AE 451 Aeronautical Engineering Design I

Aerodynamics

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Lift curve

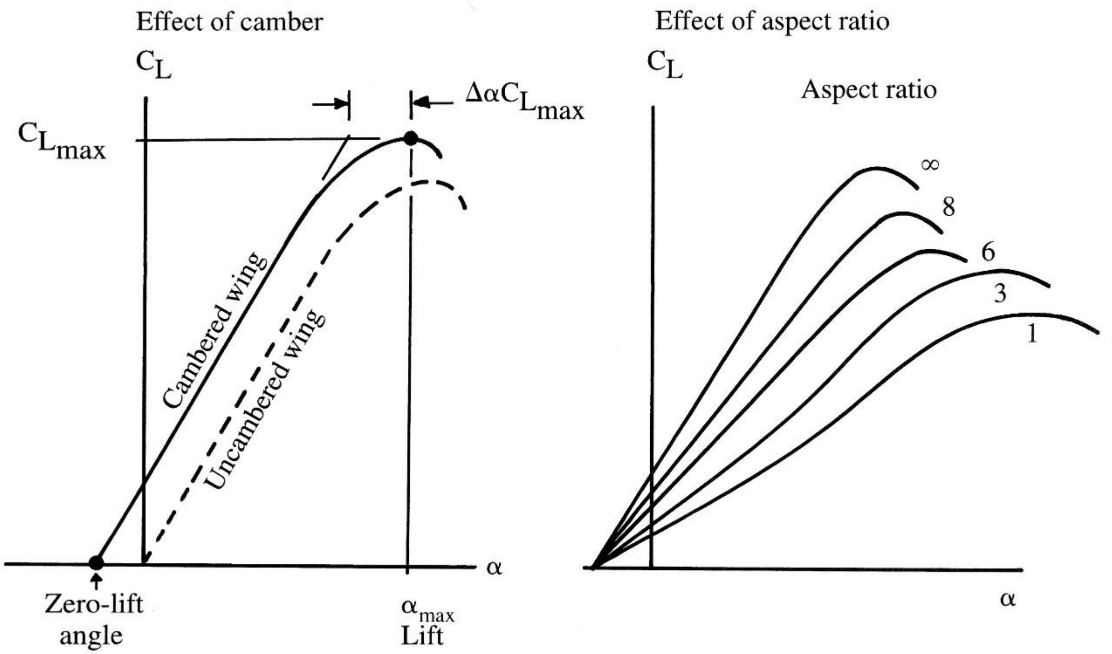


Fig. 12.4 Wing lift curve.

Lift curve slope

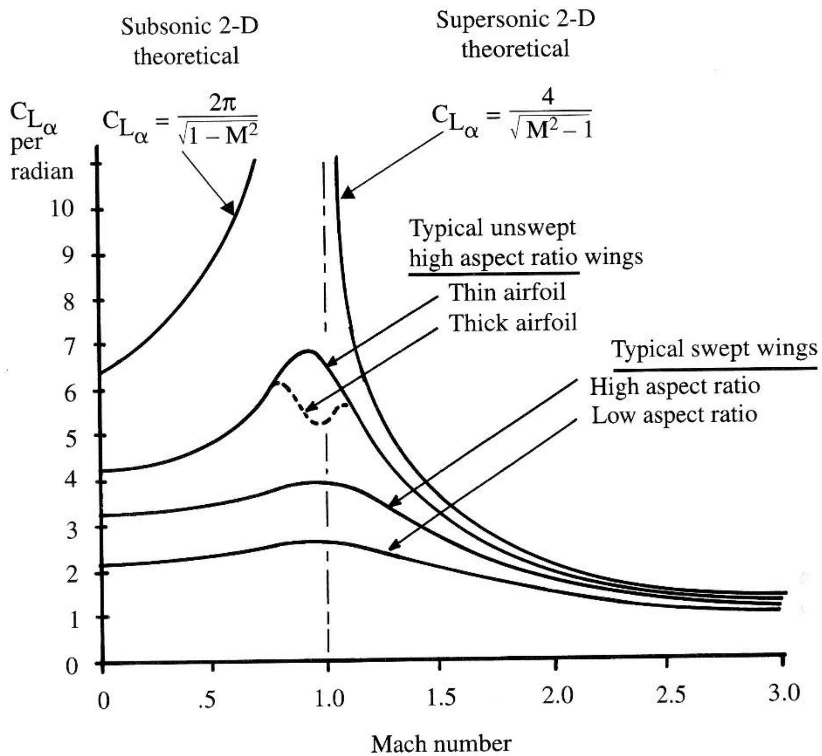


Fig. 12.5 Lift curve slope vs Mach number.

Subsonic lift curve slope

$$C_{L_\alpha} = \frac{2\pi AR}{2 + \sqrt{4 + \frac{AR^2\beta^2}{\eta^2}\left(1 + \frac{tan^2\Lambda_{max,t}}{\beta^2}\right)}} \frac{S_{exposed}}{S} F$$

Valid until M_{dd}, fairly accurate until M=1.

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

η: airfoil efficiency, $= 0.95$ for most airfoils.

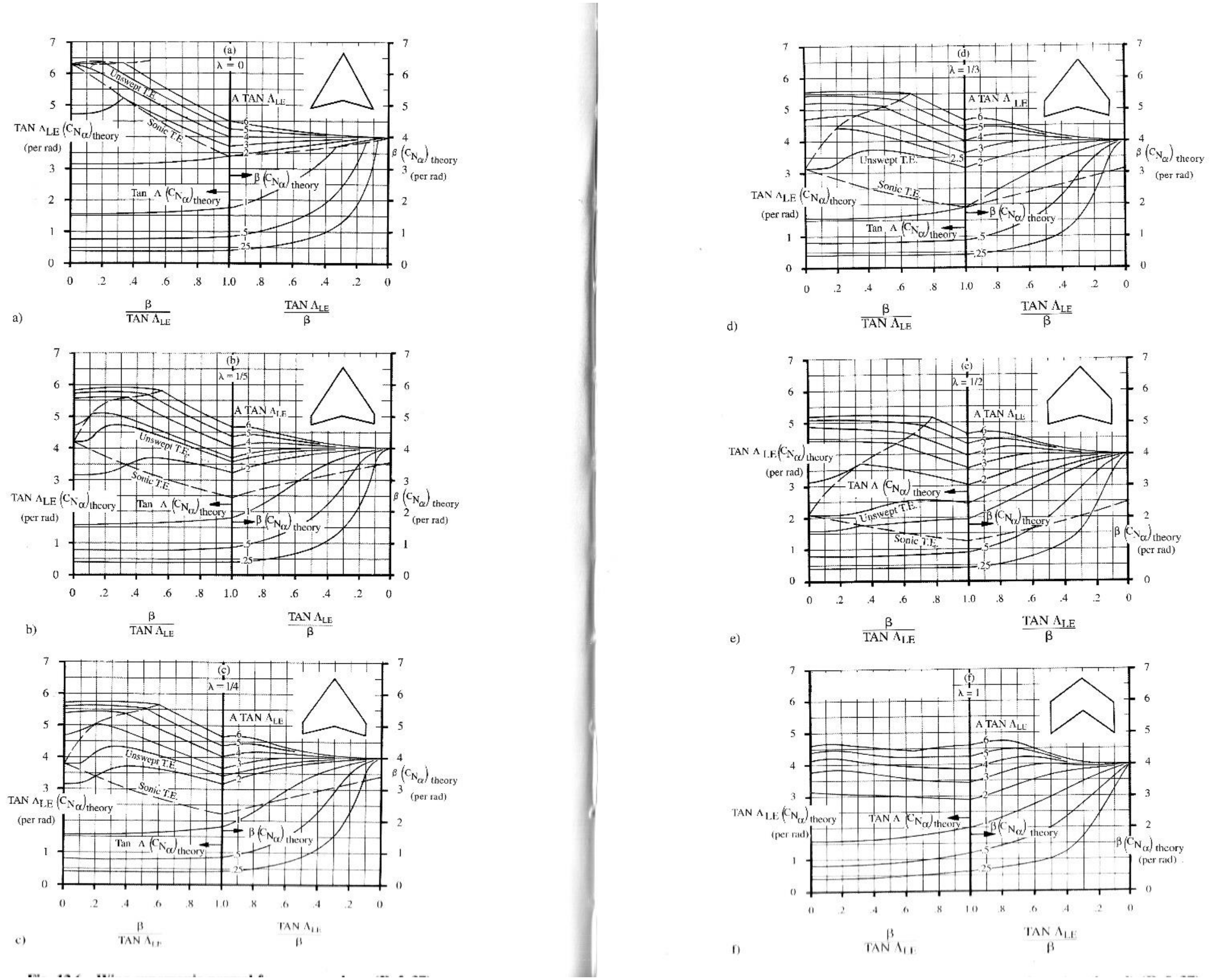
$F = 1.07(1 + d/b)^2$, fuselage lift factor.

- $AR_{eff} = AR(1 + 1.9\, h/b)$; **effective AR with endplates**, h: height of the endplate.
- $AR_{eff} \cong 1.2AR$; **effective AR with winglets**.

Supersonic lift curve slope

- Theory: $C_{L_\alpha} = \frac{4}{\beta}$
- Practice: use the charts valid for trapezoidal wings.
- Correct the values read with $\frac{S_{exposed}}{S} F$

Supersonic lift curve slope



Maximum lift (clean)

- For **moderate to high aspect ratio wings** with moderate sweep and high leading edge radius:

  $$C_{L,max} = 0.9 c_{l,max} cos\Lambda_{c/4}$$

- If a wing has **low AR or high sweep** and a sharp leading edge, maximum lift will increase due to leading edge vortices. This is a function of the shape of the upper surface of the leading edge:

  $$\Delta y = y_{0.06c} - y_{0.015c}$$

Maximum lift (clean)

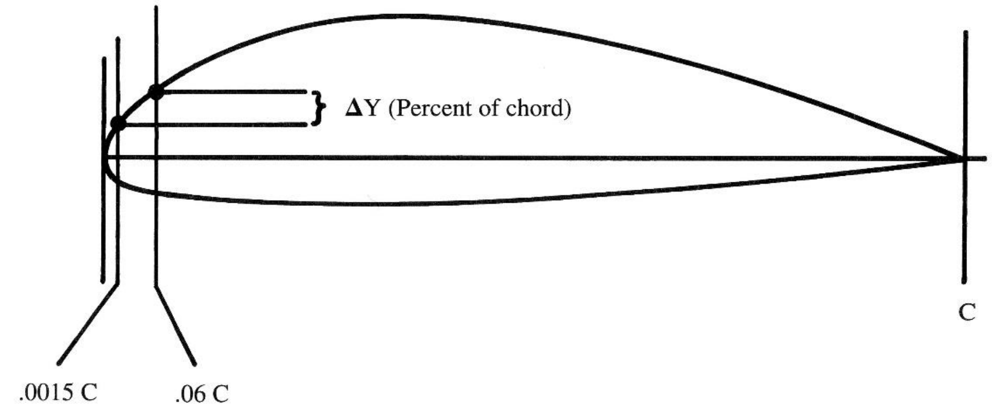


Fig. 12.7 Airfoil leading edge sharpness parameter.

Maximum lift (clean)

Table 12.1 Δy for common airfoils

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

Maximum lift (clean)

- For high aspect ratio wings:

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

Correct for $F, \frac{S_{exposed}}{S}$.

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

Maximum lift (clean)

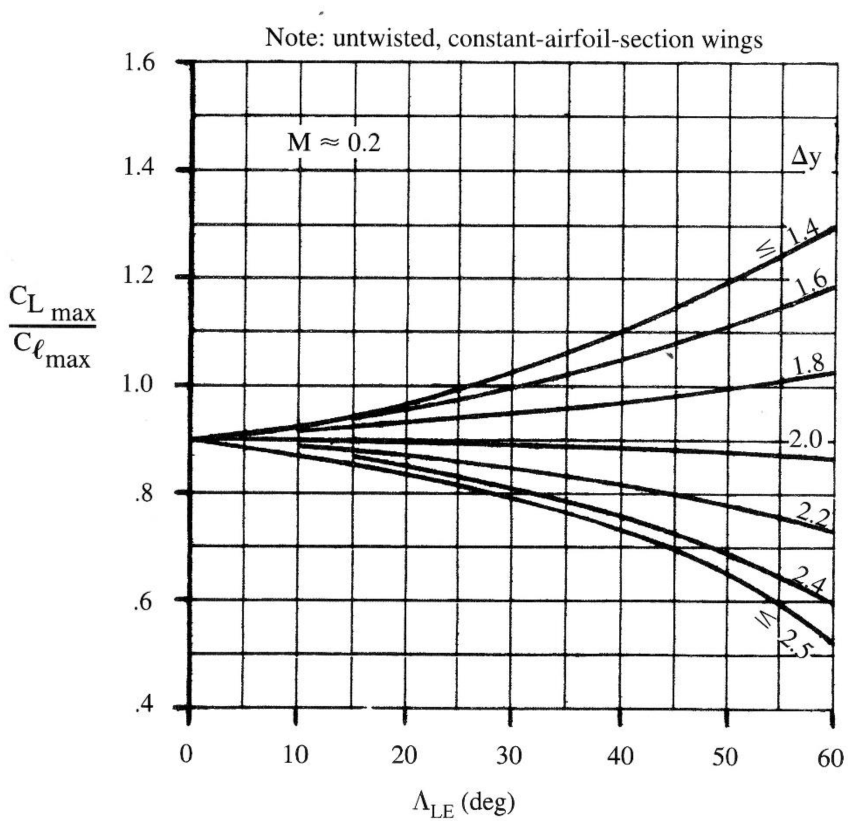


Fig. 12.8 Subsonic maximum lift of high-aspect-ratio wings (Ref. 37).

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Maximum lift (clean)

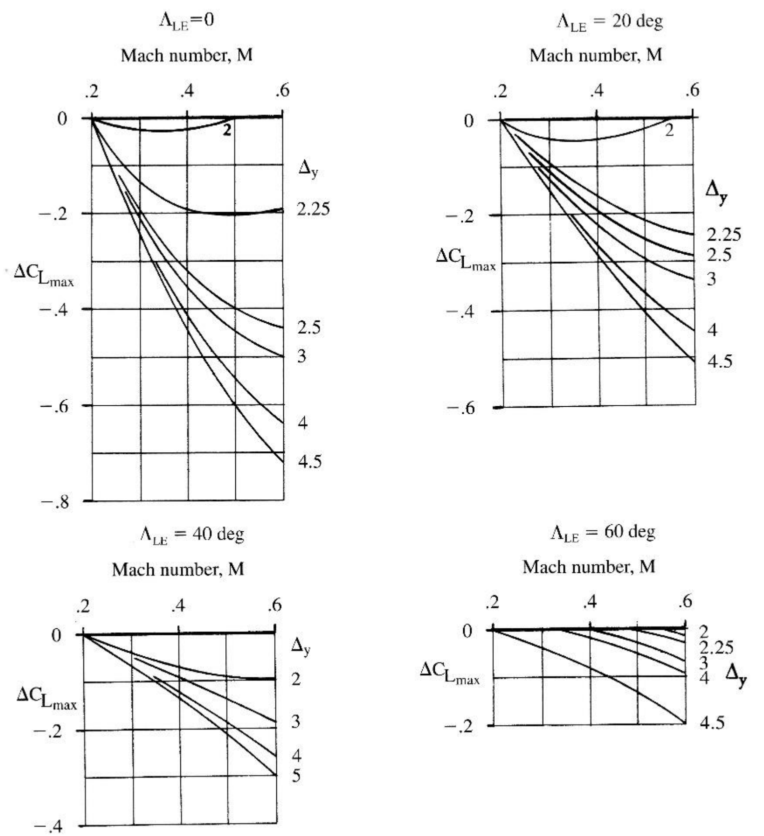

Fig. 12.9 Mach-number correction for subsonic maximum lift of high-aspect ratio wings (Ref. 37).

Maximum lift (clean)

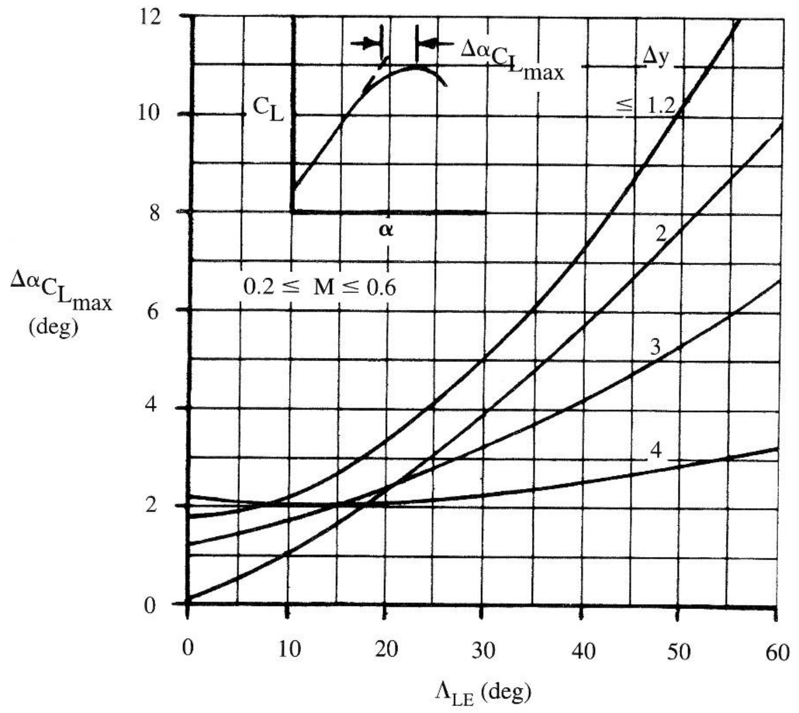

Fig. 12.10 Angle-of-attack increment for subsonic maximum lift of high-aspect-ratio wings (Ref. 37).

Maximum lift (clean)

- A wing has **low AR** if:

$$AR \leq \frac{3}{(C_1+1)\cos\Lambda_{LE}}.$$

$$C_{L,max} = C_{L,max,base} + \Delta C_{L,max}.$$

$$\alpha_{C_{L,max}} = \alpha_{C_{L,max,base}} + \Delta\alpha_{C_{L,max}}$$

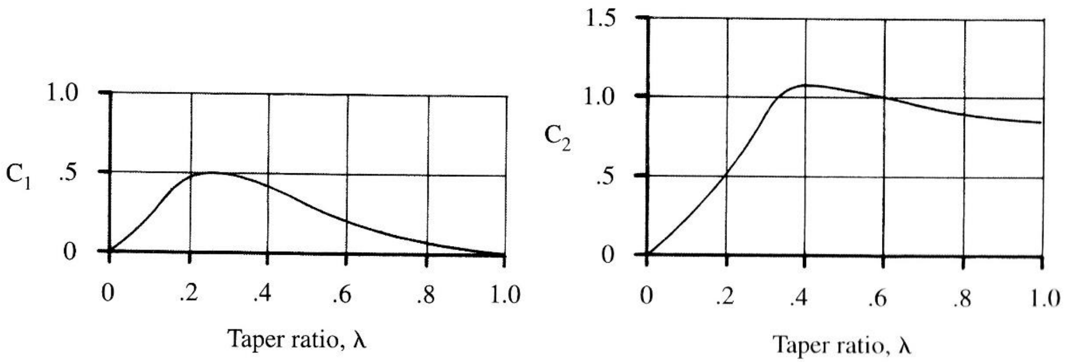

Fig. 12.11 Taper-ratio correction factors for low-aspect-ratio wings (Ref. 37).

Maximum lift (clean)

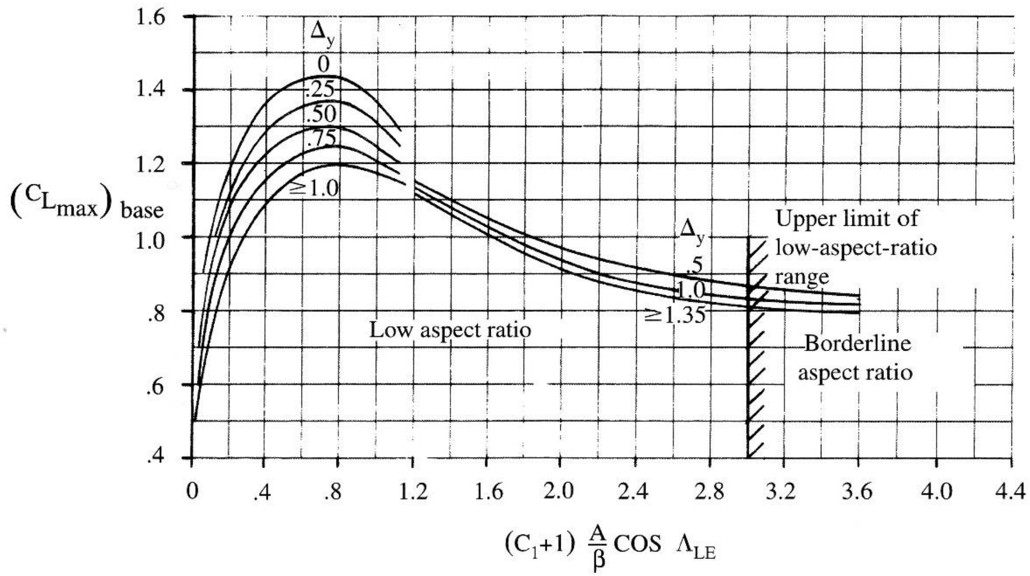

Fig. 12.12 Maximum subsonic lift of low-aspect-ratio wings (Ref. 37).

Maximum lift (clean)

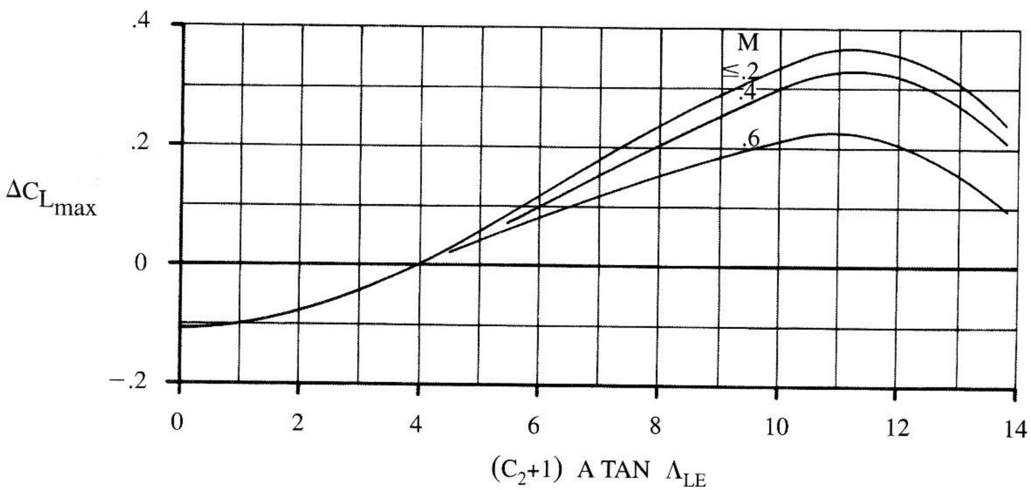

Fig. 12.13 Maximum-lift increment for low-aspect-ratio wings (Ref. 37).

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Maximum lift (clean)

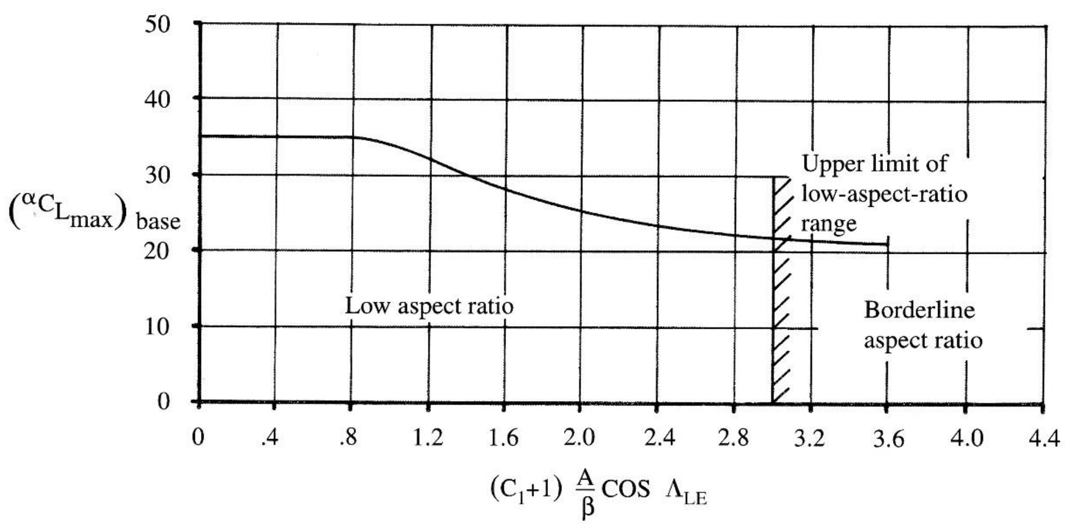

Fig. 12.15 Angle of attack for subsonic maximum lift of low-aspect-ratio wings (Ref. 37).

Maximum lift (clean)

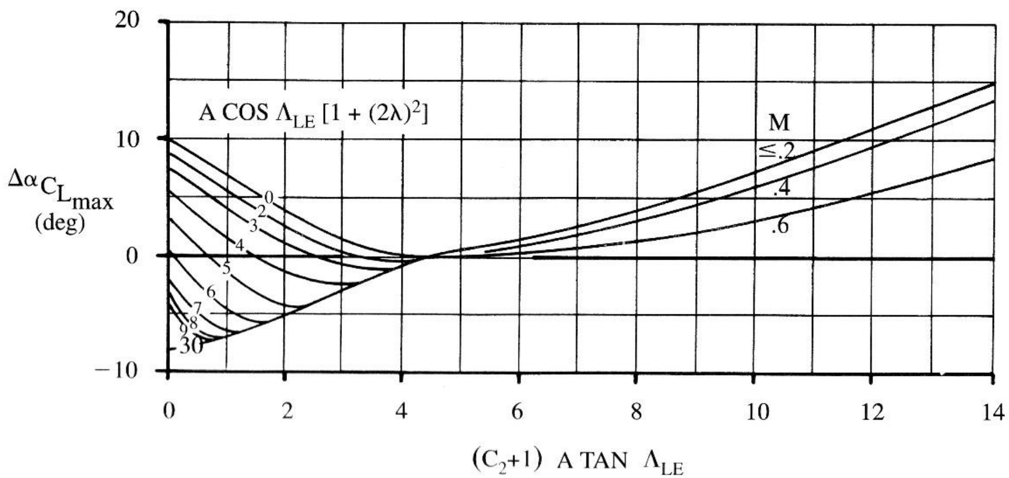

Fig. 12.16 Angle-of-attack increment for subsonic maximum lift of low-aspect-ratio wings (Ref. 37).

Maximum lift (clean)

- At transonic speeds, maximum lift is limited by **structural buffeting and controllability** considerations rather than aerodynamics.

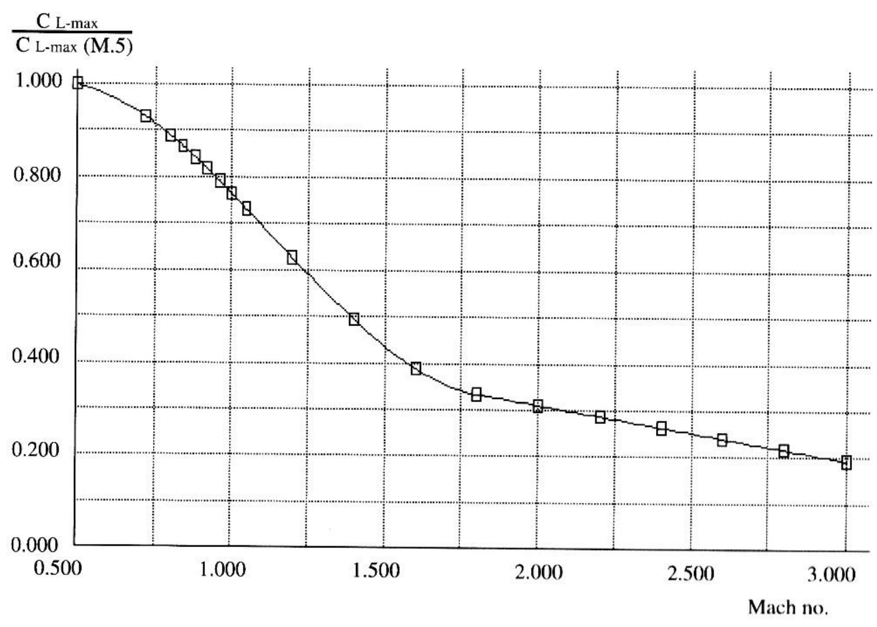

Fig. 12.14 Maximum lift adjustment at higher Mach numbers.

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Maximum lift (with high lift devices)

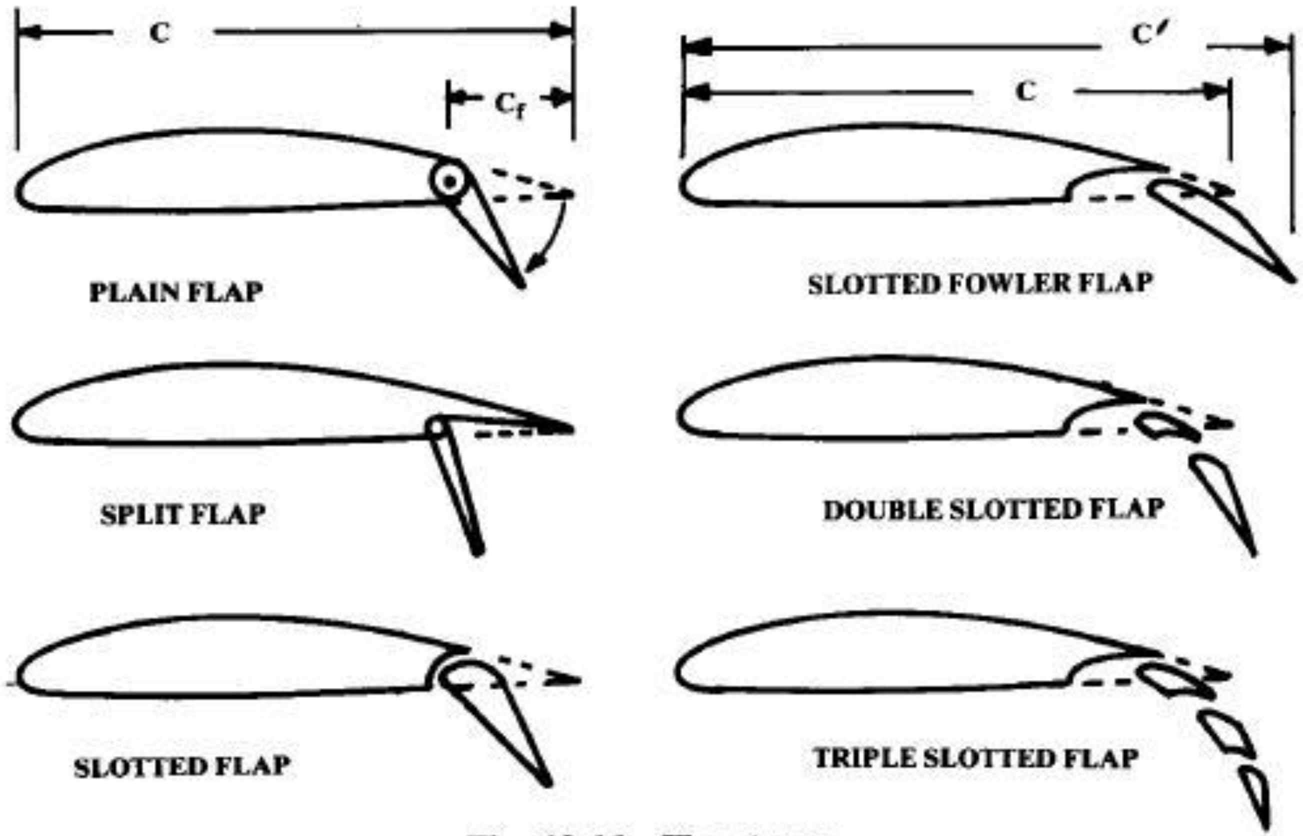

Fig. 12.16 Flap types.

Maximum lift (with high lift devices)

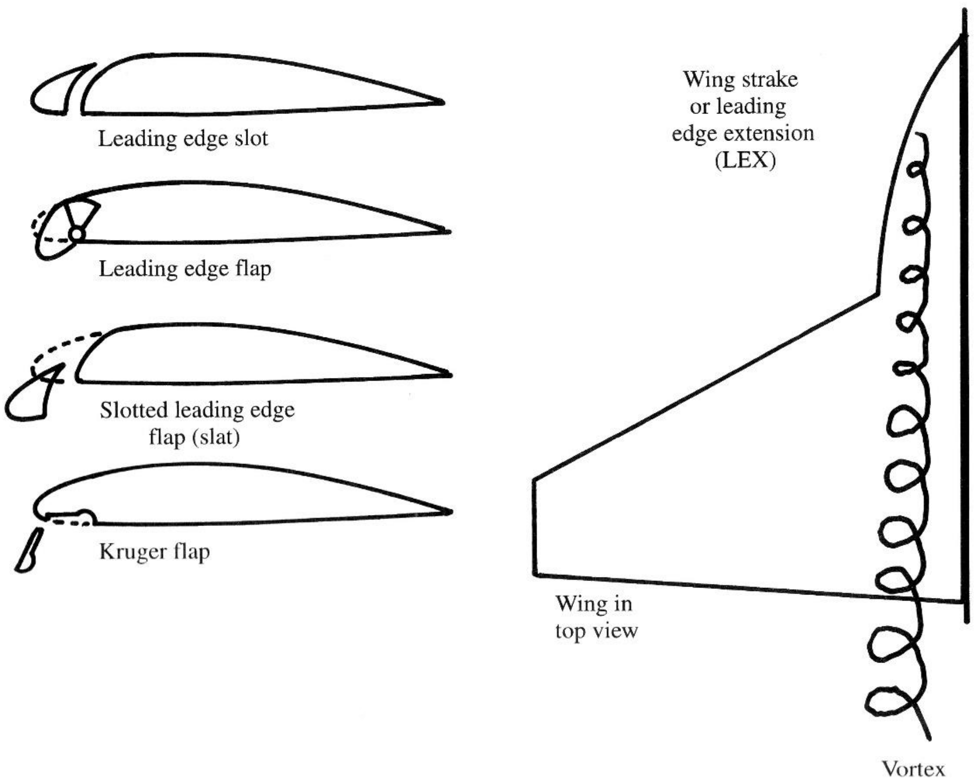

Fig. 12.18 Leading-edge devices.

Maximum lift (with high lift devices)

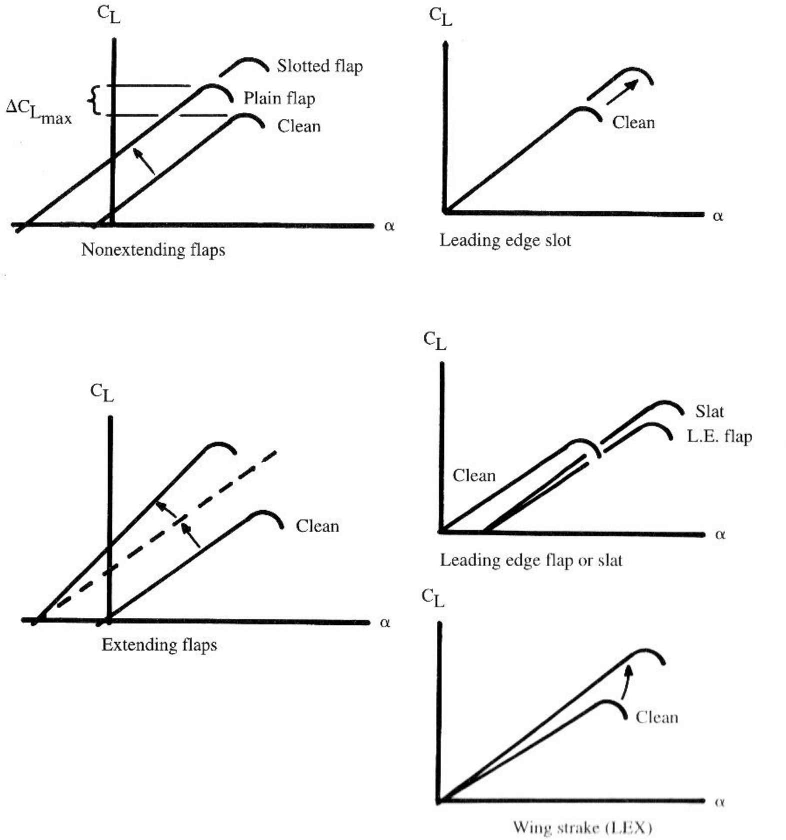

Fig. 12.19 Effects of high-lift devices.

Maximum lift (with high lift devices)

- **Trailing edge devices decrease the stall angle of attack** by increasing the pressure drop over the top of the airfoil promoting flow separation.

- In order to increase α_{stall} a **leading edge device** must be used.

$$\Delta C_{L,max} = 0.9\Delta c_{l,max}\frac{S_{flapped}}{S}cos\Lambda_{HL}$$

$$\Delta\alpha_{0L} = \Delta\alpha_{0L,airfoil}\frac{S_{flapped}}{S}cos\Lambda_{HL}$$

HL: hinge line of the high lift device

Maximum lift (with high lift devices)

- For takeoff, the increments of about 60-80% of the increment calculated above should be used.
- Maximum lift occurs at a flap setting of about 40°-45°.

$\Delta_{\alpha_{0L,airfoil}} \cong -15^{o}$ (landing setting),

$\Delta_{\alpha_{0L,airfoil}} \cong -10^{o}$ (takeoff setting),

Maximum lift (with high lift devices)

Table 12.2 Approximate lift contributions of high-lift devices

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

Maximum lift (with high lift devices)

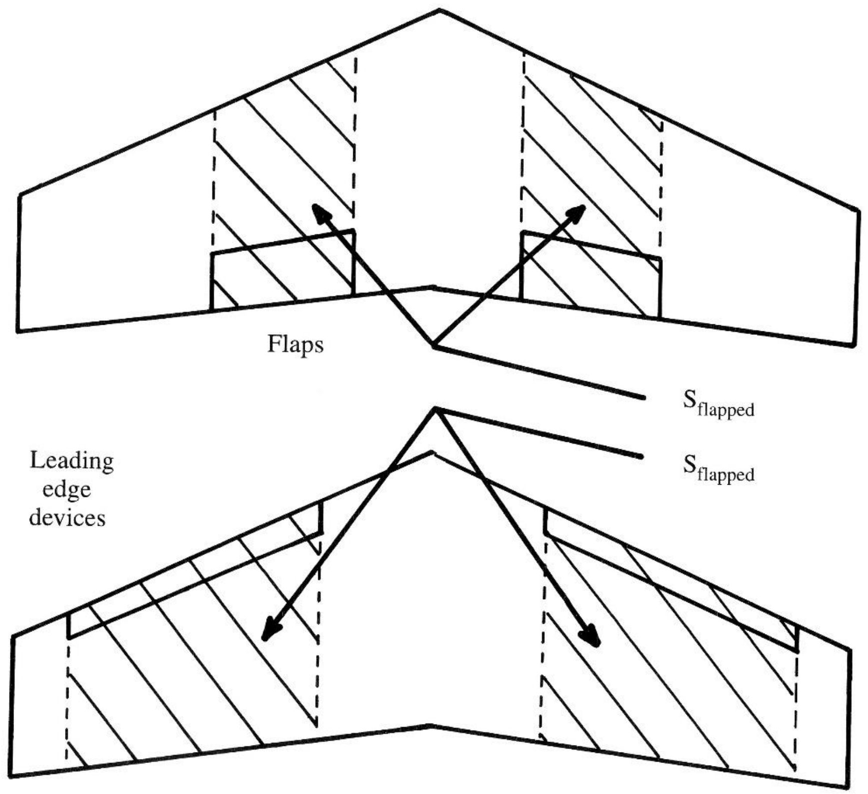

Fig. 12.20 "Flapped" wing area.

Maximum lift (with high lift devices)

- **Leading edge devices** increase lift by:
  - Increasing camber,
  - Increasing wing area,
  - Delaying separation.
- Leading edge devices are particularly useful at **high α**.
- During takeoff and landing, they are useful when in combination with trailing edge devices as they prevent stall.

Estimation of C_{Do}, equivalent skin friction method

$$C_{Do} = \frac{S_{wet}}{S} C_{fe}$$

- C_{fe}: equivalent skin friction coefficient is a function of the **Reynolds number**, *Re.*

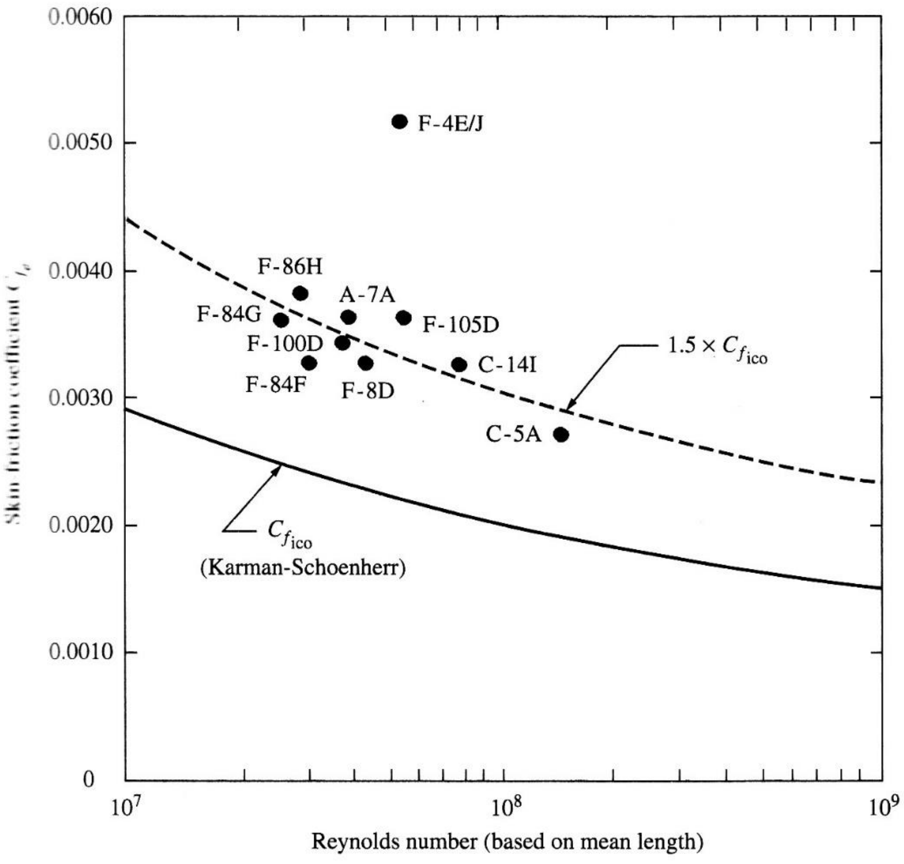

Figure 2.55 Equivalent skin-friction drag for a variety of airplanes. (After Jobe, Ref. 27.)

Equivalent skin friction coefficients

Table 12.3 Equivalent skin friction coefficients

$C_{D_0} = C_{fe} \frac{S_{wet}}{S_{ref}}$	C_{fe}-subsonic
Bomber and civil transport	0.0030
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

Wetted area ratio

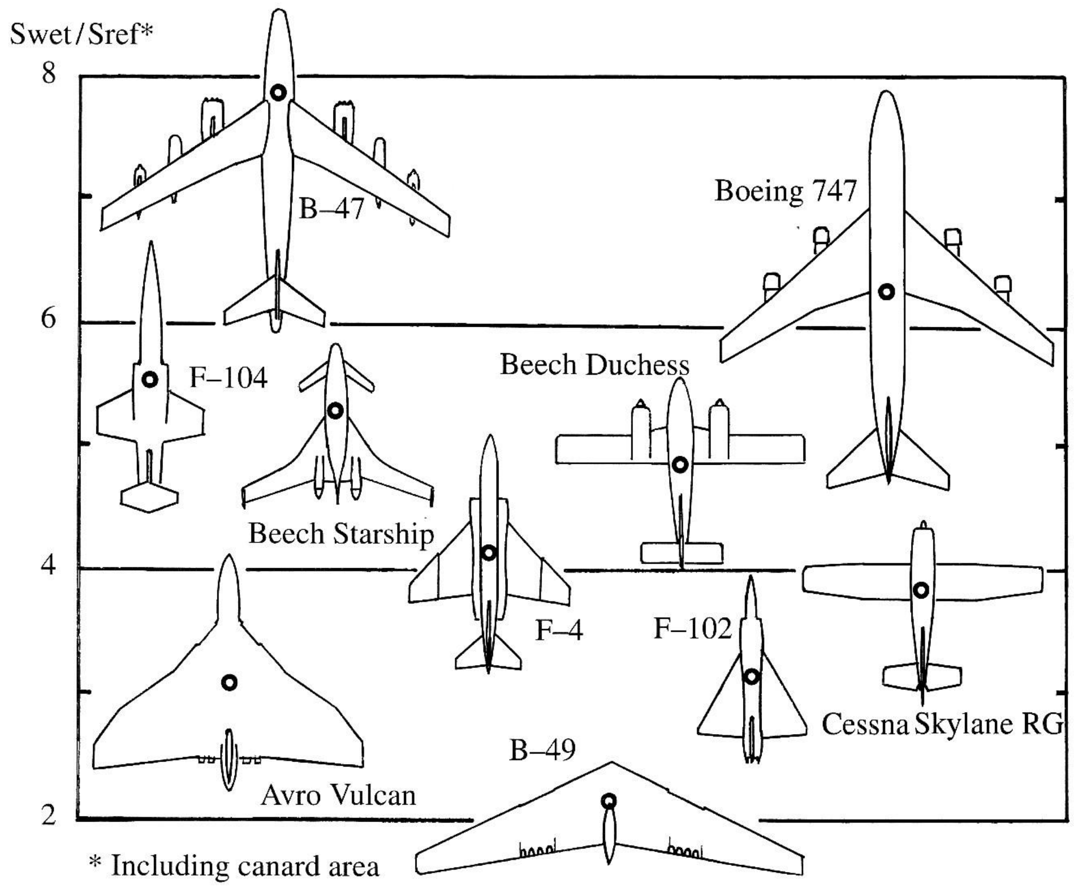

Fig. 3.5 Wetted area ratios.

Estimation of C_{Do}, component build-up method

- Total parasite drag coefficient:

$$C_{Do})_{subsonic} = \frac{\sum C_{fc} FF_c Q_c S_{wet,c}}{S} + C_{D,misc} + C_{D,L\&P}$$

C_{fc}: flat plate skin friction coefficient,

$C_{fc} = C_{fc}(Re, M, k)$; k: skin roughness.

FF_c: form factor, estimates pressure drag due to separation,

Q: interference factor.

$C_{D,misc}$: drag of flaps, landing gears, upswept aft fuselage, base area.

$C_{D,L\&P}$: drag of leakages and protuberances.

Flat plate skin friction coefficient

- Laminar flow: $C_f = 1.328/\sqrt{Re}, \quad Re = \frac{\rho_\infty V_\infty l}{\mu_\infty}$,
  l: characteristic length.
- Turbulent flow:

$$C_f = \frac{0.455}{(\log Re)^{2.58}(1 + 0.144M^2)^{0.65}}$$

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Flat plate skin friction coefficient

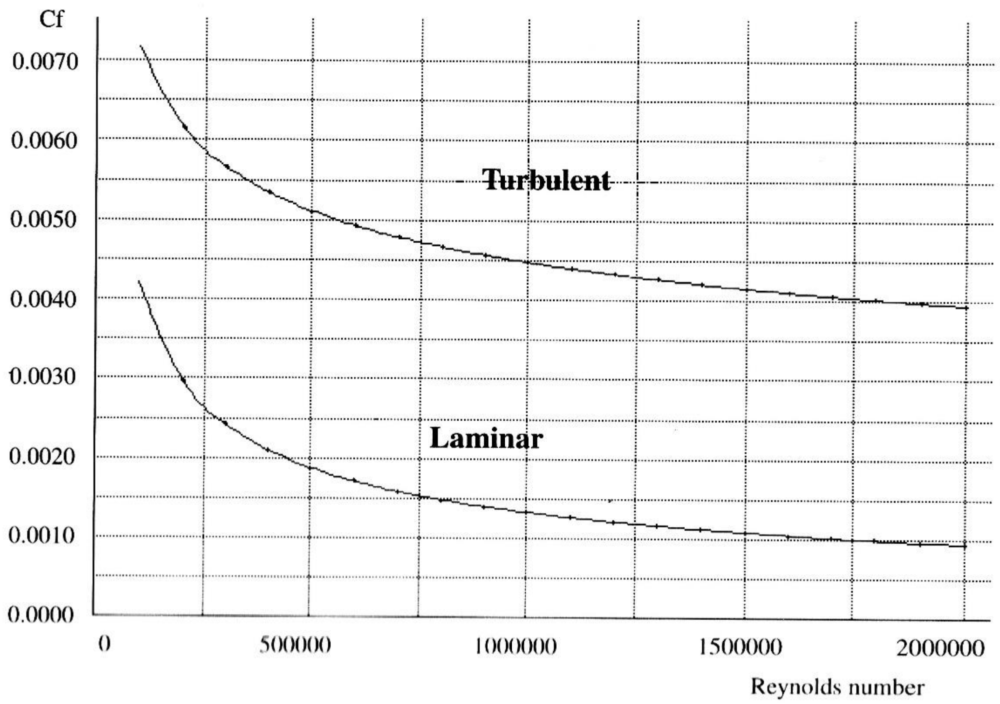


Fig. 12.21 Flat plate skin friction coefficient vs Reynolds number.

Flat plate skin friction coefficient

- If the surface is **rough**, the skin friction coefficient will be higher.
- The **smaller** of the cut-off Reynolds number and the actual Reynolds number shall be used.
- Subsonic flow:

$$Re_{cutoff} = 38.21(l/k)^{1.053},$$

- Transonic or Supersonic flow:

$$Re_{cutoff} = 44.62(l/k)^{1.053}M^{1.16}$$

Flat plate skin friction coefficient

Table 12.4 Skin roughness value (*k*)

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	0.17×10^{-5}	0.052×10^{-5}

Component form factors

- Wing, tail, strut and pylon:

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

$(x/c)_m$: chordwise location of the maximum thickness point,

Λ_m: sweep angle at the same location

Component form factors

- Fuselage and smooth canopy:

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

$f = \frac{l}{d} = \frac{l}{\sqrt{(4/\pi)A_{max}}}$: fineness ratio.

- Nacelle and external stores:

$$FF = 1 + \frac{0.35}{f}$$

Component form factors

- For a tail surface with a hinged control surface: +10%
- A square sided fuselage: +40%
- For a two piece canopy: +40%
- For an external boundary-layer diverter for a fuselage mounted inlet:
  - Double wedge: $FF = 1 + d/l$,
  - Single wedge: $FF = 1 + 2d/l$.

Component form factors

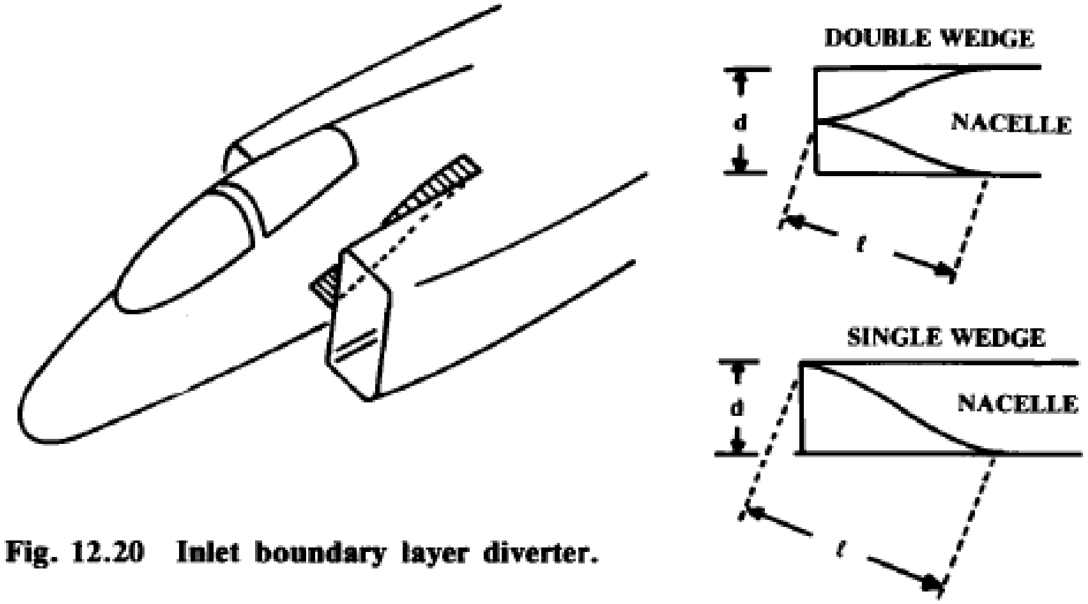


Fig. 12.20 Inlet boundary layer diverter.

Component interference factors

- Nacelle or external store mounted on wing or fuselage: Q=1.5.
- Nacelle or external store mounted on wing or fuselage: Q=1.3 (if mounted less than one diameter away).
- Nacelle or external store mounted on wing or fuselage: Q=1.1 (if mounted more than one diameter away).
- Wingtip mounted missiles: Q=1.25.
- High-wing, mid-wing or a well-filleted low-wing: Q=1.0.
- Unfilleted low-wing: Q=1.1-1.4.
- Fuselage: Q=1.0.
- Tail surfaces: Q=1.03 (V-tail), 1.08 (H-Tail), 1.04-1.05 (conventional tail).

Miscellaneous drag

- Upswept aft fuselage:

$$\frac{D}{q} = 3.83\theta^{2.5}A_{max}.$$

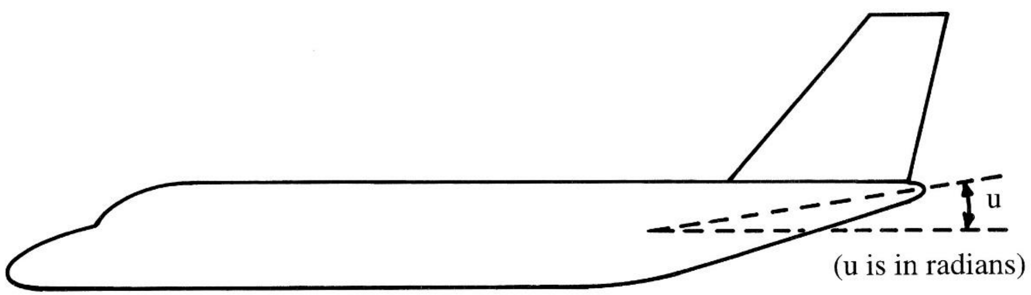


Fig. 12.26 Fuselage upsweep.

Miscellaneous drag

- Landing gear: summation of the drags of the wheels, struts, and other gear components.
- Q=1.2, *1.07 for retractable landing gears accounting for the hollow landing gear well.

Table 12.5 Landing gear component drags

	$\frac{D/q}{\text{Frontal area}}$
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
Streamline strut ($1/6 < t/c < 1/3$)	0.05
Round strut or wire	0.30
Flat spring gear leg	1.40
Fork, bogey, irregular fitting	1.0–1.4

Miscellaneous drag

- Flaps:

$$\Delta C_{Do,flap} = F_{flap}\left(\frac{c_{flap}}{c}\right)\frac{S_{flapped}}{S}\left(\delta_{flap} - 10^{o}\right).$$

$F_{flap} = 0.0144$: plain flaps,

$F_{flap} = 0.0074$: slotted flaps.

- Speed brakes:

Fuselage mounted: $\frac{D}{q} = 1.0A_{frontal}$

Wing mounted: $\frac{D}{q} = 1.6A_{frontal}$

Miscellaneous drag

- Canopies (transport and light aircraft):

$$\frac{D}{q} = 0.50 A_{frontal,wind\ shield}$$

- Cannon port:

$$\frac{D}{q} = 0.2\ \text{ft}^2.$$

Leakage and protuberance drag

- Antennas, lights, door edges, fuel vents, control surface external hinges, actuator fairings, rivets, rough or misaligned panels…
- Jet transports and bombers: 2-5% parasite drag,
- Propeller aircraft: 5-10%,
- Fighters: 10-15% (old), 5-10% (new).

Supersonic Wave Drag

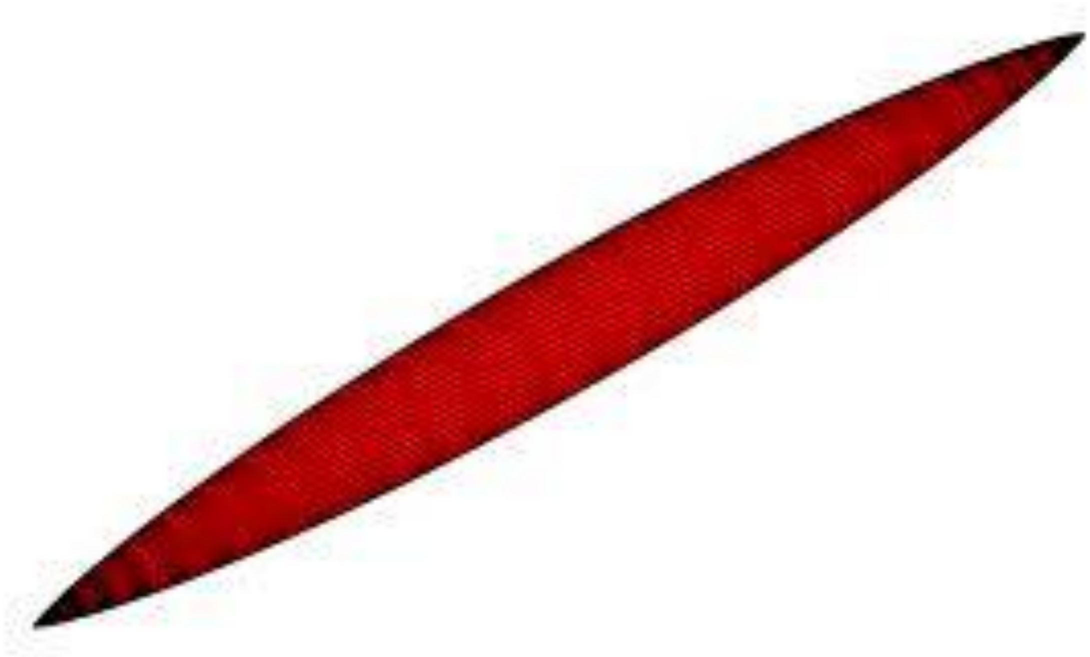
- For supersonic skin friction drag $Q = FF = 1$.

$$C_{D0})_{s.sonic} = \frac{\sum C_{fc} S_{wet}}{S} + C_{D,misc} + C_{D,L\&P} + C_{D,wave}$$

- Leakage and protuberance drag percentages apply only to skin-friction drag.
- For preliminary wave drag analysis ($M \geq 1.2$):

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

Sears-Haack body



Supersonic wave drag

- E_{wd}: wave drag efficiency factor.

=1.0 for a perfect Sears-Haack body,

=1.2 for a smooth volume distribution, blended delta wing,

=1.8-2.2 for a supersonic fighter, bomber.

- $\left.\frac{D}{q}\right)_{Sears-Haack} = \frac{9\pi}{2}\left(\frac{A_{max}}{l}\right)^2$; subtract inlet capture area.

l: aircraft length – length with constant cross sectional area.

Transonic wave drag

- Boeing formulation:

$$M_{DD} = M_{DD,L=0} LF_{DD} - 0.05 C_{L,design} \ (wing).$$

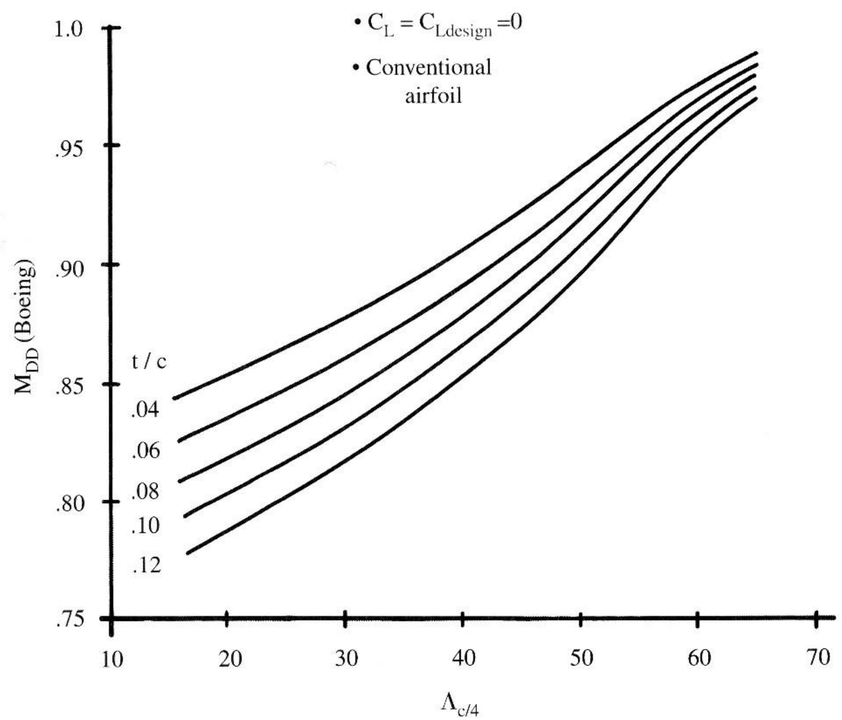


Fig. 12.28 Wing drag-divergence Mach number.

Transonic wave drag

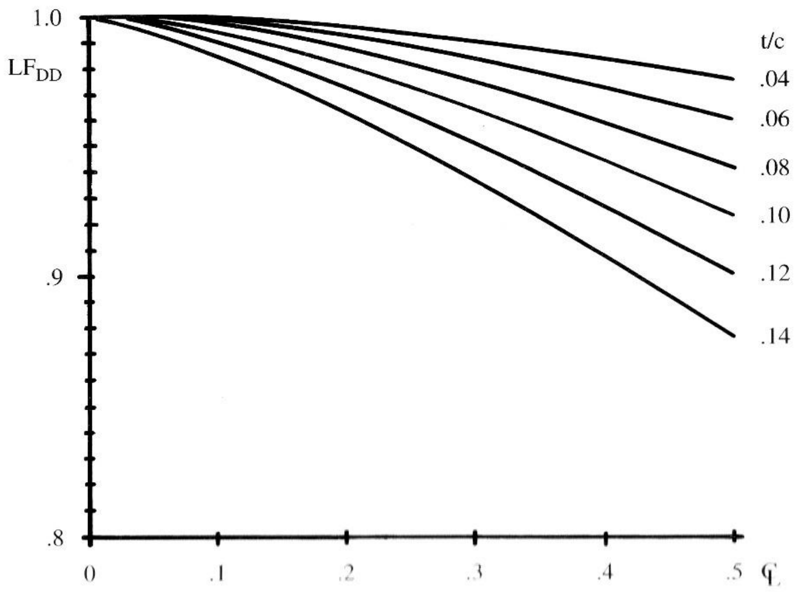


Fig. 12.29 Lift adjustment for M_{DD}.

Transonic wave drag

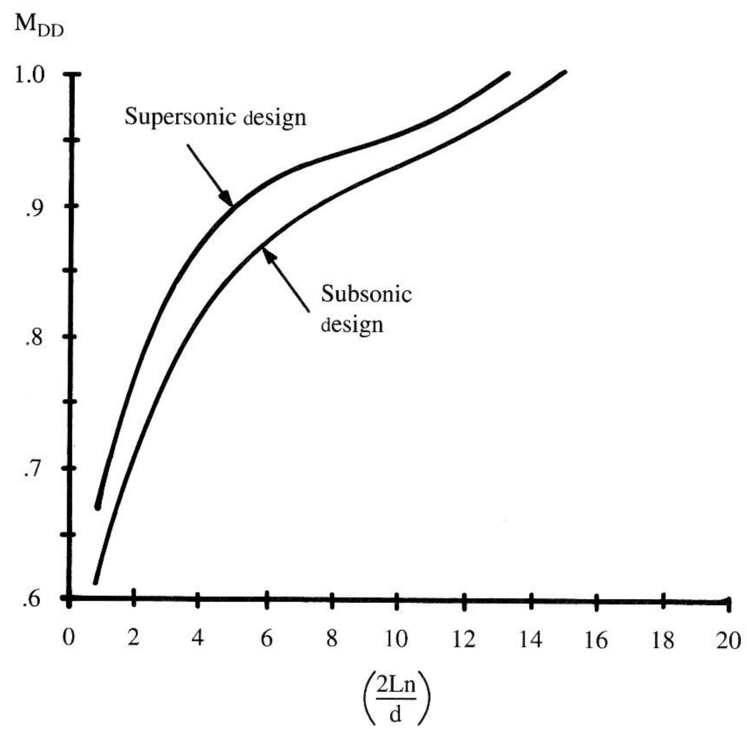


Fig. 12.30 Body drag-divergent Mach number.

Transonic wave drag

L_n: length of fuselage from nose to the location where fuselage cross section becomes constant.

d: equivalent diameter of the fuselage there.

Choose the **smaller** of the M_{dd} found for wing and fuselage for the drag divergence Mach number of the airplane.

Transonic wave drag

For initial analysis:

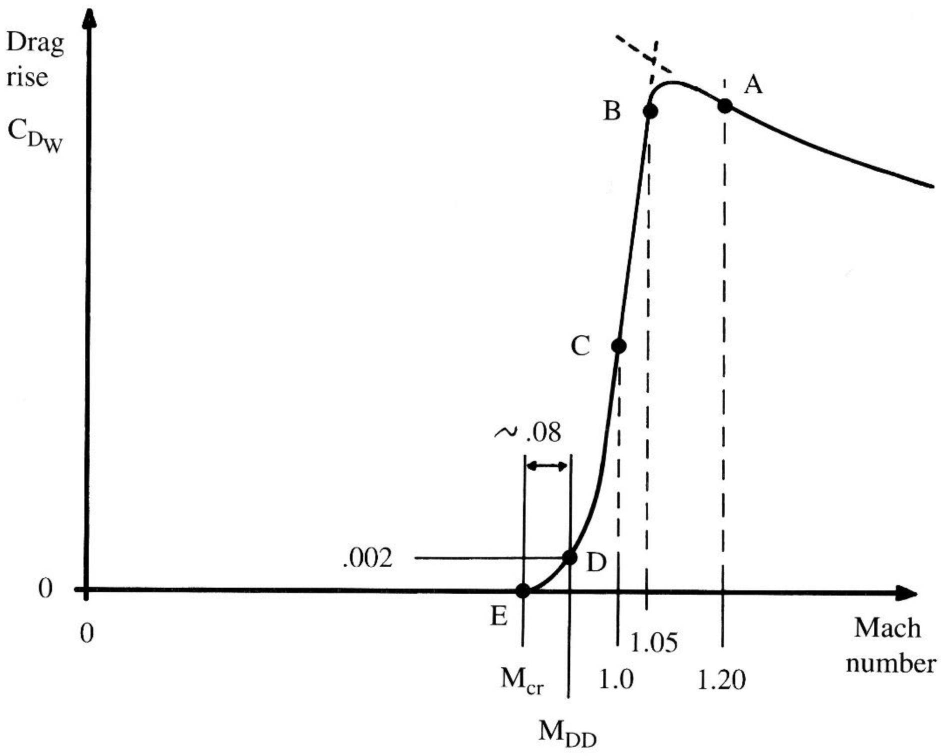


Fig. 12.31 Transonic drag rise estimation.

Transonic wave drag

- $M \geq 1.2$: use supersonic wave drag expression.
- $C_{D,wave}(M = 1.05) = C_{D,wave}(M = 1.2)$.
- $C_{D,wave}(M = 1.0) = \frac{C_{D,wave}(M=1.05)}{2}$.
- $M_{cr} = M_{DD} - 0.08$.
- $C_D(M_{DD}) = C_D(M_{cr}) + 0.002$.

Complete drag build-up

- **Subsonic drag:** skin friction drag (including form factor and interference) + miscellaneous drag + leakage & protuberance drag
- **Supersonic drag:** skin friction drag + miscellaneous drag + leakage and protuberance drag + wave drag.

Complete drag build-up

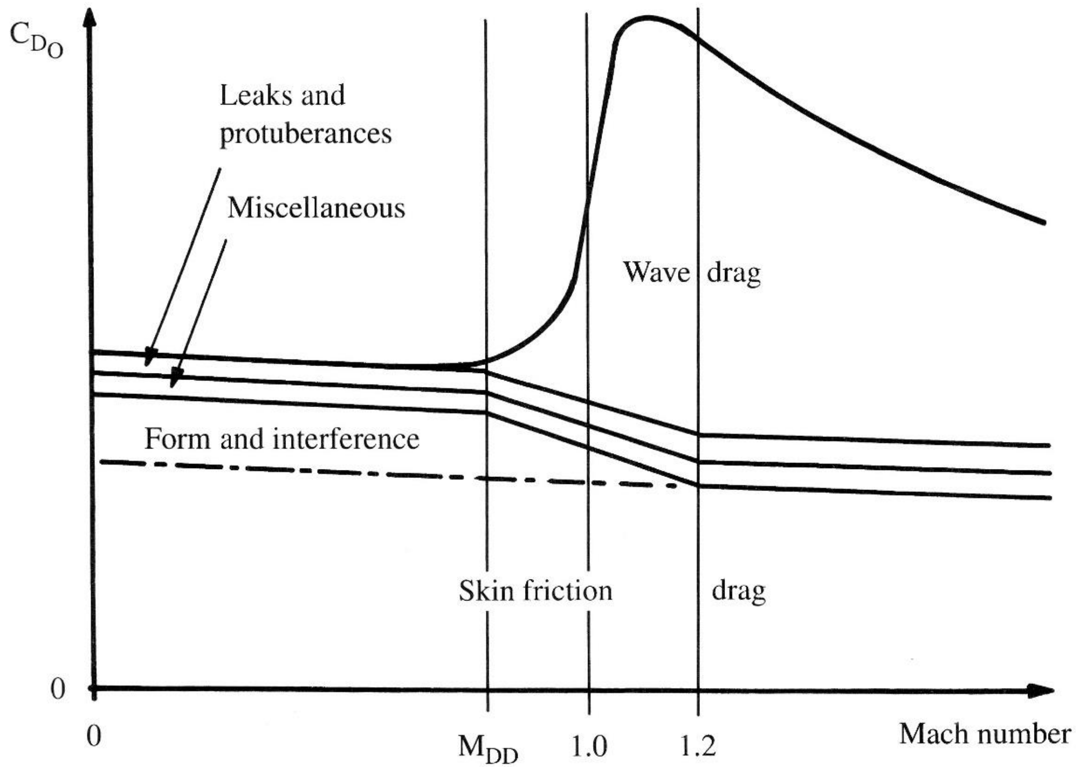


Fig. 12.32 Complete parasite drag vs Mach number.

Complete drag build-up

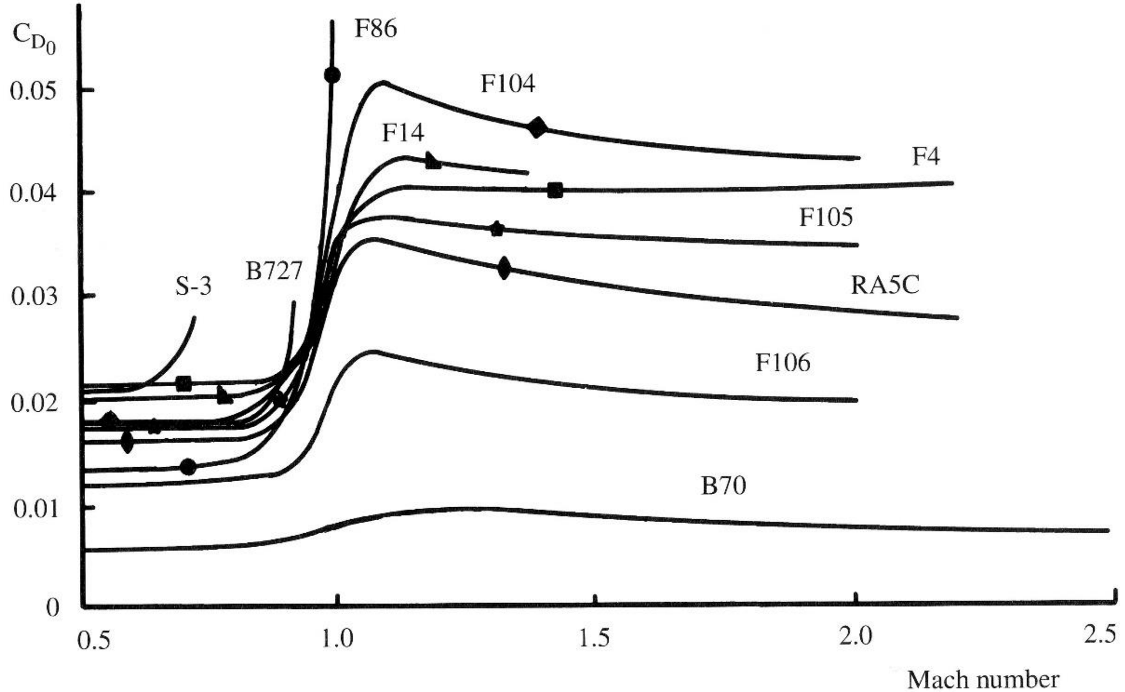


Fig. 12.33 Parasite drag and drag rise.

Drag due to lift (induced drag)

- Induced drag coefficient:

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

- Straight-winged airplane:

$$e = 1.78(1 - 0.045AR^{0.68}) - 0.64 \; (\Lambda_{LE} < 30^o)$$

- Swept winged airplane:

$$e = 4.61(1 - 0.045AR^{0.68}) \cos \Lambda_{LE}^{0.15} - 3.1 \; (\Lambda_{LE} > 30^o)$$

- At supersonic speeds:

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

Drag due to lift (induced drag)

- Flap effect on induced drag:

$$\Delta C_{Di} = K_f^2 (\Delta C_{L,flap})^2 \cos \Lambda_{\bar{c}/4},$$

$K_f = 0.14$: full span flaps,

$K_f = 0.28$: partial span flaps.