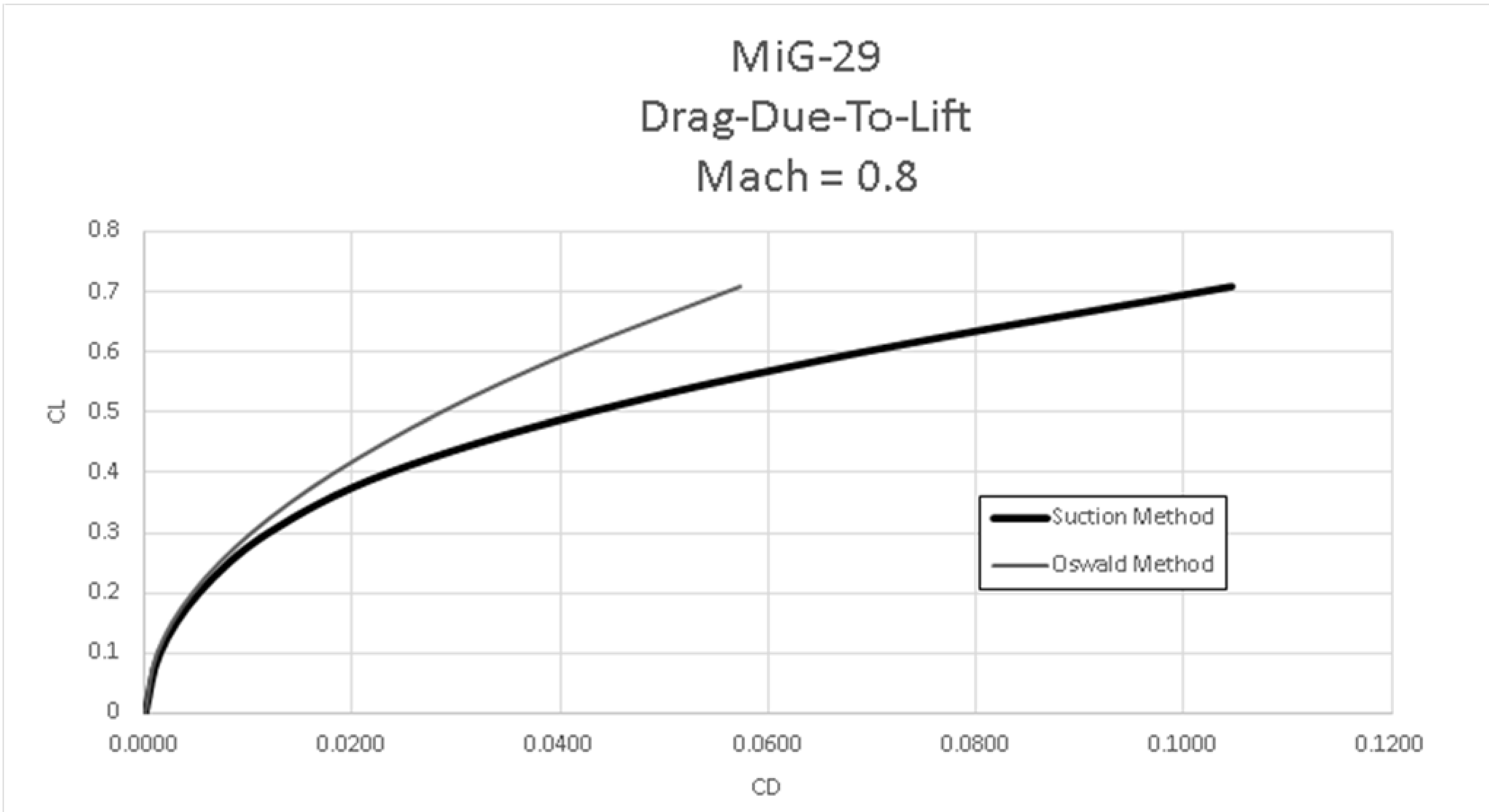
Drag due to Lift, Leading Edge Suction Method:



Source: Aircraft Design by Daniel P. Raymer

Drag due to Lift, Leading Edge Suction Method:

- Actual calculation of S for an actual wing is complex
- For a supersonic design, initially use fig. 12.38
- For subsonic wing with large L.E. radius use S=0.93
- If A is high, calculate S for e = 0.8 up to CL = Design CL + 0.1 and at higher CL's diminish S to 80% (at stall)

$$e = \frac{1}{(\pi A / C_{L_\alpha})(1 - S) + S}$$

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Other Drags/Adjustments:

- Trim Drag.- Caused by the horizontal tail having to trim moment at all flight conditions. For the aircraft to generate a certain CL, the tail may be generating a down-force, so the wing CL may be higher (higher AOA) and therefore a higher total (wing, body and tail) drag! Performance calculations are done with trimmed data.

- Ground Effect.- When wing is less than b/2 away from the ground, air is trapped under it, reducing K! Important in takeoff and landing calculations.

$$\frac{K_{\text{effective}}}{K} = \frac{33(h/b)^{1.5}}{1 + 33(h/b)^{1.5}}$$

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Other Drags/Adjustments (continued):

- Flap Drag.- when flaps are deployed, they increase both parasite and induced drag. This is due to increased flow separation due to flap deflection, and the deviation from an elliptical lift distribution since flaps normally span only a portion of the total wingspan.

$$\Delta C_{D_{0\,\text{flap}}} = F_{\text{flap}}(C_f/C)(S_{\text{flapped}}/S_{\text{ref}})(\delta_{\text{flap}} - 10)$$

where

δ_{flap} = in degrees
F_{flap} = 0.0144 for plain flaps = 0.0074 for slotted flaps
C_f = chord length of flap (see Fig. 12.18)

$$\Delta C_{D\,i} = k_f^2(\Delta C_{L\,\text{flap}})^2 \cos \Lambda_{\bar{c}/4}$$

k_f = 0.14 for full-span flaps and 0.28 for half-span flaps

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CFD:

- Used more and more to understand why a certain geometry works or not and how to improve it

- Navier-Stokes are some of the nastiest differential equations in theoretical physics

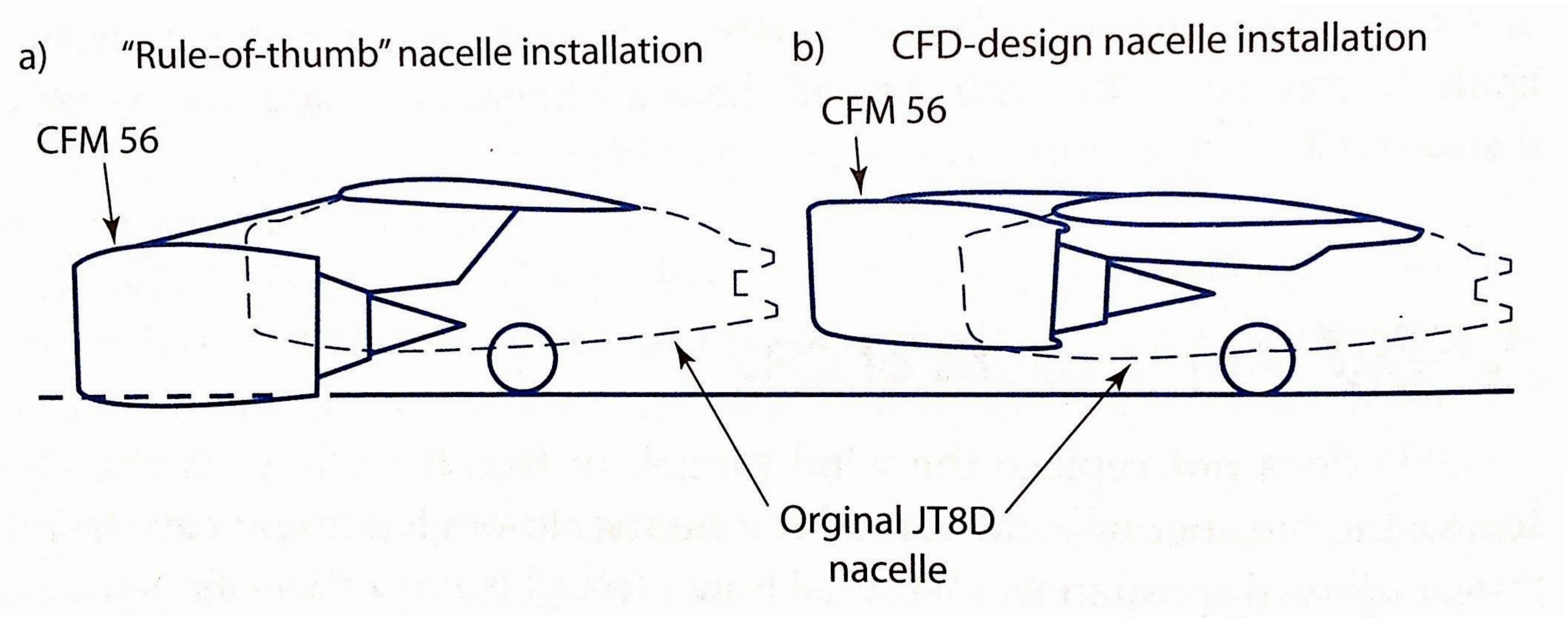
- Turbulence is a big problem. It occurs at the molecular level - gridding problem

- Common simplifications

- Euler Codes (inviscid, o.k. outside of B.L., to study vortices, etc.)

- Potential Codes (no rotation, o.k. to study shock formation, cruise...)

CFD:



Source: Aircraft Design by Daniel P. Raymer

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HOMEWORK