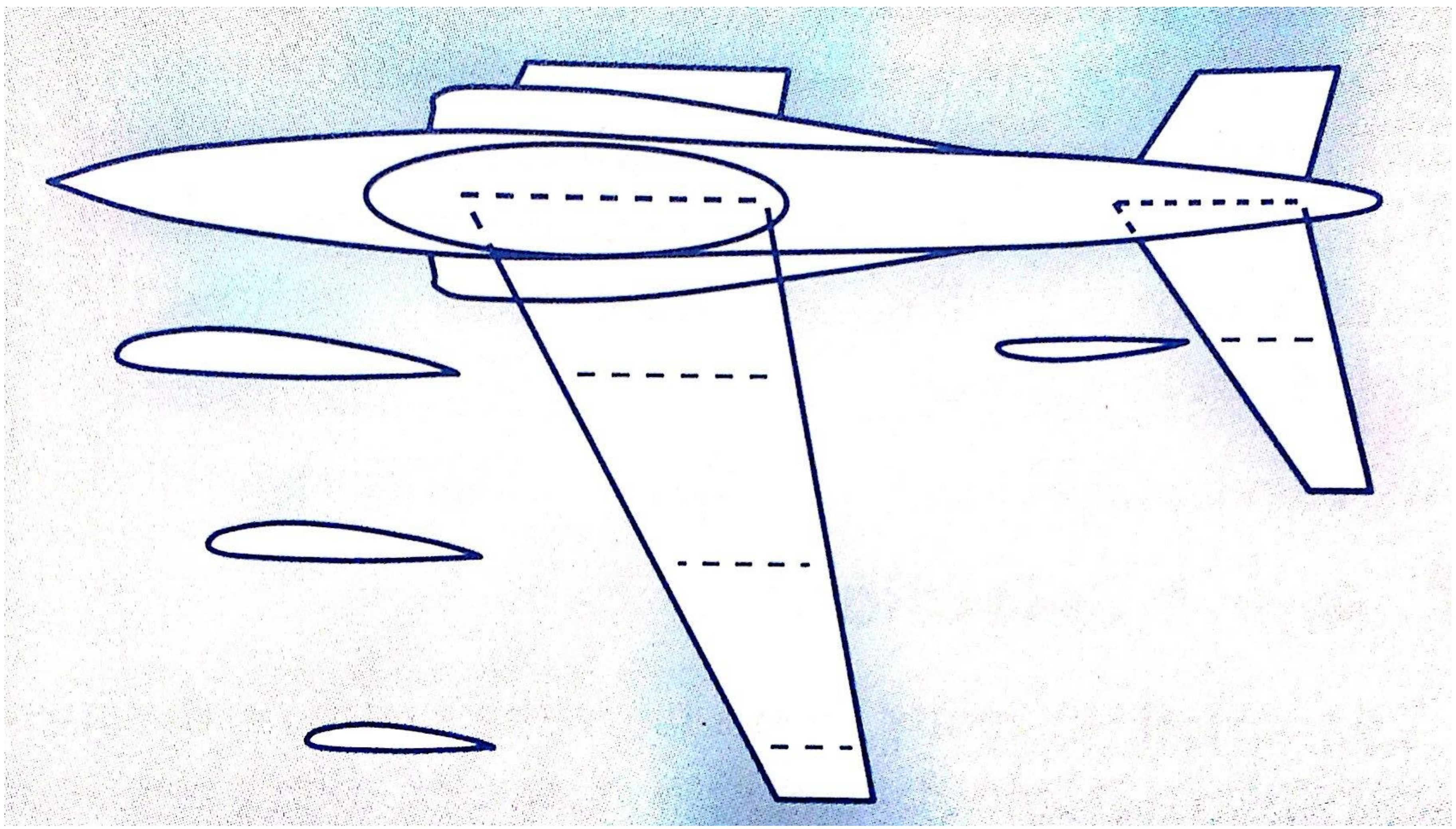
ME4932 Aircraft Performance & Design

Airfoil and Wing/Tail Geometry Selection (Chapter 4)



Source: Aircraft Design by Daniel P. Raymer

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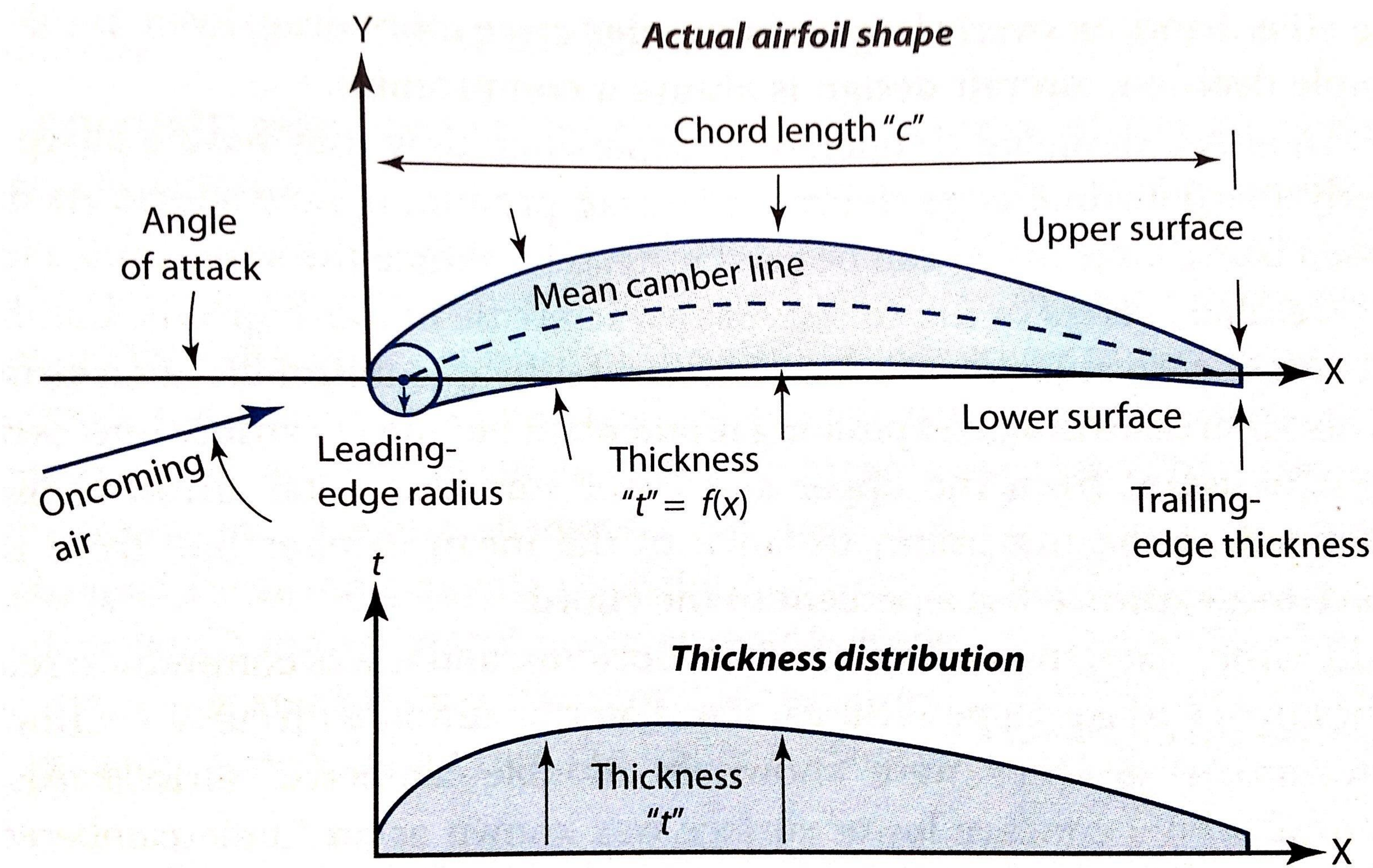

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- Chord = Straight line from leading edge to trailing edge
- Mean Camber Line = Line equidistant from upper/lower surface
- Thickness = Distance from upper to lower surface measured perpendicular to the mean camber line
- t/c = maximum thickness to chord

Thickness distribution → Profile Drag

Camber → Lift, Drag due to Lift, Pitching Moment

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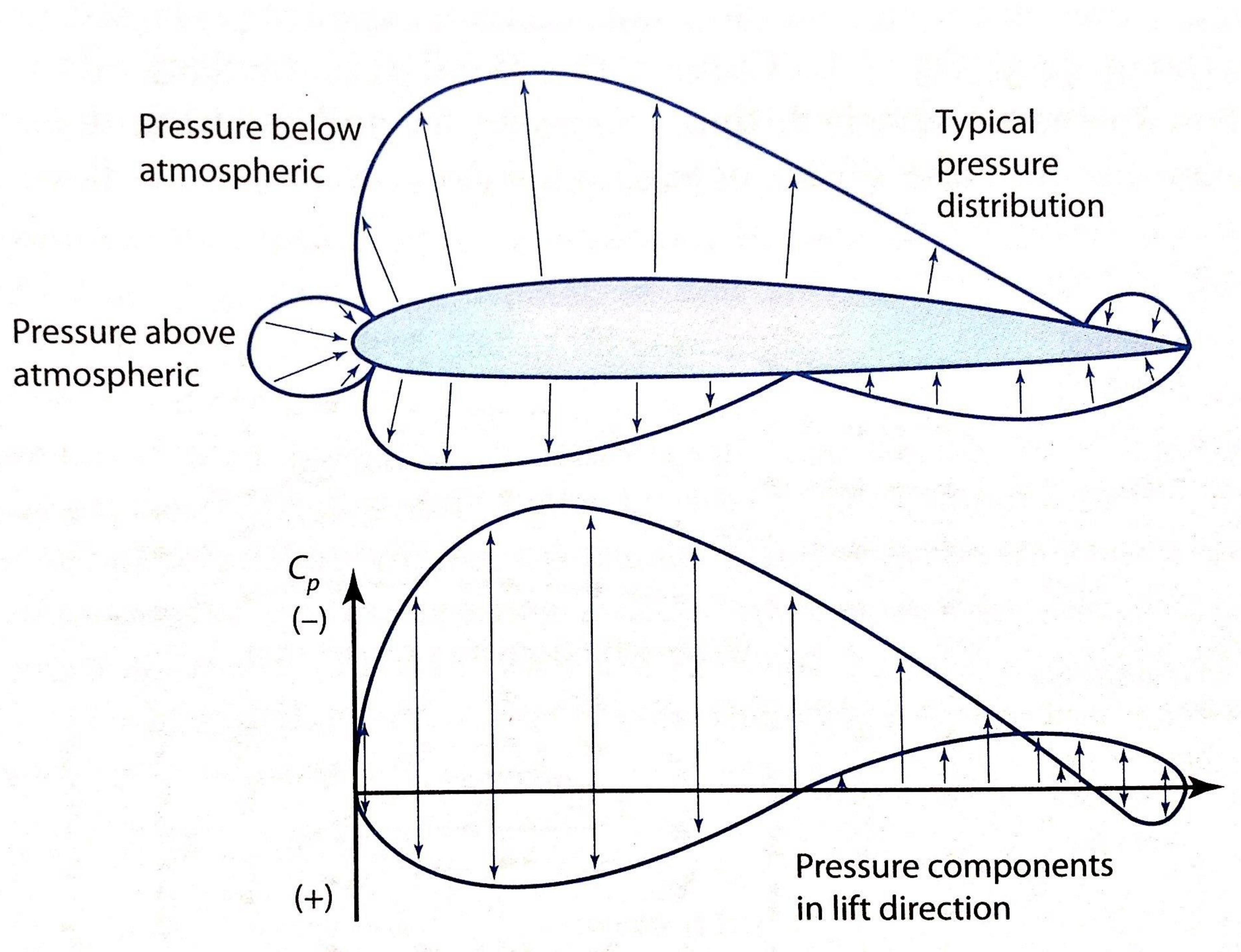

- About 2/3 of the lift is produced by negative pressures over the top of the airfoil. So, if design features are to disturb a wing, it better be the bottom of it!

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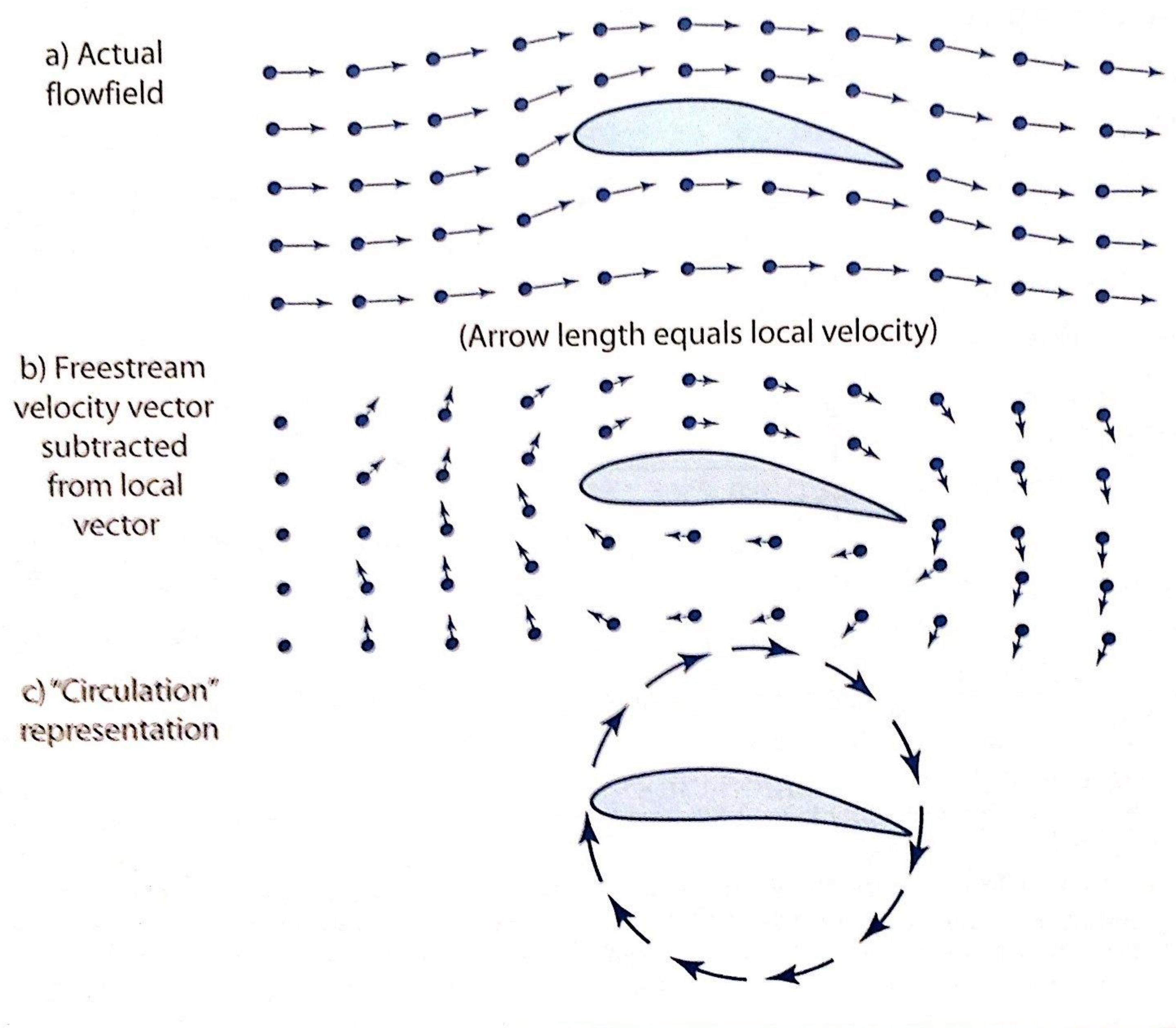

- When you look at velocity vectors around the airfoil/wing, and subtract the free-stream vector, the result is the circulation.
- This is the classical basis for lift and drag due to lift calculations.

Source: Aircraft Design by Daniel P. Raymer

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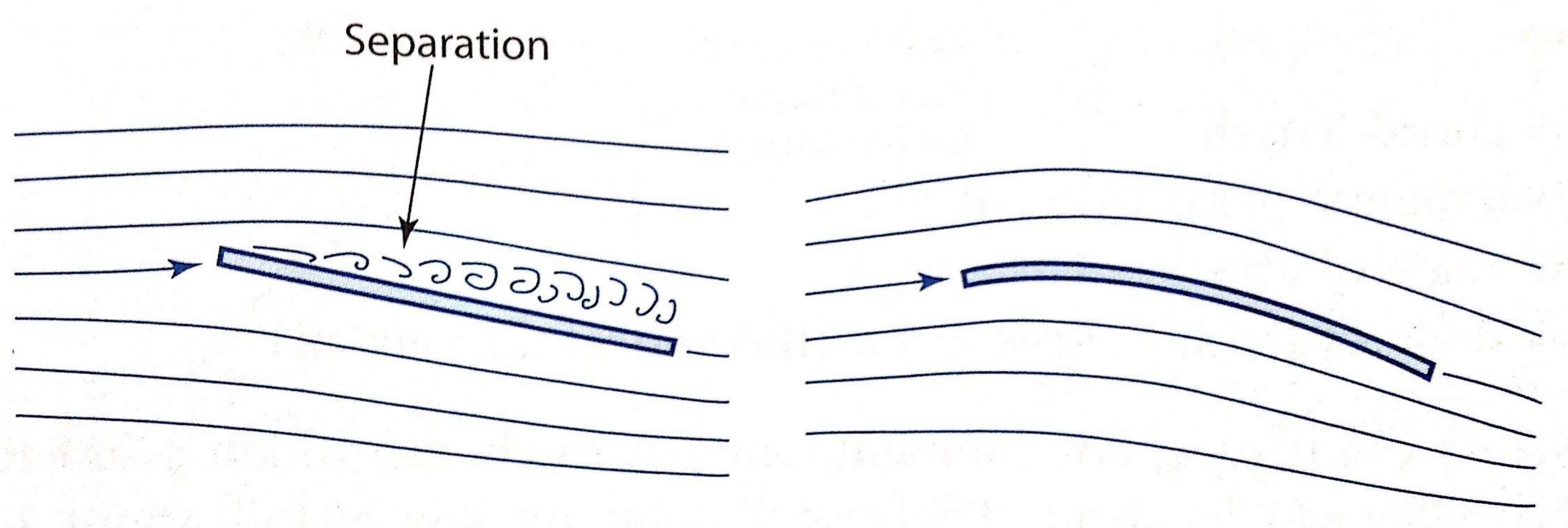

- A flat plate will generate lift, but the flow will separate at moderate angles of attack and spoil L/D. Curving the plate (adding camber) will greatly delay separation and improve L/D.

Source: Aircraft Design by Daniel P. Raymer

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Airfoil and Wing/Tail Geometry Selection (Chapter 4)

- Airfoil section in 2-D inviscid flow, does not experience drag-due-to-lift as defined normally. Drag is due to friction and pressure effects due to separation.

Section lift coefficient:

$$C_l = \frac{\text{Section lift}}{qc}$$

(Perpendicular to V)

Section drag coefficient:

$$C_d = \frac{\text{Section drag}}{qc}$$

(Parallel to V)

Section moment coefficient:

$$C_m = \frac{\text{Section moment}}{qc^2}$$

(Normally negative, meaning nose-down when taken about a.c.)

c = chord length

q = dynamic pressure = $\rho V^2/2$

α = angle of attack

$C_{l\alpha}$ = slope of the lift curve = 2π (theoretical thin airfoil)

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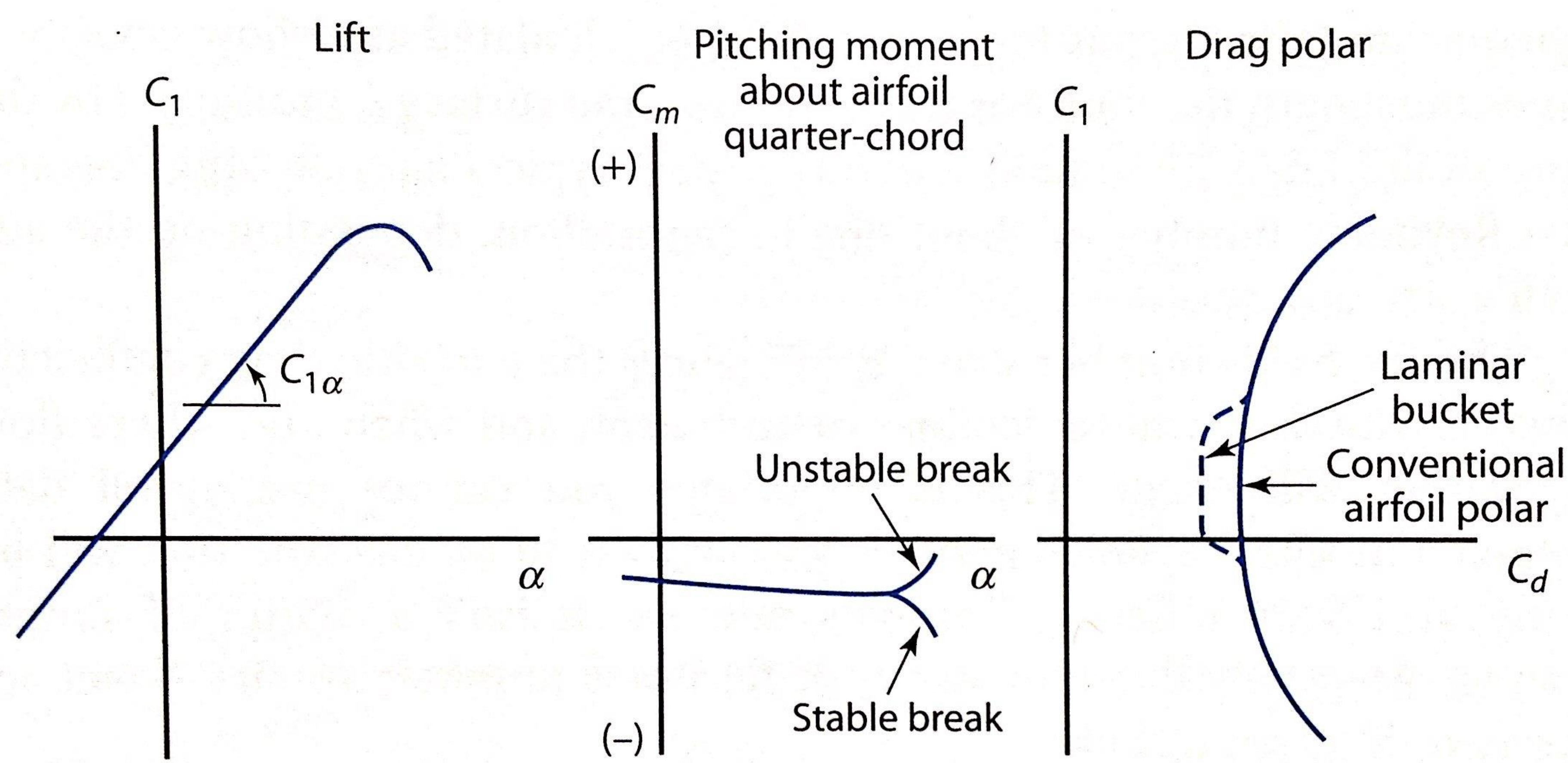
Airfoil and Wing/Tail Geometry Selection (Chapter 4)

- a.c. = Aerodynamic center, where pitching moment is not a function of angle of attack. The a.c. is approximately at 25% of the chord for subsonic flight. The moment is NOT zero, just its derivative. Only symmetric airfoils have their pitching moment equal to zero.



Source: Aircraft Design by Daniel P. Raymer

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Airfoil and Wing/Tail Geometry Selection (Chapter 4)

- Section aerodynamic data is for a given Reynolds number. Re will determine where will the flow separate; will flow be turbulent; and how large will parasite drag be.

$$R_e = \frac{DynamicForces}{ViscousForces} = \frac{vl\rho}{\mu}$$

(1,000,000 < Re < 10,000,000)

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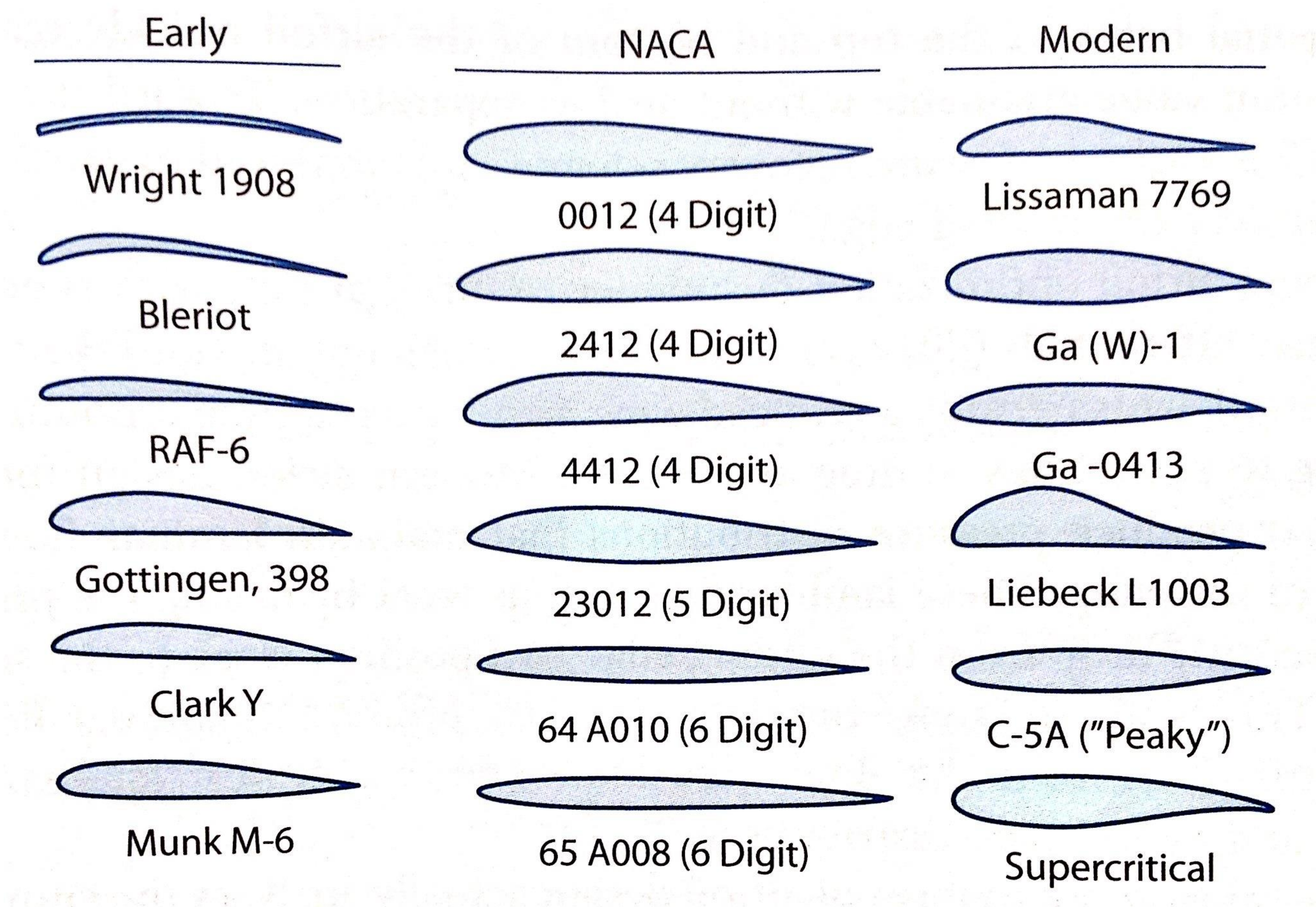

Source: Aircraft Design by Daniel P. Raymer

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Airfoil and Wing/Tail Geometry Selection (Chapter 4)

- 1930's NACA defined the 4-digit airfoils, still used for tails of subsonic a/c.
    - 1st digit = percent camber
    - 2nd digit = location of max camber
    - Last 2 digits = % t/c
- NACA 5-digit = developed to shift max camber forward for max lift
- NACA 6-digit = developed for laminar flow. Still used for high speed (F-15)
- Many others, like Whitcomb's supercritical airfoils
- Nowadays, airfoils are increasingly custom-designed as software is readily available

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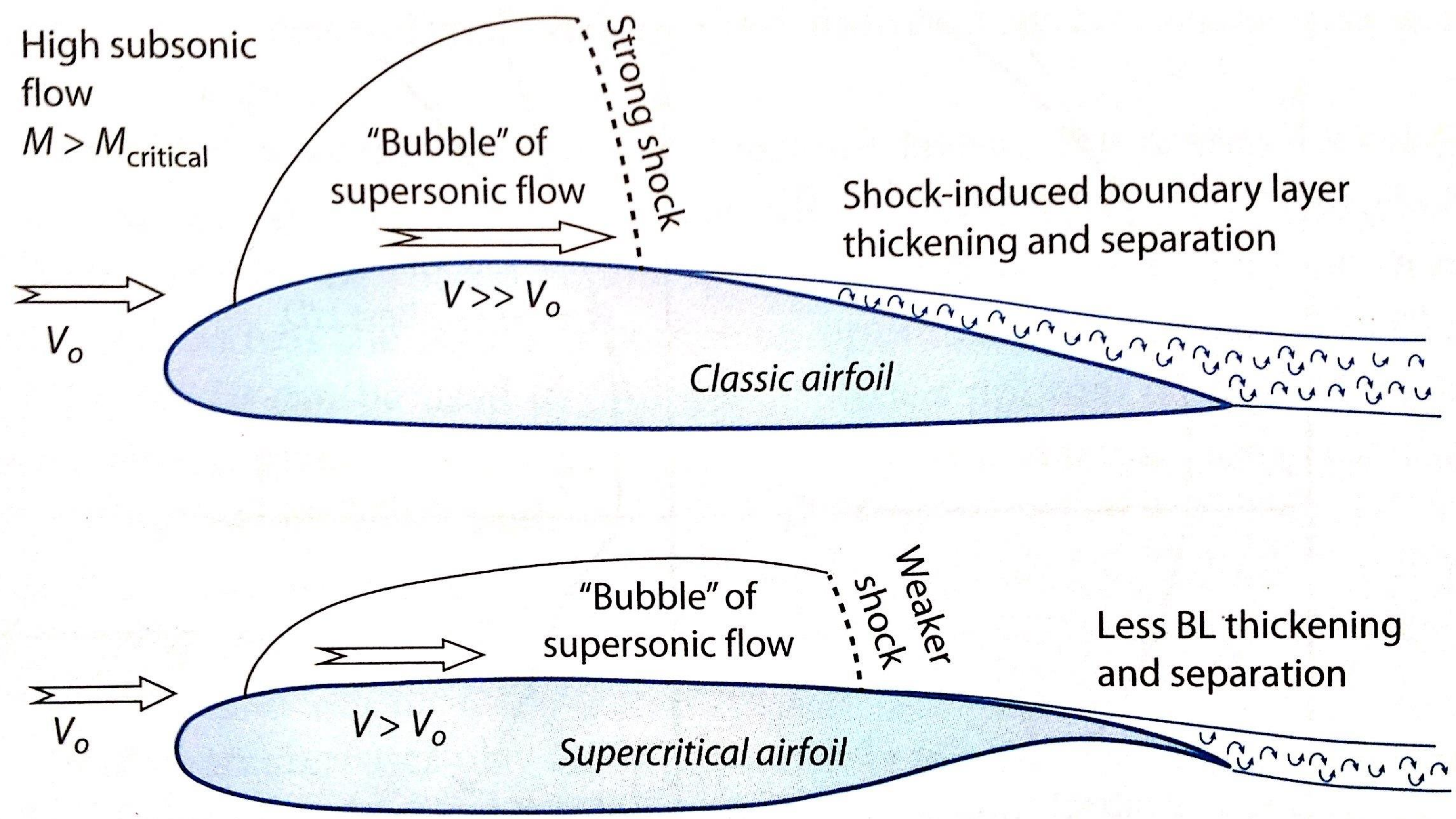

- The supercritical airfoil increases critical mach number Mcr, thus retarding drag divergence.

Source: Aircraft Design by Daniel P. Raymer

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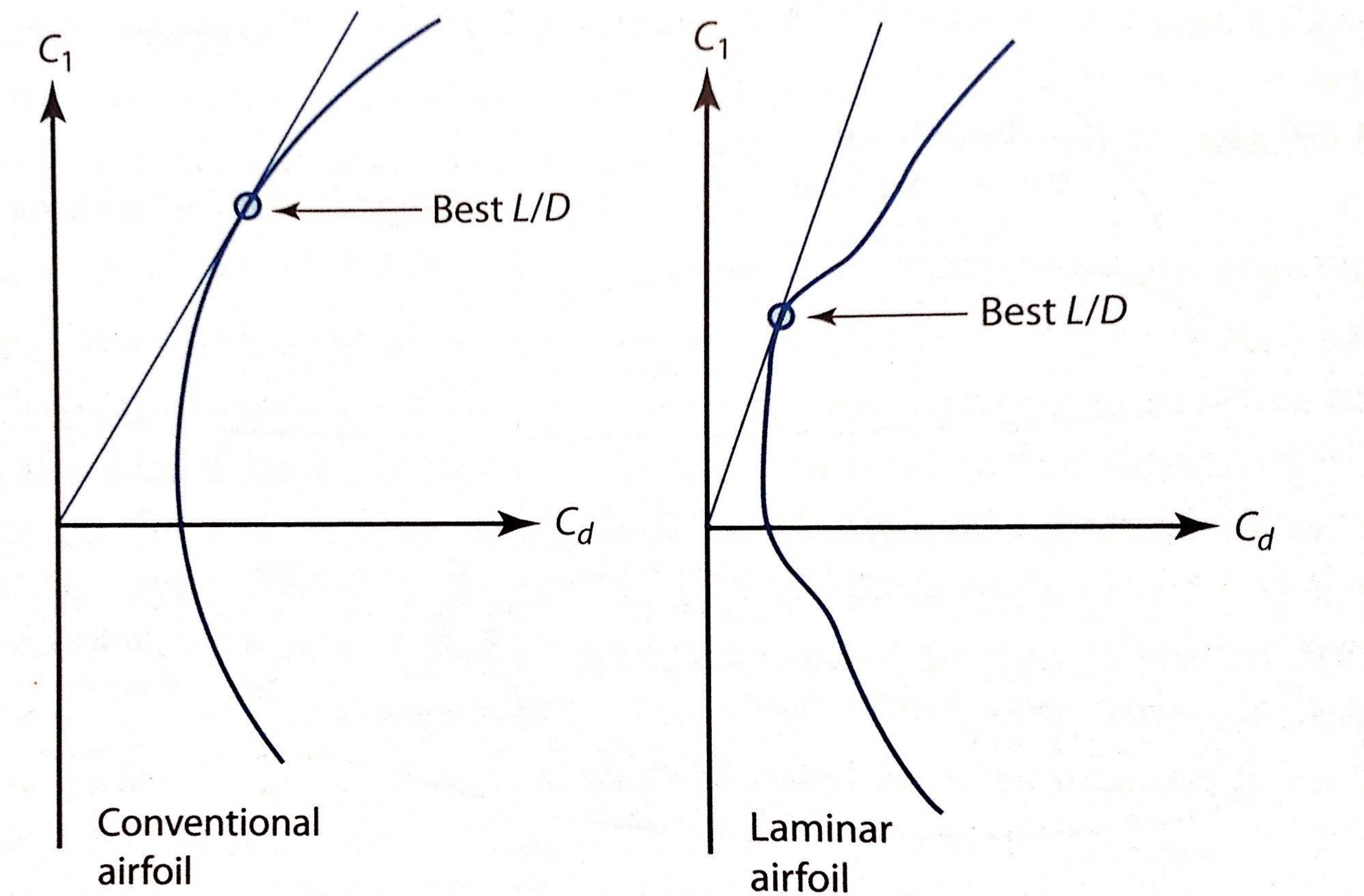

- Airfoil design lift coefficient is the Cl for maximum L/D

Source: Aircraft Design by Daniel P. Raymer

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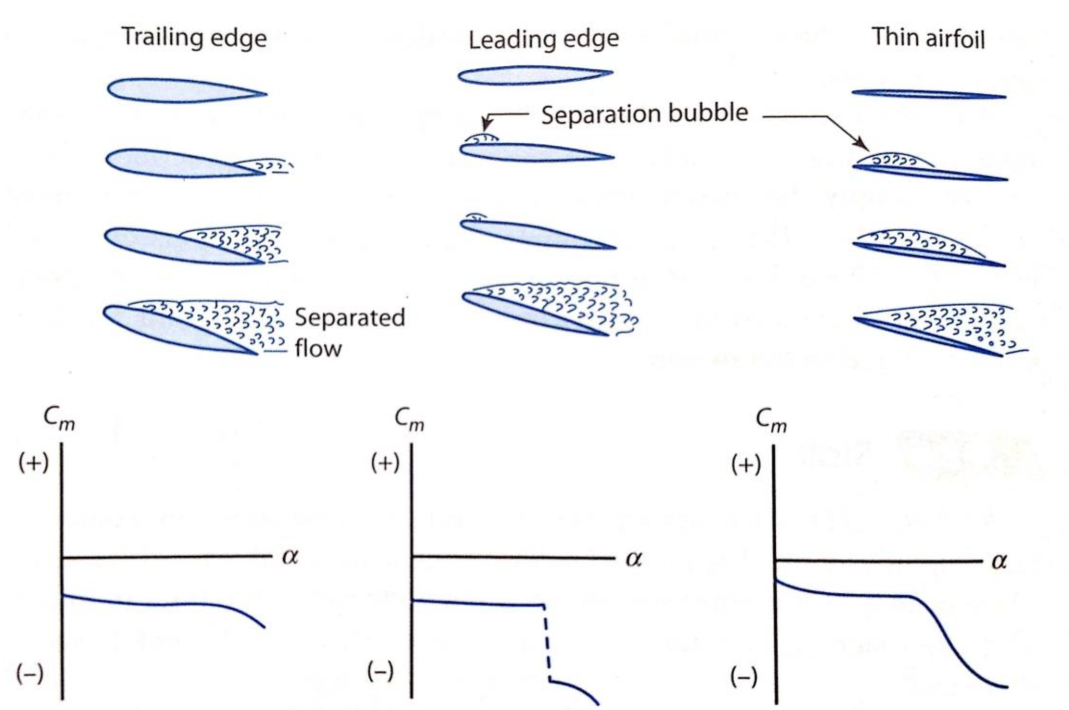
Airfoil and Wing/Tail Geometry Selection (Chapter 4)

- Stall characteristics of 2-D airfoils are useful in airfoil selection for high aspect ratio, unswept wings. However, for swept, or low aspect ratio wings, 2-D characteristics could be ignored! Finite wing effects dominate.

- The designer can not only choose an airfoil for its stall characteristics, but it is common to choose different airfoils and/or incidence angles for wing root and tip to achieve the desired stall characteristics.



Source: Aircraft Design by Daniel P. Raymer

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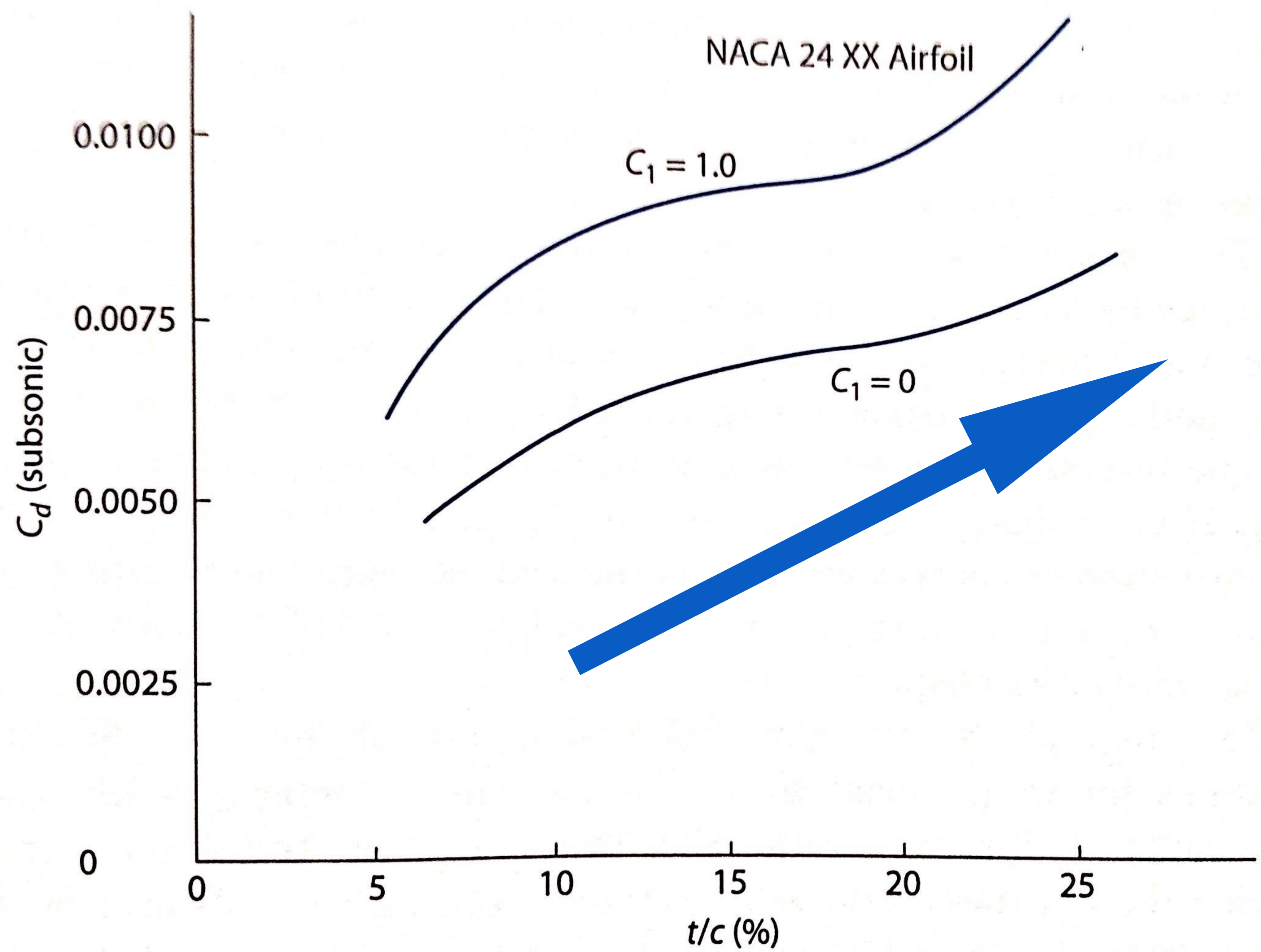
- t/c has a direct effect on subsonic drag due to separation



Source: Aircraft Design by Daniel P. Raymer

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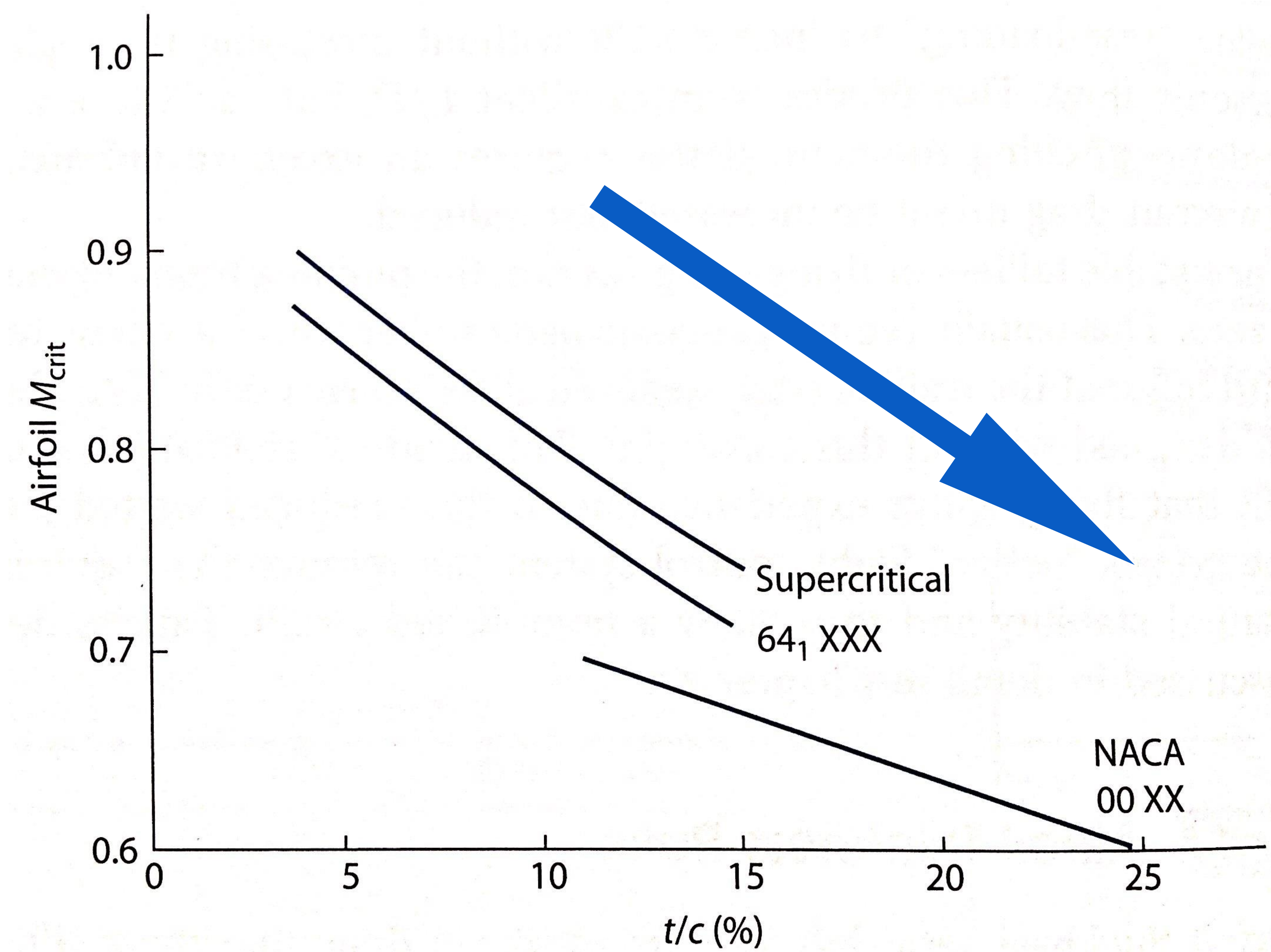
Airfoil and Wing/Tail Geometry Selection (Chapter 4)

- t/c has a direct effect critical mach number



Source: Aircraft Design by Daniel P. Raymer

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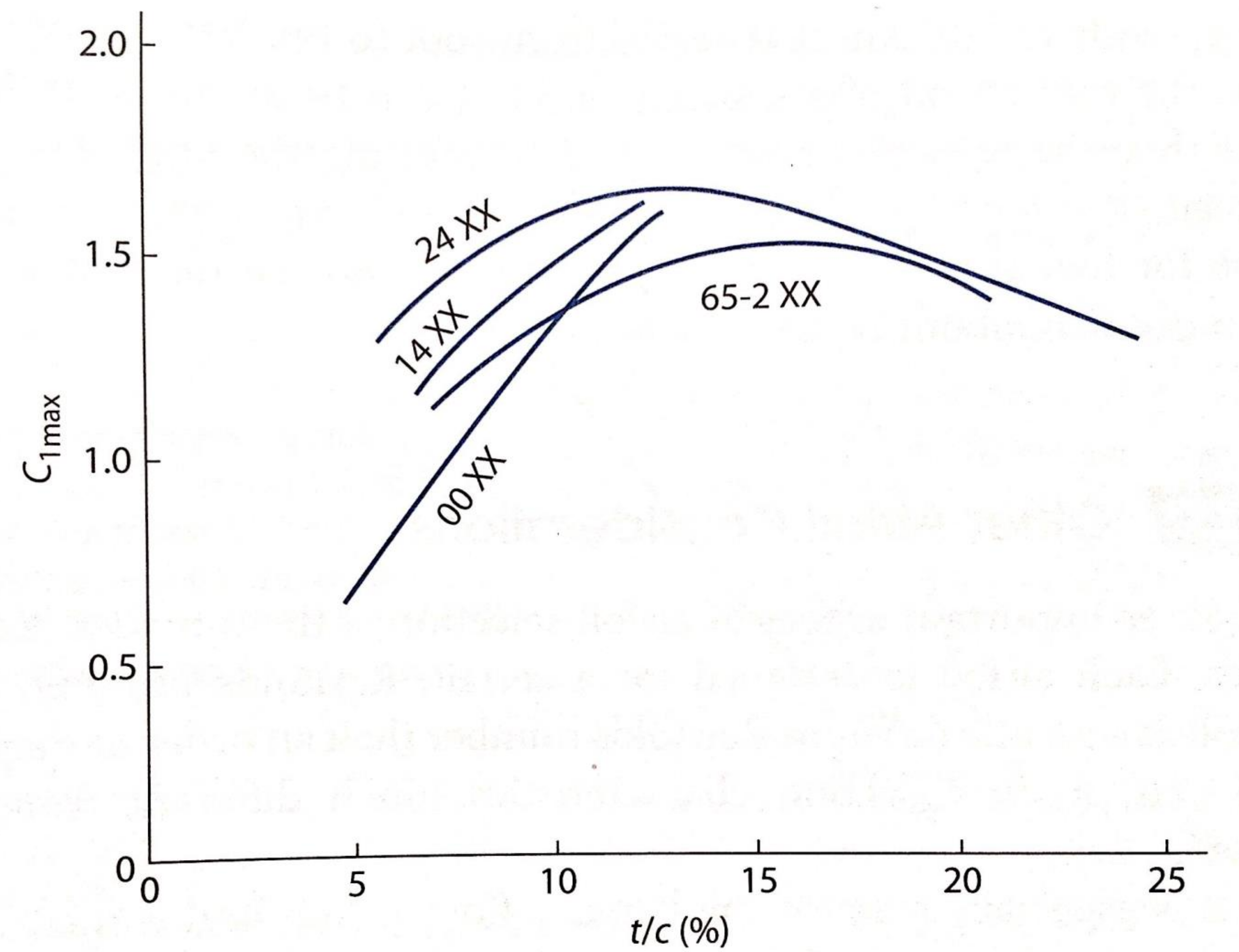
Airfoil and Wing/Tail Geometry Selection (Chapter 4)

- t/c affects maximum lift coefficient due to the shape of the nose of the airfoil
- For moderate sweep and fairly high aspect ratio, the thicker airfoil increases Clmax.
- For low aspect ratio/large sweep, the opposite is true. A sharper leading edge induces vortices that increase Clmax.



Source: Aircraft Design by Daniel P. Raymer

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Airfoil and Wing/Tail Geometry Selection (Chapter 4)

- Structurally, thicker wings can withstand wing bending moments with lower structural weight. Since the wing weight can be 15% of Wo, halving t/c can increase Wo 6%!

- t/c can be designed to vary along the span. Larger t/c from root to up to 30% semispan can provide more volume for landing gear and fuel, and lower structural weight!

- At early conceptual design, airfoil selection can have a lot to do with how much thickness is available for structure, landing gear, and fuel.

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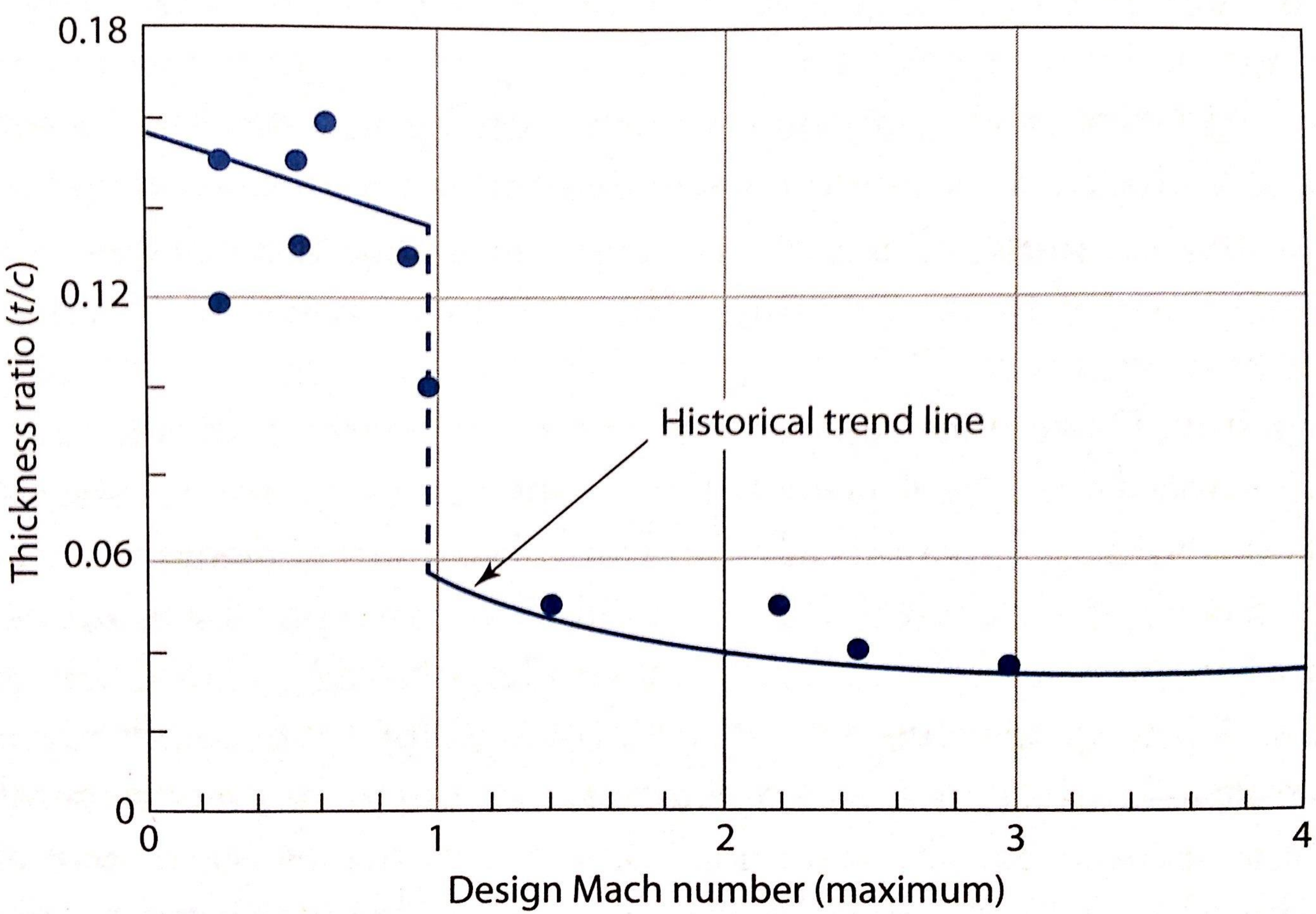
Airfoil and Wing/Tail Geometry Selection (Chapter 4)



Source: Aircraft Design by Daniel P. Raymer

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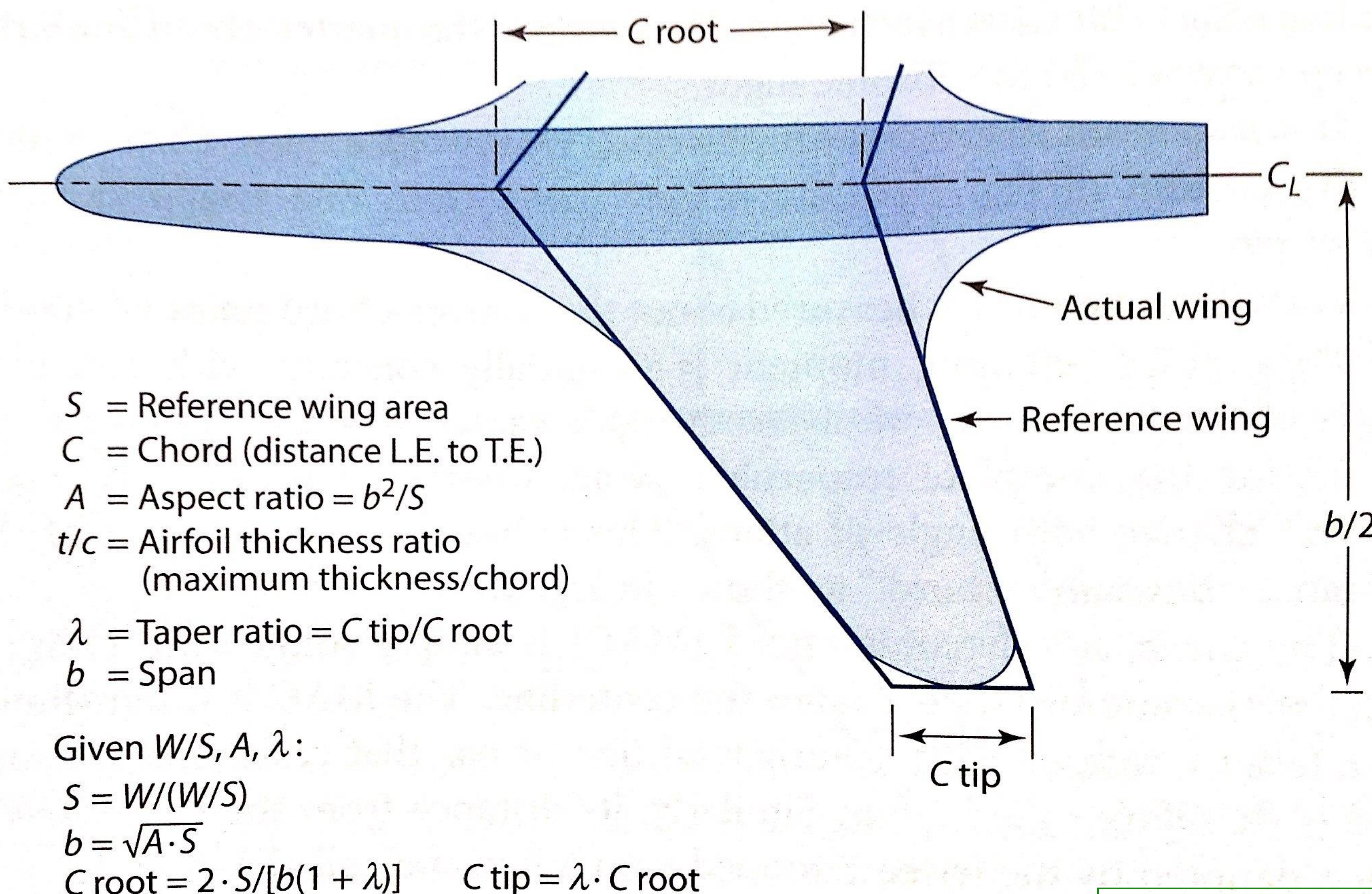
- Sref, the reference wing area is for the trapezoidal wing area, including the area covered by the fuselage



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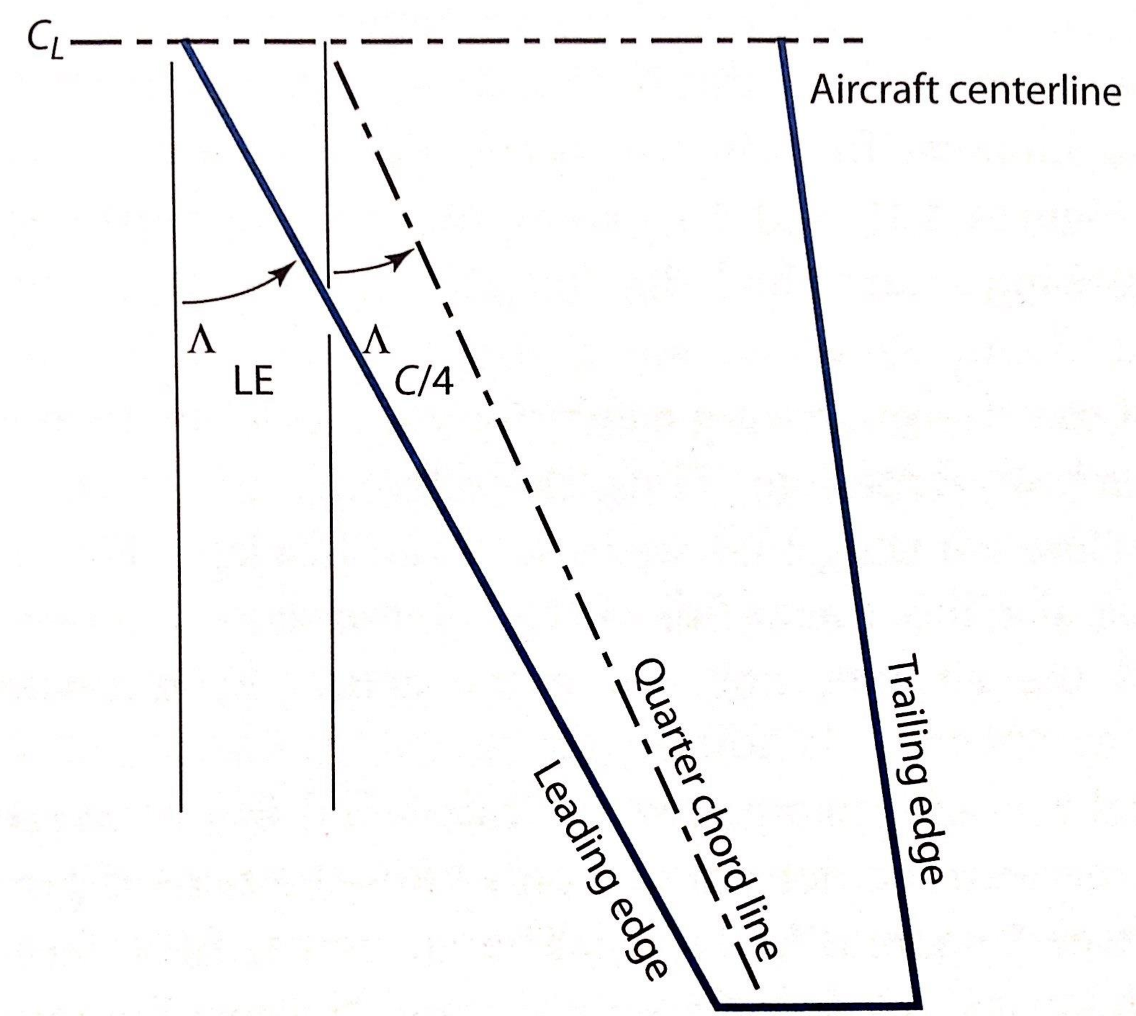

- Leading edge sweep is important for supersonic flight when trying to keep the leading edge behind the mach cone (subsonic leading edge)
- The sweep at 25% chord is of concern for subsonic flight.

Source: Aircraft Design by Daniel P. Raymer

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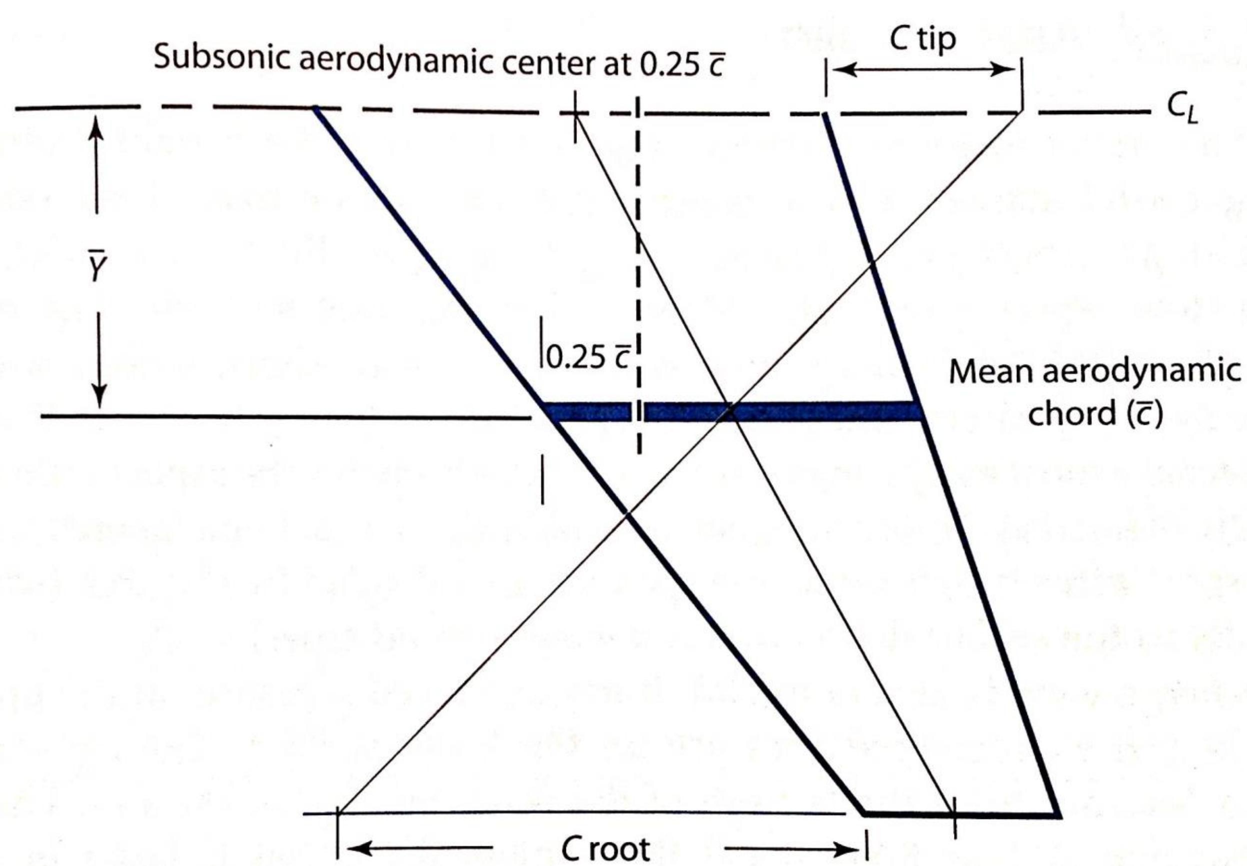
Airfoil and Wing/Tail Geometry Selection (Chapter 4)

- The mean aerodynamic chord (c-bar or m.a.c.), is a wing chord, at a distance y-bar that acts as if the entire wing is concentrated at that location! The entire wing has its aerodynamic center at approximately 25% m.a.c., so we use this point to position the wing on the fuselage to obtain the desired stability.



$\bar{c} = (2/3)\, C\text{root}\, (1 + \lambda + \lambda^2)/(1+ \lambda)$

$\bar{Y} = (b/6)[(1 + 2\lambda)/(1 + \lambda)]$ (assuming lift is proportional to chord)

$\bar{Y}$ must be doubled for a vertical tail

Source: Aircraft Design by Daniel P. Raymer

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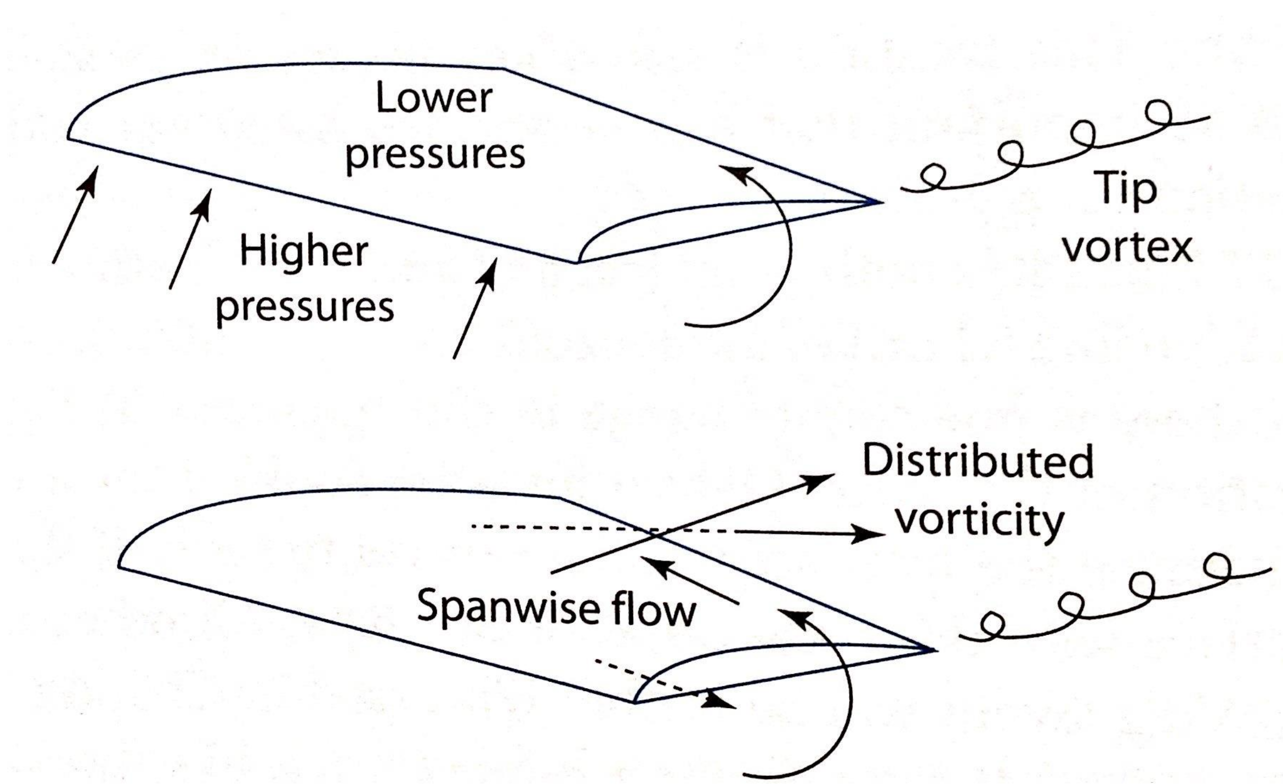
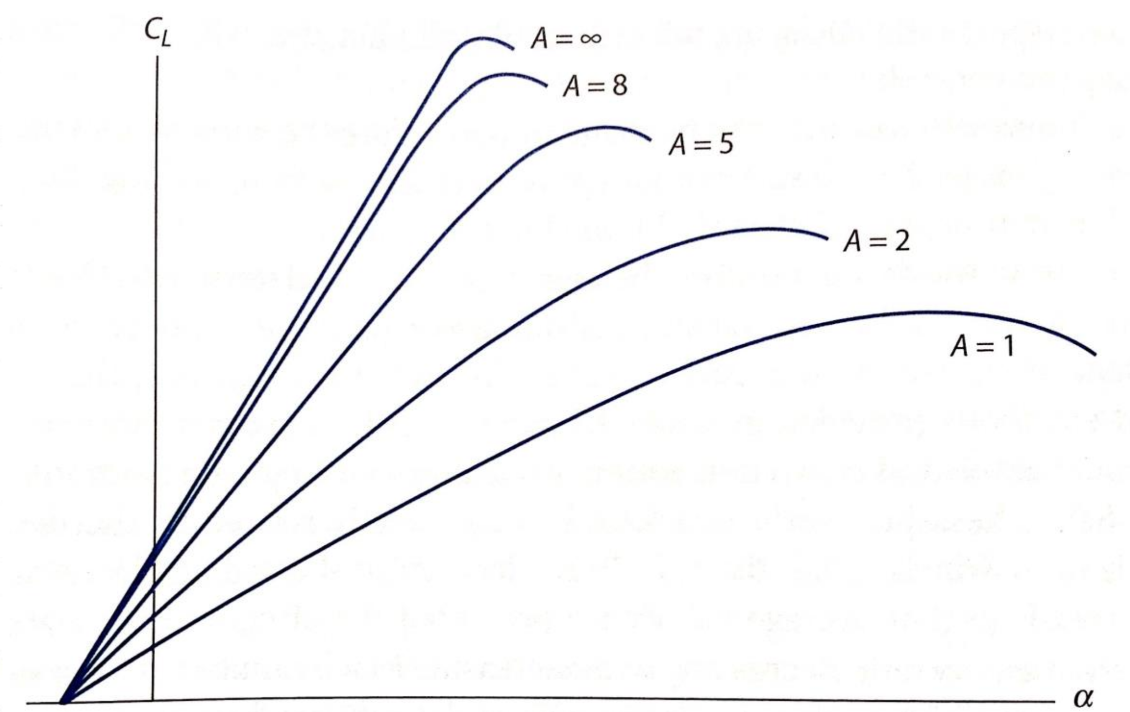
Airfoil and Wing/Tail Geometry Selection (Chapter 4)

- Aspect ratio (b^2/Sref) is a parameter of major importance to the generation of lift. High pressure air under the finite wing curls around the wing tips inducing vortices and reducing lift in the outboard section of the wing. Lower aspect ratio wings have a larger portion of their area affected by this.





Source: Aircraft Design by Daniel P. Raymer

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Airfoil and Wing/Tail Geometry Selection (Chapter 4)

- While L/D max increases with the square root of aspect ratio (keeping Swet/Sref constant, the wing weight increases with increasing aspect ratio by about the same factor!

- Lower aspect ratio wings stall at a larger angle of attack. Tails have lower aspect ratio to keep their flow attached for control after the wing has stalled. The opposite is used in canards.

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Airfoil and Wing/Tail Geometry Selection (Chapter 4)

	Equivalent aspect ratio
Sailplane	$0.19\ (\text{best } L/D)^{1.3}$
Propeller aircraft	**Equivalent aspect ratio**
Homebuilt	6.0
General aviation—single engine	7.6
General aviation—twin engine	7.8
Agricultural aircraft	7.5
Twin turboprop	9.2
Flying boat	8.0

	Equivalent aspect ratio $= aM_{max}^{C}$	
Jet aircraft	***a***	***C***
Jet trainer	4.737	−0.979
Jet fighter (dogfighter)	5.416	−0.622
Jet fighter (other)	4.110	−0.622
Military cargo/bomber	5.570	−1.075
Jet transport	7.50 to 10	0

Source: Aircraft Design by Daniel P. Raymer

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Airfoil and Wing/Tail Geometry Selection (Chapter 4)

- Shock formation is determined by the air velocity in a direction perpendicular to the leading edge. Increased sweep angle increases the critical mach number

- At supersonic mach numbers, sweep angle is used to keep the leading edge behind the mach cone (arcsin(1/M)) thus avoiding higher wave drag.

- Sweep angle can be used to aid balance issues by places a.c. farther aft.

- Sweep angle increases structural weight and Wo.

- Variable sweep excellent aerodynamically but carries a heavy Wo penalty.

- Sweep increases dihedral effect.

- High aspect ratio / sweep configurations may exhibit pitch-p at high angles of attack.

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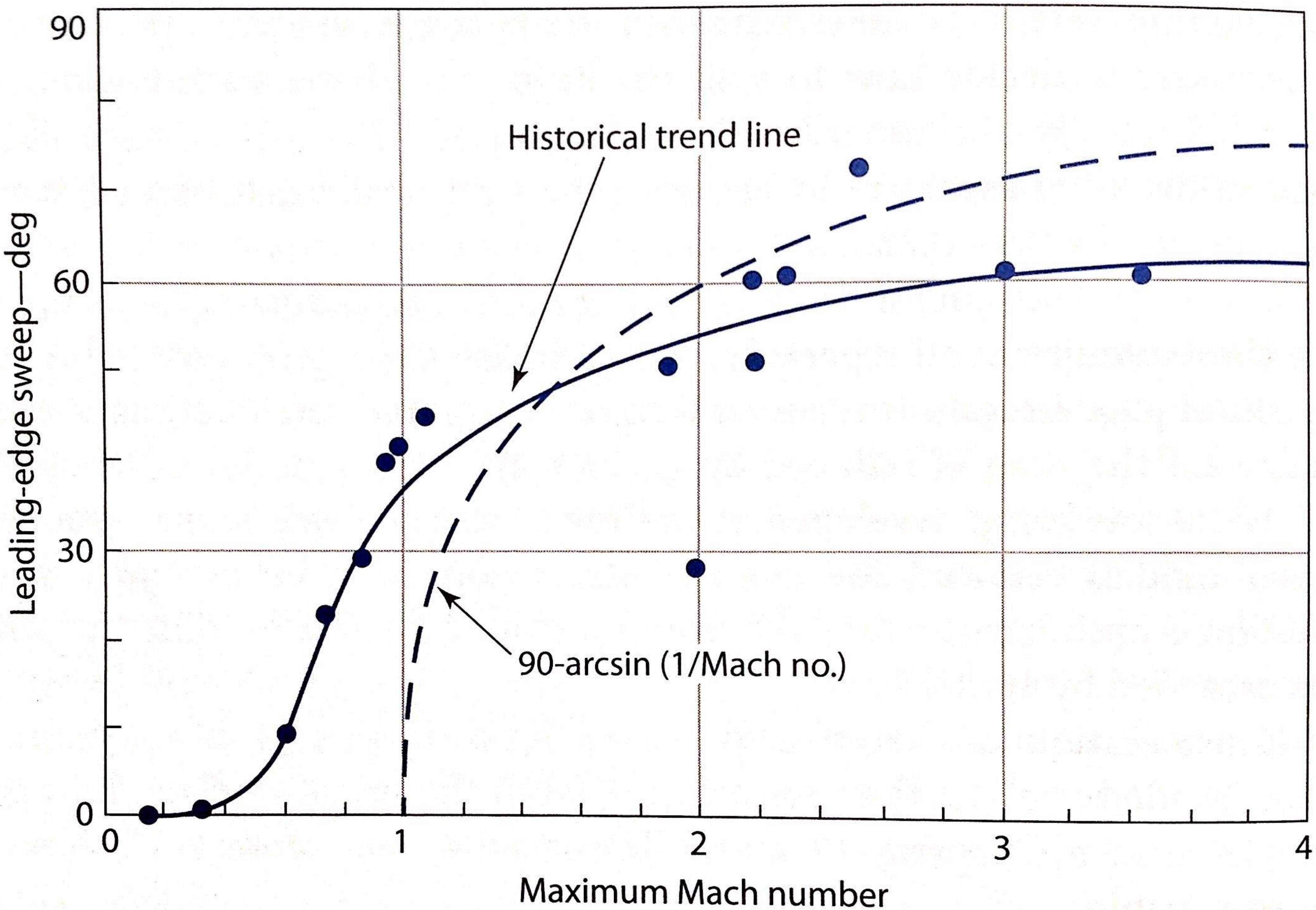
Airfoil and Wing/Tail Geometry Selection (Chapter 4)



Source: Aircraft Design by Daniel P. Raymer

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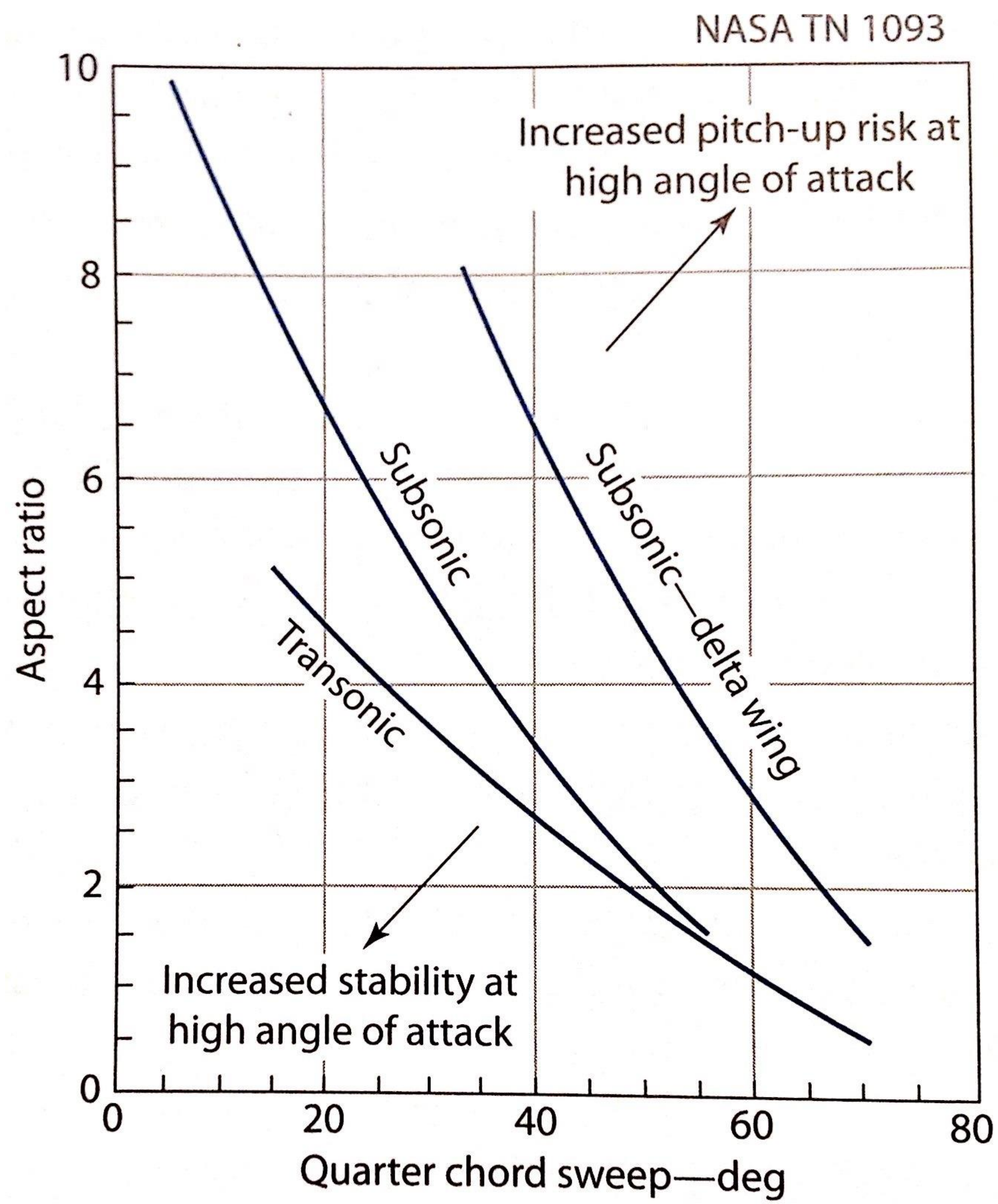
Airfoil and Wing/Tail Geometry Selection (Chapter 4)

Tail-off Pitch-up Boundaries



Source: Aircraft Design by Daniel P. Raymer

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Airfoil and Wing/Tail Geometry Selection (Chapter 4)

- Taper ratio is the ratio of tip chord to root chord.
- Most low sweep wings have ratios between 0.4-0.5
- Most swept wings have ratios between 0.2-0.3
- Minimum induced drag occurs with an elliptical lift distribution. Taper ratio directly affects this lift distribution (0.45 for minimum induced drag).
- However, a lower taper ratio, lowers structural weight and Wo.
- Higher sweep angle "loads the tips", so taper ratio must be lower to achieve a good lift distribution.

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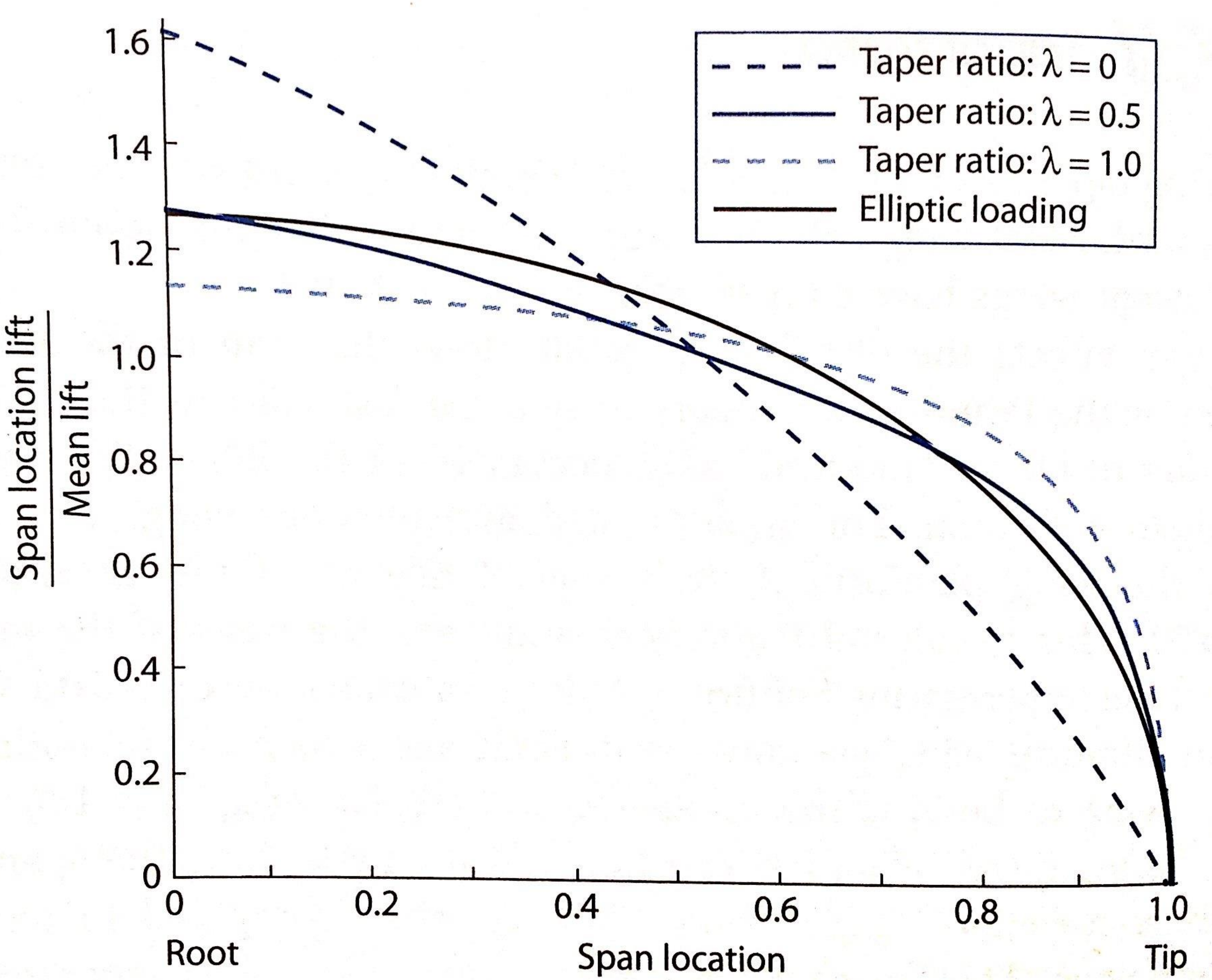

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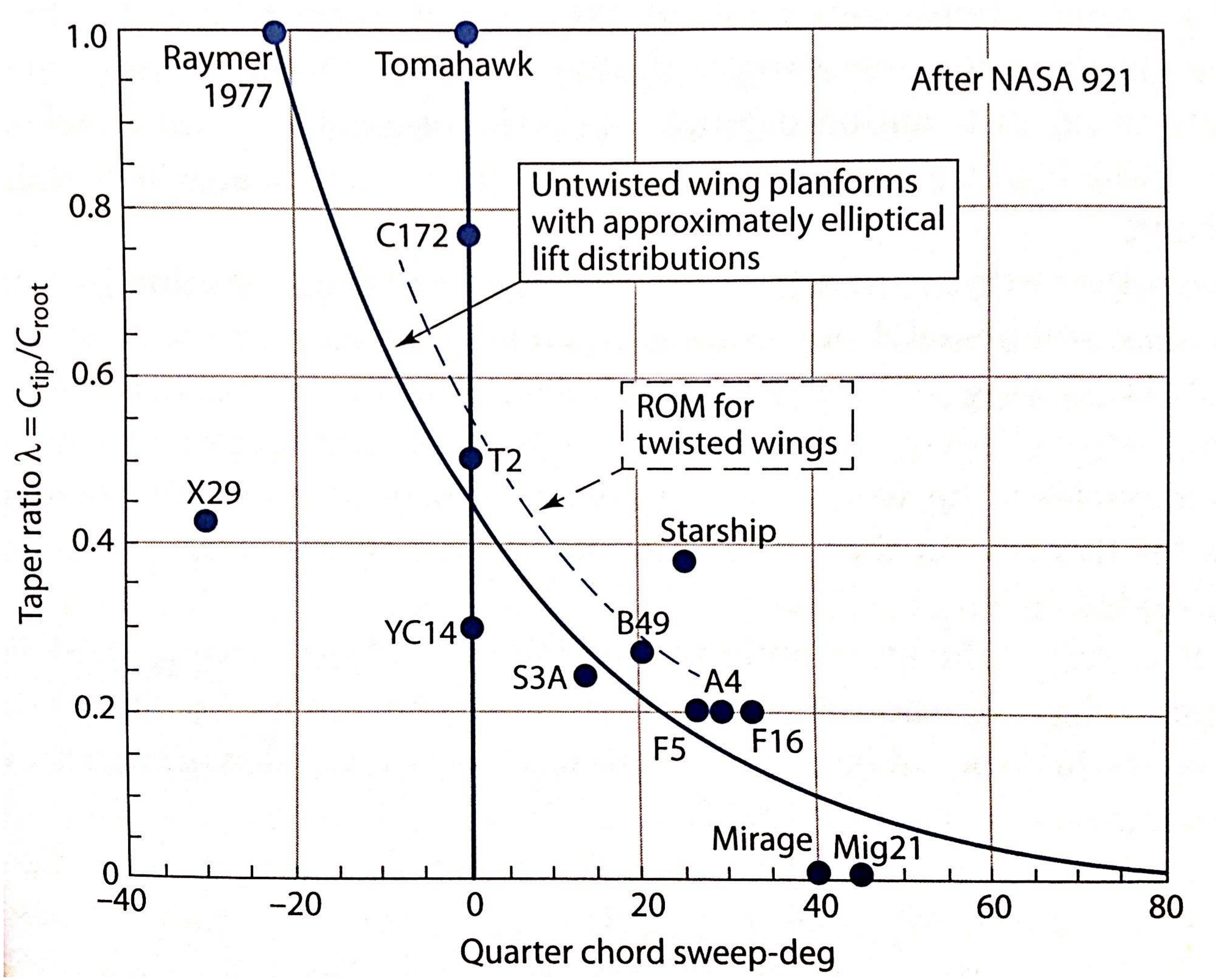

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Airfoil and Wing/Tail Geometry Selection (Chapter 4)

- Twist, the relative angle of attack difference from root to tip, is used to optimize the lift distribution and to avoid tip-stall. Typically a washout (wing tip a.o.a. lower) of less than 5 degrees is used to maintain lateral control at high angles of attack.

- Wing incidence is the wing angle of attack with respect to the fuselage waterline. It is used to minimize drag at a given flight condition, like cruise. Usually decided using wind tunnel data (less than 3 degrees).

- Dihedral is the angle of the wing wit respect to horizontal when seen from the front. Dihedral effect tends to restore wings to a level position whenever banked. High wings have a built-in dihedral effect. 10 degrees of sweep equal to about 1 degree of dihedral.

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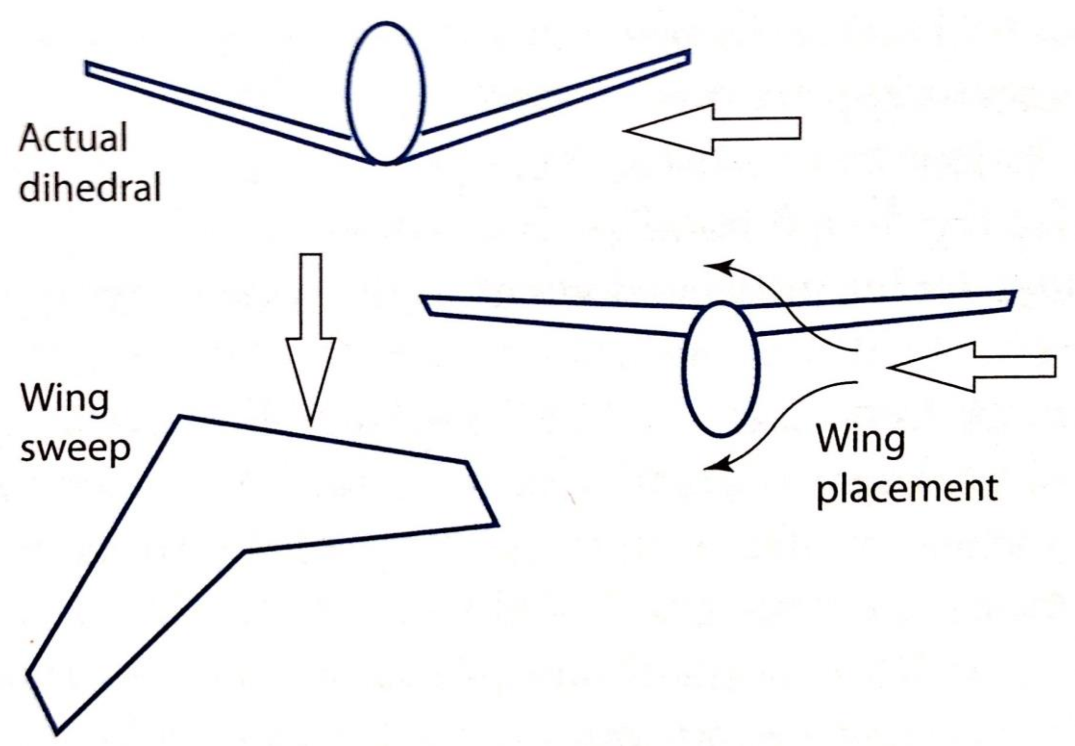

	Wing position		
	Low	Mid	High
Unswept (civil)	5 to 7	2 to 4	0 to 2
Subsonic swept wing	3 to 7	−2 to 2	−5 to −2
Supersonic swept wing	0 to 5	−5 to 0	−5 to 0

Source: Aircraft Design by Daniel P. Raymer

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Airfoil and Wing/Tail Geometry Selection (Chapter 4)

Wing vertical location is in many ways an answer to "where do you want the fuselage?"

- High Wing:

+ fuselage close to the ground (loading/unloading)

+ engine/prop clearance or maintenance

+ wing tip clearance

+ external struts for low structural weight attached to bottom of wing

+ wing carry-through box

+ clearance for high-lift devices

+ no floating due to ground effect

- heavier fuselage weight due to landing gear attachment

- pilot upward visibility blocked in turns or climbs

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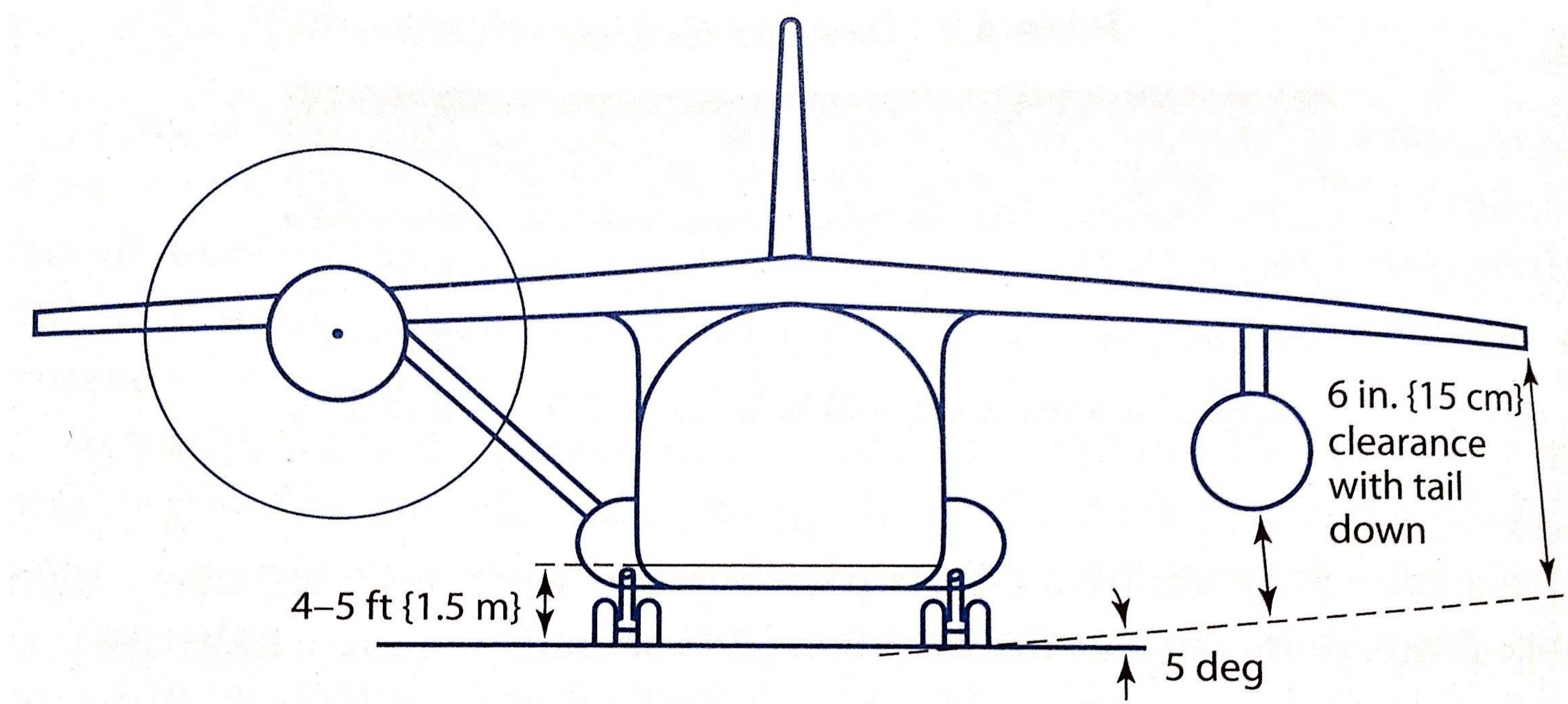

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Airfoil and Wing/Tail Geometry Selection (Chapter 4)

- Mid-Wing:

+ lowest drag (no fairing/interference)

+ good ground clearance

- hard to pass wing loads (ring structure). Box too difficult.

- Low-Wing:

+ landing gear stowage in the wing box

+ wing carry-through structure (box) creates aft/forward cargo compartments

- engine/prop clearance --> longer/heavier landing gear

-difficult loading/unloading (o.k. for established airports, bad for improvised ops.)

- mandatory dihedral for wing tip clearance!

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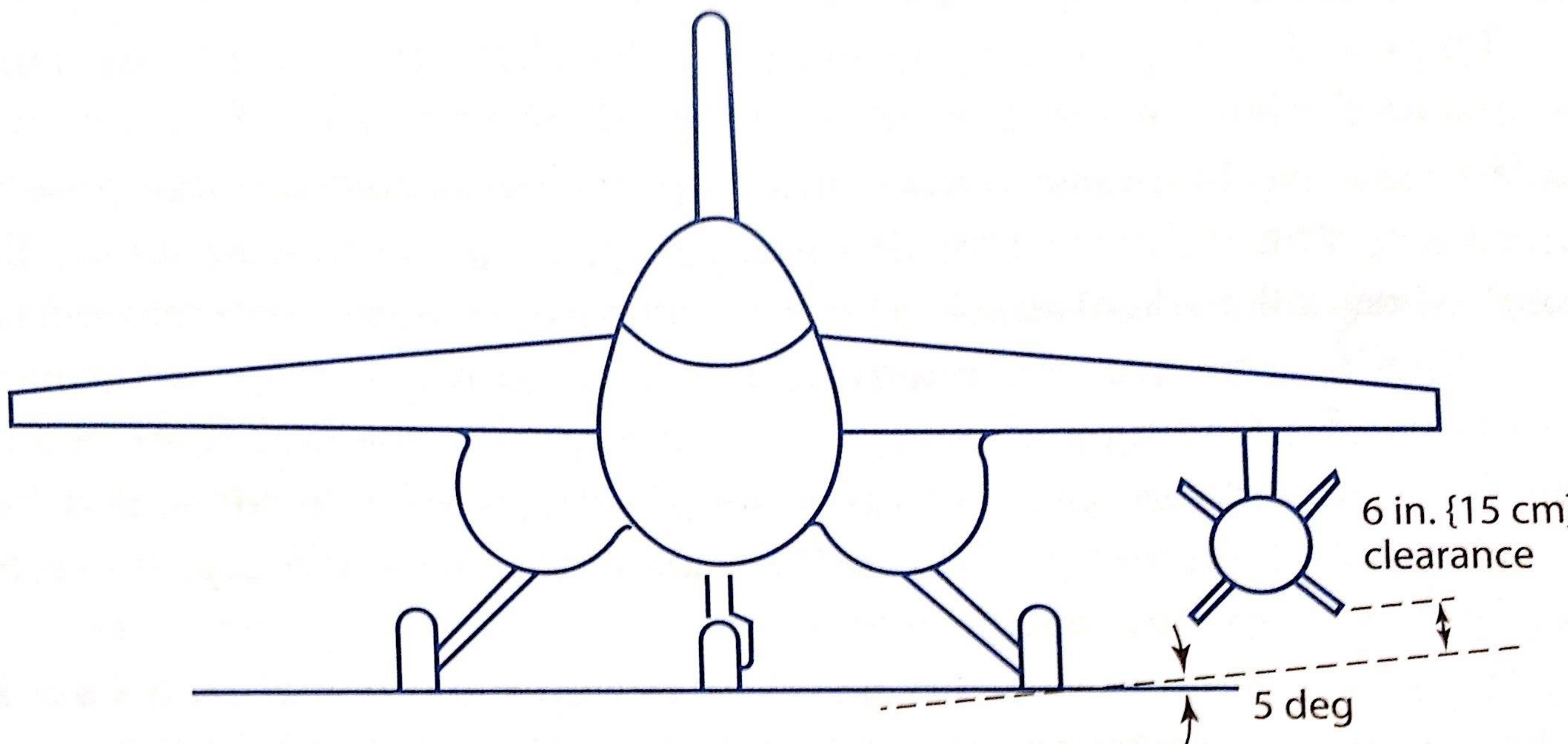

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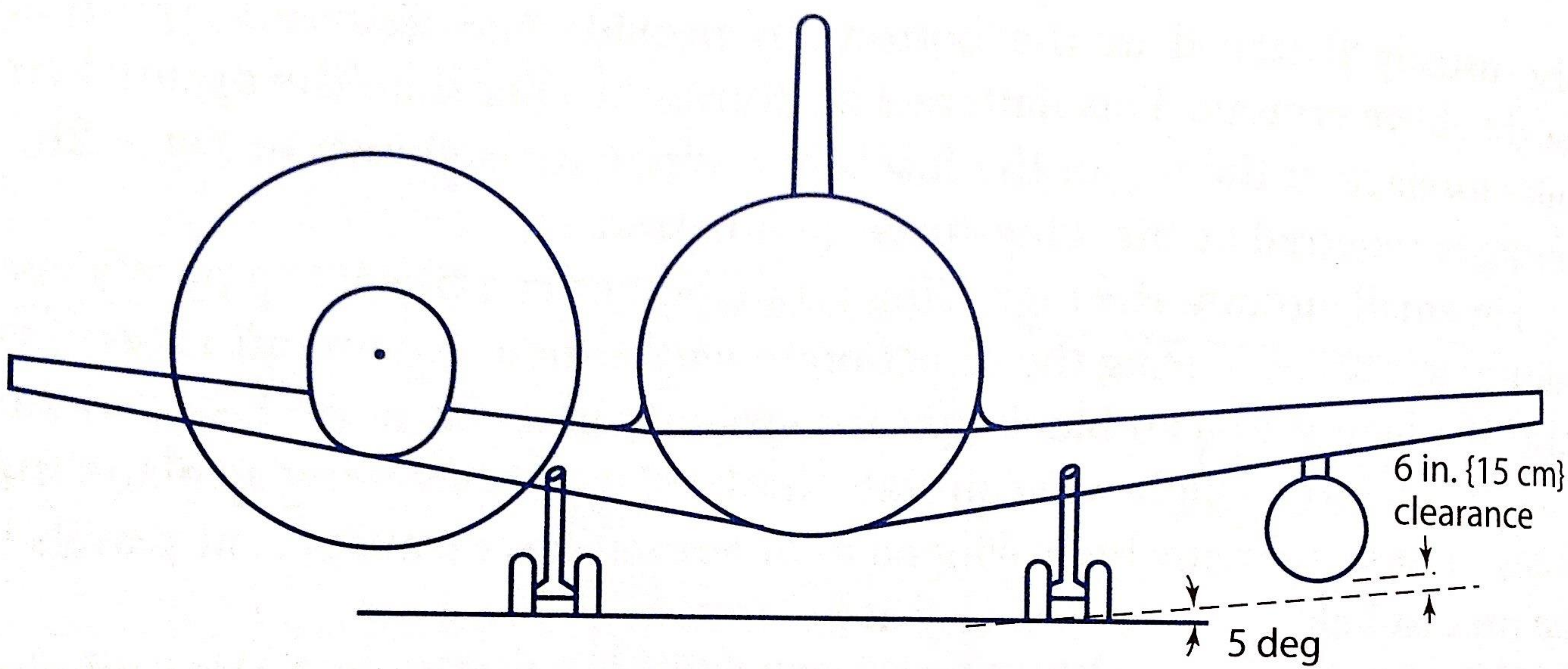

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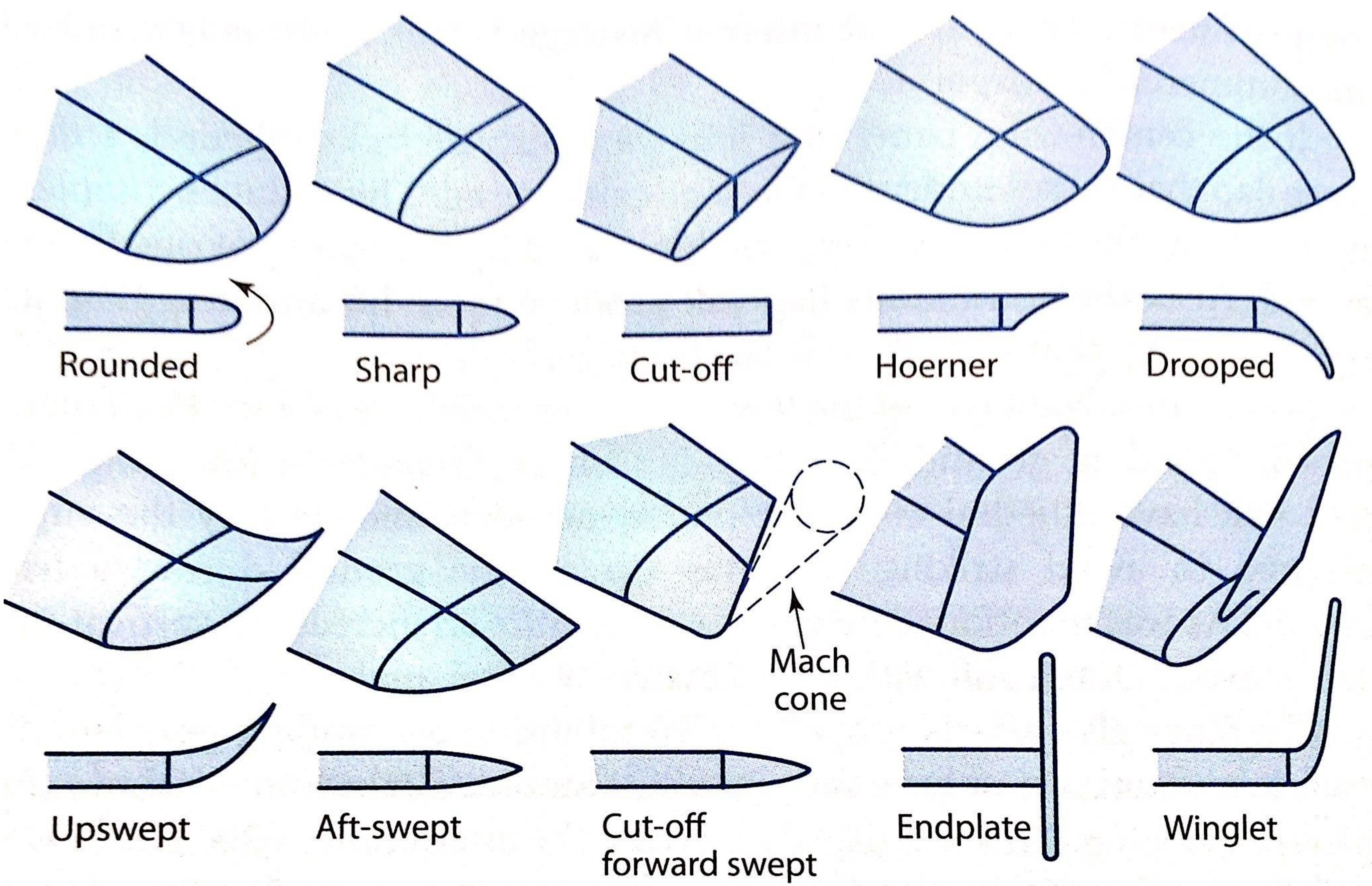

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Airfoil and Wing/Tail Geometry Selection (Chapter 4)

Wing tips (to alleviate induced drag):

- Sharp edge prevents air to migrate from bottom of wing around the tip.
- Drooped tip better but increases wetted area.
- Cutoff forward swept wing tip better in supersonic flow.
- Winglets increase L/D by about 20% (better in low aspect ratio wings)
    - Better as add-ons on existing designs
    - Brand-new design better off with a longer span!

Biplane wings:

+ Low structural weight (truss)

+ More lift without high lift devices

+ 30% less CDL the monoplane of equal span

+ Smaller geometry

- More parasite drag (struts, cables, etc.)

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Airfoil and Wing/Tail Geometry Selection (Chapter 4)

Tails

- Everything learned with wings applies. But tails do not routinely carry a lot of lift; in fact if they are close to stall, something is very wrong!

- Trim - Stability - Control

- Horizontal tail usually at about 3 degrees negative incidence to trim wing moment

- Horizontal tail sized for nose gear unstick and low speed flight with flaps down, transonic maneuvering.

- Vertical tail at an angle to counter the p-effect on propeller a/c

- Vertical tail sized for spin recovery.

- Vertical tail on multi-engine a/c sized for one engine-out scenario.

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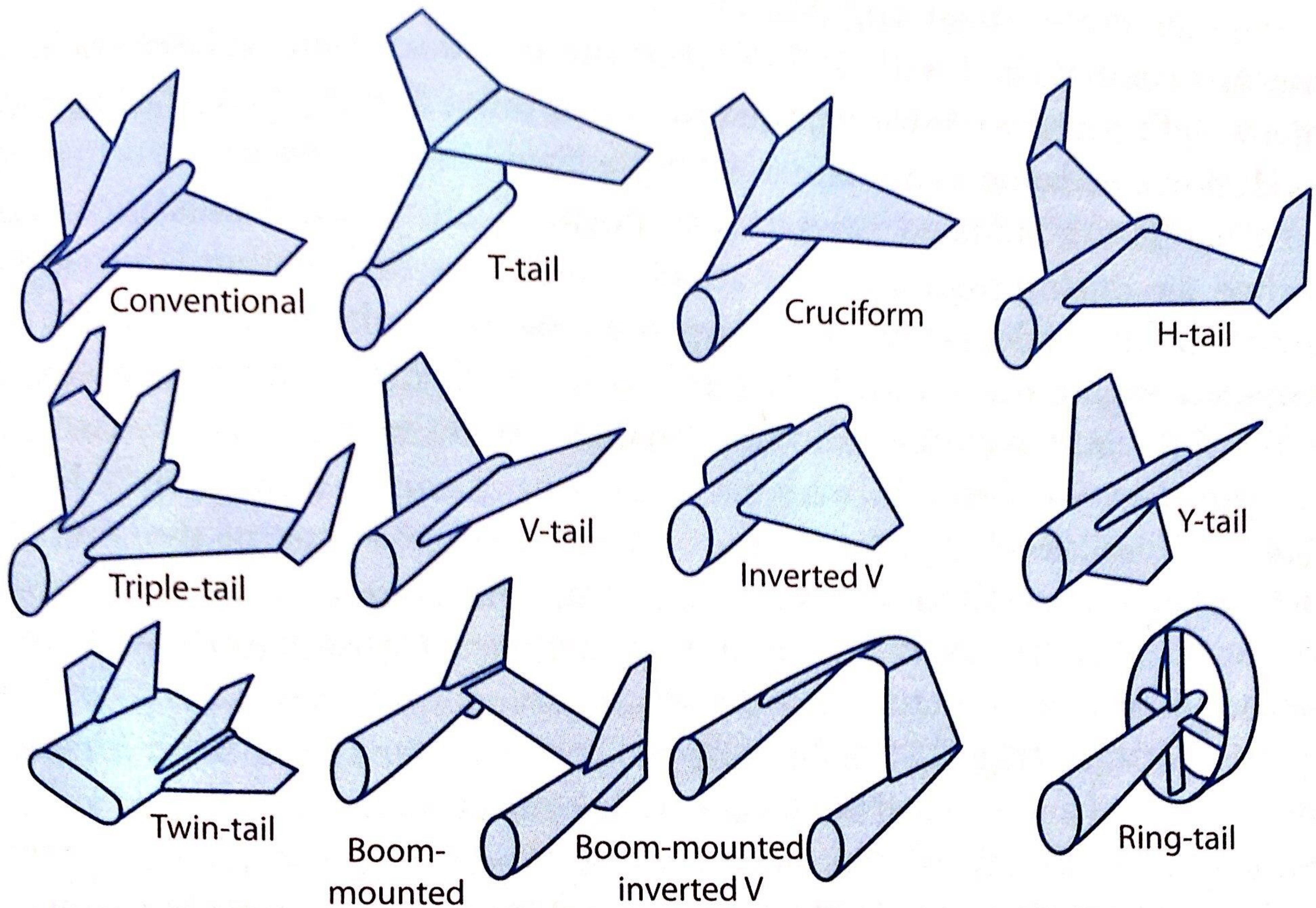

Source: Aircraft Design by Daniel P. Raymer

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Airfoil and Wing/Tail Geometry Selection (Chapter 4)

- 70% of all A/C have a conventional aft tail arrangement. Adequate stability and control and lightest Wo.
- T-tail:
    - Heavier
    - Horizontal tail away from washes
    - Smaller vertical tail due to endplate effect
- Cruciform: not as heavy as t-tail but less endplate effect
- H-tail: vertical away from washes, (used on A-10 to hide engine IR), endplate effect
- V-tail: reduced interference drag, reduced wetted area?, stealth?
- Twin tails: reduce height, redundancy

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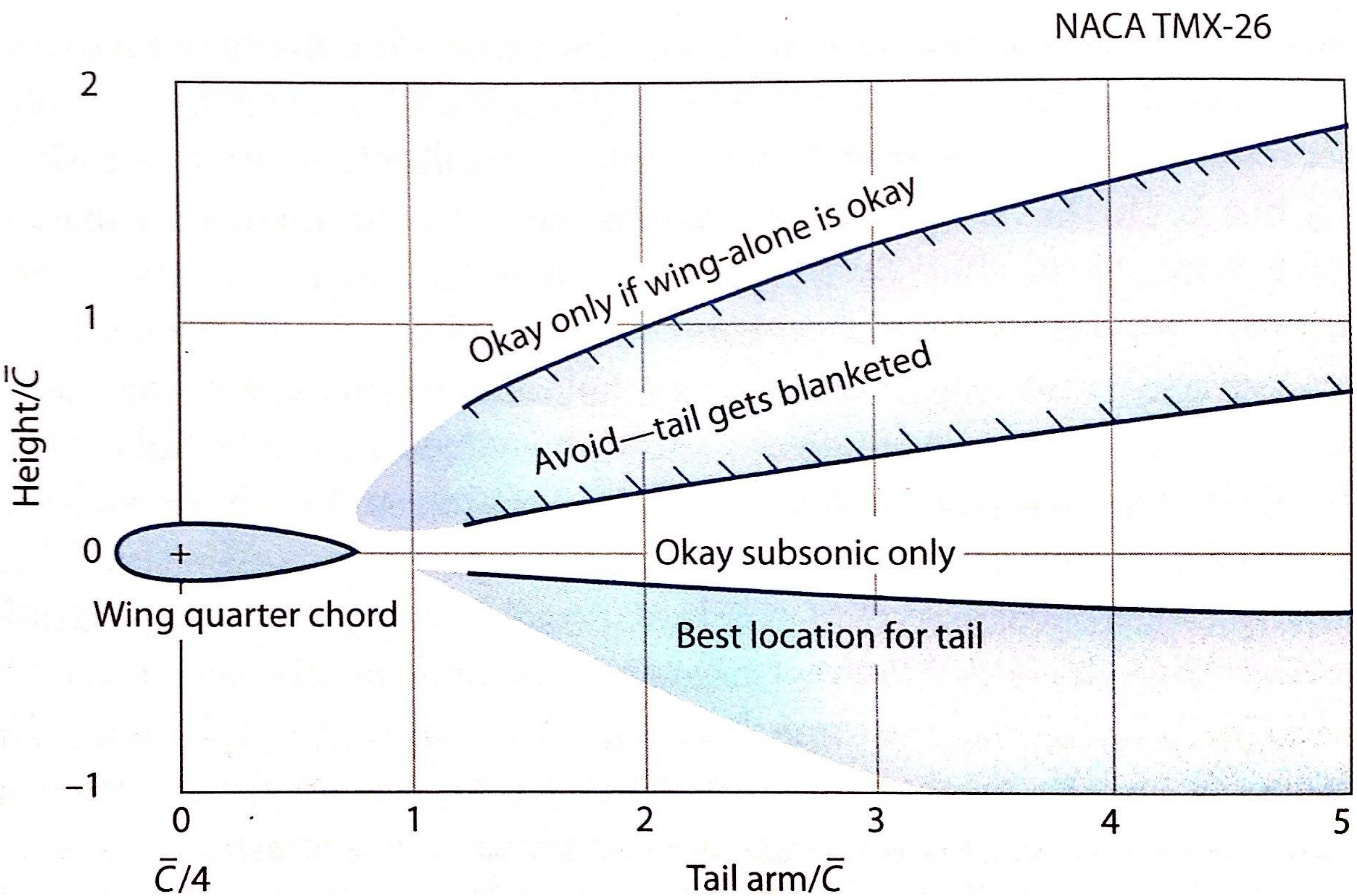
Airfoil and Wing/Tail Geometry Selection (Chapter 4)



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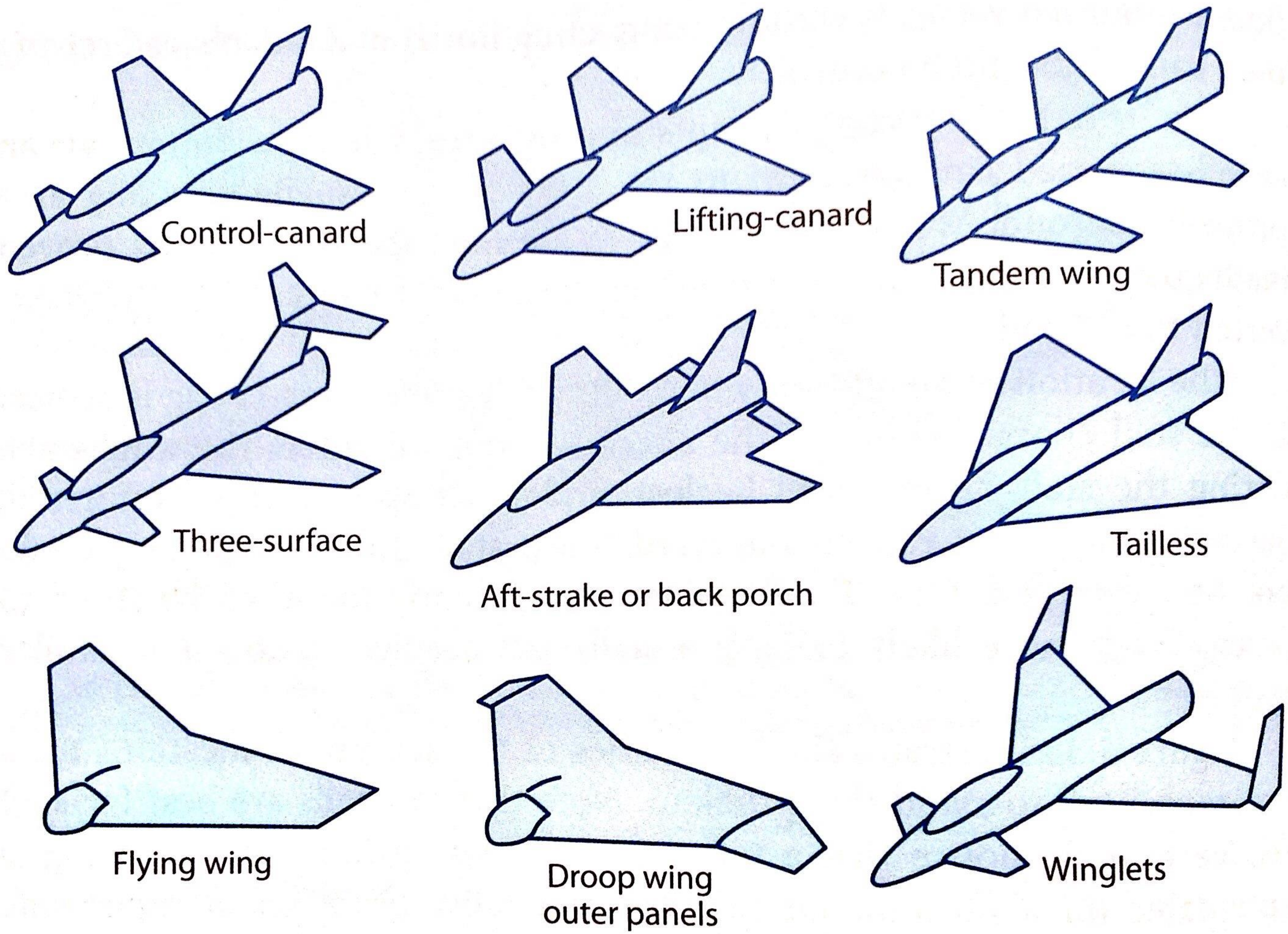

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Airfoil and Wing/Tail Geometry Selection (Chapter 4)

- Canards
  - Pitch control in undisturbed, predictable flow
  - Can be designed to stall before the wing (high aspect ratio)
  - Can control stall pitch-up
  - Trims A/C by lifting
  - Difficult to trim flap moments when using a lifting canard, as the wing is so far aft, generating a huge nose-down moment increase

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Airfoil and Wing/Tail Geometry Selection (Chapter 4)

- Tandem wings
    - In theory, would have 25% of the induced drag of a single wing of the same total area. But in reality, the single wing would have twice the aspect ratio!
    - Lift on the aft wing is tilted aft by the forward wing's downwash, thus creating a component in the drag direction!
    - When reacting to a gust, aft wing only produces only a fraction of the forward wing's increase in lift causing a pitch-up
    - Hard to trim moments due to flaps, so wings must be large to match stall speed requirements

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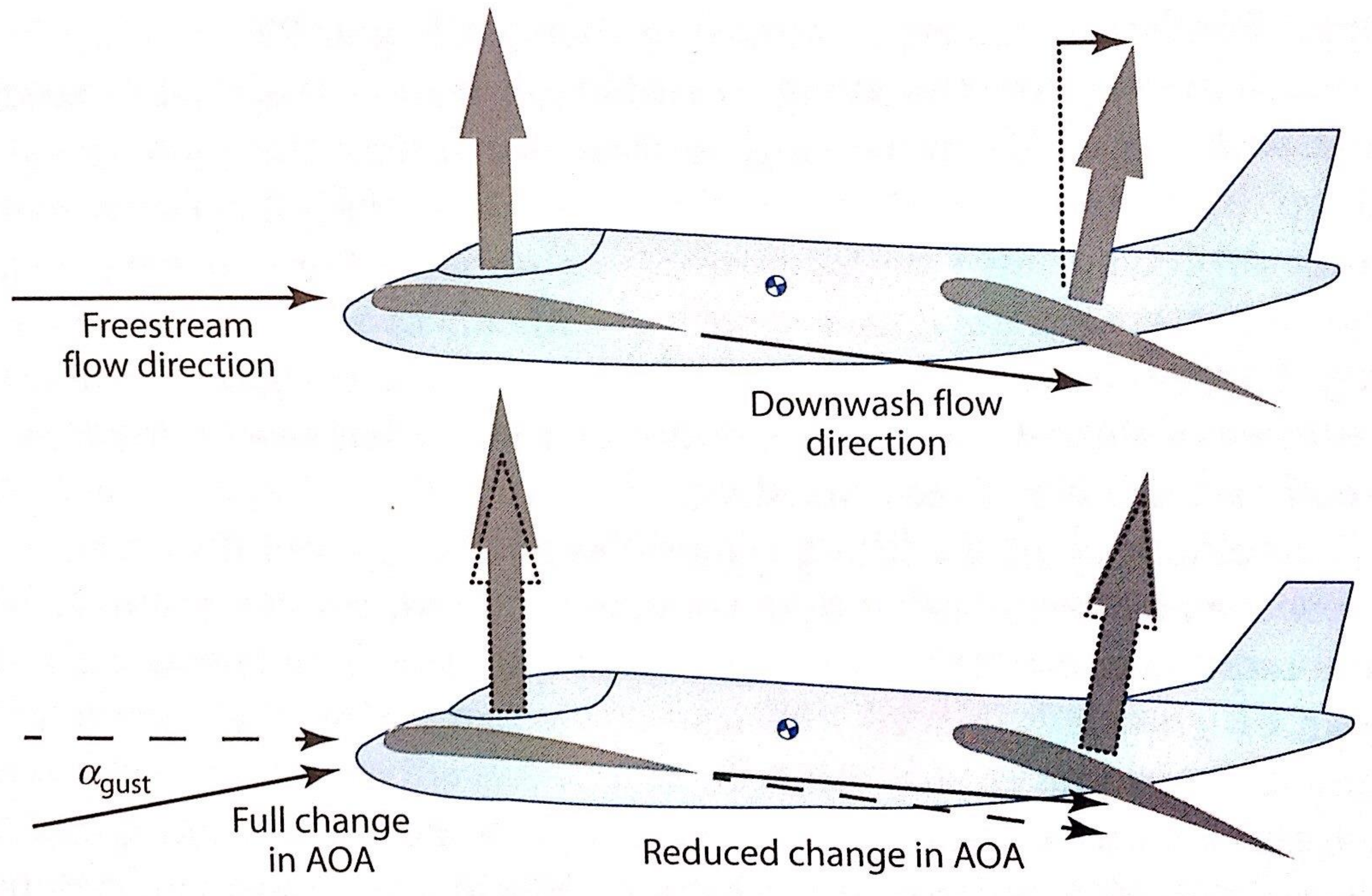

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Airfoil and Wing/Tail Geometry Selection (Chapter 4)

- Tail-less
  - On stable A/C, must reflex/twist wing to provide natural stability, thus hurting lift distribution. For fly-by-wire augmented stability flight control system this is not necessary
  - If no vertical surface is used, wing tip drag devices or thrust vectoring and computer-controlled augmented stability must be used. Otherwise, endplates or winglets, combined with very high wing sweep must be used.
  - Lower wetted area

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Airfoil and Wing/Tail Geometry Selection (Chapter 4)

- Spin-recovery
  - In a spin, A/C is falling vertically, rotating about a vertical axis with the inside wing fully stalled typically at a very large sideslip angle that must be reduced with the rudder.
  - 1/3 of rudder should be out of wake of stalled horizontal tail
  - Dorsal fin increases vertical tail area and induces a vortex that energizes vertical tail flow
  - Ventral fin, located in undisturbed flow offers lateral stability

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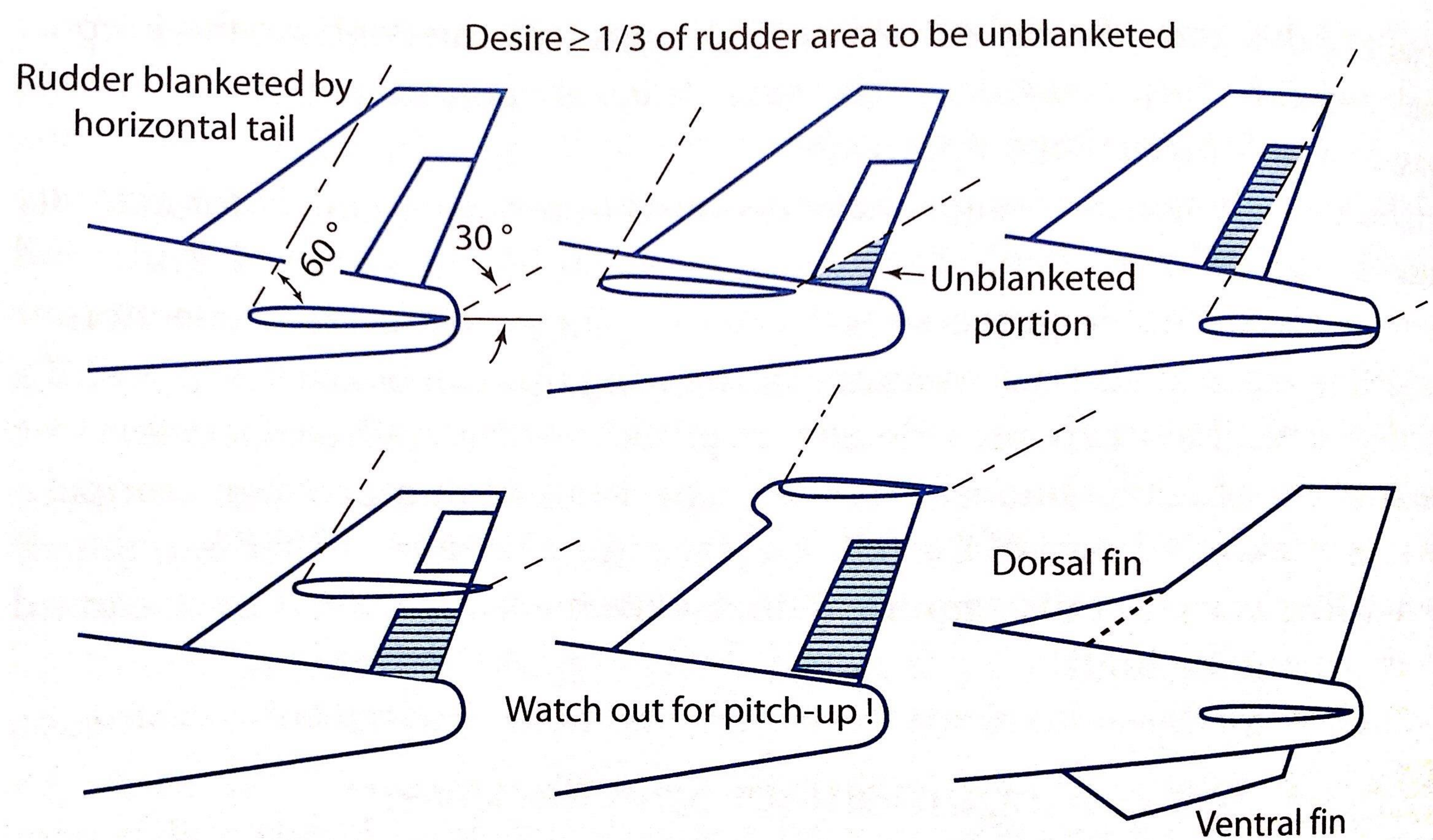

Source: Aircraft Design by Daniel P. Raymer

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- Tail Geometry
    - On t-tails, vertical aspect and taper ratio are lower to reduce structural weight penalty.
    - Taper ratio of one is cheaper to manufacture
    - Horizontal tail sweep is usually 5 degrees higher than wing to ensure the wing stalls first or to increase the tail's critical mach number.
    - Vertical tail sweep between 35 and 55 degrees or set to increase its critical mach number. In slow A/C, no need other than aesthetics to go higher than 20 degrees.
    - Tail t/c similar to wing's. On faster A/C, 10% thinner to increase critical mach number.

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	Horizontal tail		Vertical tail	
	A	λ	A	λ
Fighter	3–4	0.2–0.4	0.6–1.4	0.2–0.4
Sailplane	6–10	0.3–0.5	1.5–2.0	0.4–0.6
Others	3–5	0.3–0.6	1.3–2.0	0.3–0.6
T-tail	–	–	0.7–1.2	0.6–1.0

* Vertical tail aspect ratio is computed with semi-span!

Source: Aircraft Design by Daniel P. Raymer

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- Homework
- 4.1, 4.3
- For a wing with Aspect ratio = 3.0, Sref = 300 sq.ft., Taper ratio = 0.3, Leading edge sweep = 35 degrees: calculate span, root chord, tip chord, c-bar (mean aerodynamic chord), y-bar (c-bar's span-wise location). Draw this wing to scale, showing all these results.

Source: Aircraft Design by Daniel P. Raymer