Advance Aircraft Design

Advanced Aircraft Design I

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Make exams related to lowest passing rates.

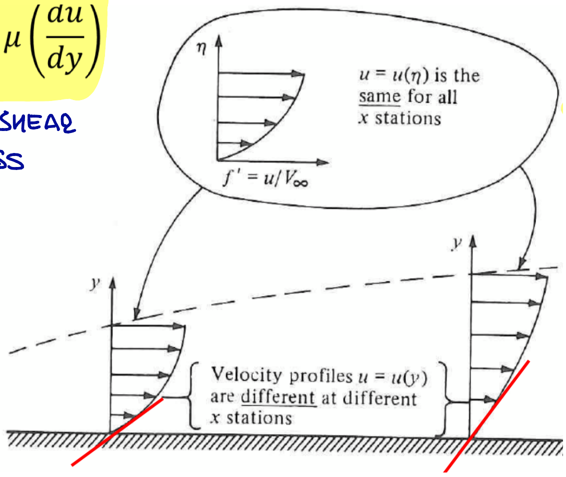
- Aerodynamic design of transport aircraft
- Introduction to transonic Aerodynamics

Q1: The local friction coefficient over a flat plate without a pressure distribution

Is decreased downstream

$$\tau_w = \mu \left(\frac{du}{dy}\right)$$

LOCAL SHEAR STRESS



- The boundary layer gets thicker the more the flow advances. This reduces the shear stress

SKIN FRICTION DRAG

$$D_f = \int_0^c \tau_w(x)\, dx \longrightarrow C_f = \frac{D_f}{q_\infty \cdot S}$$

FOR A FLAT PLATE

$$C_f = \frac{1.328}{\sqrt{Re_c}}$$

Laminar

you can just use half the plate

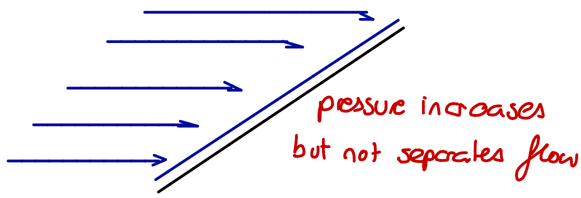
$$C_f \approx \frac{0.074}{Re^{1/5}}$$

Turbulent

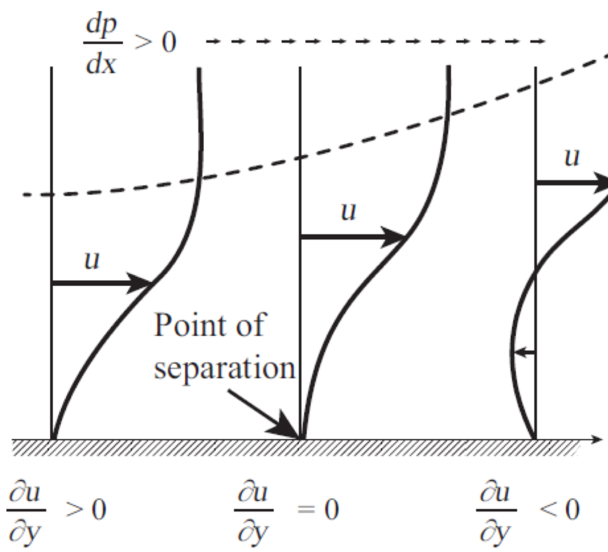
$$Re = \frac{\rho_\infty \cdot V_\infty \cdot c}{\mu_\infty} \quad \begin{matrix} \longrightarrow \text{inertial forces} \\ \longrightarrow \text{viscous forces} \end{matrix}$$

Q2: Favorable pressure gradient to prevent separation:

Pressure increases downstream over the body



Boundary Layer Separation



adverse pressure gradiant

Creates a good shear stress but a bad pressure distribution.

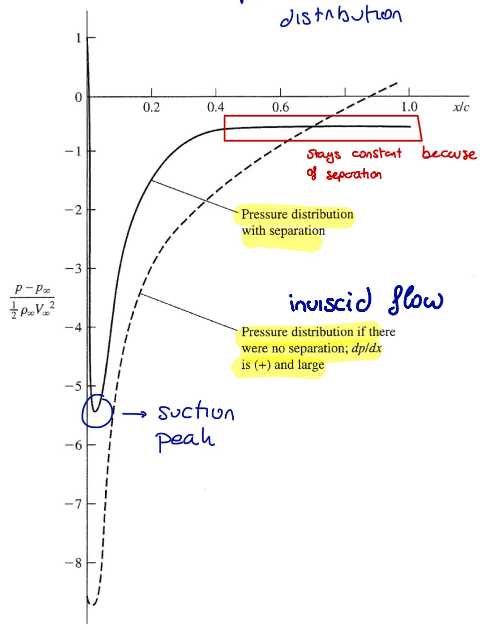
adverse pressure gradient

$P_0 < P_1$

more pressure, more potential energy, less kinetic energy causes separation and reversed flow maybe.

SEPARATION OF BOUNDARY LAYER

pressure coefficient distribution



} generates significant pressure drag

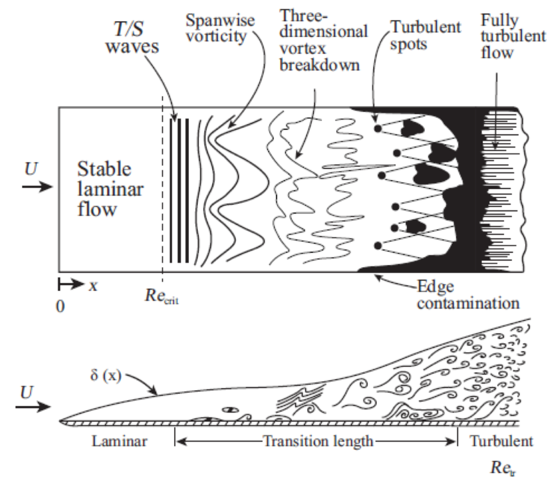
BOUNDARY LAYER TRANSITION

Q3: What is a favorable pressure gradient if one would like to postpone transition?

Pressure decreases downstream over the body, dumps the waves and postpones transition.

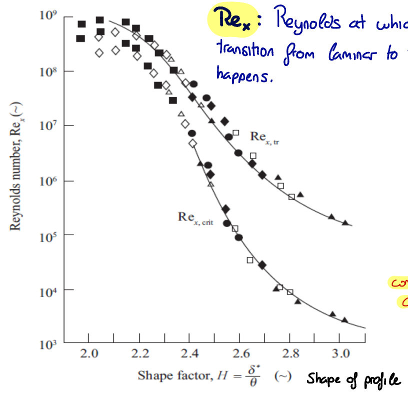
Instability depends

- Reynolds Number
- Pressure Gradient
- Receptivity



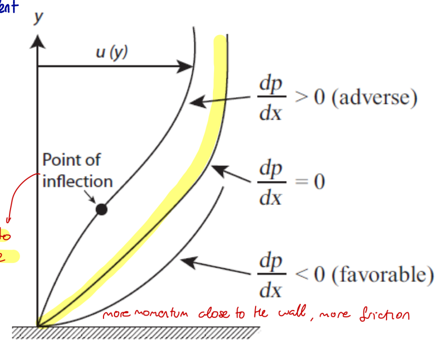
Q4: True?

A laminar boundary layer separates earlier than a turbulent boundary layer given an identical adverse pressure gradient.

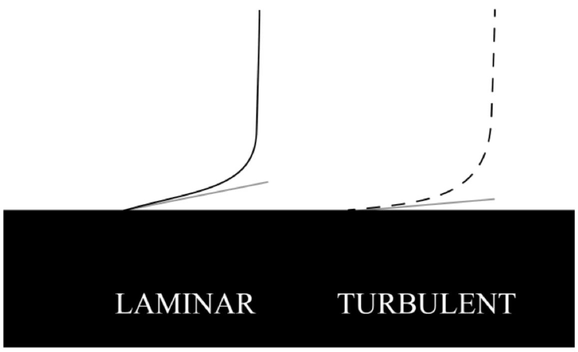


Re_x: Reynolds at which transition from laminar to turbulent happens.

boundary layer profile



LAMINAR VS TURBULENT



Subsonic Cruise Drag

Contributions to drag:

Zero lift drag: C_{D_0} | Lift dependent drag | Compressibility drag | Trim drag

- Friction drag
- Pressure drag
- Excresences
- Interference drag

Lift induced drag

$\frac{C_L}{C_D}$ $\quad C_D = C_L^2 \cdot k$

High speed drag

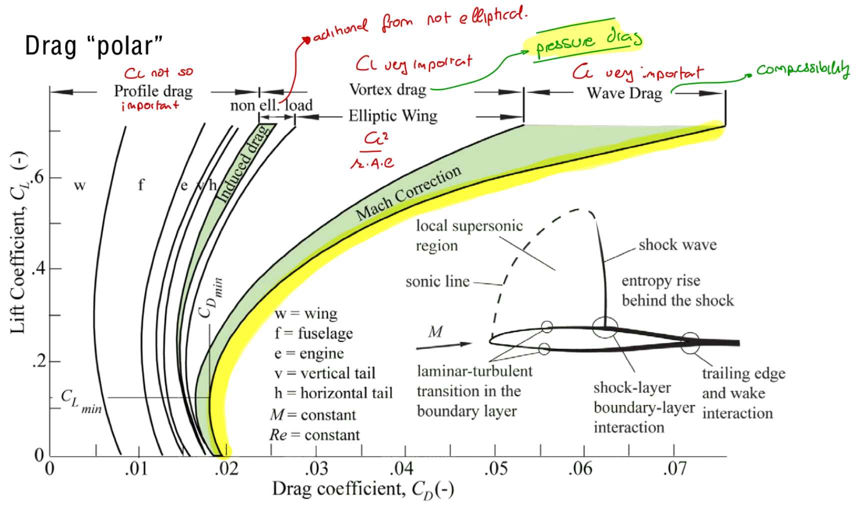
Due to stability trim or extra lift.

Q5: High-subsonic transport aircraft drag which component is the highest.

Q6: Higher trim drag — Moment arm

Q7: Higher zero-lift drag — + wetted area ↑C_{D_0}

Q8: Higher lift dependent — Both the same



Friction Drag

Main contributors are:

Welted area, Surface Roughness, Shape { local supervelocities / Pressure drag components

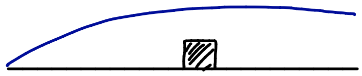
Q9: Does the size of the aircraft have an effect on its friction coefficient?

Yes, the larger the aircraft the smaller the C_f Higher Re! up to a point 10 000 000 Re

Q10: Why does the C_D stay constant after certain Re — then constant

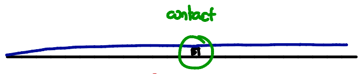
Due to aditional friction drag from excrescenses

This excrescenses average gives the equivalent sand grain roughness k_s (height)



Re = 1000000 due to chord

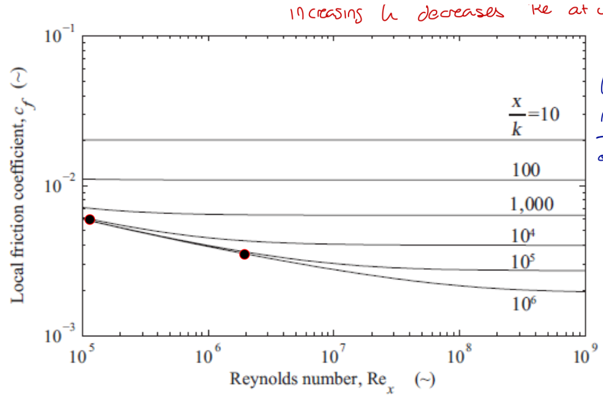
contact



Re 10 000 000 due to chord

increasing k decreases Re at which C_f is stable

k: found on reference! or experimentally



Improvements in excrescenses:

Composites, closer tolerances...

At higher Re the roughness has to be lower.

Q11: The C_D of a wind tunnel model

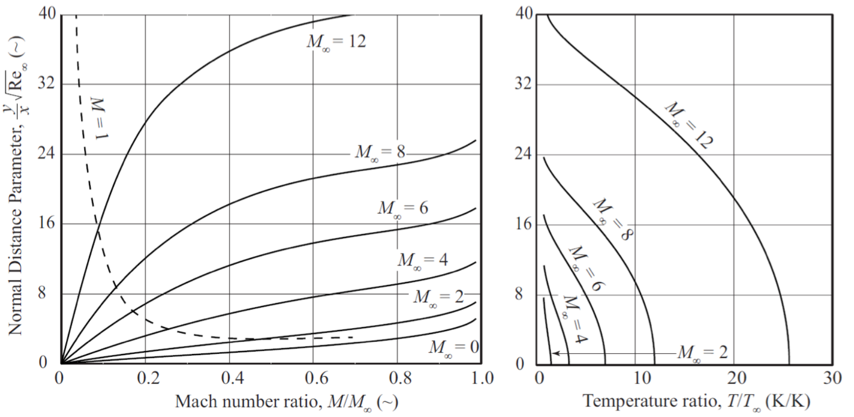
Is higher than that of a full scale a/c due to Re relief.

Same happens with interference!

Q12: Why does C_f decrease with M in supersonic flow

Due to the aerodynamic heating of the wetted surface.

The surface heats and changes the properties of air.



+ effect of temperature on viscosity... $\mu = \mu_0 \frac{T_0 + C}{T + C}\left(\frac{T}{T_0}\right)^{3/2}$

Lift Dependent Drag

Q13: The oswald factor:

Is a factor that accounts for both the change in profile drag and non-elliptical lift distribution. Its value can be higher than 1.

$$C_D = C_{D_0} + P + \frac{1}{\pi \cdot A \cdot \varphi} \longrightarrow C_D = C_{D_0} + \frac{1}{\pi \cdot A \cdot e}$$

Depends on elliptic lift distribution

Profile and parasite drag dependent on angle of attack

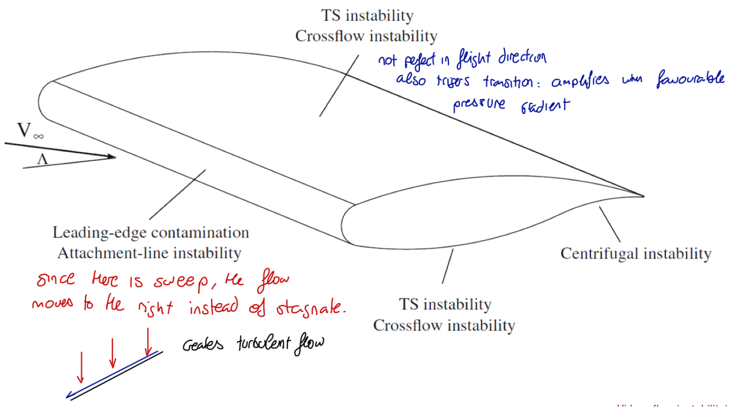
Oswald efficiency factor

Summary

- Boundary layer state is influenced by: pressure distribution, Reynolds number, Mach number, roughness, and atmospheric turbulence
- Boundary layer is responsible for friction drag and separation
- Aircraft drag can be represented by a drag polar plus corrections
- Zero lift drag is combination of theoretical friction drag, roughness effects and shape factor
- Friction drag coefficient decreases with Reynolds number up to the cut-off Reynolds number. The latter is dependent on roughness
- Lift dependent drag is consists of vortex drag and the change in profile drag due to angle-of-attack. They are lumped in the Oswald factor

Geometry vs. Pressure Distribution

Transition



Conflicting design requirements w.r.t aerodynamics:

Sweep angle effects:

- Attachment line instabilities: low Λ
- Cross flow instabilities: low Λ
- Wave drag: high Λ

Leading edge-radius effects:

- Attachment line instabilities: low r/c
- Maximum lift coefficient: high r/c

Pressure distribution effects:

Tollmien Schlichting waves: − pressure gradient

Cross flow instabilities: too large amplifies

Aerodynamic Design

Reduce and Eliminate:

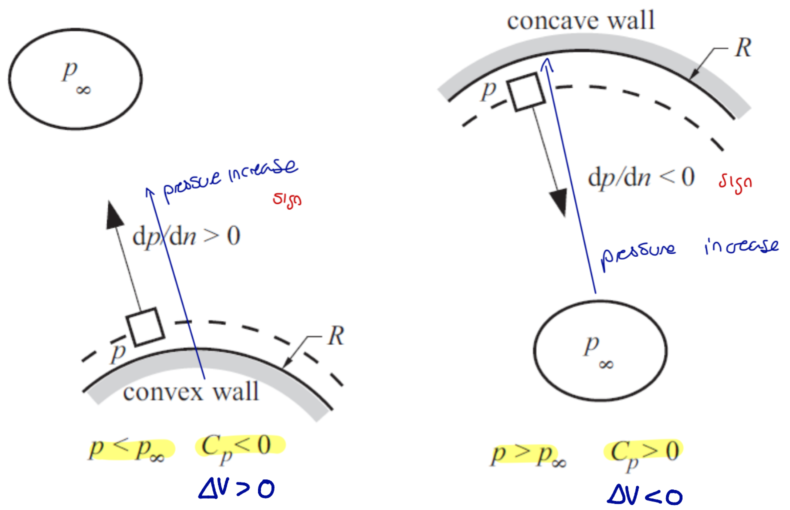
Shock waves, Separation and Friction Drag.

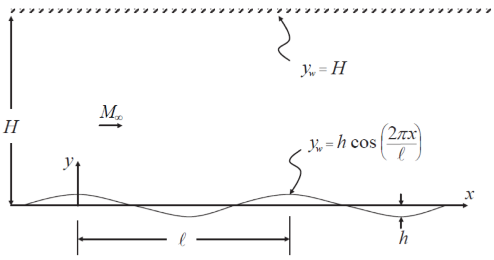
from:

Cockpit, Fuselage, Nacelle/Wing interference, Aft body shapes.

Q24: For subsonic flow over a wavy wall, the flow in the concave parts

Has a positive pressure coefficient



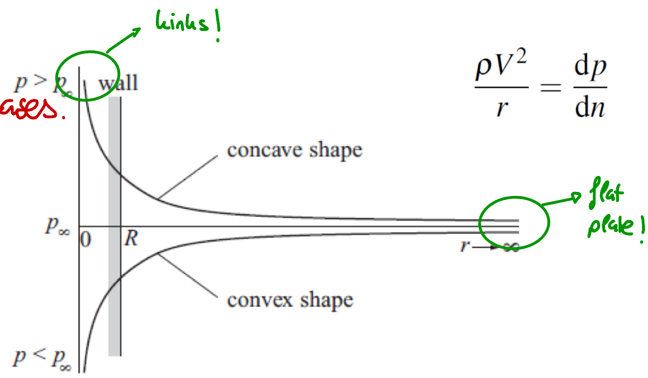


$$C_{pw} \approx -\frac{2hk}{\beta}\cos(kx)$$

Q25: If the radius of curvature of the convex shapes increases.

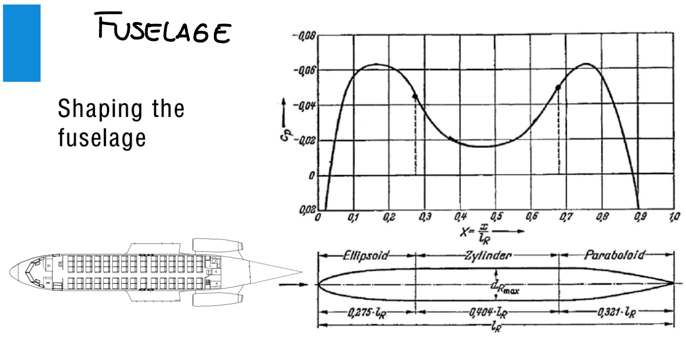
The pressure coefficient also increases.

$$\frac{\rho V^2}{r} = \frac{dp}{dn}$$

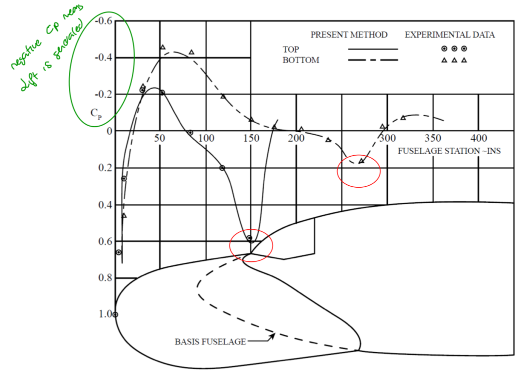


Fuselage

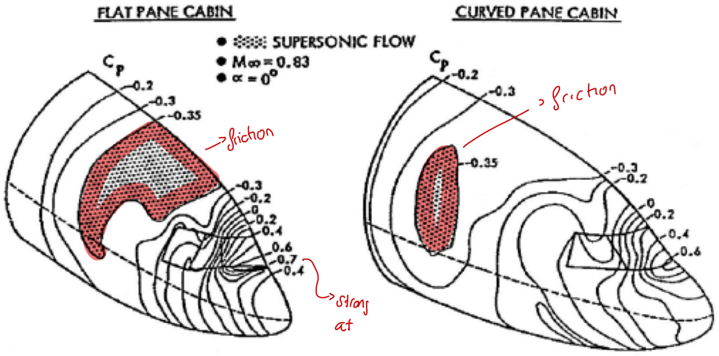
Shaping the fuselage



Nose

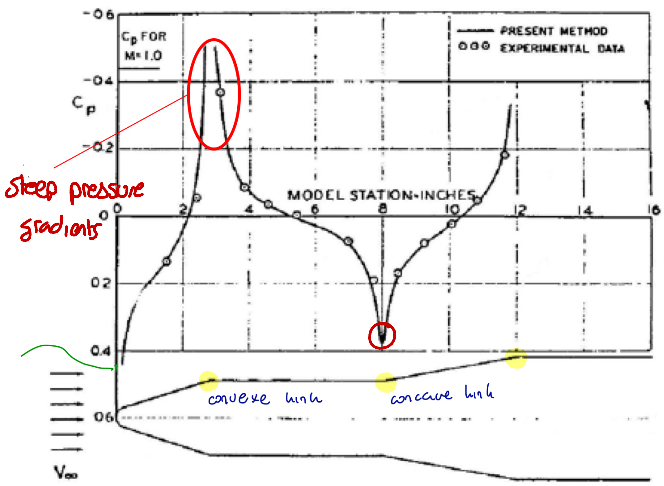


Cockpit Design



- The supervelocities cause aditional drag. Thus they must be eliminated or reduced.
- The momentum thickness is the loss of momentum of the boundary layer. Used to measure "drag"

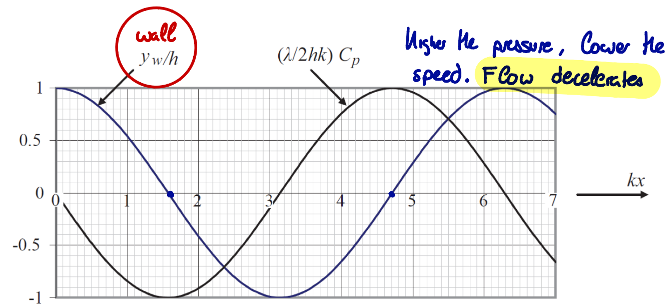
Geometry and Cp, example



On the airfoil, the leading and trailing edge do not work. Since those are stagnation points.

Moreover, compressibility has not been investigated yet.

Q16: For supersonic flow over a wavy wall, the flow in the concave parts...



Compressibility Effects

$$\tau = -\frac{1}{V}\cdot\frac{\partial V}{\partial p} = \frac{1}{\rho}\cdot\frac{\partial \rho}{\partial p}$$

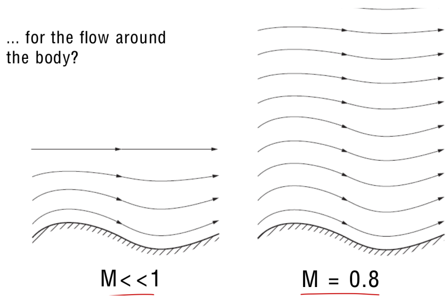
Compressibility boundary.

For flows at low speeds: the magnitude of changes in pressure is small compared to the pressure itself. dp is small and dp can be dominated by dp

For high speed flows: dp can be large thus density plays a more important role.

Q17: What is the effect of a high-subsonic Mach number on the flowfield around a body compared to the flowfield at a low-subsonic Mach number.

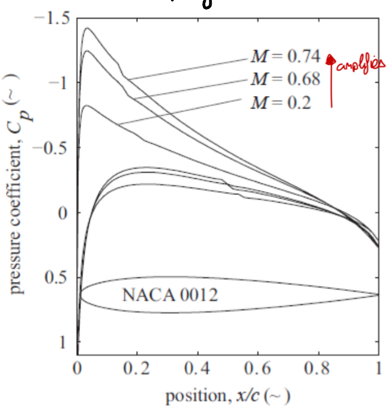
Local curvature has a larger region of influence:



Q18: What is the effect of a high subsonic Mach number on the pressure distribution?

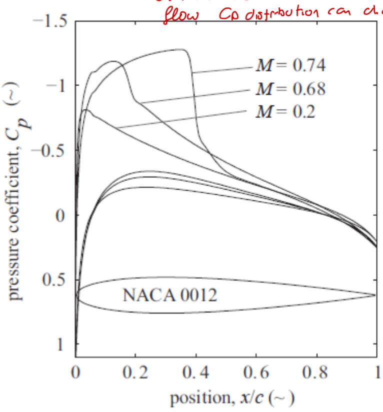
Depends

Amplifies



Changes shape

when we have buckets of supersonic flow Cp distribution can change.

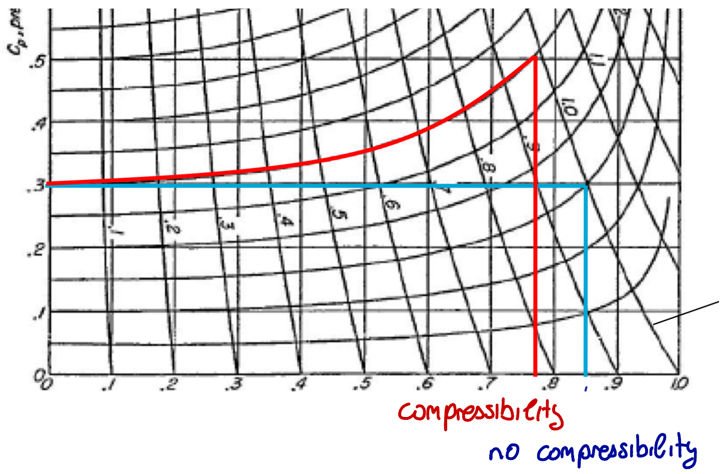


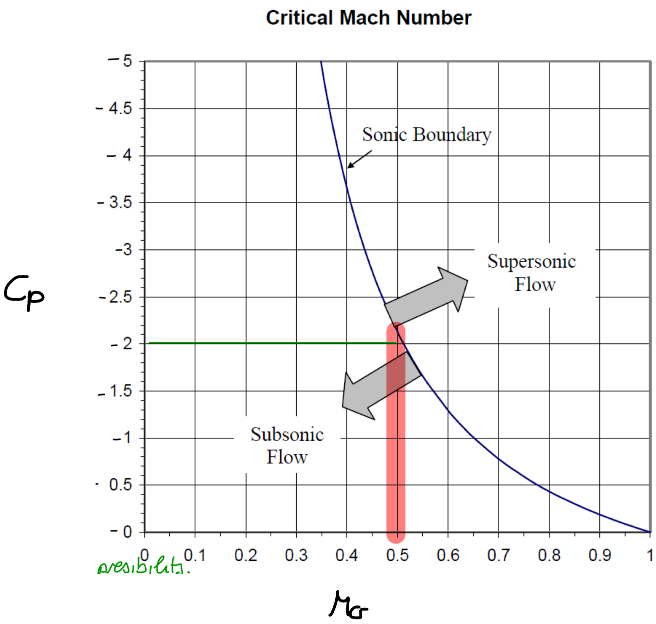
Compressibility corrections:

- Prandtl - Glauert
- Laitone
- Karman - Tsien

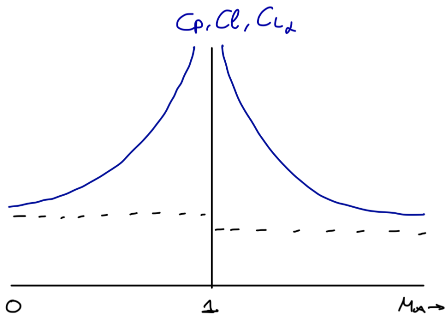
Cp Critical

$$C_{p,cr} = \frac{2}{\gamma M_{cr}^2}\left[\left(\frac{1+\frac{\gamma+1}{2}M_{cr}^2}{\frac{\gamma+1}{2}}\right)^{\frac{\gamma}{\gamma-1}} - 1\right]$$



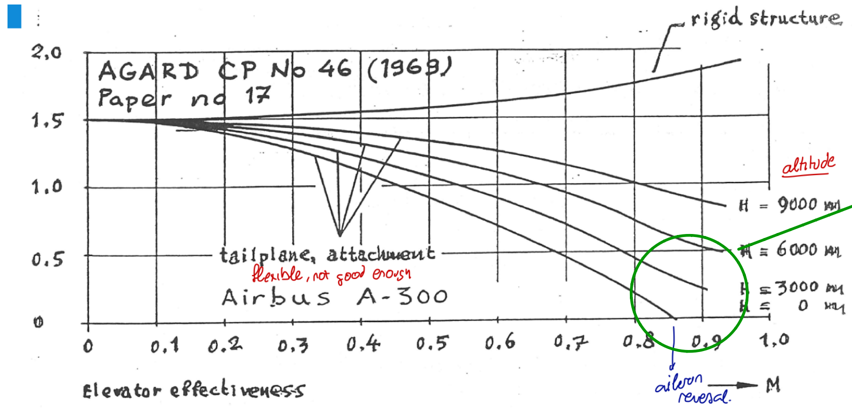


Compressibility Effects on Forces



Q19: What is the compressibility effect on control surface effectiveness.

Depends on dynamic pressure and structural layout.



High dynamic pressure creates a high aeroelastic effects.

Worst case is at high speed low altitude

Q20: Airplane P-47

Q21 Why do transport a/c never cruise at speeds beyond $M = 0.9$

Due to excessive pressure drag: form of shock waves.

zero lift drag increases exponentially after M_{DD} due to the formation of shock waves

M_{DD} has different definitions depending on the aircraft manufacturer.

Summary

- Local shape changes effect the pressure coefficient.
- The effect on the pressure coefficient depends on the Mach number of the flow: subsonic versus supersonic
- Gradual changes in shape result to a smoother pressure distribution reducing friction drag and/or eliminating separation
- The Mach number has an effect on the region of influence of a body, the pressure coefficient over the body, the sensitivity of the forces with respect to inflow angle, the drag of a body, the effectiveness of control surfaces, and the handling characteristics of an aircraft.

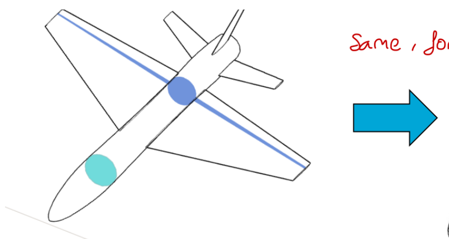
Area Ruling and Interference Effects

Q22: Why was the F102A faster than the F102

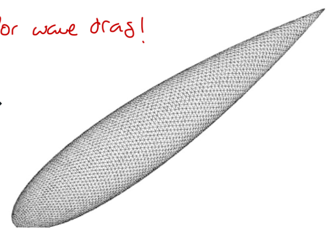
Due to area ruling of the cross-sectional area distribution the wave drag of the aircraft reduced

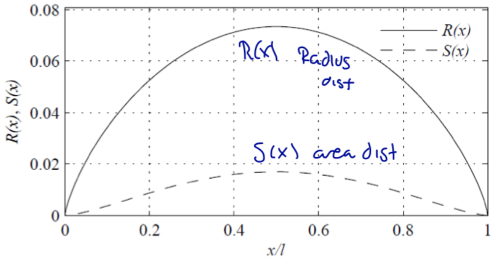
Fundamentals of Area Ruling

Drag produced by slender body of arbitrary dimensions in supersonic flow may be modelled by an equivalent body

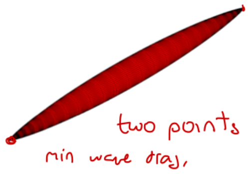


Same, for wave drag!





Sears-Haack body for given length and volume



For fundamentals:

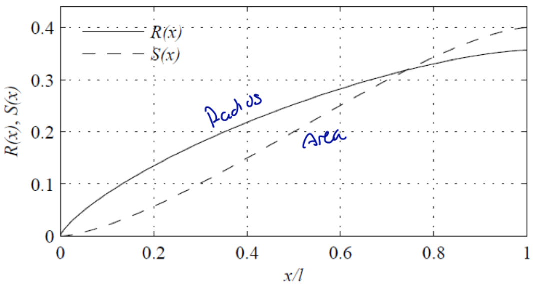
Wave drag only dependent on cross-sectional area distribution: not always true

Wave drag dependent on second derivative of area

small changes: low drag

large changes: high drag

Von-Karman ogive for given length and base area



Shortcomings

No lift is considered

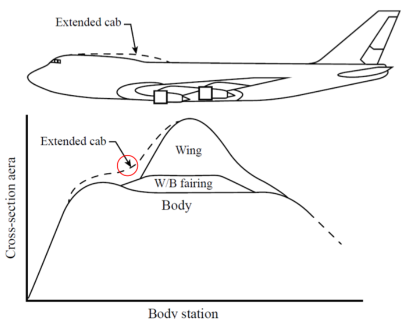
Flow is assumed irrotational

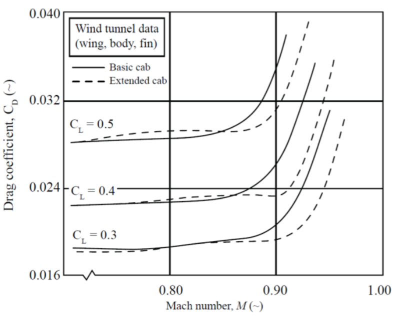
No viscous effects considered

Q23: Why is the drag of the equivalent body lower than the swept-wing configuration.

The swept-wing configuration develops shocks over the wing surface, causing separation while the equivalent body does not.

EXAMPLE



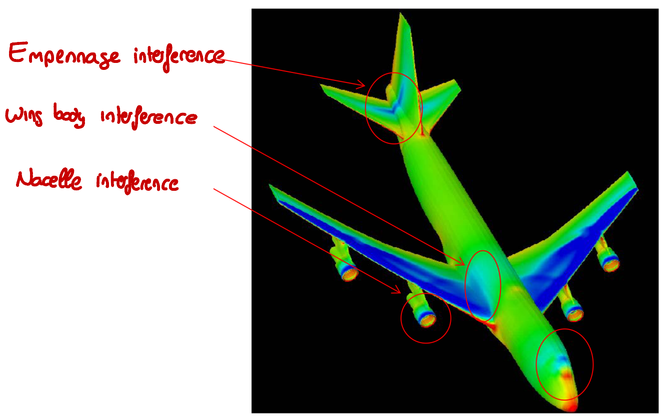


Q24: How does the addition of these bodies lead to a reduction in drag coefficient at the design Mach Number?

They promote isentropic compression of the supersonic flow and postpone shock-induced separation.

For engine nacelles, you can consider only 20% of the area.

INTERFERENCE EFFECTS



Every curvature generates supervelocities and at junctions these supervelocities are added.

Q25: Why are interference effects more pronounced in high subsonic conditions?

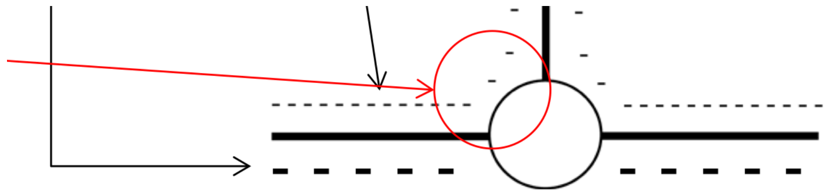
Due to compressibility the region of influence is larger

Wing Body Interferences

Q26: Effect of the fuselage on the lift distribution over the wing of a high-subsonic transport aircraft in cruise conditions?

To reduce these interferences, fairings can be introduced, reducing supervelocities

Increases lift over inboard of wing but has no effect on the outboard wing. Depends on high/low wing.



Empennage Interference

Q27: Why are Vt and Ht often staggered?

To prevent a nose-down pitching moment in cruise conditions.

Higher speeds on tail upper surface, decreasing downforce, nose down

Tuck-under phenomenon:

Overspeeds on horizontal and vertical tail coincide. Also possible to remove fuselage.

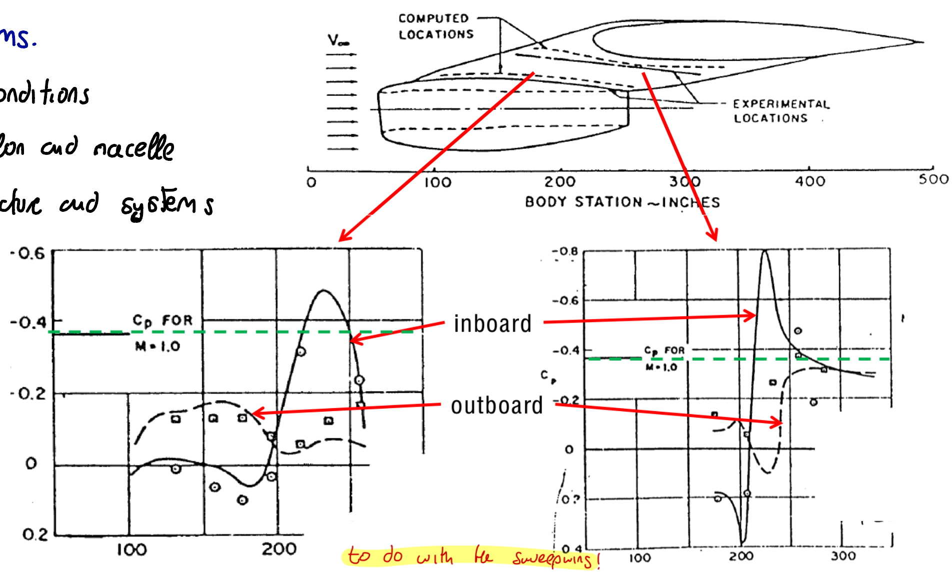
Solutions:

Staggered, remove fuselage, acorn → reduces local Cp peaks

Wing - Nacelle - Pylon Interference

Constraints of these systems.

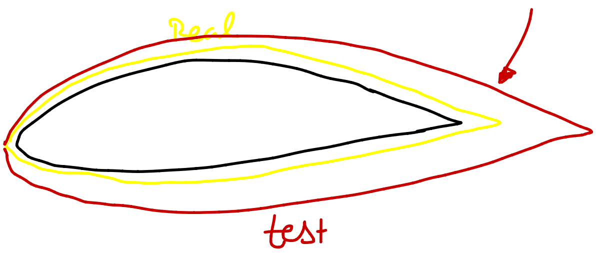
- Attached inflow in all conditions
- Structural rigidity of pylon and nacelle
- Sufficient space for structure and systems



Inboard supervelocities always higher than outboard!

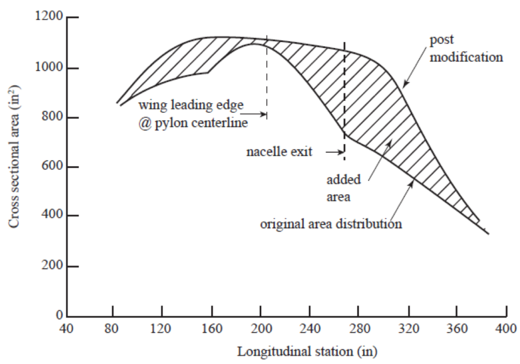
Q28: Why is there a difference btw wind tunnel test and flight test?

The wind tunnel model has lower effective curvature, making the supervelocities lower.



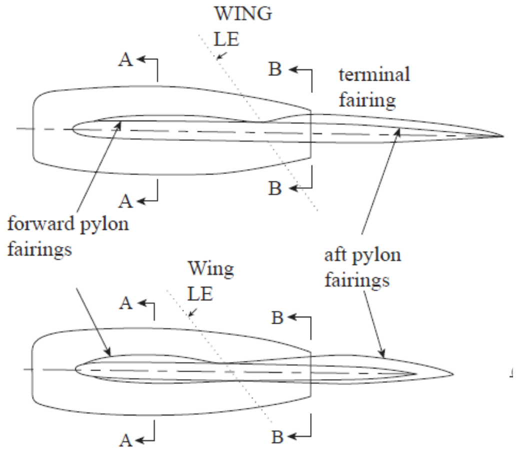
Solutions of Nacelle - Wing interference

Design pylon using local area rule



Outboard pylon nacelle

Inboard pylon nacelle



Transonic Airfoil Characteristics

Airflows in subsonic flow

Characteristics of pressure distribution:

- A stagnation point at or near the leading edge ($C_p = 1$)
- Height and location the maximum super velocity ($C_{p_{min}}$)
- The ratio between $C_{p_{min}}$ and C_p^*
- Pressure gradient dp/dx behind $C_{p_{min}}$
- The T.E. Pressure (for inviscid flow $C_{P_{TE}} <= 1$)

Include boundary layer effects:

- Displacement thickness, δ^*
- Momentum thickness, θ
- Local friction coefficient, C_f

Q29: Why does the C_f decrease with chordwise position?

The boundary layer thickness is higher downstream

Thin vs Thick Airfoil

Low angle of attack and low Reynolds number

Thin Airfoil

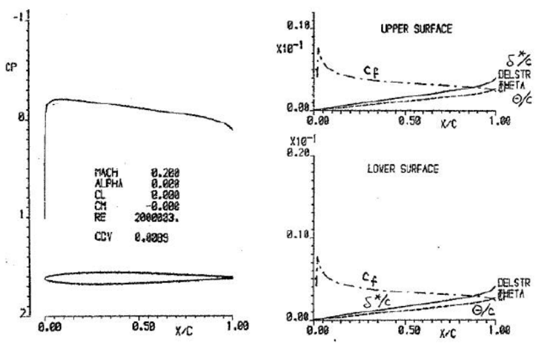
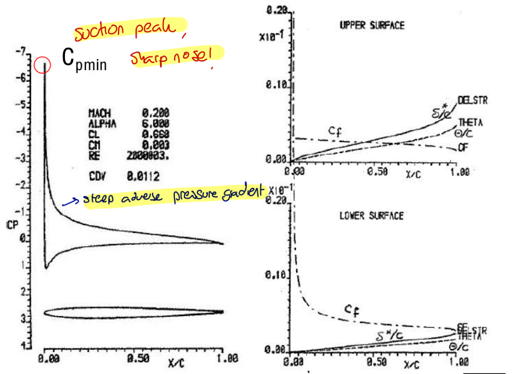


Figure 15.1 - Pressure distribution for NACA 0006 airfoil section at a = 0° and Re = 2· 10⁶

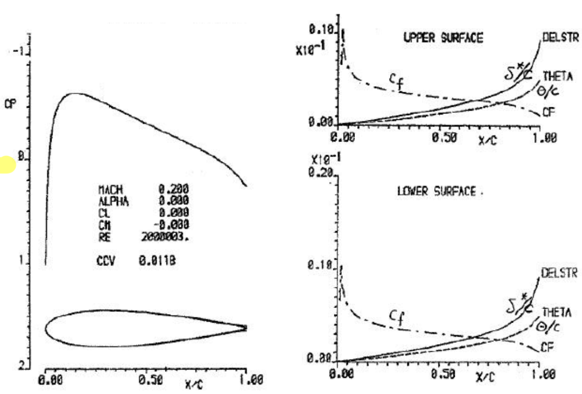
Thin Airfoil

Increasing the angle-of-attack



Thick Airfoil

Low angle of attack and low Reynolds number



Thick Airfoil

Increasing the angle-of-attack

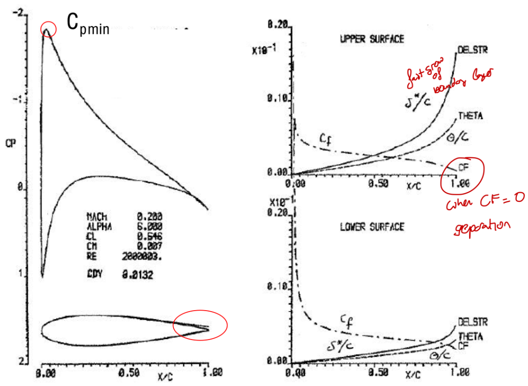
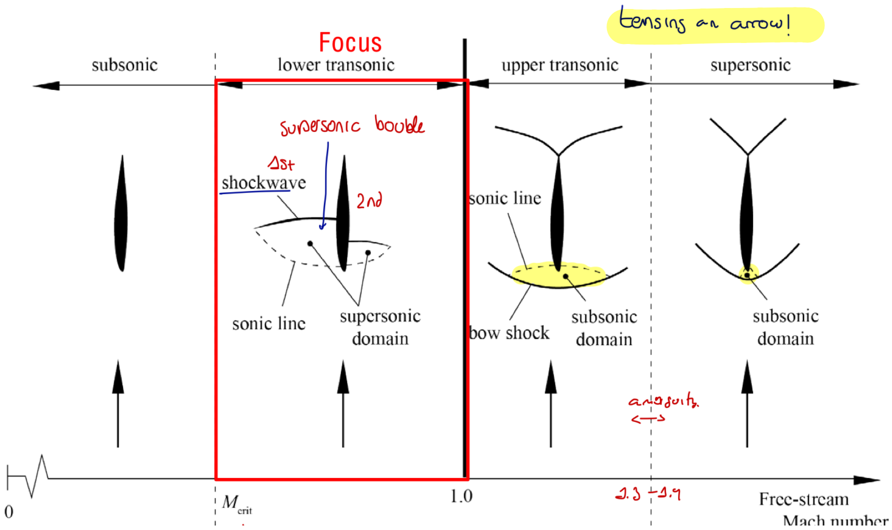
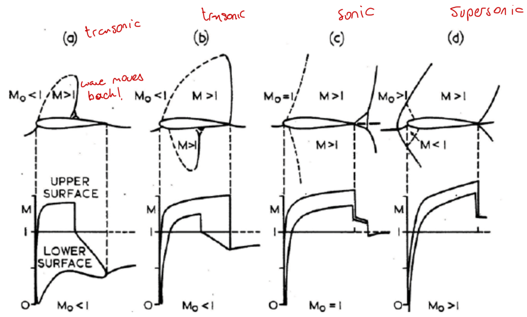


Figure 15.6 - Pressure distribution for NACA 0018 airfoil section at a = 6° and Re = 2·10⁶

Airfoils in Transonic Flow



Q30: In transonic conditions, when the freestream Mach number increases, the shock moves downstream



Shock Position

slides 18-22 on Pressure distribution about airfoils

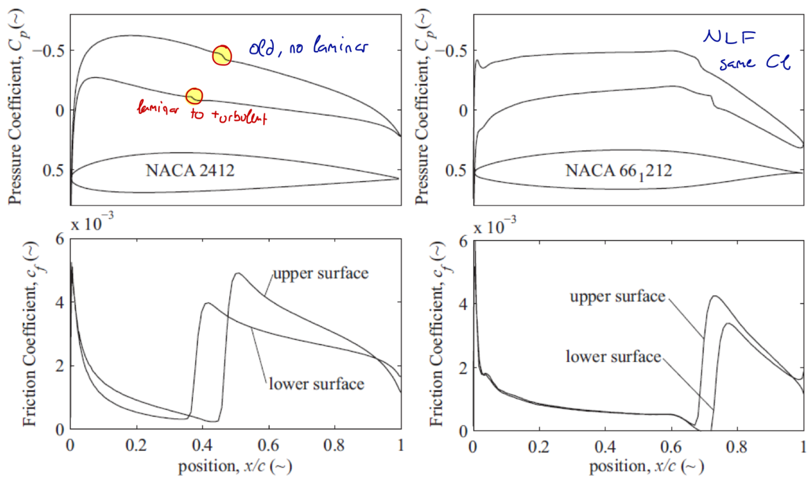
Lower M in front of shock ⟶ shock pulled forward

Higher M in front of shock ⟶ shock pushed back

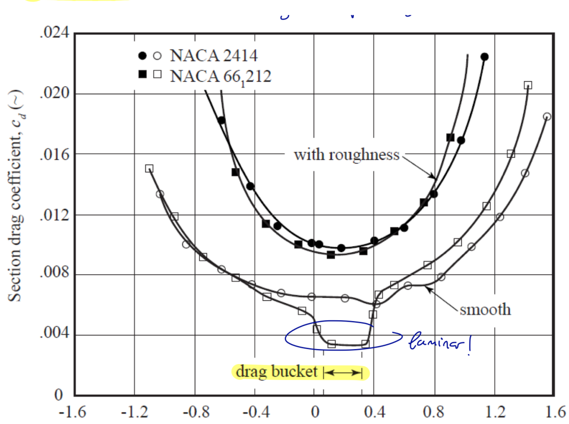
Transonic Airfoils

NOT GOOD FOR TRANSONIC

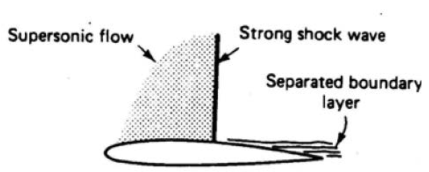
NLF airfoils: Natural Laminar Flows

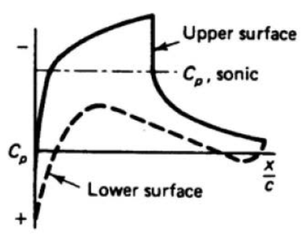


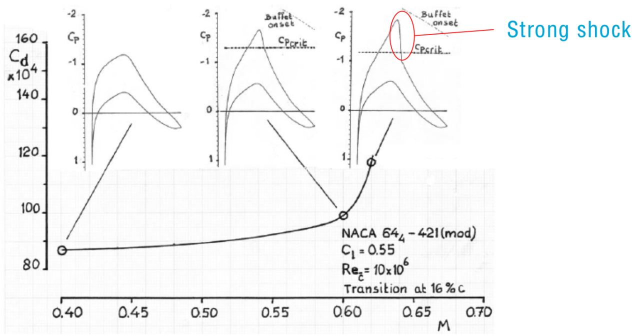
NLF have a special feature called Drag bucket



Bad behaviour due to supersonic flow:



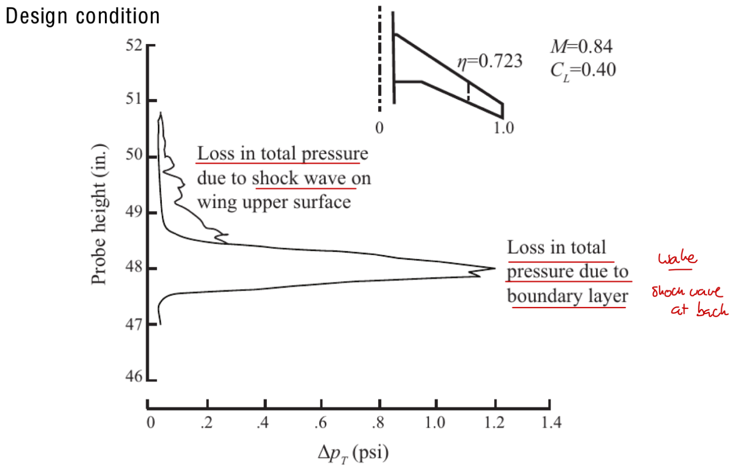




Q31: Why is the shock wave causing an exponential increase in drag?

Due to pressure increase due to boundary layer separation

Drag on Supercritical Airfoil

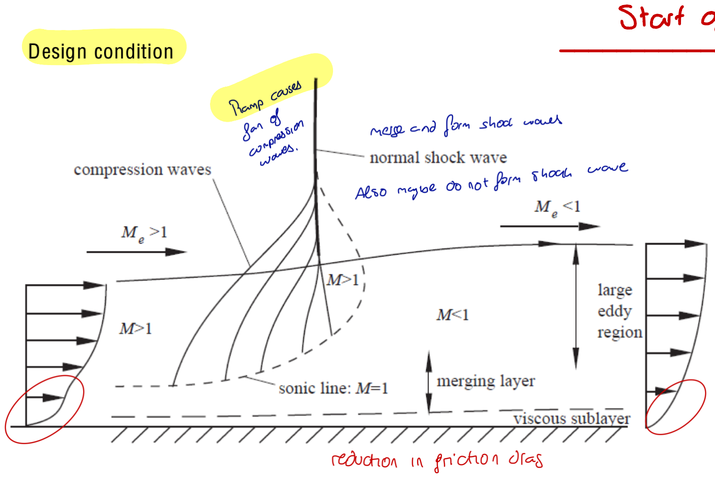


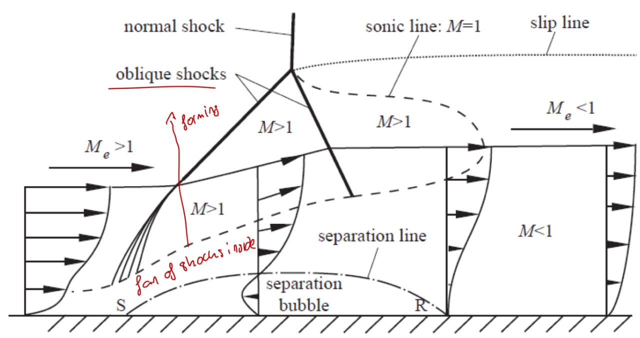
Q32: Why would the result be disappointing in terms of wave drag?

Due to the effect of Re on the boundary layer

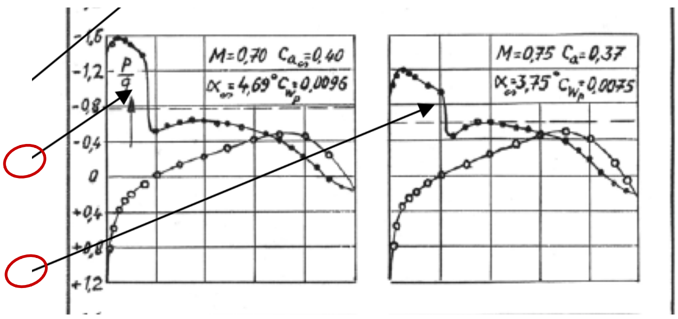
Drag Rise

Start of drag rise





Shock wave on a Cp graph

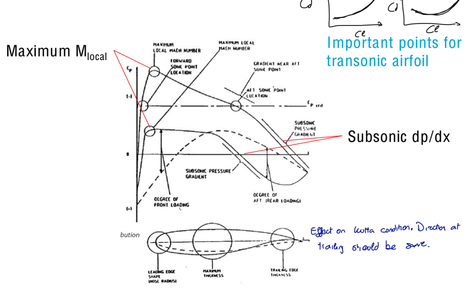


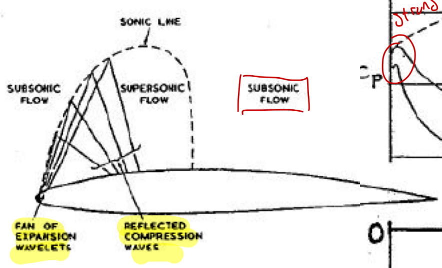
Solutions:

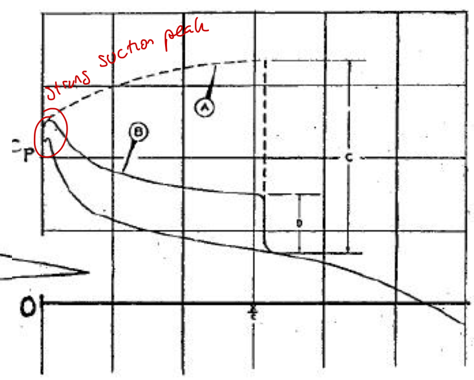
- NACA 4 airfoils, modified leading edge radius and position of maximum thickness.
- These are designed to reflect the expansion waves caused by the leading edge on the sonic line to create compression waves that

- Another solution is to create shockless Airfoils

Shockless Airfoils

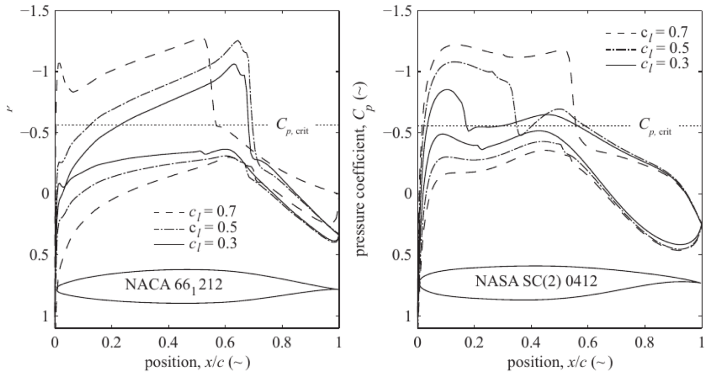




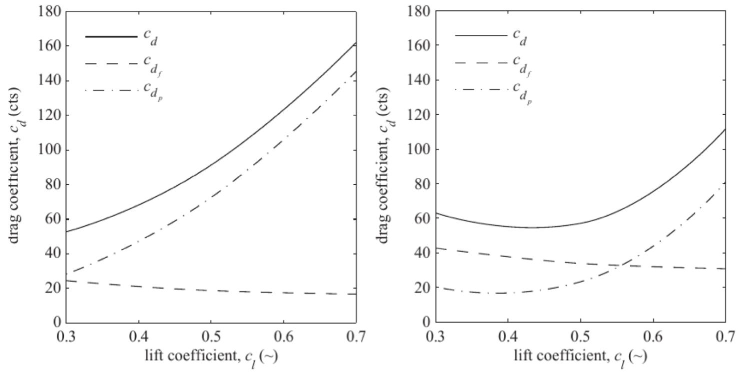


Reynolds Number Effects

Design of Supercritical Airfoils



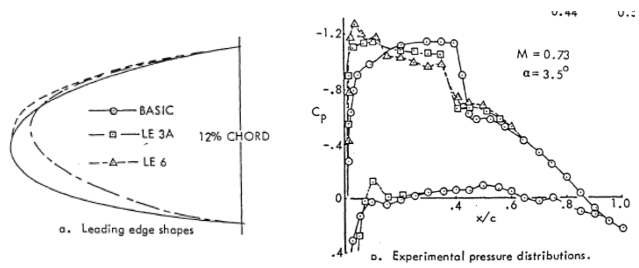
NLF | Supercritical

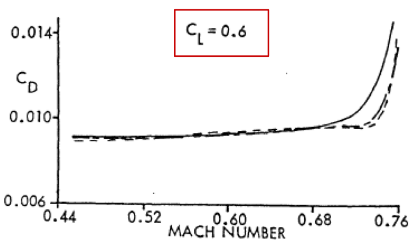


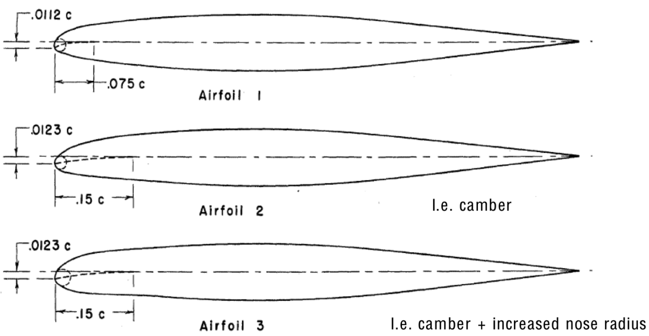
NLF | Supercritical

What to modify:

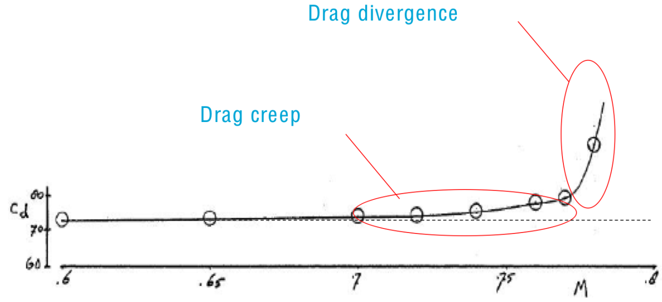
leading edge shape effects on wave drag







Drag on supercritical airfoils.

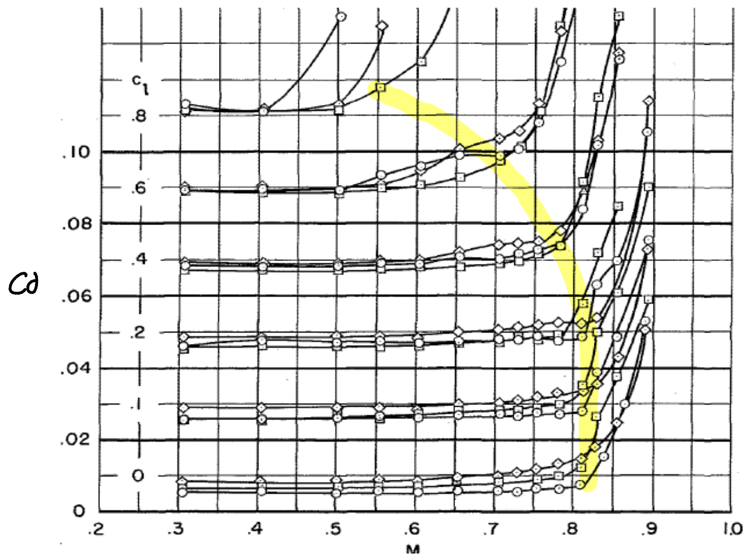


Drag creep:

Caused by the weak shocks close to leading edge

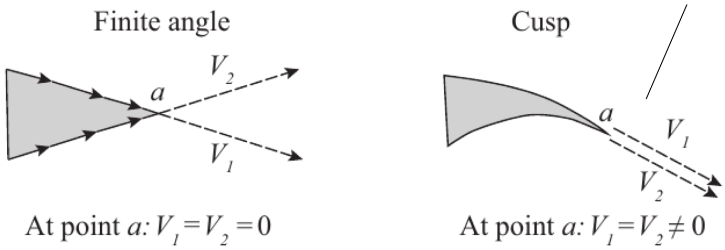
Related to nose radius of airfoil

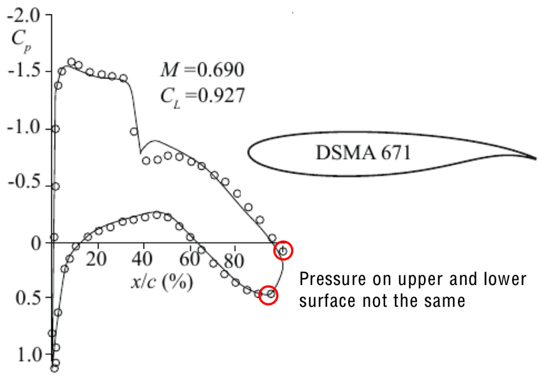
- Smaller radius: less drag creep
- Larger radius: more drag creep

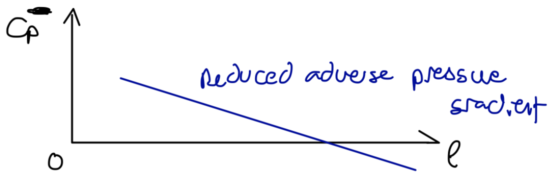


Q33: Why do many supercritical airfoils feature a cusp in the trailing edge?

To reduce the adverse pressure gradient behind the shock and postpone separation.





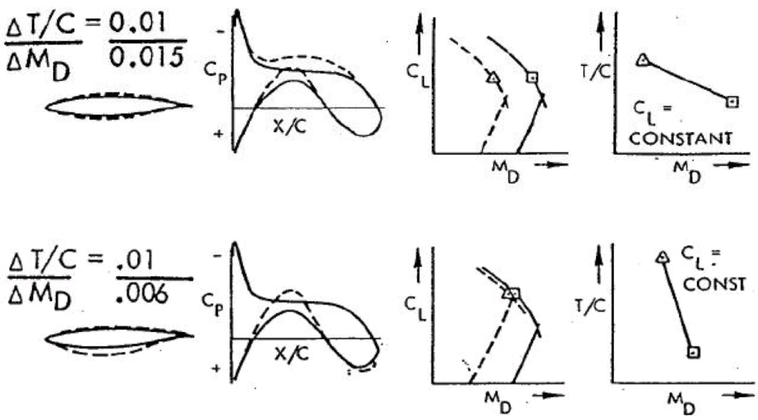


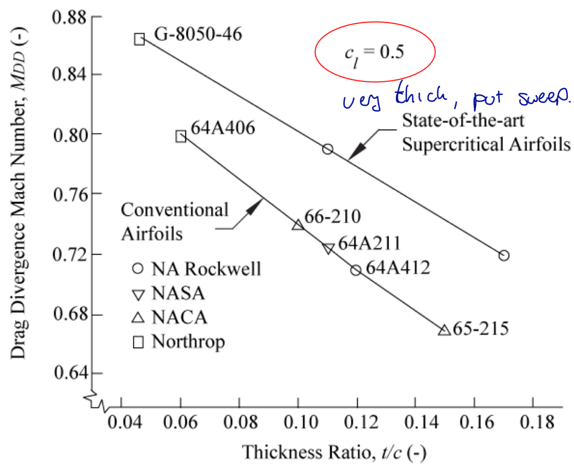
Q34: A blunt trailing edge

Increases the drag of a supercritical airfoil, but can also decrease. Depends on the Mach.
It must be used due to manufacturing constraints.

Q35: If the thickness-to-chord ratio increases

The drag-divergence Mach number decreases



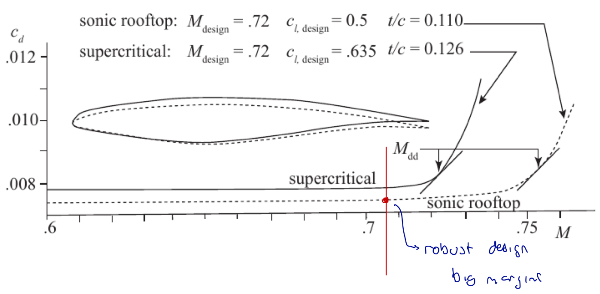


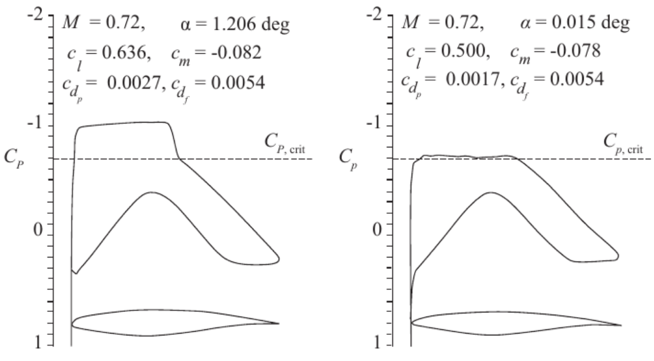
To prevent drag creep, we can use the sonic roof top approach

Design such that C_p is C_p^* from leading edge to 0.3-0.6 x/c

keep the maximum local velocity around $M=1$

No mixed subsonic/supersonic flow.

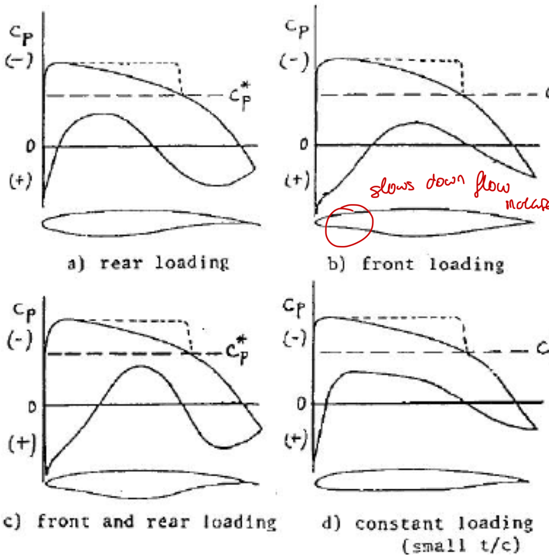




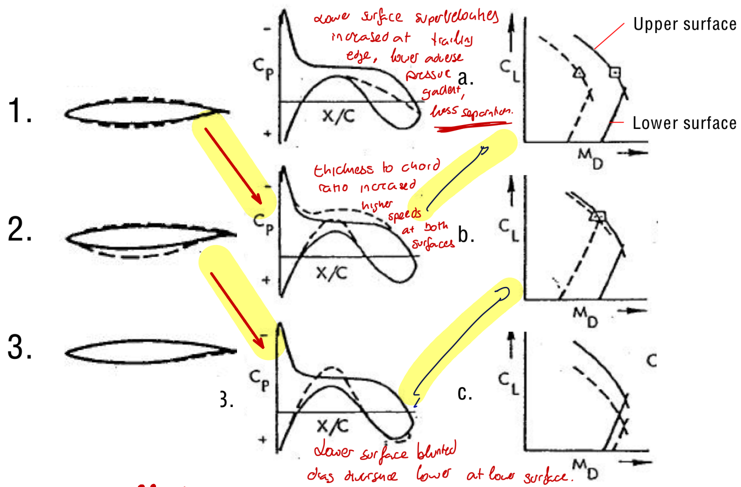
(a) Supercritical airfoil (b) Sonic rooftop airfoil

Lower Surface Design

Loadings on front, rear or constant. More negative Cp on position at airfoil.



Q36: Match subsonic pressure distribution to corresponding drag divergence Mach Number



Effect of M and C_L

Slide 33 of Reynolds effects.

- Increasing C_L comes with a decrease in Cp from 0 to 50 % of the chord.
- Increasing the M comes with a constant pressure area extending from 0 to 50 % of chord.

Q37: Why is the shock predicted to be further aft by the inviscid model?

Due to the higher effective curvature of the airfoil. Why tho?

Reynolds Number Effects

Q38: With increasing Re the total friction drag coefficient on a typical airfoil...

Decreases due to lower relative momentum thickness Why tho?

Thin airfoil, increase on Re

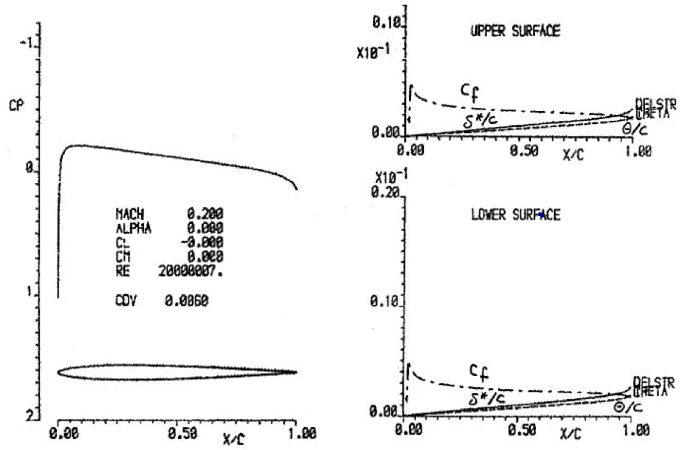


Figure 15.3 - Pressure distribution for NACA 0006 airfoil at a = 0° and Re = 20 · 10⁶

Thick airfoil, increase on Re

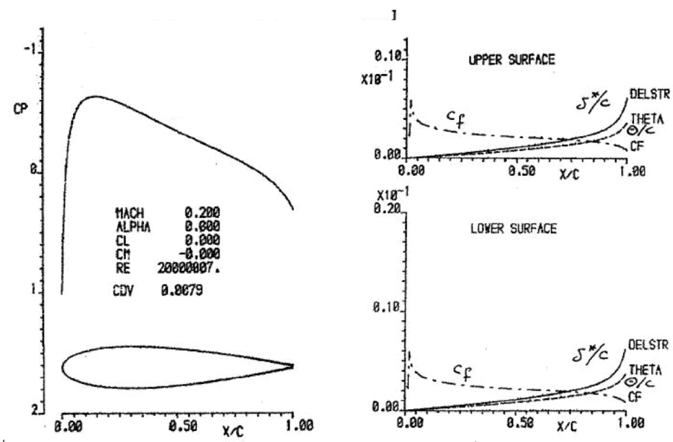


Figure 15.7 - Pressure distribution for NACA 0018 airfoil at a = 0° and Re = 20 · 10⁶

Thin airfoil, high α increase Re

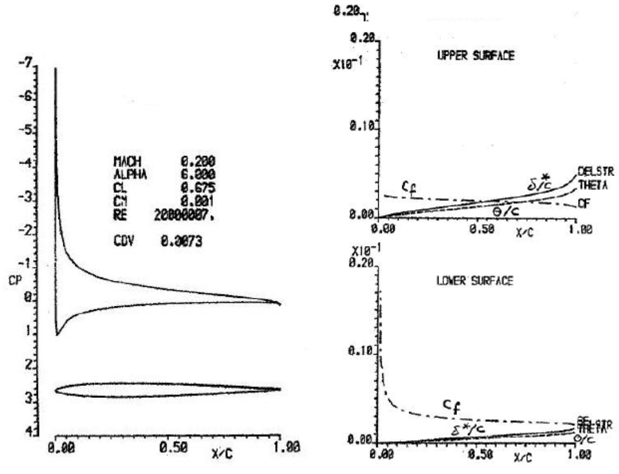


Figure 15.4 - Pressure distribution for NACA 0006 airfoil at $\alpha = 6°$ and $Re = 20 \cdot 10^6$

Thick airfoil, high α increase Re

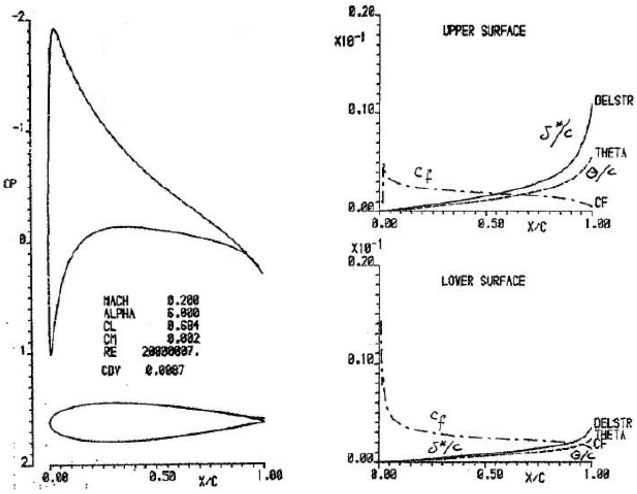
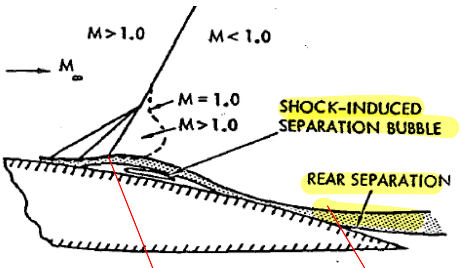


Figure 15.8 - Pressure distribution for NACA 0018 airfoil at $\alpha = 6°$ and $Re = 20 \cdot 10^6$

Re effects at high Mach

2 types of separation

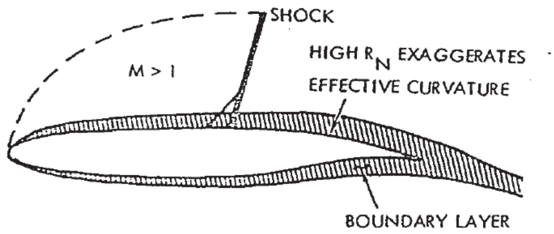


Model of Transonic Shock/Boundary-Layer Interaction

low dependence on Re

Highly dependence on Re

Airfoil with reynolds effect



Q39: What happens to C_L in transonic conditions when the Re increases, while the rest stays the same.

It becomes larger, thickness is increased more speed over the airfoil, more C_L.

Tables can be found in slides 47-52 of Re effects.

SHOCK FORMATION: moves backwards when increasing Re

$C_M - C_L$: moves to the right when increasing Re

MDD: increases when increasing Re

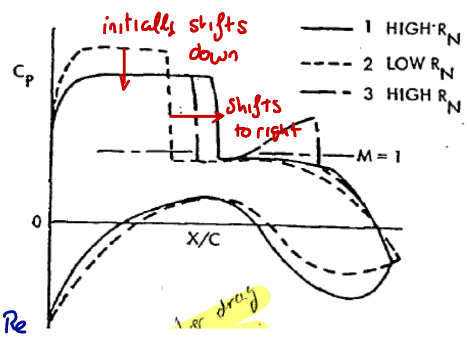
C_L: increases while increasing Re.

Drag creep: decreases while increasing Re

C_D: on fixed transition, decreases while increasing Re

on free transition, increases until $9 \cdot 10^5$ and then decreases increasing Re

Cp plot:



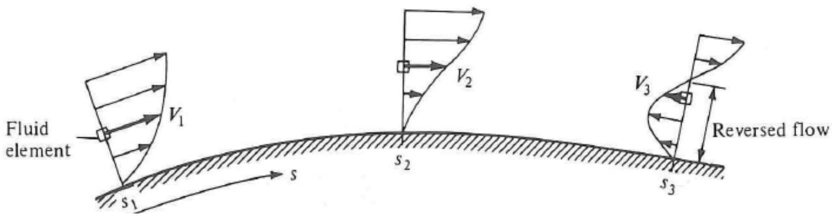
Summary

- At low Re, laminar b.l. and lambda shock
- At high Re, transition before shock wave, turbulent b.l. vs. shock
- Increasing Re, moves transition forward
- Increasing Re decreases displacement thickness of turbulent b.l.
  - Effective increase in curvature
  - Higher supervelocities
  - More aft position of the shockwave
  - May cause increase in shock strength or second shock

Low Speed and High Speed Stall

Low Speed Stalling Characteristics

Stall, is the separation of the boundary layer. An adverse pressure gradient could potentially create reverse flow.

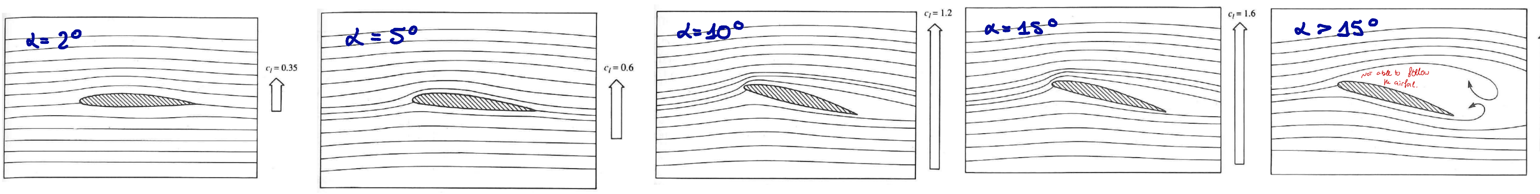


Qu0: How can we recognize b-l separation in the Cp plot?

- Suction peak drop
- Cp becomes constant
- Trailing-edge Cp remains negative.

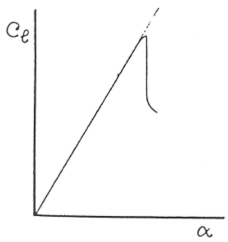
Types of Stall

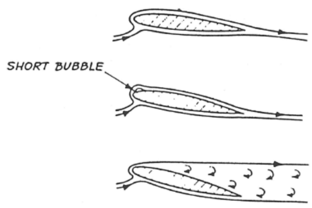
Leading edge stall



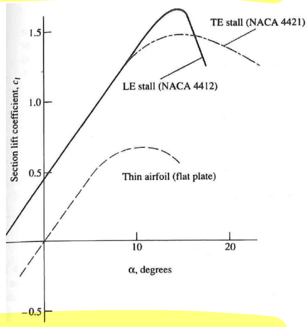
Abrupt stall, Flow separation over entire airfoil, Present on airfoils with moderate L.E. radii (initial pressure gradient too big)

L.E. radius has significant effect on lift coefficient

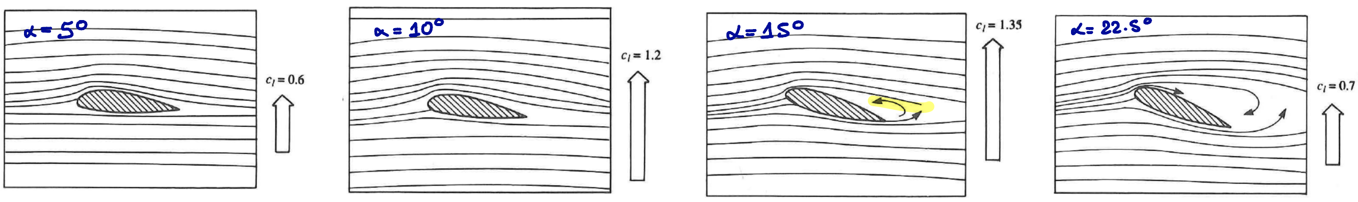




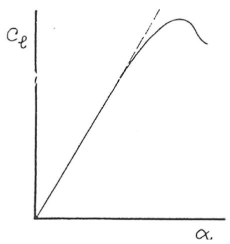
Comparison btw the three!

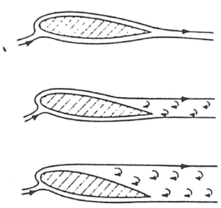


Trailing edge stall



Gradual stall, Flow separation moves fwd with α, Occurs on airfoils with large l.e. radius and strong upper surface curvature.



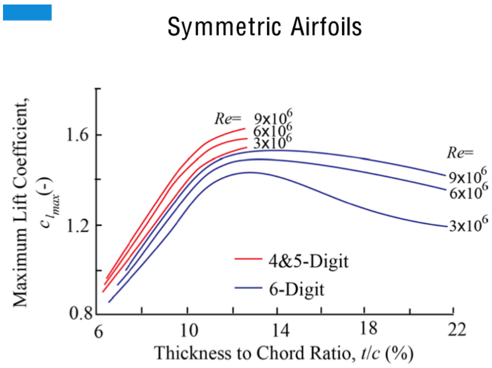


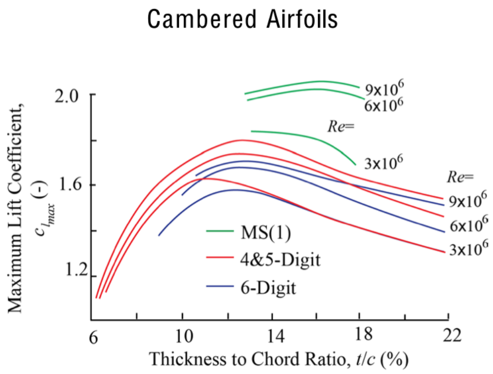
Qu1: Why can a strong upper-surface curvature induce trailing edge stall?

It causes a large adverse pressure gradient

Geometric Effects

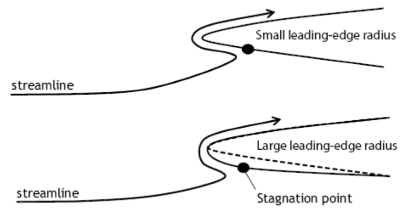
Camber and thickness vs Stall





Q41: a sharp leading edge

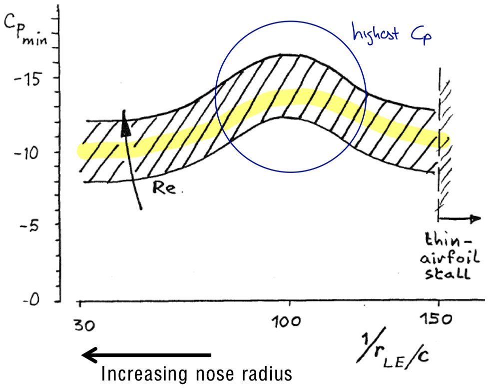
Hastens the onset of full-chord separation due to the high l.e. curvature and steep adverse pressure gradient



Leading Edge

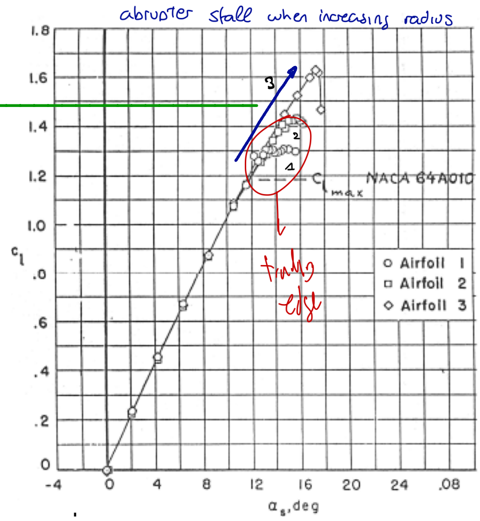
Decreasing the radius increases overspeeds, increases a.p.g and promotes l.e.-separation.

Increasing the nose radius first increases the Cp peak and then decreases it.

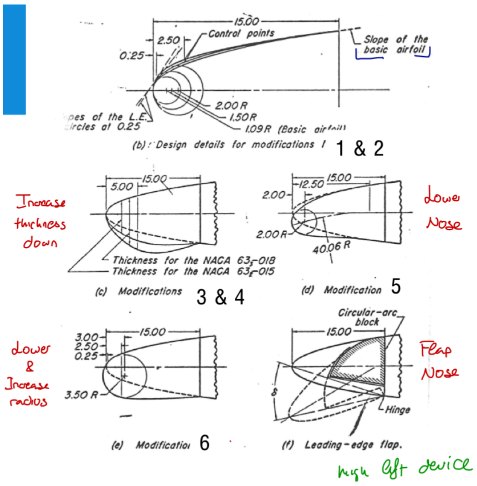


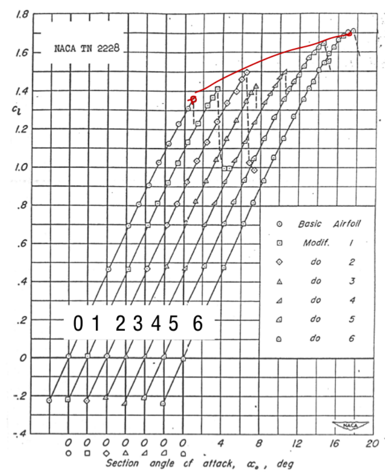
Cp at which stall occurs!

Increasing L.E camber and radius



If other l.e. parameters are modified



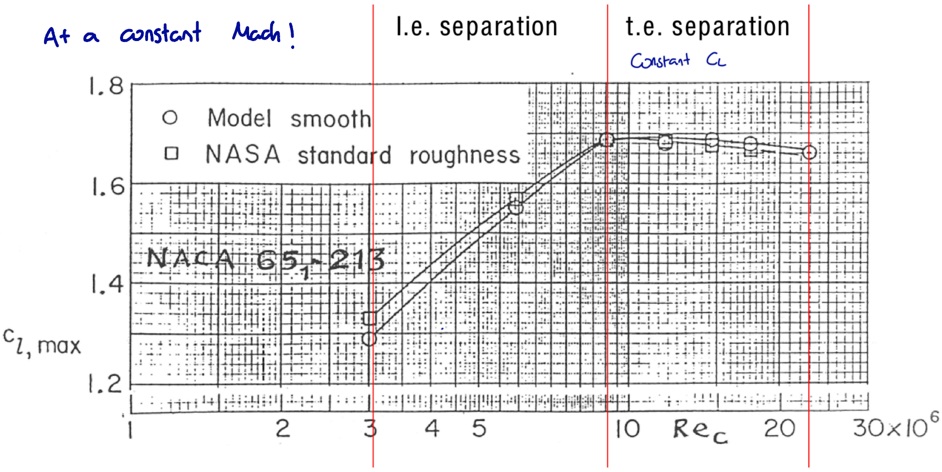


Reynolds & Mach Effects

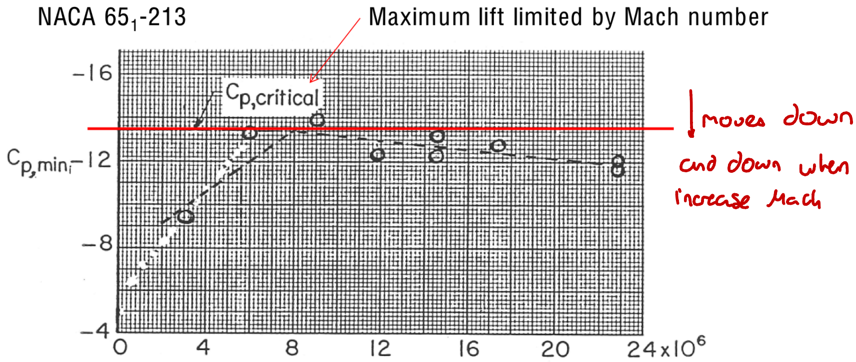
Q42: Increasing the Re

Increases the maximum C_L up to a maximum

At a constant Mach!



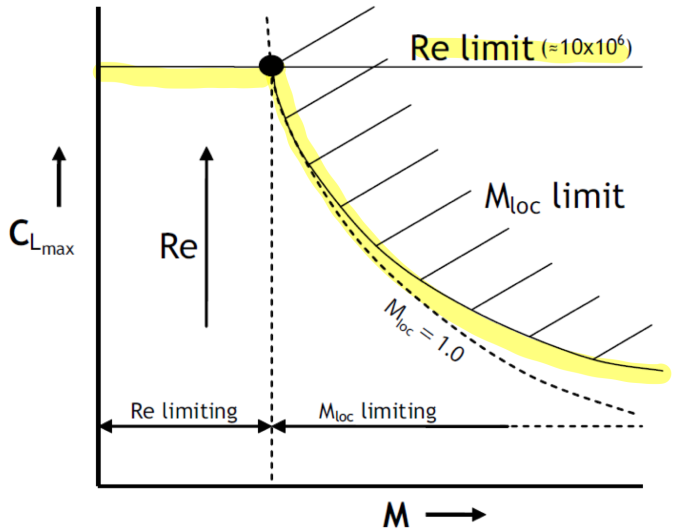
The maximum lift is limited by the mach number:



at constant mach!

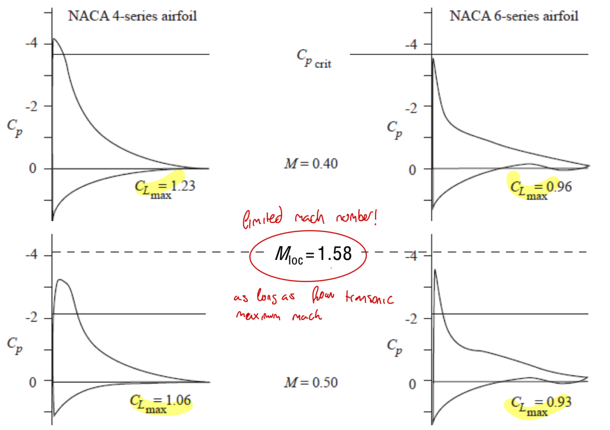
Re

C_L is first limited by Re at low numbers of M.
and limited later by M_{loc} at high numbers of M.



Re Effect on $C_{L_{max}}$

- ↑ Re decreases relative b-l thickness
- ↑ Re shifts transition forward
- ↑ Re reduces relative size of laminar sep. bubble
- Beyond certain Re, the transition happens before the formation of a bubble and b-l becomes turbulent
- Separation type might switch from leading edge to trailing edge
- ↑ Re_c increases tolerance to strong a.p.g. behind suction peak
- Airfoil can achieve higher angles of attack without L.E. stall
- Higher C_l can be achieved
- ↑ Re_c moves t.e. separation point upstream
- Result: lift coefficient decreases.

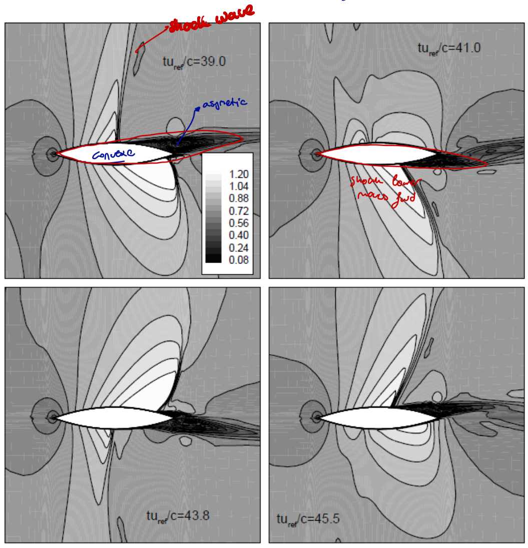


Buffet onset and Beyond

Buffeting is the airframe vibration by pressure fluctuations in separated flow. It has different forms

- Low speed buffet due to flow separation close to stall
- Buffet due to lift dumper or speed brake
- Buffet due to local flow separation
- Buffet due to separation caused by shock waves. ⟶

This happens because the effective airfoil varies after a shock wave which induces upper and bottom shocks.

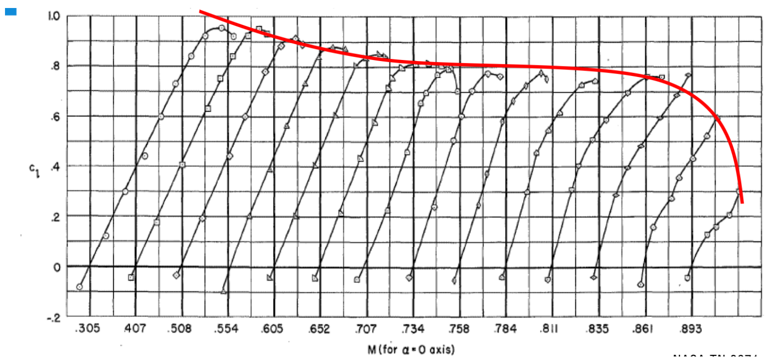


Predicting Buffet: pg. 53 Low-speed stall... Limits on $C_{l_{max}}$

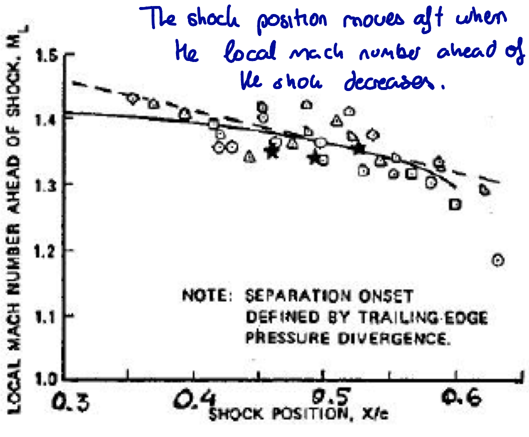
Different profiles arrive almost to the same C_p distribution in the L.E. Arrive to the same Mach number in front of shock at the buffet onset.

- Correlation based on local M.

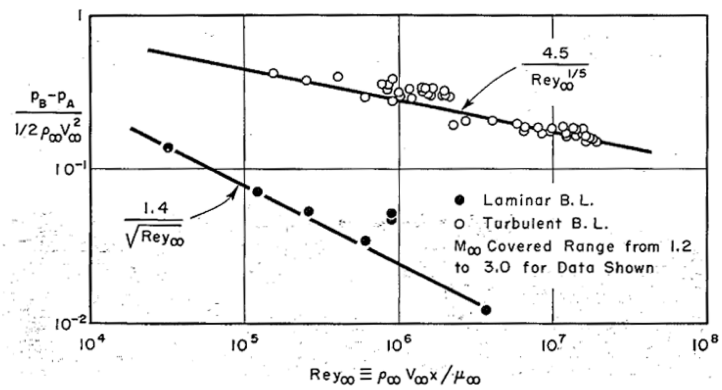
At buffet onset:



The shock position moves aft when the local mach number ahead of the shock decreases.



Decreasing the Re decreases C_p



Correlation to shape factor $H = \frac{\theta}{\delta^*}$

Buffet criterion:

- $H > 3.3$
- $y/b \geq 0.25$

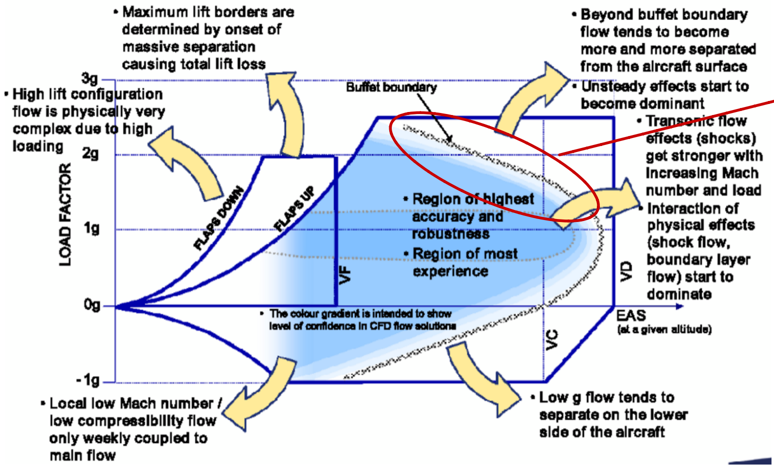
Influence of Buffet:

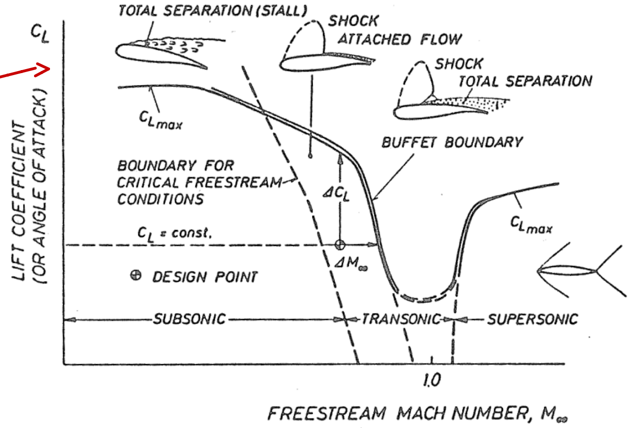
Determines maximum C_L @ a certain M

Determines maximum M @ certain C_L

Determines the aircraft ceiling @ certain M.

Buffet Envelope





Summary

Maximum lift coefficient affected by:

- Radius
- Thickness
- Camber
- Reynolds number
- Mach number

Radius, Thickness, Camber → geometric
Reynolds number, Mach number → Flow characteristics

geometric + Flow characteristics → Different types of stall

Airfoils With High Lift Devices

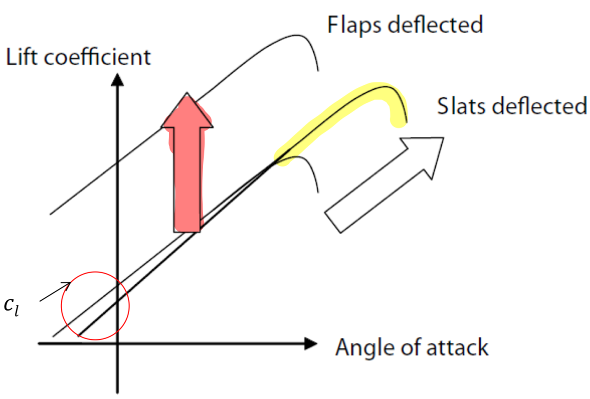
High Lift Devices

Q43: Why do we need high lift devices?

To have acceptable field performance

Reasons for high lift devices:

- Increases $C_{L\max}$ for landing with high drag penalty
  1. Reduces the stall speed of the aircraft
  2. Allows for shorter landing length
- Increases $C_{L\max}$ during take-off with high drag penalty
  1. Reduces the minimum unstick field
  2. Reduces the take-off field length
- Reduce pitch angle at low speeds



leading edge droop reduces c_l

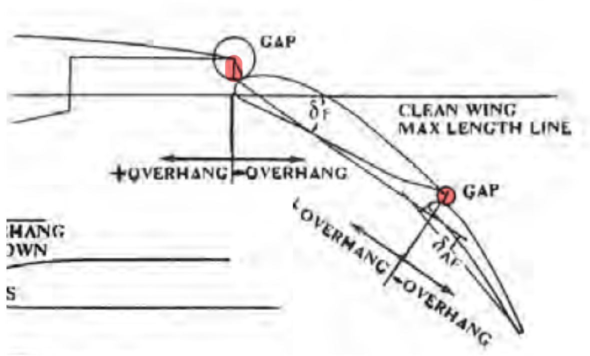
flat plate hinged!

Due to links in the "modified" airfoil, it is possible that sharp adverse pressure gradients happen!

To solve the hinged flat plate problem: we introduce slots. Which are spaces between the airfoil and the high lift device. This:

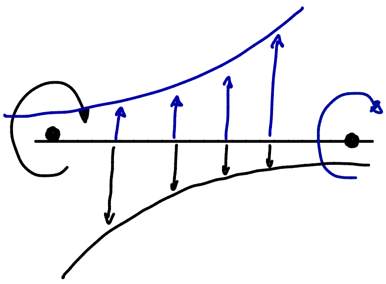
- Suppresses the suction peaks through mutual interference
- Creates new boundary layer on each component, postponing stall
- Generates additional drag

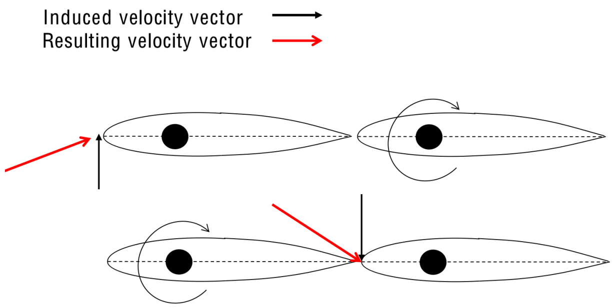
Definitions:



Mutual Interference

Assume that each lifting airfoil can be represented by a vortex.





As a result, for the front airfoil:

Higher suction peak

Higher supervelocities on upper side

Lower supervelocities on lower side

As a result for the back airfoil

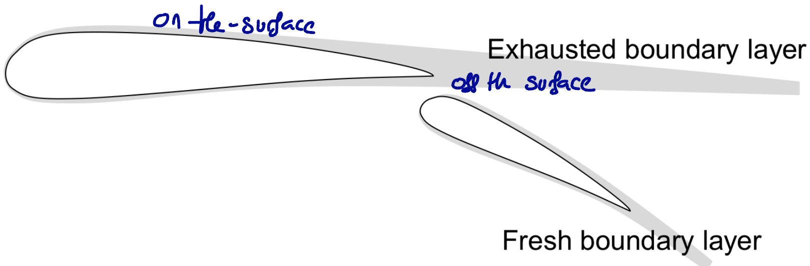
Lower suction peak

Lower supervelocities on upper side

Higher supervelocities on lower side

With mutual interference we arrive to a smoother pressure change between components and a smoother velocity change.

Boundary Layer and Wake



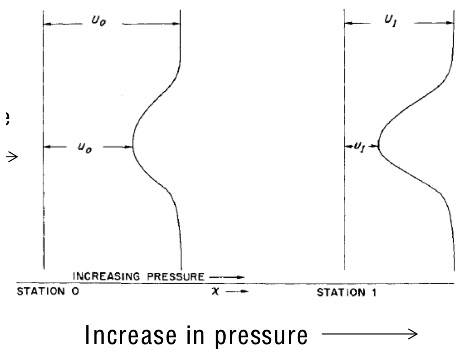
Q44: Why does a fresh b-l postpone separation?

It is thinner, so it can withstand a higher adverse pressure gradient

Wake develops with every element.

- It grows with an adverse gradient
- It smoothens with an increase in viscosity.

$$\left.\right\} \frac{1}{1-C_p}\cdot\frac{dC_p}{dx} > \frac{0.007}{\delta^*}$$



Unmerged boundary layer flows off element:

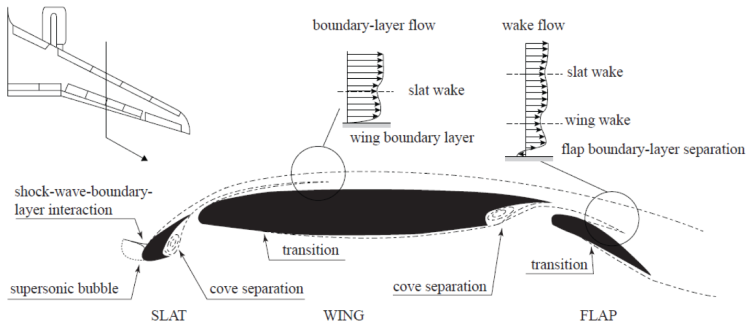
On-the-surface pressure recovery (normal) +

Off-the-surface pressure recovery (deceleration of wake not in contact with body)

Merged (confluent) boundary layers: → good to have spaces between.

Should be avoided due to early separation.

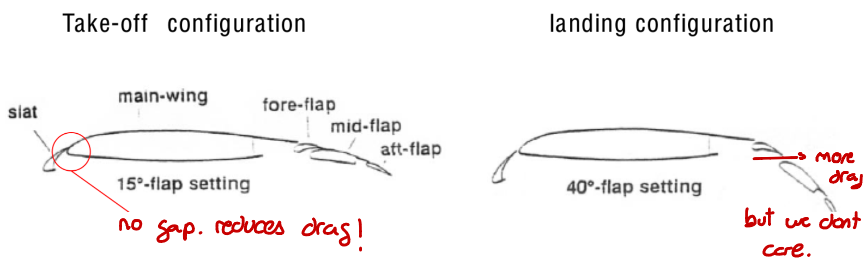
Example:



To arrive to the optimal design:

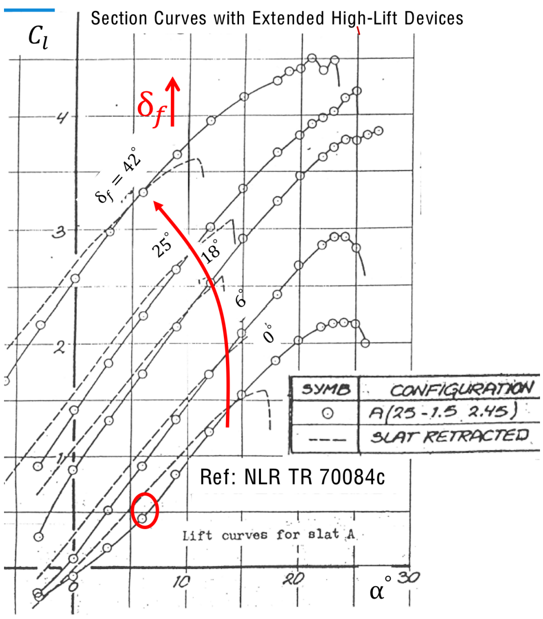
Appropriate gap/overlap between elements. Increases stability and reduces no 'confluent' boundary layers.

Gap increases drag: thus depending for t-o or landing different configurations are possible.

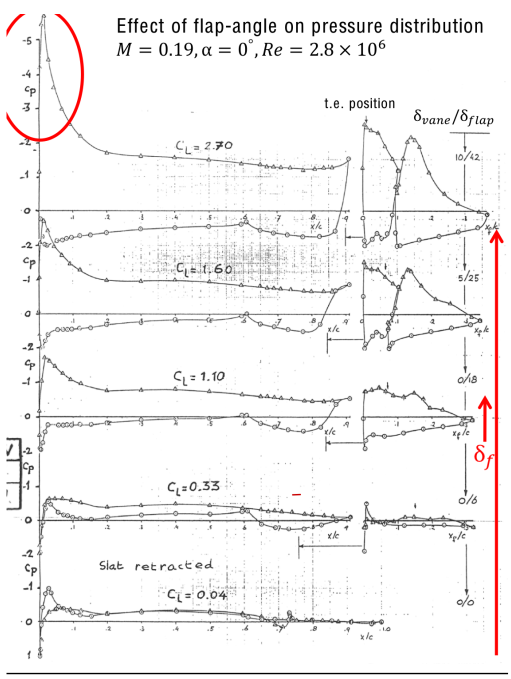


Design for Stall Characteristics

The most effective is when separation is reached at the same time on all components.



In the Cp plot:



Increases the suction peak on the Cp. And increases the overall Cp distribution of the airfoil.

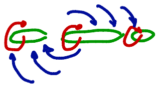
Slope of suction peak stays the same.

Q45: Where does stall originate?

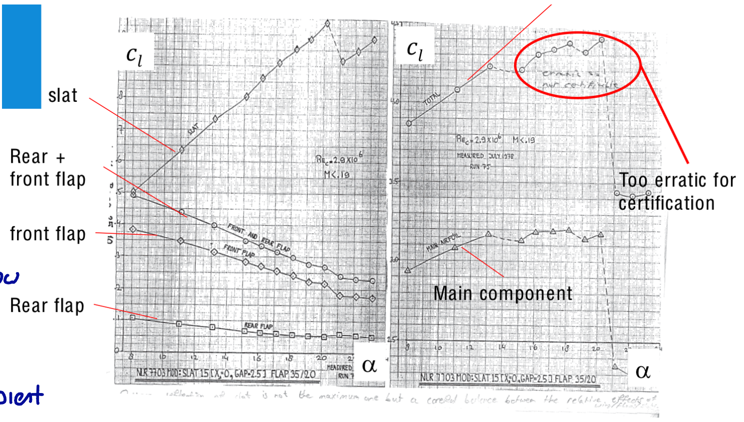
Near the leading edge of the main component

Q46: With increasing α ...

The lift coefficient on the slat increases while the lift coefficient on the flap decreases

Due to circulation  Can be observed on next page

The effect of Mach and Reynolds



High Re allows for high $C_{p_{min}}$ (−) values

High $C_{p_{min}}$ implies high supervelocities over L.E

If high take-off and landing speeds, leads to supersonic flow

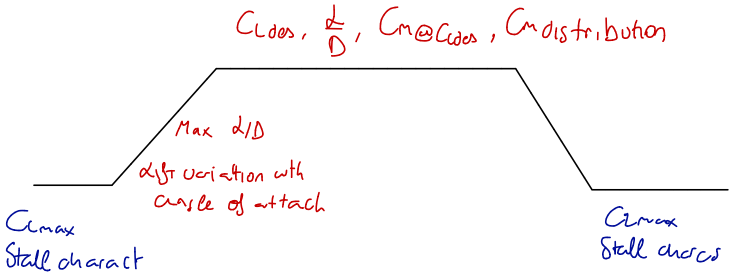
As a general rule $M_{local} < 1.58$, limits $C_{L_{max}}$

Minimum air pressure may then be less than 30% ambient

This result can be properly translated to 3D.

Swept Wing Concept

Wing Design Requirements



- At cruise Mach and cruise altitude
  - Design lift coefficient at top of climb.
  - Lift-to-drag ratio at design lift coefficient.
  - Pitching moment coefficient at design lift coefficient.
  - Pitching moment distribution with span (to limit structural warping)
- At low-speed conditions:
  - $C_{L_{max}}$ for all aircraft configuration (clean, take-off, landing)
  - Stalling characteristics for all aircraft configurations over the complete cg. range (pitch and roll)
  - Maximum lift-to-drag ratio (to meet climb requirement, AEO_L, OEI_{TO})
  - Lift curve slope and maximum angle of attack in ground effect (for rotation req.)
- Stability & Control (everywhere in flight)

WING + FUSELAGE
  - Pitching moment due to angle-of-attack negative
  - Rolling moment due to sideslip negative
  - Rolling moment due to aileron deflection / spoiler deflection. balance btw stability & controlability

  } Stable
- Around the boundaries of cruise flight conditions:

AIRPLANE
  - Margin (ΔC_L and ΔM) between design point and buffet onset boundary
  - Acceptable stability and control (pitch and roll) between buffet onset and maximum buffet penetration boundary (ΔC_L and ΔM)
  - Acceptable stability and control between M_{MO} and M_D

- Structural and Volume Constraints
  - Wing weight
  - Landing gear volume
  - Lighting strike protection
  - Fixation points engines
  - Tank volume
  - Space for systems: kinematics systems for wing movables, anti-icing systems, fuel system, hydraulic system, electric system.

WING:

Prime characteristics of wing design are:

1. Aerodynamic: M_{design} and $C_{L\,design}$ Not from scratch, Given.
2. Geometric: Aspect Ratio (A), taper ratio (λ), twist distribution (θ), sweep (Λ) and airfoil selection in outward wing.

Q47: Given an elliptical lift distribution and identical wing loadings, why is a tapered wing preferred over a straight wing?

It has a lower weight

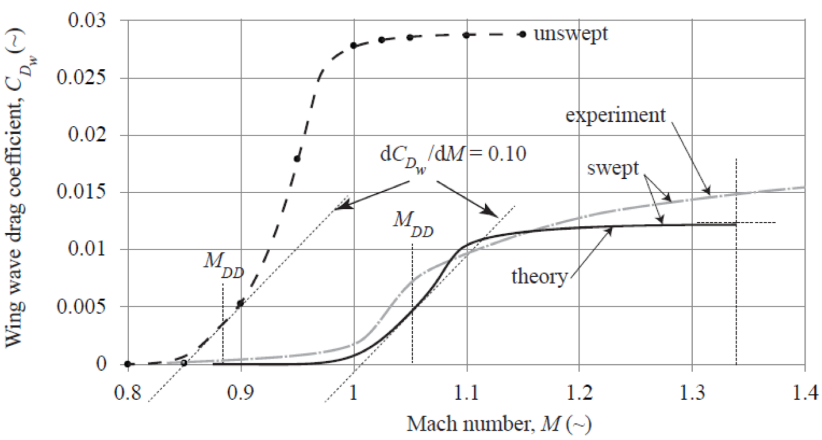
Q48: Given an elliptical lift distribution and a tapered wing, where do you expect the highest section lift coefficient?

Around 65 % of semispan.

HISTORICAL BACKGROUND

Q49: Why do high-subsonic airplanes have swept wings?

To increase the M_{DD} for a given lift coefficient.



Sweep:

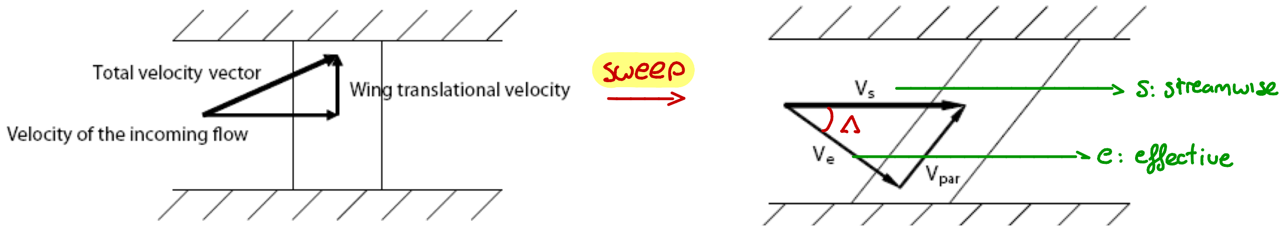
Shifts center of pressure

Shifts control surfaces aft

Shifts a.c. aft

Wings in history where limiting the maximum Mach!

Simple Sweep Theory

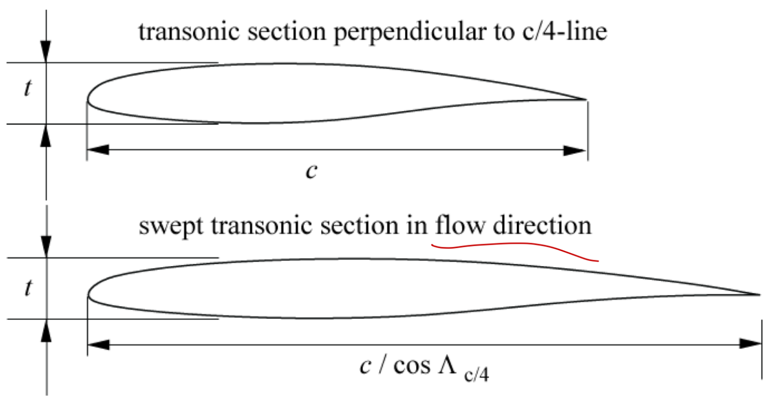


Calculate:

1. C_{ps} as a function of V_s $\longrightarrow$ $C_{ps} = -2 \cdot \frac{\Delta V_s}{V_s} = -2 \cdot \frac{\Delta V_e \cos\Lambda}{V_e/\cos\Lambda} = -2 \cdot \frac{\Delta V_e}{V_e} \cos^2\Lambda$
2. C_{pe} as a function of V_e $\longrightarrow$ $C_{p_e} = \frac{-2\Delta V_e}{V_e}$
3. C_{pe} as a function of C_{ps} and Λ $\xrightarrow{C_{ps}}$ $= C_{pe} \cdot \cos^2\Lambda$

FORMULAS: $\boxed{C_{pe} = \frac{C_{ps}}{\cos^2\Lambda}}$ $\boxed{C_{le} = \frac{C_{ls}}{\cos^2\Lambda}}$ $\boxed{\alpha_e = \frac{\alpha_s}{\cos\Lambda}}$ $\boxed{\left(\frac{z}{c}\right)_e = \left(\frac{z}{c}\right)_s / \cos\Lambda}$

effective curvature

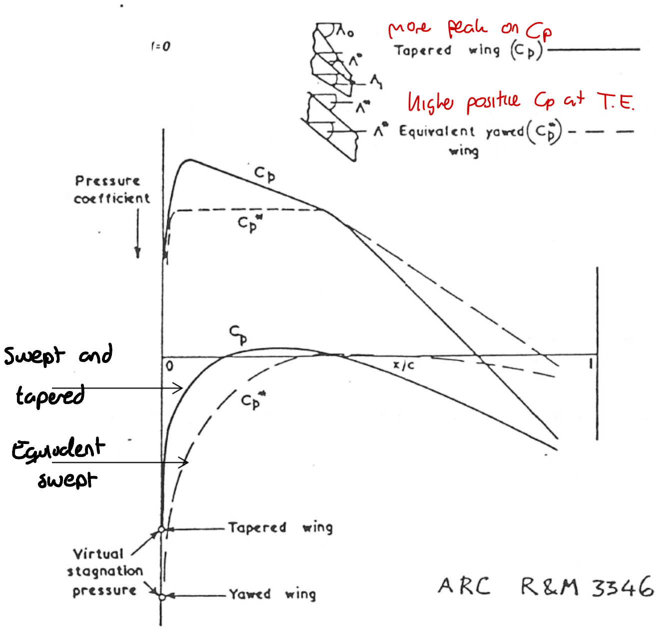


The effective curvature decreases
→ Causes lower overspeeds
→ Strong shock wave occur at higher M.
→ M_{DD} increased

If there is taper and sweep, account for $\boxed{\Lambda_{c/4}}$
Sweep quarter chord

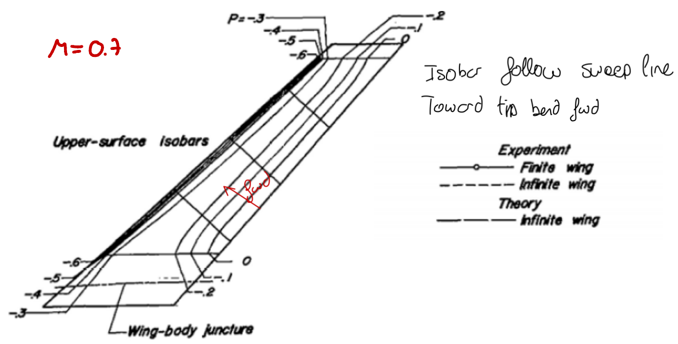
Effect of Taper

For high sweep and taper, Cp distribution can differ significantly



Flow over wing due to Sweep.

- Reasonable behaviour, but isobars start to curve rearward near root and forward near tip.
- Good correlation between theory and experiment.



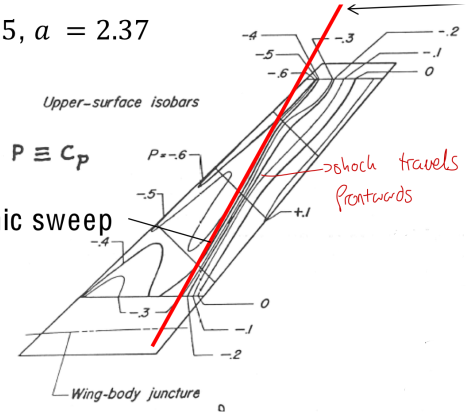
When mach increases: the effect becomes stronger, but the prediction is bad.

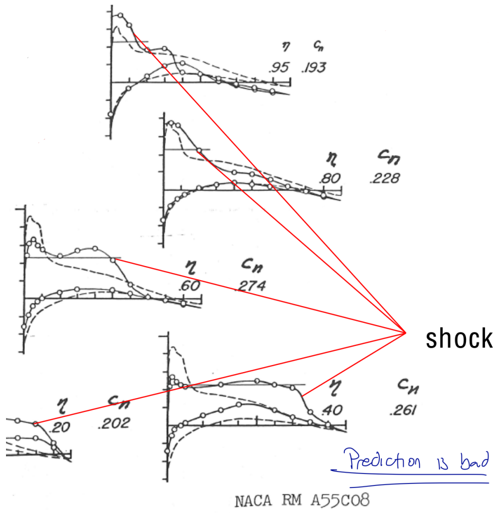
M= 0.95

$M = 0.95,\ a = 2.37$

$P \equiv C_p$

Aerodynamic sweep





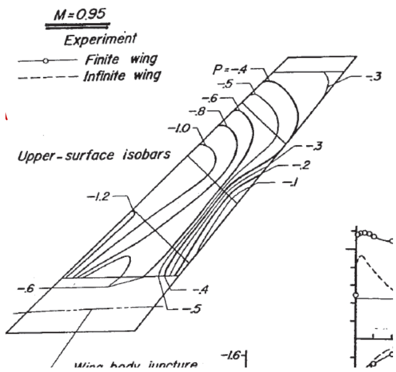
keep increasing Mach: we have shock induced separation

Strong shock near t.e.

Separation

Curved isobars

Bad prediction



Observations:

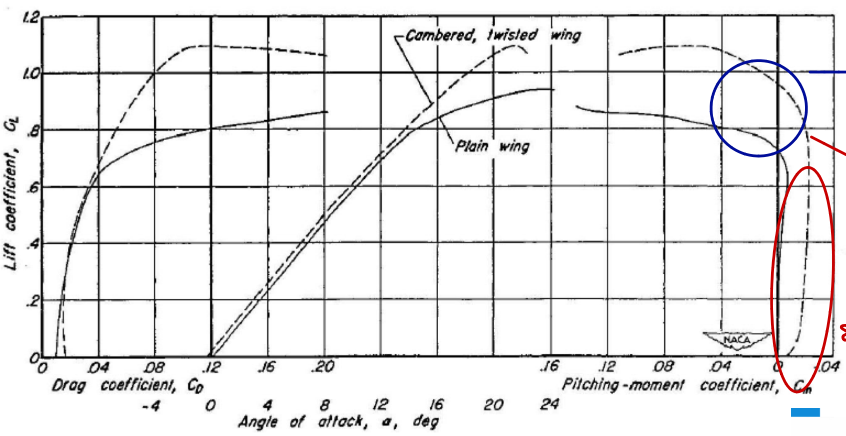
- Near root, Cp deviates increasingly from the prediction accordingly to simple sweep theory.
- The increasing supervelocities over the aft part of the wing root region may lead to the formation of shock waves and flow separation.
- These may then spread further outboard and lead to sharp drag rise much earlier than would be expected from simple sweep theory.
- At M=0.95, sweep theory looses meaning.

Effects of Wing Sweep at Low Speed

Lowers maximum section lift coefficient of outboard wing/tip

→ Wing $C_{L max}$ is reduced

→ Effective high-lift devices are required for landing and take-off.

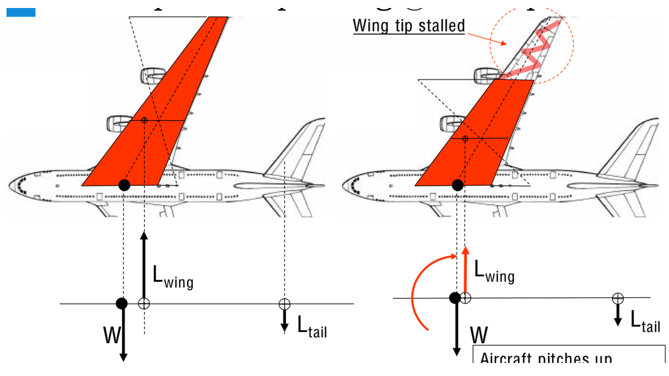


change in Cm happens because of tip stall.

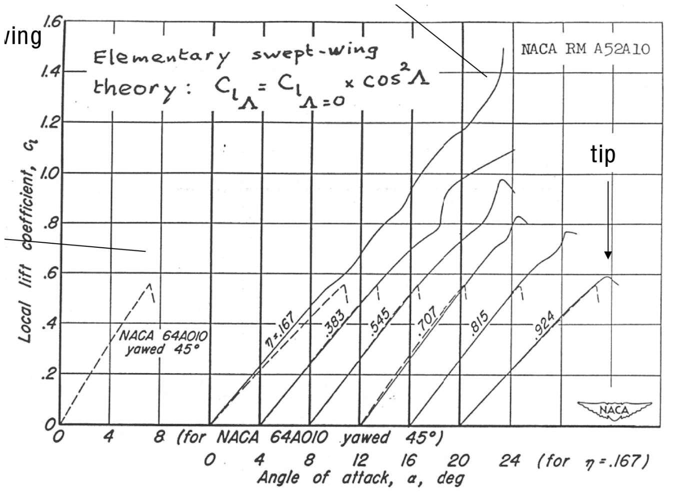
suddenly pitch up.

slightly nose down

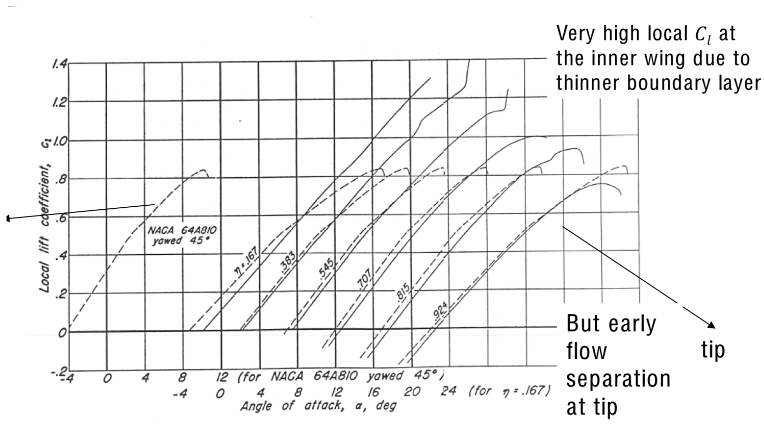
Wing tip stalled: why does Cm move so much?



Symmetrical

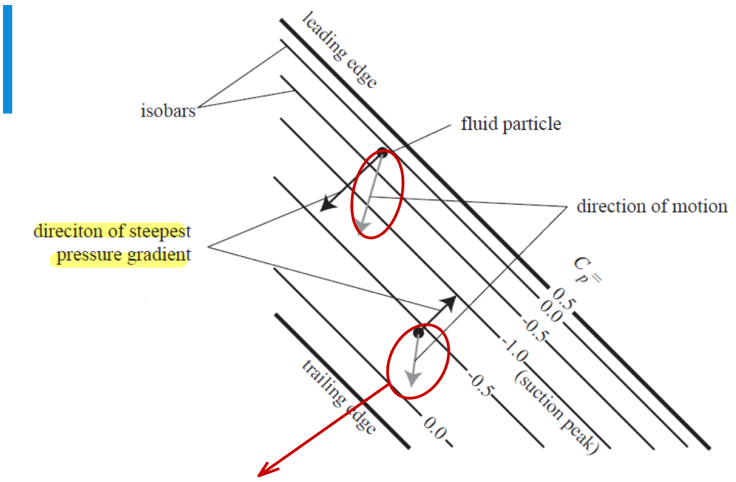


Cambered



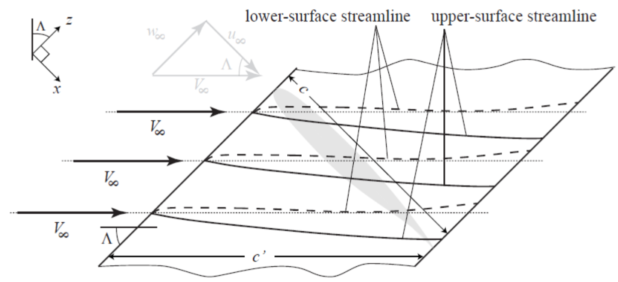
How does Sweep Influence the Flow

Cross-Flow

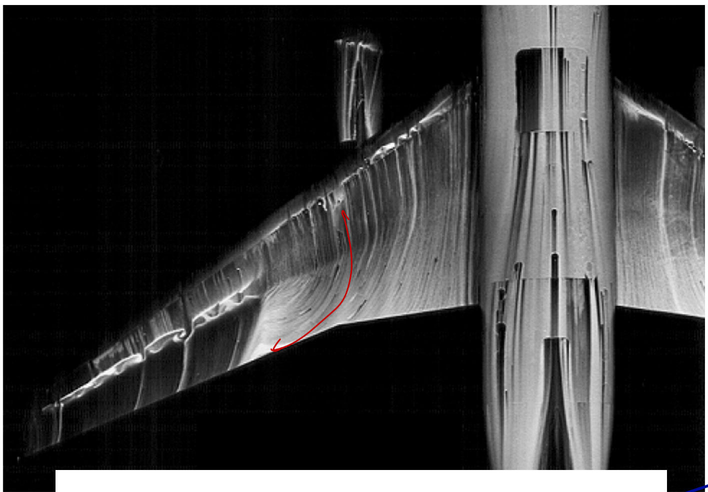


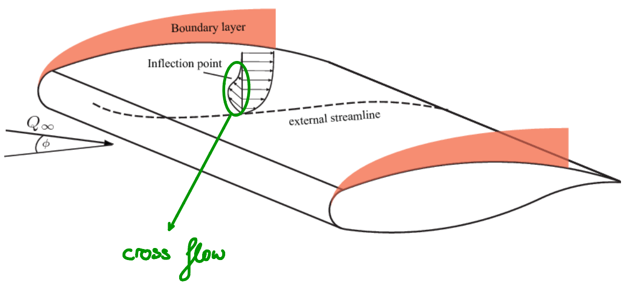
Cp gradients are a good way to represent the flow over the wing.

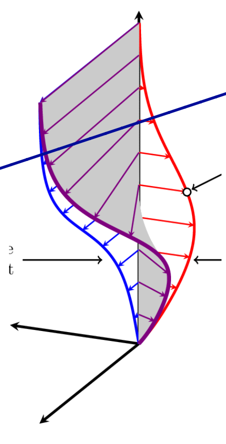
In a sheered wing the flow does not follow the original airfoil but they curve a bit



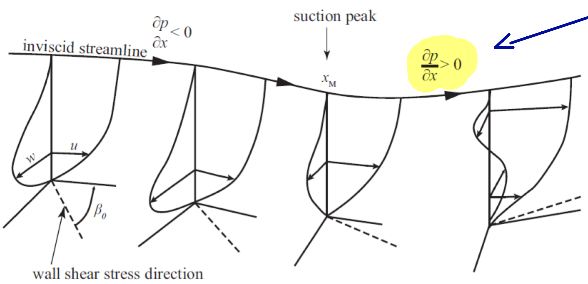
This generates boundary layer cross flow, as observed in the next picture.







Negative pressure gradient promotes cross flow



Boundary Layer Cross Flow

The boundary layer thickens more and more towards the tip. This is due to flow over a plate thickens. Same as with normal airfoils.

Observations:

- B-L cross flow leads to higher C_{Lmax} on inner wing sections
- But this can not be feasible many times due to the stalling behaviour of the tip. Thus α can not be increased that much.
- Tip stall leads to pitch-up (on aft swept wings) and probability of wing drop.
- Sweepback will lead to a decrease in the usable C_{Lmax} compared to an equivalent straight wing

Summary

- Adding wing sweep is effective in increasing the drag-divergence Mach number (M_{DD})
- Adding wing sweep effects pressure distribution, lift coefficient and pitching moment coefficient.
- Simple sweep theory has limited applicability as a predictive means for M_{DD}
- Wing sweep results in a lower (effective) wing maximum lift coefficient due to tip stall and an unstable pitch-up
- Swept wings cause cross flow inside and outside the boundary layer
- Boundary-layer cross flow causes crossflow instabilities resulting in early transition

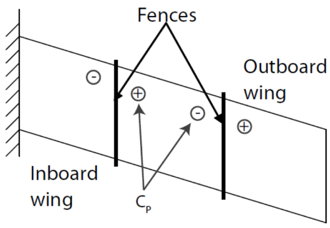
Tip Stall and Aeroelastic Effects

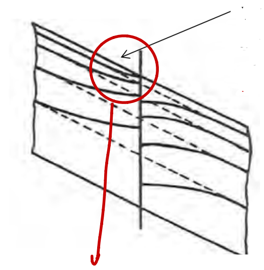
Q50: Why do swept wings sometimes have fences?

To prevent tip stall locally renewing the b-l.

These fences are installed experimentally.

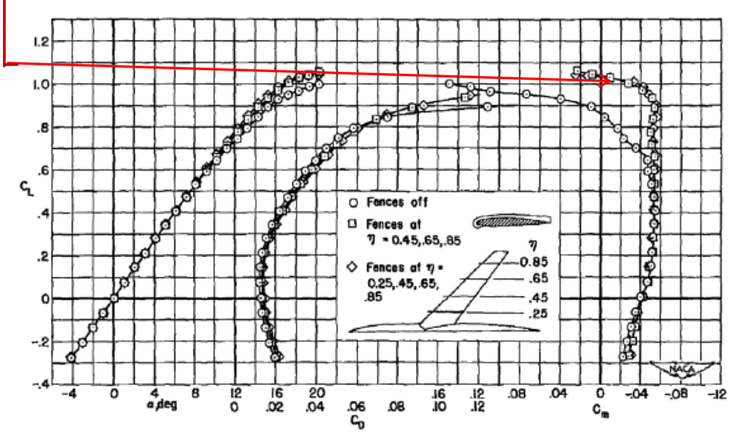
Effect of Fence on Flow





high supervelocities here might lead to separation

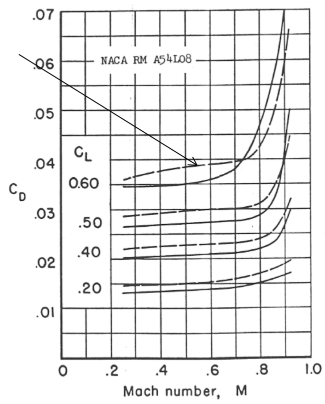
Prevent tip stall which improves the moment coefficient characteristics



If a fence is installed, the drag in cruise is increased.

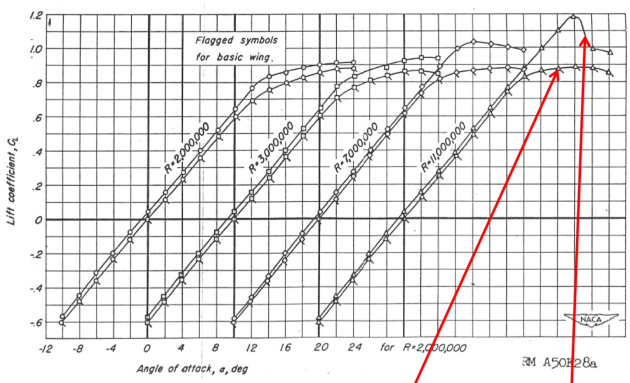
At certain C_L it increases M_{DD}.

Fences should be applied as an aerodynamic fix not as a design.



Pilons and Shark teeth wings and vortilons can also be used as fences.

Other ways:
- Chord increase in inner wing.
- Increase the L.E. radius without modifying the upper surface curvature.



Tip stall spreading slowly: bad for certification

Clean stall over large part of wing

Recap: effects of wing sweep.

- Increases drag divergence Mach number
- Reduces maximum lift coefficient
- Reduces lift-curve slope
- Shifts aerodynamic center and center of pressure aft

Result:

- Fancy high-lift devices required to increase maximum lift coefficient
- Geometrical modifications to prevent tip stall required

First Generation of Swept Wings

The problem was that swept wings were designed as if they were straight wings.

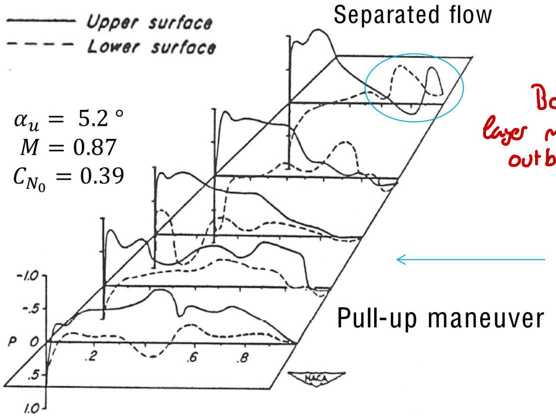
- Root and tip sections were selected.
- + aspect ratio
- + taper ratio
- wing shape determined by interpolation tip and root sections

Results:

Bad stall characteristics

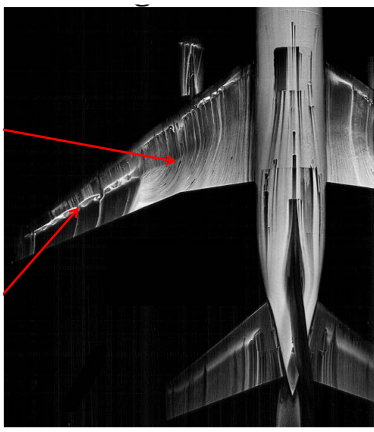
Pitch up tendencies at high and low speeds.

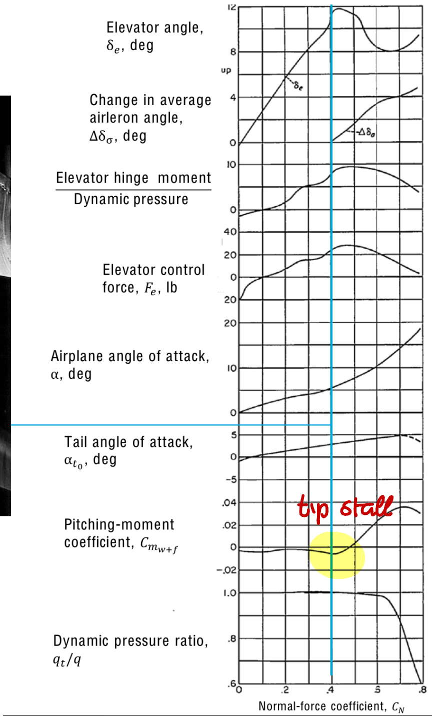
Aerodynamic sweep lower than geometric sweep.



Boundary layer moves outboard

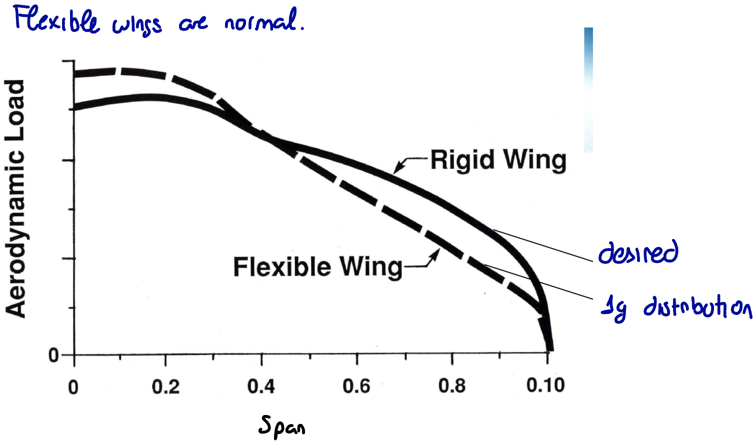
Shock induced separation



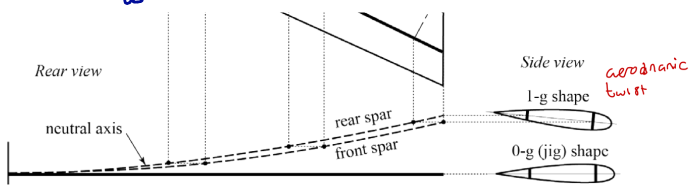


Aeroelastic Effects of Wing Sweep

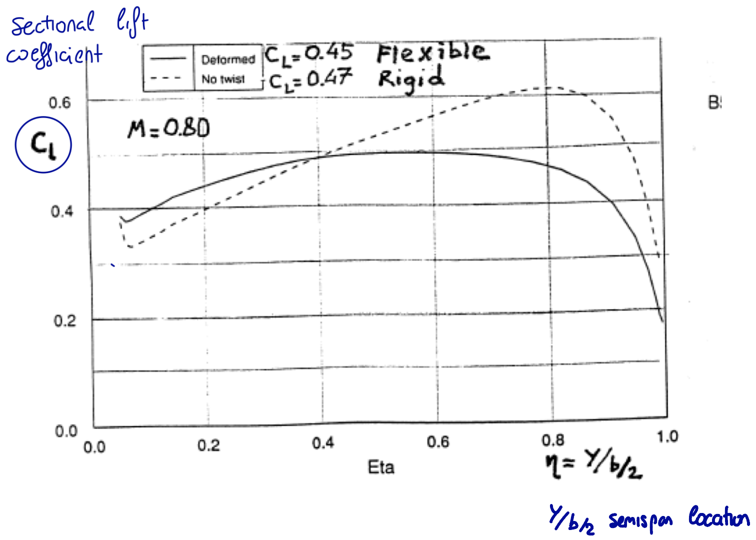
On a flexible wing the load differs from that of a rigid wing.
Flexible wings are normal.



When a wing with sweep deflects it does not only bend upwards but it also rotates, decreasing the effective α.



The aerodynamic twist produces the following C_L distribution.



QS1: How does wing bending affect the stability of a swept-wing aircraft?

Neutral point shifts forward wich decreases the static margin.

Forward Sweep

QS2: Why do you think the Germans used forward sweep on the Ju-287 bomber?

To have acceptable stall characteristics at take-off and landing speeds.

It was believed that forward sweep increased wing weight, but this is not necessarily true.

Forward Sweep

Advantages:

- Not prone to tip stall
  - No asymmetric wing drop
  - Aileron control up to high AoA
- Higher sweep angle of shock wave for given $\Lambda_{c/4}$
  - Either less geometric sweep is desired for the same shock sweep
  - Or for the same geometric sweep there is less wave drag
- Possibility of NLF:
  - Reduction of leading-edge sweep → attachment line instability reduced

Disadvantages:

- Highly swept trailing edge: reduces effectiveness of high-lift devices
- Could reduce divergence speed (or have a heavier wing)
- Reduced stability in Dutch roll mode
- Root stall can cause rapid loss in lift (abrupt stall) and pitch-up

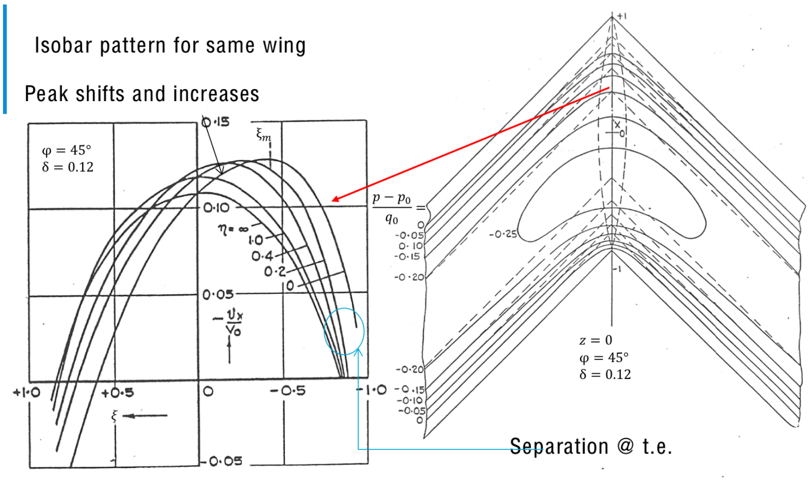
Note: To postpone root stall, a close coupled canard can be used to decrease the effective angle of attack near the root

Summary

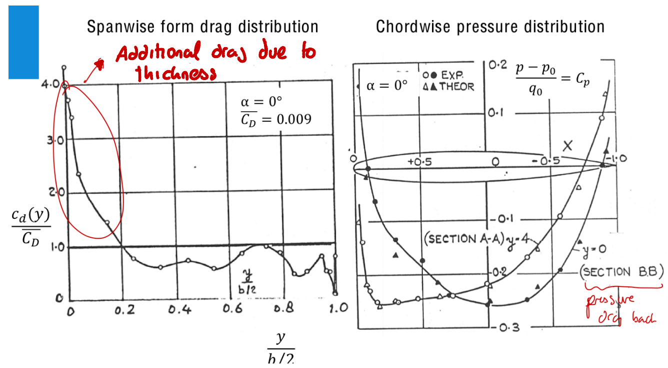
- Boundary-layer cross flow makes outboard wing and wing tip stall sensitive
- Stall over the outboard wing creates an unstable pitch break (i.e. an increase in nose-up pitching moment with angle-of attack)
- To prevent boundary-layer crossflow one can install fences, leading-edge snags, vortilons or modify the airfoil profile
- Due to aerodynamic twisting of the wing, the 1-g lift and pressure distribution is changed compared to the wing in jig-shape
- Wing flexibility reduces the change in lift due to angle-of-attack
- Forward-swept wings benefit from a stall-resistant outboard wing and increased lift-curve slope due to wing aeroelastic effects
- To mitigate an undesirably low divergence speed at acceptable wing weight, forward-swept wings need tailored structures to offset the interaction between wing bending and aerodynamic twist.

Root and Tip Effects

▸ Root design of swept wings



Root effects on swept wings

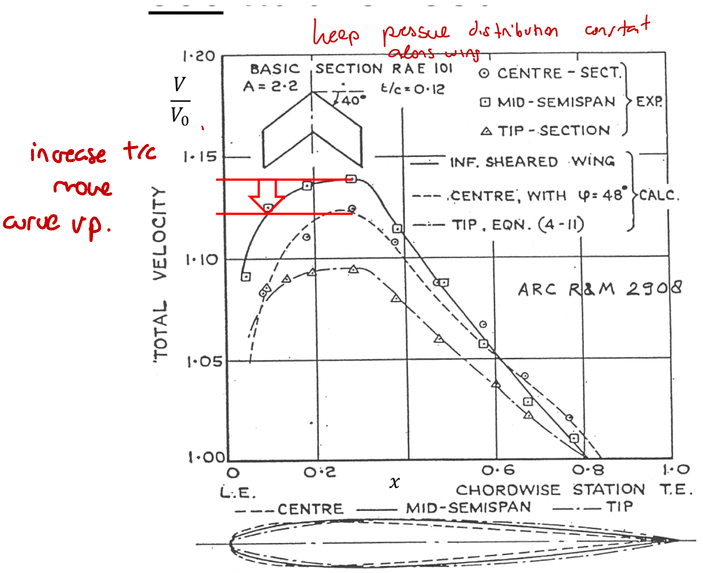


We have to improve the velocity distribution due to thickness at the root.

2D solution for the 3D distribution:

- Forward part of root section must be thickened
- The rear part must be made thinner.

} More parallel isobars up to the root
less form drag
less steep pressure gradient near t.e.



keep similar shape and same height.

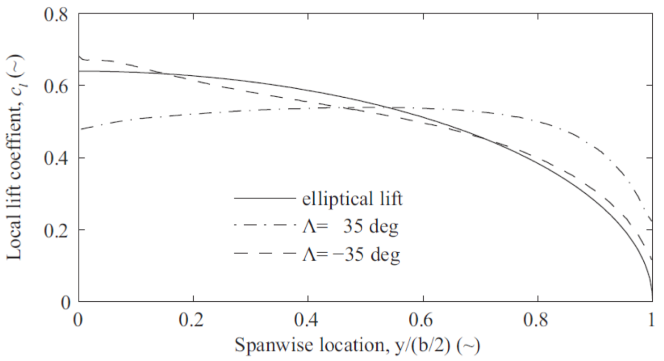
Conclusion:

- Thickest point should move forward
- Overall thickness should be increased

Supervelocities due to lift.

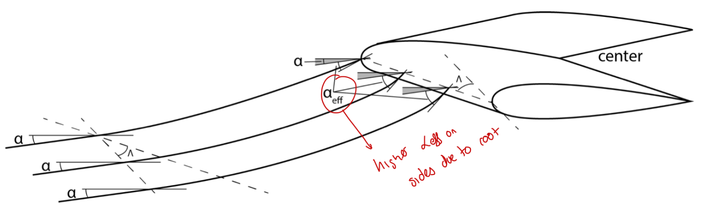
Lift-curve slope is smaller near the root

For a given α, lift is lost near root.



QS3: Why do we loose lift near the root of an untapered symmetric swept wing?

The "loss" in lift is a result of the higher outboard effective α.



Observations:

Lift ads velocity distribution to thickness-induced velocity distribution.

Sweep concentrates lift near trailing edge.

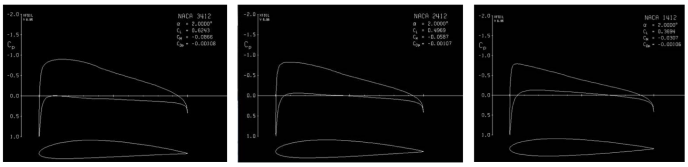
Solution

Reduce camber at root profile to shift pressure peak more forward → this reduces lift

Increase root incidence to increase lift coefficient to match desired Cp distribution.

Reducing camber →

	3%	2%	1%

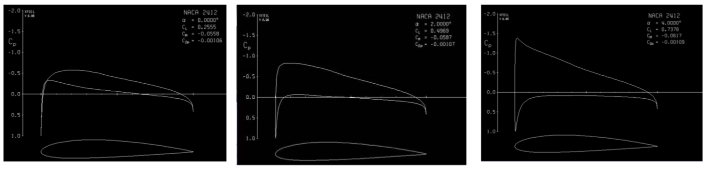


$\left(\frac{x}{c}\right)_{C_{p,min}}$	16%	10%	5%
c_l	0.62	0.50	0.37

Suction peak more forward, lift coefficient decreased

Increasing AoA →

	0	2	4



$\left(\frac{x}{c}\right)_{C_{p,min}}$	20%	10%	3%
c_l	0.26	0.50	0.74

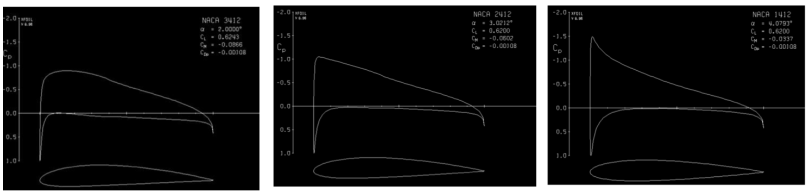
Suction peak more forward, lift coefficient increased

Find optimal to keep C_l

but decrease camber and increase α → or incidence angle

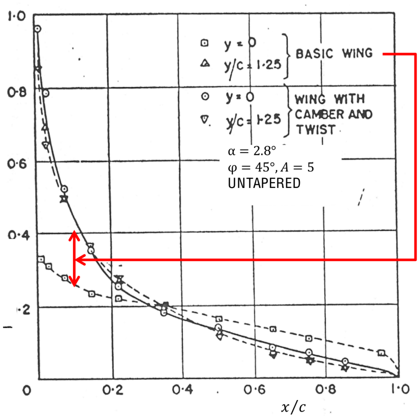
Reducing camber, constant lift coefficient →

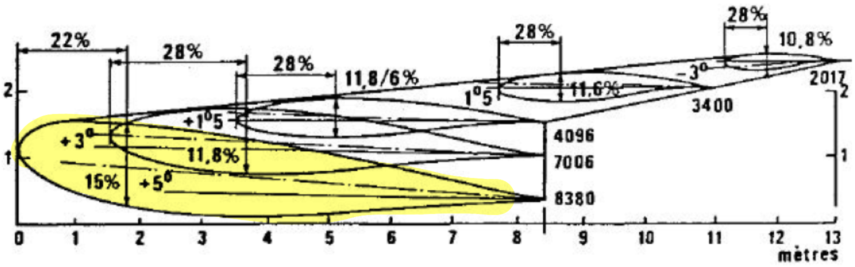
	3%	2%	1%



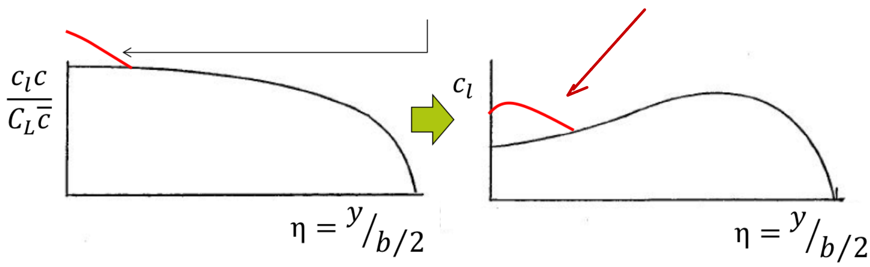
$\left(\frac{x}{c}\right)_{C_{p,min}}$	16%	4%	2%
α	2.0	3.0	4.0

Incidence angle increased, suction peak more forward





Too much lift on the root can happen, to reduce it



Increase the root section thickness via the lower airfoil contour.

good for wing weight, tank volume

Minimizing Root Effects

- Difficult to design a wing with straight isobars between fuselage and tip
  design objective high subsonic wings
  - Geometric sweep affects isobaric pattern
  - Thickness affects isobaric pattern
  - Circulation distribution affects isobaric pattern
    lift distribution
- Near the root various design changes should be made: 4 modifications
  - Increase in thickness
  - Thickest point moves forward
  - Increase in incidence angle
  - Decrease in camber (or even negative camber)

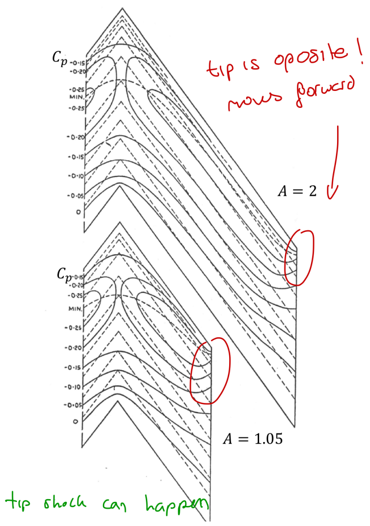
Fuselage:

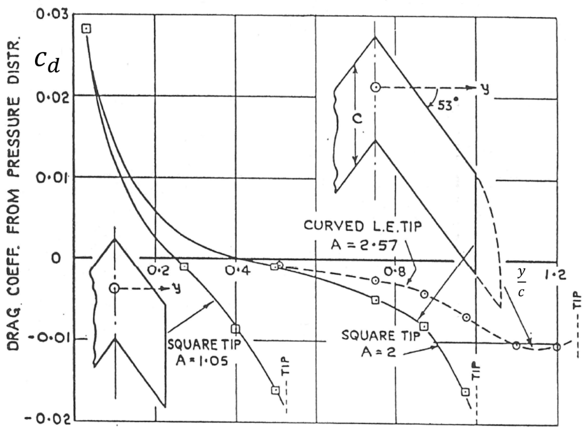
The fuselage has limited effects on the isobaric pattern.

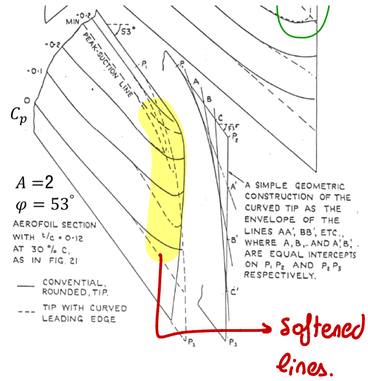
Tip Design of Swept Wings

QS4: Why do we often see Kuechemann tips on high subsonic airplanes?

To align isobars and reduce wave drag.







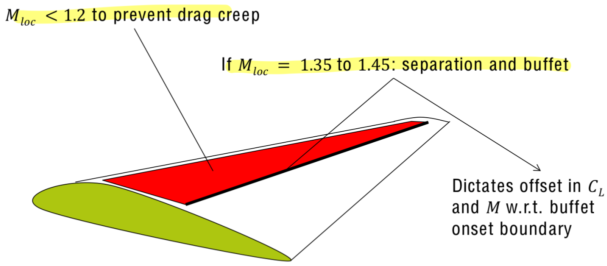
Design Method for Swept Wings

Refine aerodynamic design using the given parameters S, A, Λ, λ

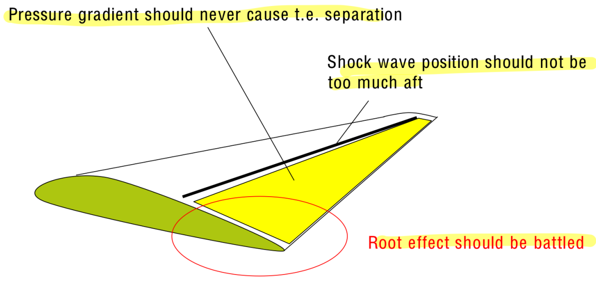
Have a good low and high speed performance.

Mod. no	Modification	Reason
1	Increase the thickness of the forward part of the root section. Decrease the thickness of the rear part of the root section.	To obtain similar chordwise upper-surface velocity distributions due to thickness along the span.
2	Increase the thickness-chord ratio of the root section.	To obtain identical chordwise upper-surface velocity distributions due to thickness along the span.
3	Decrease the positive camber or apply negative camber on the root section.	To adapt the pattern of the chordwise upper-surface velocity distribution due to lift to that of the basic airfoil section.
4	Increase the incidence of the root section.	To obtain identical chordwise upper-surface velocity distributions along the span.
These four modifications together should lead to straight swept isobars over most of the wing upper surface in the design condition.		
5	Modify the wing lower surface along the span (mostly on the inner wing).	To obtain the desired spanwise distribution of the local lift coefficient.
6	Modify the lower surface velocity distribution on the root section regarding front and rear loading.	To minimise the wing pitching moment.
7	Modify the leading-edge region on the outer wing	To obtain satisfactory stalling characteristics

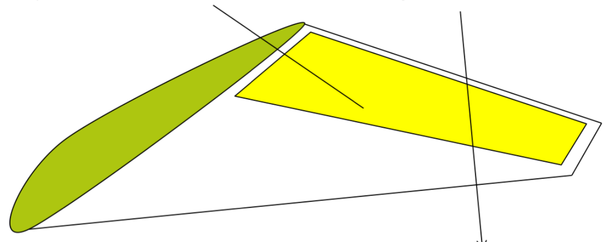
Prevent drag creep and separation

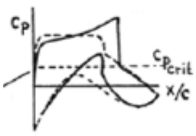


Prevent T.E. separation



Pressure gradient should never cause t.e. separation

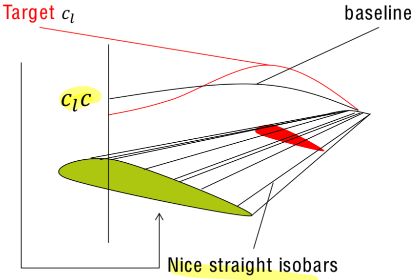




Limits maximum amount of aft loading

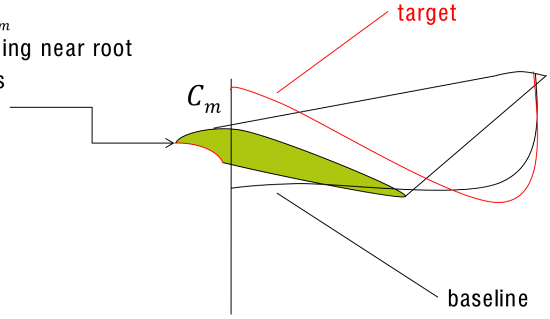
Objective Cl distribution

- Modify bottom side of wing to get target lift distribution
- Start with airfoil at
- 60 – 70% span: highest c_l



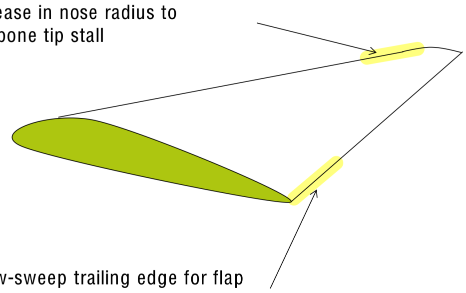
Objective Cm distribution

- High aft loading outboard results in highly negative C_m
- Increased front loading near root can compensate this



Reduce tip stall

Increase in nose radius to postpone tip stall

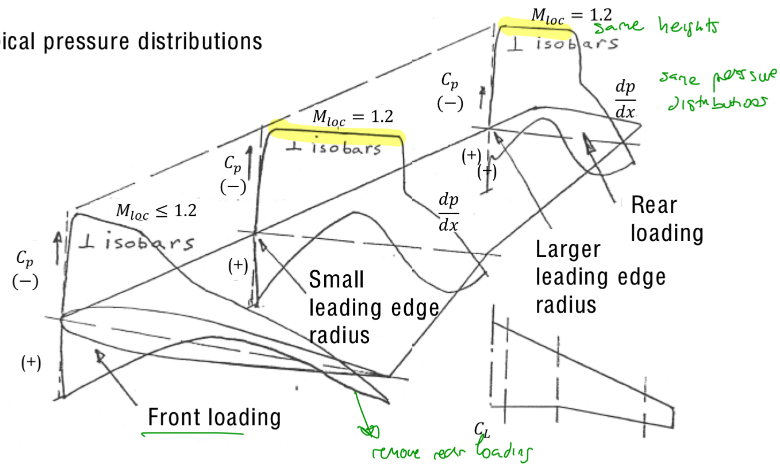


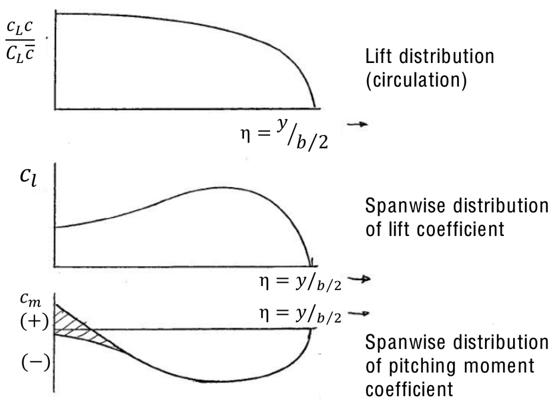
Low-sweep trailing edge for flap effectiveness

Improve flap effectiveness

Design Objectives

Typical pressure distributions





Final Remarks on Swept Wings

- For more modern swept wings the starting point is a supercritical airfoil section with transonic flow in the design condition.
- Using CFD, many iterations, including engines and pylons increases it.

Winglets

End plates:

Increase lift curve slope
Decrease induced drag

Demonstrations:

T-tails
Horizontal tails with two fins on either end.

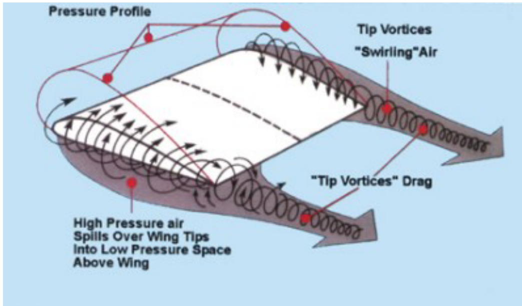
Winglets:

Less induced drag
More friction drag

Winglets

Aerodynamics about the tip with no winglet:

- Tip vortex is created due to pressure difference on top and bottom.
- Induced angle of attack is produced, causing induced drag.



CLASIC WINGLET DESIGN: S8 Root and Tip effects

QSS: Winglets

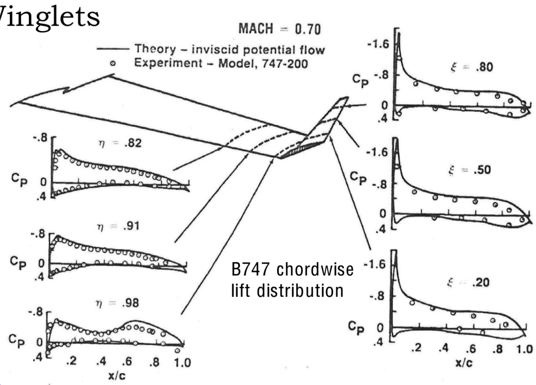
Increase the effective aspect ratio of the wing

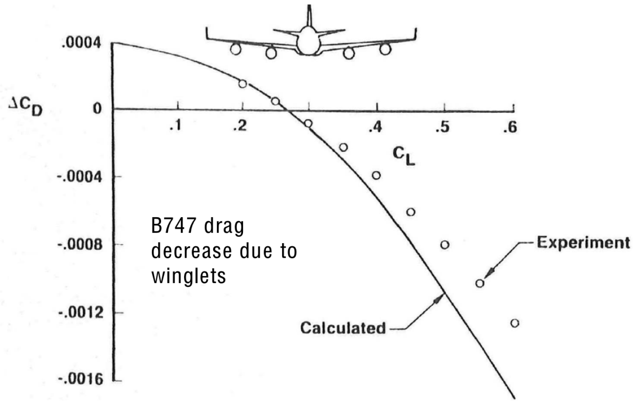
Shape:

The radius of the inner curve must be large enough to prevent interference drag.

Depends on toe-in toe-out angle w.r.t the interference, resulting on drag decrease at particular C_L.

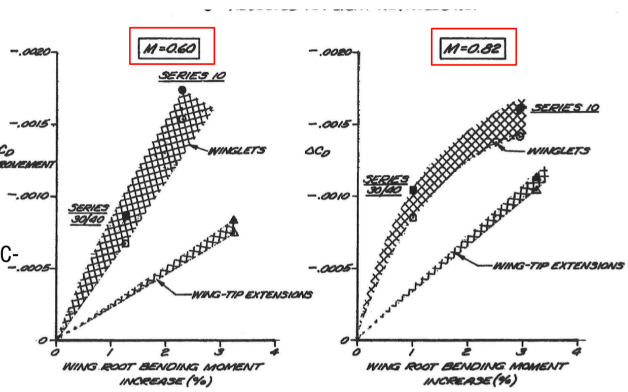
Winglets





Comparison of winglets and wing tip extensions

Comparison wing tip and winglet on DC-10



Winglets can be problematic as an add-on and therefore wings should be designed with winglets.

Problematic because it influences many things.

- Root bending moment, dependent on control surface deflection and roll maneuves.
- Flutter considerations
- Stability and control considerations

Summary

- Tapered, swept wings of constant airfoil section have high pressure drag near the root and wave drag stemming from the tip
- Root airfoils need to be modified to ensure that supervelocities due to thickness and lift are similar to those in the outboard wing resulting in a reduced pressured drag
- Wing tips can be modified in planform (i.e. Kuechemann tip) or in sectional shape to prevent the early formation of a tip-shock and subsequent wave drag
- Winglets or wingtip extensions can be added to increase the (effective) aspect ratio of wings resulting in increased wing-root bending moment and reduced drag at lift coefficients above a certain threshold

High Lift Devices

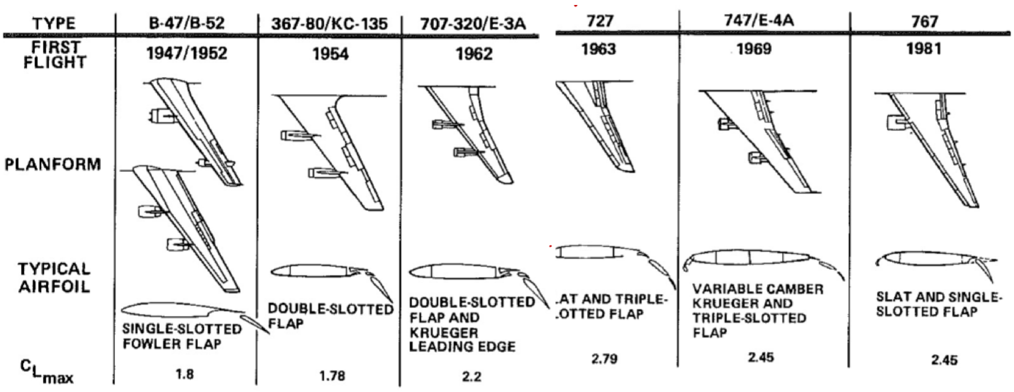
High lift devices are used to have a good behaviour on low-speed performance. On landing and take-off.

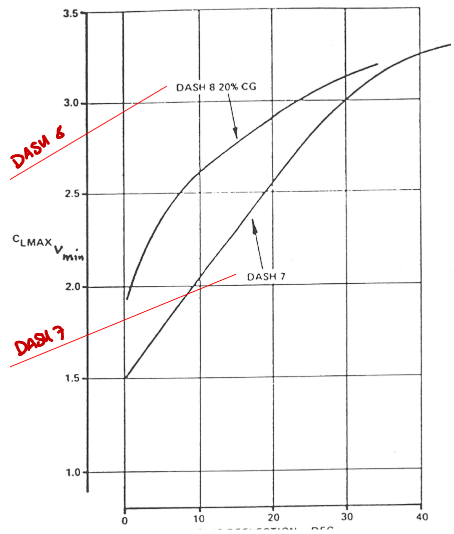
QS6: Why do aircraft that fly faster have a lower $C_{L max}$?

Due to higher sweep angle of high-subsonic aircraft.

Types of Flaps

EXAMPLES





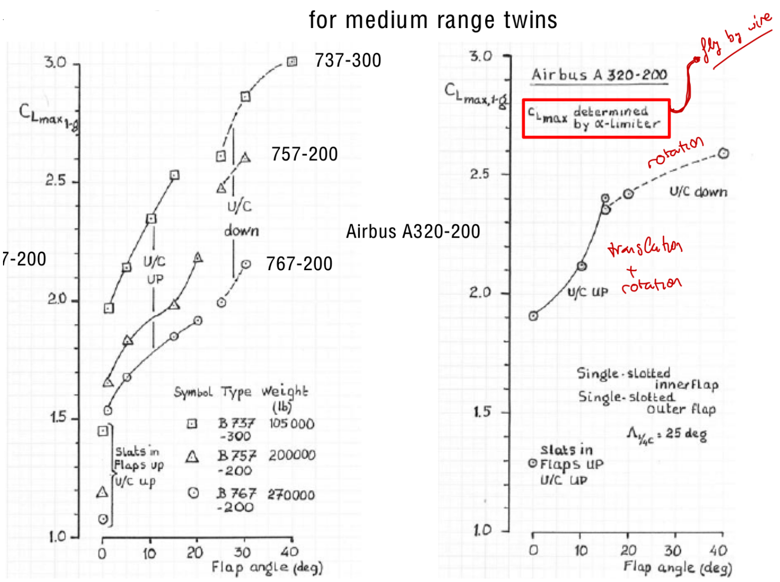
translation in flap, increases chord length

↳ Nothing below the wing

krueger:

Take off performance examples

for medium range twins



If the weight is increased or reduced, the C_{Lmax} changes to adapt for the c.g. change.

MORE PERFORMANCE GRAPHS IN 24-28 High lift devices

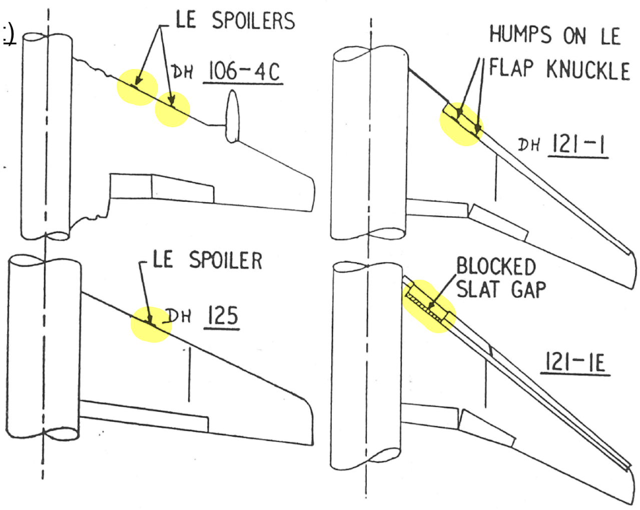
Stall Characteristics

Requirements

1. Flow separation should start on the inboard wing so control surfaces are effective in stall (Make sure that peak $C_{p_{min}}$-values at leading edge occur on the inward wing)
2. When stall occurs the tailplane elevator shall not lose effectiveness due to the wake of separated flow.

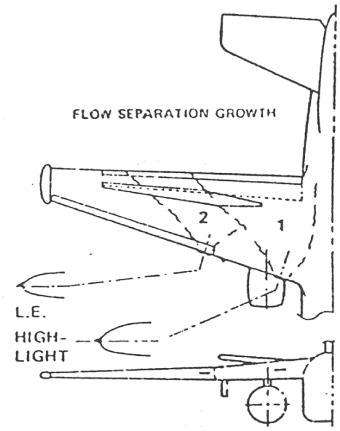
Reduce $C_{L_{max}}$ as little as possible

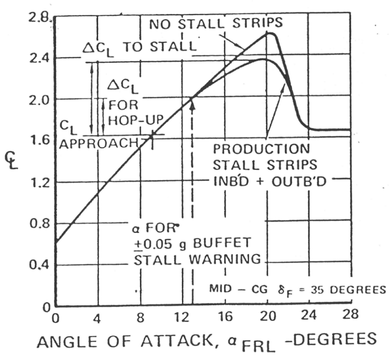
Stall Control Devices: ⟶ Controlling Stall



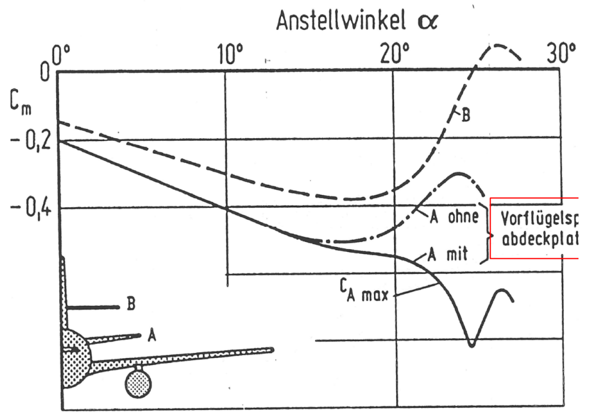
1. Sufficient detatchment in this area to provide +0.05g at 23 degrees α. Horizontal tail picks turbulence. Airplane vibrates, thus we know we are approaching stall.

2. Progressive separation in area 2



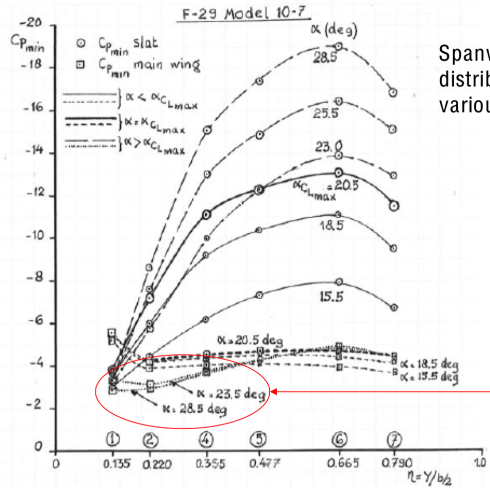


Effect of tailplane position and slot blocker on C_m



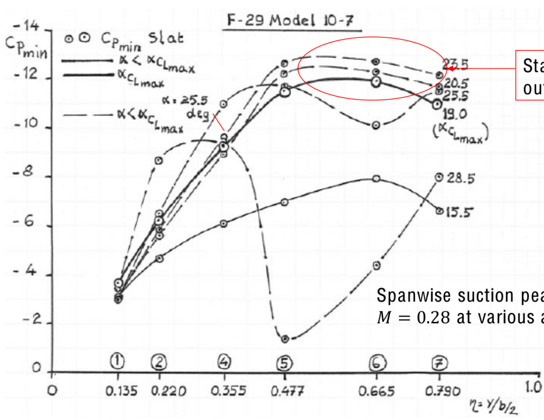
QS7: Why is there a difference in stall behaviour with Mach number?

The location of stall changes with Mach number.



Spanwise suction peak distribution at $M = 0.19$ at various angles-of-attack

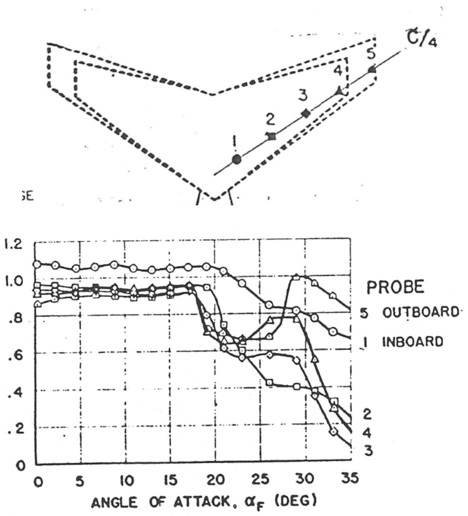
Stall starts here: Inboard, main wing

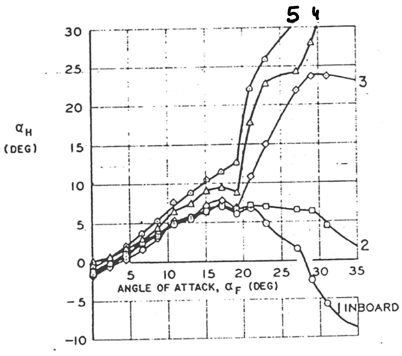


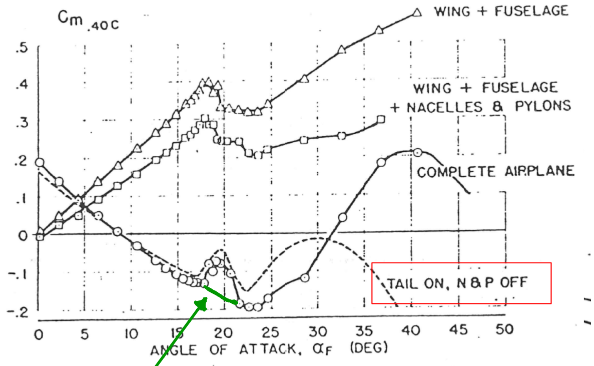
Stall starts here: outboard, slat

Spanwise suction peak distribution at $M = 0.28$ at various angles-of-attack

TAIL STALL BECAUSE OF WAKE

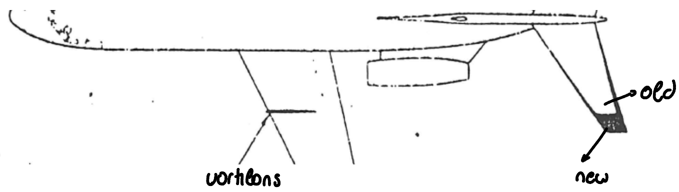






How to SOLVE IT ? green on graphs

Increasing tail span and including vortilons on wing, to reset b-layer.

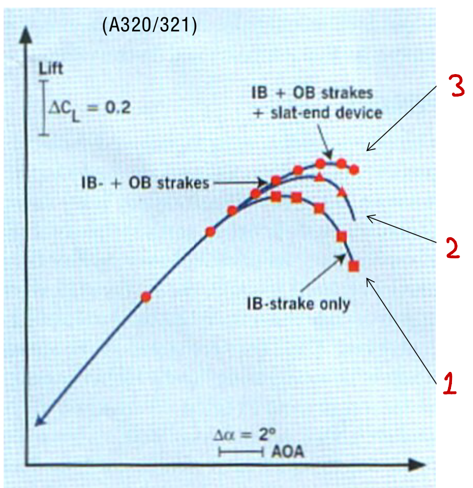


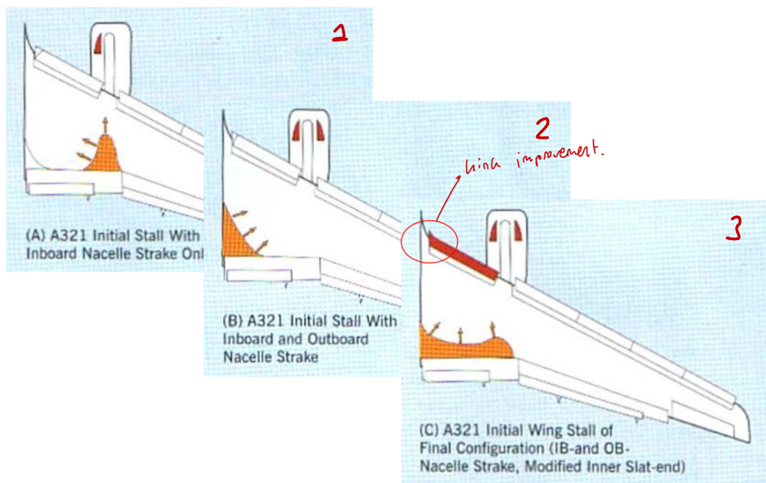
Reynolds effect on stall:

- Postponement of tip stall
- Longer linear range
- Increase in usable $C_{L_{max}}$

Vortex generators on engines in front of inwards wing:

Create vortices and reduces the flow separation at high α.
Create a slat cut out.





(A) A321 Initial Stall With Inboard Nacelle Strake Onl

(B) A321 Initial Stall With Inboard and Outboard Nacelle Strake

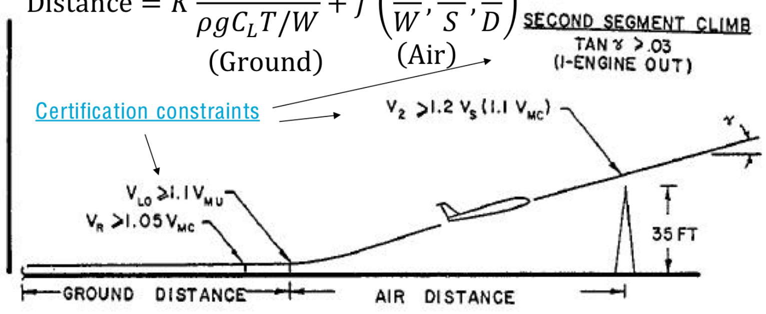
(C) A321 Initial Wing Stall of Final Configuration (IB-and OB-Nacelle Strake, Modified Inner Slat-end)

LIFT TO DRAG RATIO

Lift off moment was related to $C_{L_{max}}$, but climb ratio is a function of L/D.

$$\text{Distance} = K\frac{W/S}{\rho g C_L T/W} + f\left(\frac{T}{W},\frac{W}{S},\frac{L}{D}\right)$$

(Ground) (Air)



Q58: At high fields, why do we need a high L/D?

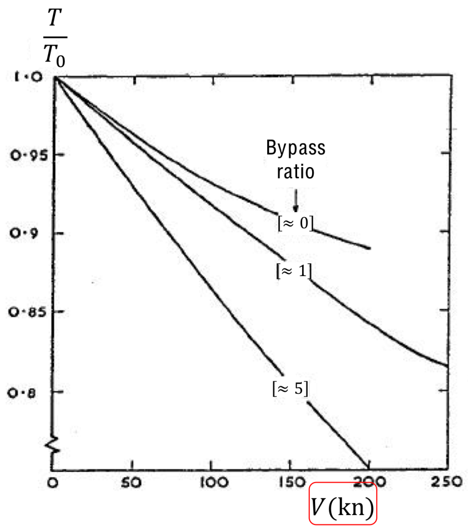
To compensate for lower thrust and reduce the ground roll distance ground roll

To compensate for lower thrust and reduce the air distance climbout.

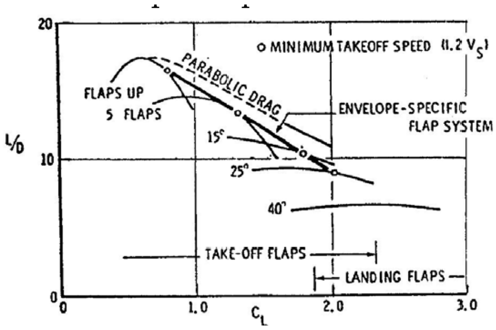
To compensate for lower T and meet the climb gradient requirement. climb gradient

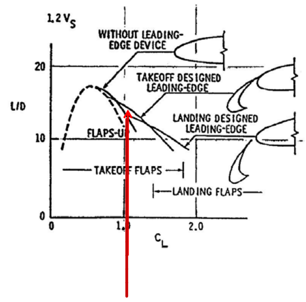
Less thrust at higher altitudes. Thrust depends on ρ, height and temperature.

Increased temperature and height might cause thrust loss.



The flaps increase more the drag than the lift. Thus:





Slats decrease L/D when deployment but increase $C_{L_{max}}$

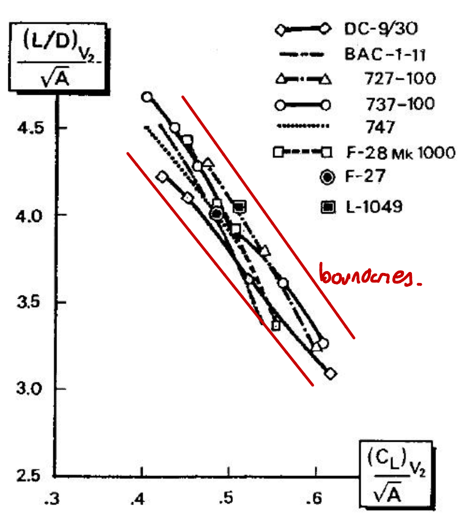
Take-off Performance

Best one-engine-out climb requires a high L/D and high C_L.

The induced drag is the largest component.

A high aspect ratio is beneficial.

If one is increased the other decreases

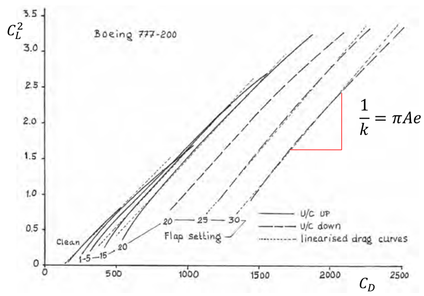


useful parameter to compare different flap systems

Low Speed Drag Polar

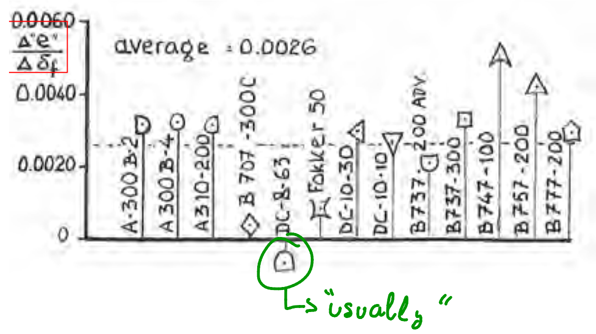
$C_D \sim kC_L^2$

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



Q59: Effect of flap deflection on e.

Oswald increases



Summary

After this lecture, you will be able to:

- High sweep angles yield lower maximum lift coefficient of the clean wing, making high-lift devices important to have acceptable field performance
- The larger the flapped area of a trailing edge, the higher the lift coefficient that can be attained.
- Deploying the undercarriage reduces the maximum lift coefficient through the nose-down pitching moment it generates
- Stall starts at the location where the combination of a high adverse pressure gradient and boundary layer state is most critical
- The effect of Mach number changes the pressure distribution over high-lift devices and can therefore alter the location of stall onset
- Deployment of flaps increases the zero-lift drag coefficient and the Oswald factor
- To minimize field length, a trade-off needs to be made between lift-off speed (CL) and attainable climb gradient (L/D)

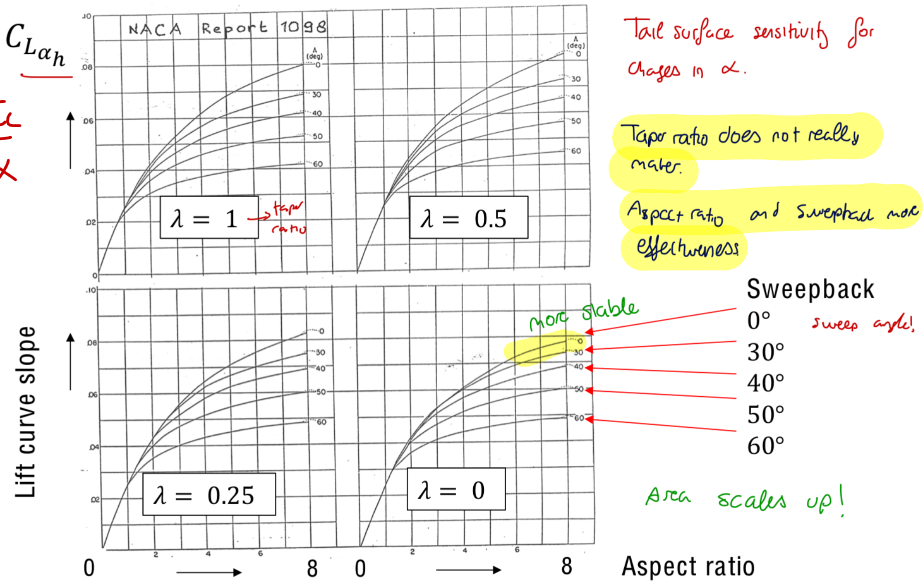
Horizontal Tail Design

Planform Design

Investigate the effect of Surface area, Aspect Ratio, Taper ratio, Sweep angle on $C_{L_{max}}$ and $\frac{\partial C_L}{\partial \alpha}$

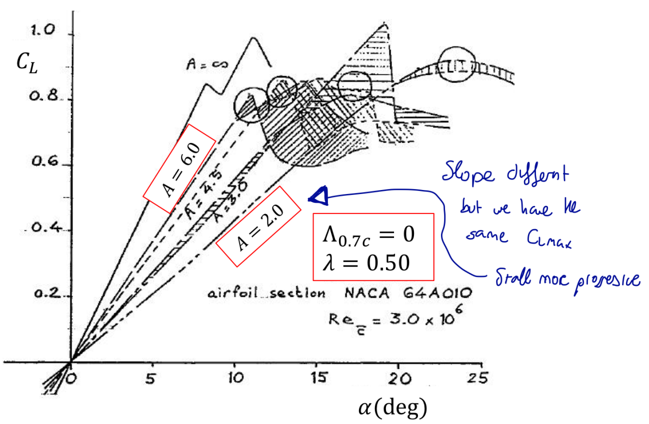
Aspect Ratio, Taper Ratio & Sweepback

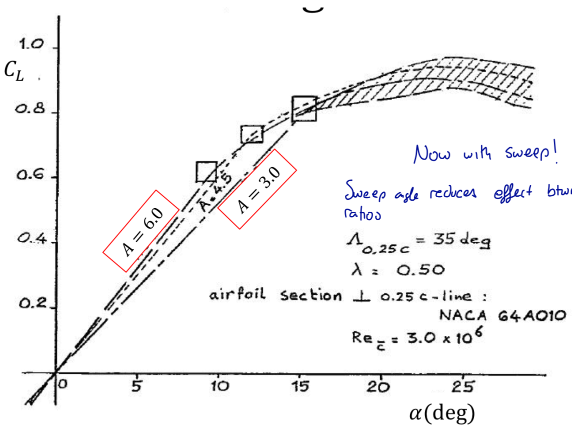
$\frac{\partial C_L}{\partial \alpha}$

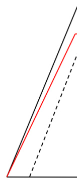


We can also observe that for low Aspect ratio, the sweep does not have an effect on C_{L_α}

C_L







$C_{L_{max}}$ is not very sensitive to A.

C_{L_α} increases with A.

α and stall may vary.

$C_{L_{max}}$ not very sensitive to sweepback

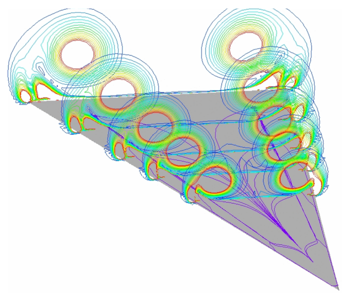
C_{L_α} increases only slightly with A.

Stall is more subtle for high A compared to low sweep angles.

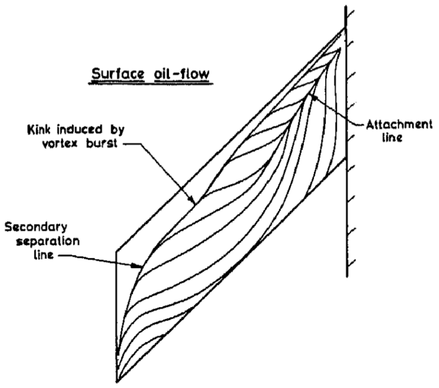
QS9: Why is $C_{L_{max}}$ higher for the wing with $\Lambda = 45°$

Because of the leading edge vortices.

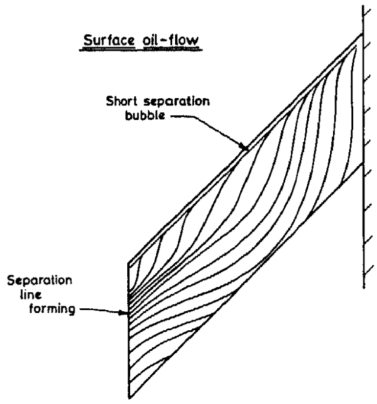
Stable vortices from leading edge, reduce the static pressure over the wing.
Increases $C_{L_{max}}$. Vortex lift



Vortex Lift

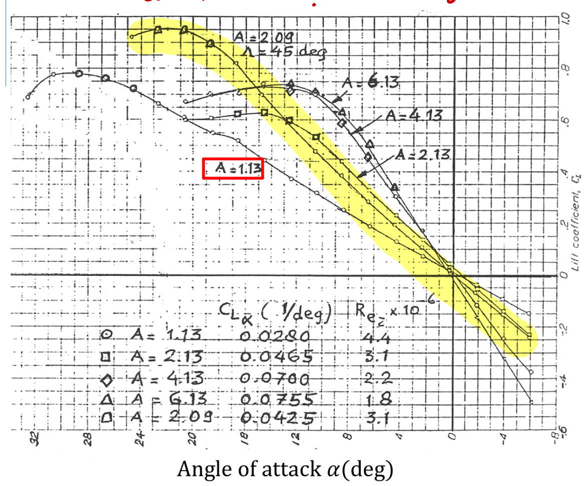


Leading edge radius = 0.03 %



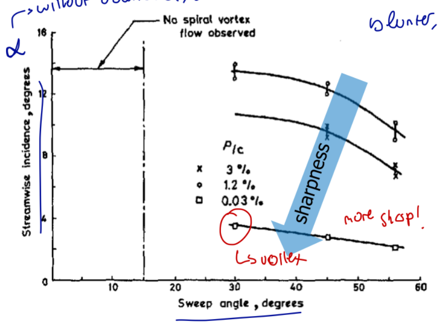
Leading edge radius = 3.0 % c

Sudden increase! Vortex lift

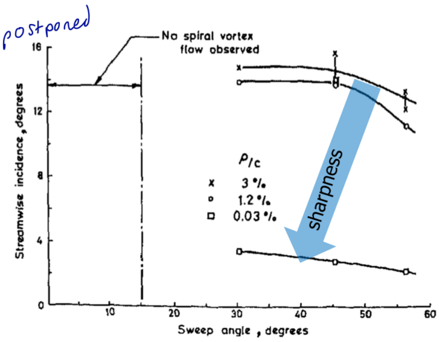


Re = 1 000 000

Re = 2 000 000



blunter, postponed



Q60: What is the primary function of the two ventral fins shown below?

Provide a restoring pitching moment at high α when the horizontal tail is on the wake of the wings.

This ventral fins rely on vortex lift. Very low A wings generate vortex at high α.

Summary:

- Aspect ratio, A, effect:
  - High A → high $dC_L/d\alpha$, low α_{stall}
  - Low A → low $dC_L/d\alpha$, high α_{stall}
  - Little effect on $C_{L_{max}}$
- Taper ratio, λ, effect:
  - Little effect on $dC_L/d\alpha$
  - Effect on $C_{L_{max}}$ depends on $\Lambda_{c/4}$:
    - High Λ_{le} yields vortex lift and high $C_{L_{max}}$
    - Low Λ_{le} and high λ result in tip stall due to low Re_{tip} and low $C_{L_{max}}$

low taper ratio, a lot of taper

- Sweep, $\Lambda_{c/4}$, effect:
  - High $\Lambda_{c/4}$ → low $dC_L/d\alpha$, high α_{stall}
  - Low $\Lambda_{c/4}$ → high $dC_L/d\alpha$, low α_{stall}
  - Effect on $C_{L_{max}}$ depends on formation of l.e. vortex

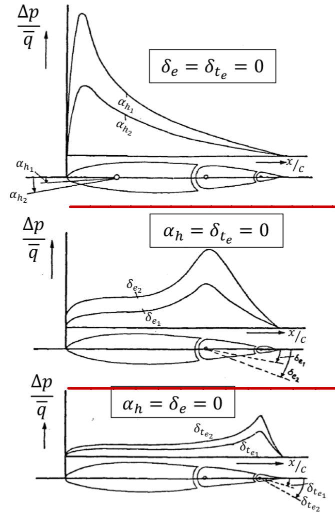
Design of Horizontal Tail Surface

Design variables

C_{L_h} depends on:

- Flow parameters:
  - *Reynolds number*
  - *Mach number*
  - *Angle of attack*
- Shape parameters:
  - Planform shape: S, A, Λ, λ
  - Airfoil shape
  - Control surface deflection
  - Chord ratio
  - Gap / Overhang
  - Tab deflection
  - Horn geometry

Design variables



Installed to provide longitudinal stability in all flight

Provides pitch control in all flight

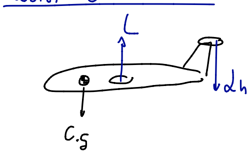
Provide a state of equilibrium in each flight

Important in extreme flight conditions

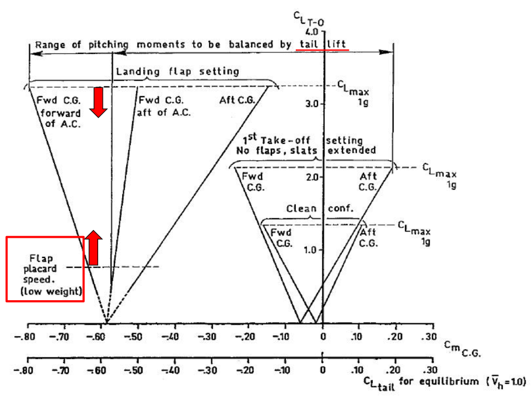
Control Surfaces Requirements

1. They shall provide a sufficiently large contribution to static and dynamic stability (longitudinal, directional, and lateral) } High $\frac{dC_{Lh}}{\partial \alpha_h} S_h$ High A minimum sweep
2. They shall provide sufficient control capability → High $\frac{dC_{Lh}}{\partial \delta_e} S_h$ High A minimum sweep
3. Control shall be possible with acceptable control forces → $F = G_e C_h \cdot \frac{1}{2}\rho V^2 \cdot S_c \bar{c}_c$ High A of control surface. G_e, kinematics C_h, influence b.l.
4. Shall be able to handle high angles of attack → High speeds and deflected flaps. Low A of control surface. Sweep positive
5. They shall provide sufficiently large forces to balance tail-off forces and moments and provide equilibrium } Achieved in all flight conditions, All aerodynamic conditions, All c.g. positions. High & low A
6. They shall be able to handle high Mach numbers without flow separation → 5 deg higher sweep than wing, 1 to 2% less t/c than outward wing

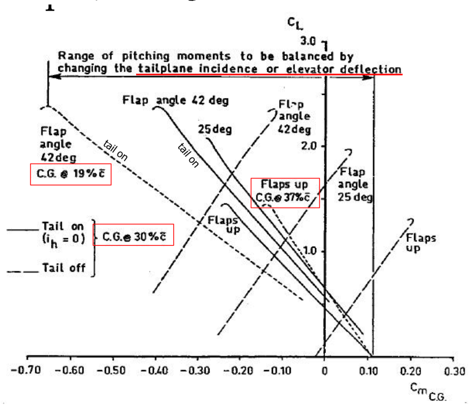
Worst Case Scenario



Equilibrium Requirements



Elevator pitching moment requirement



Tail Surfaces

High aspect ratio

Higher weight

T-tails, flutter analysis should be considered

High taper ratio

Lower weight

Premature tip stall

wing sweep aggravates effect unless l.e. vortices are formed.

Sweep makes stall more gradual.

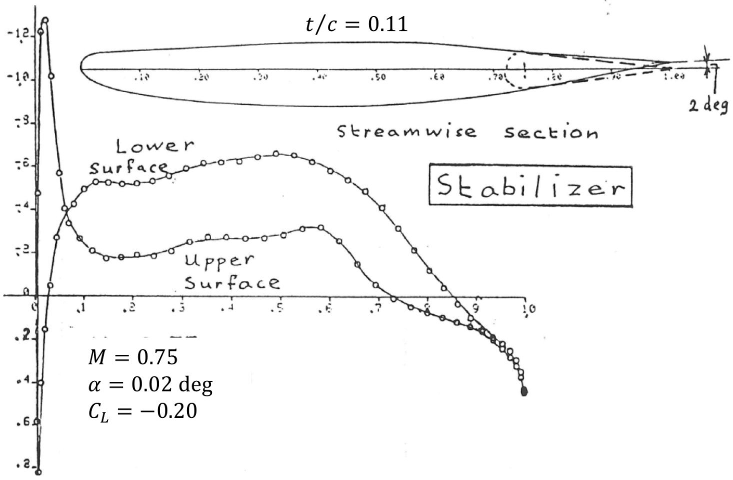
Result of analysis of requirements:

- the aspect ratio should be high and low
- the sweepback should be high and low
- the taper ratio should be high and low

Complicating factors:

- aeroelastic effects
- ice accretion

Airfoil Design



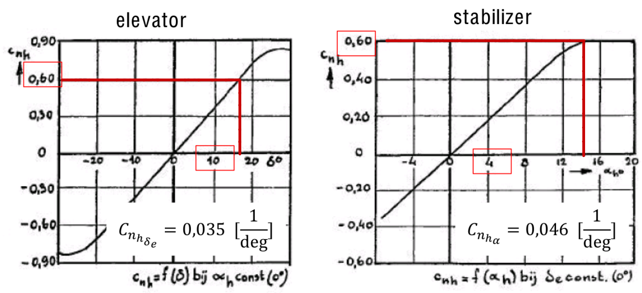
Generate downforce!

To increase lift of an airfoil:

- Increase camber by control surface deflection
- Increase angle of attack.

Q6: Which surface is more effective?

Stabilizer



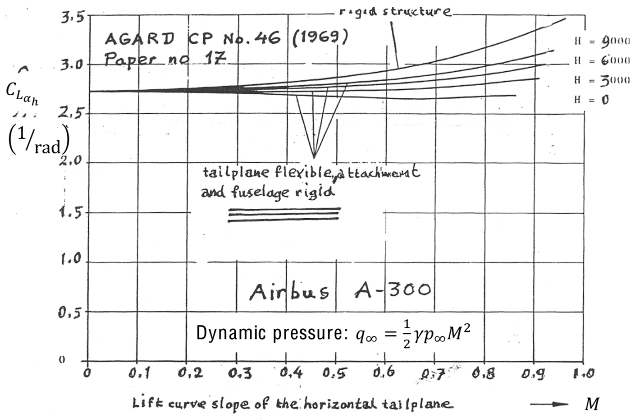
Aeroelastic Deformation

Many systems bend due to aerodynamic loads

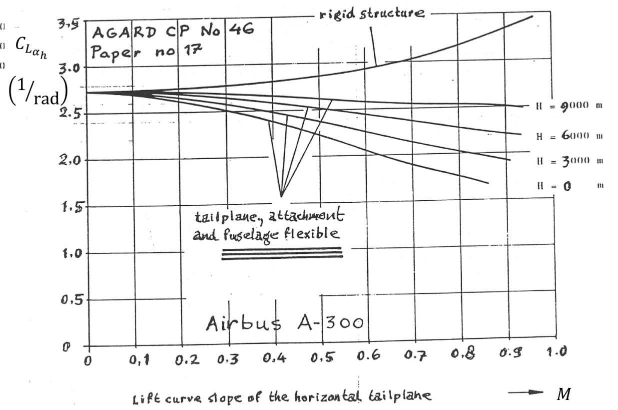
- Wing bending and torsion (including flap system)
- Fuselage bending reduces tail surface lift curve slope
- Tail surface bending and torsion reduce lift curve slope and control surface effectiveness.
- Deformation of movable stabilizer attachment effect dependent on dynamic pressure.

Static aeroelastic deformation

rigid fuselage



flexible fuselage



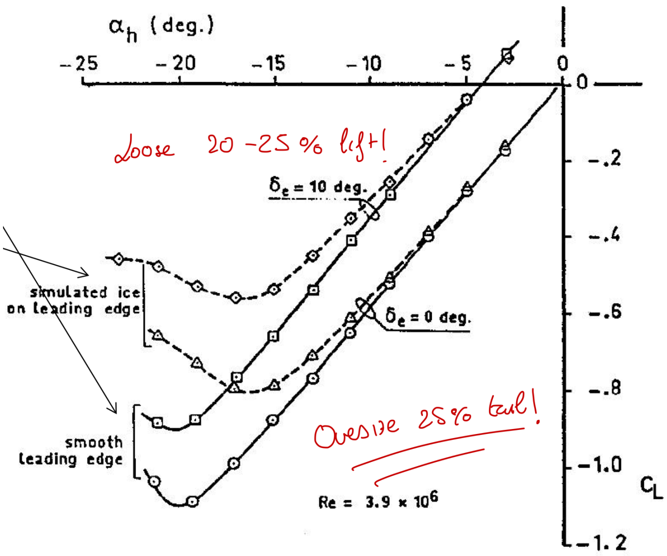
Effect of Ice

In certain atmospheric conditions ice may accrue on the leading edges of the wings and tail surfaces

Strong reduction of the stall angle of attack and thereby to a much reduced lifting capability.

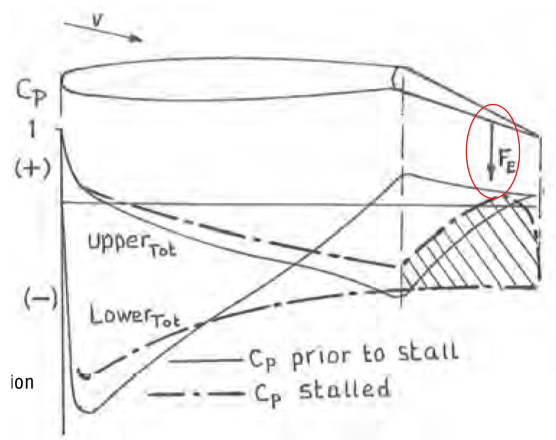
Ice accretion on tail, sudden pitching moment

Comparison Lift



Elevator Lock

Prior to stall force on elevator is upwards, when the leading edge stalls the force is reversed points downwards.



Opposite force on elevator and a larger moment arm to elevator center of pressure.

Summary

- Sweep and aspect ratio have a large effect on the lift curve slope of a lifting surface
- The leading edge sharpness and sweep angle determine at what angle of attack a stable vortex is formed that can postpone stall to a higher AoA
- The horizontal tail plane provides equilibrium, stability and control
- The planform parameters are chosen as a compromise between conflicting requirements
- The flexibility of the aircraft reduces effectiveness of tail and elevator
- Icing reduces the maximum lift coefficient of the tail surface
- Elevator lock results from netagive tail plane stall shifting the center of pressure far behind the hinge line

Flying Beyond Buffet Onset and MMO

Buffet onset boundary

Forms a limitation of the aircraft flight envelope. In which the separation starts at the foot of the shock wave and creates oscillating pressure distribution.

QG2: On the P-80 story, why did the buffeting stop?

Pressure, density and temperature increased when the aircraft went down.

Buffet and Safety

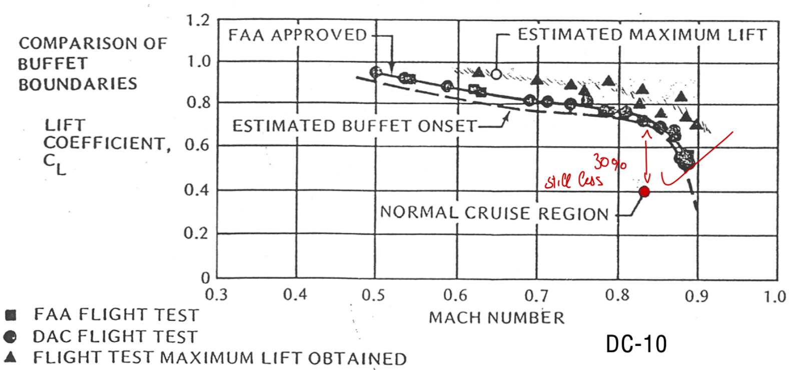
Airworthiness regulations require that buffet can only appear during a pull-up or turn over.

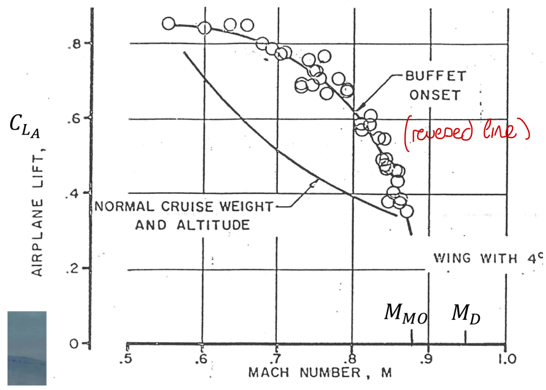
AIRWORTHINESS REQUIREMENTS

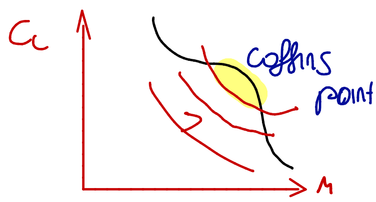
- C_L in operational cruise conditions is limited such that a factor of $n=1.3$ can be reached without buffet.
- If Buffet regime is penetrated, should be in fully controlled flight.
  Flow separation should start inboards, to not have a strong roll and pitch.
- The buffet regime is delivery penetrated during test flight. And the max has to be recorded.

Lift Coefficient Margin

Normal flight vs buffet onset boundary



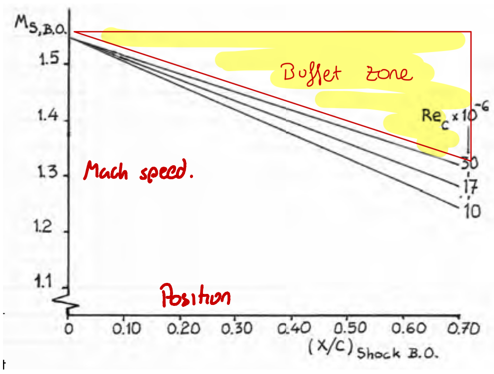




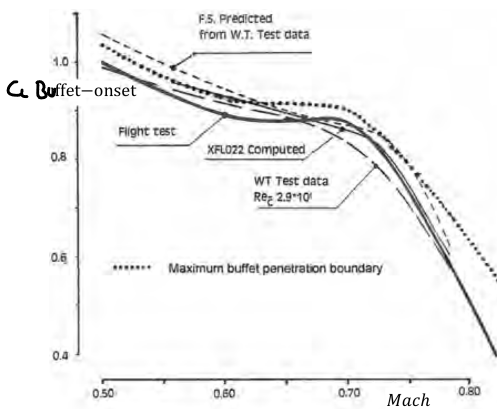
U-2 flights here

Empirical Determination of Buffet Boundary

Correlate buffet-onset mach number in front of the shock wave to shock position.



Use numerical approx of b-l equations with a suitable separation criterion

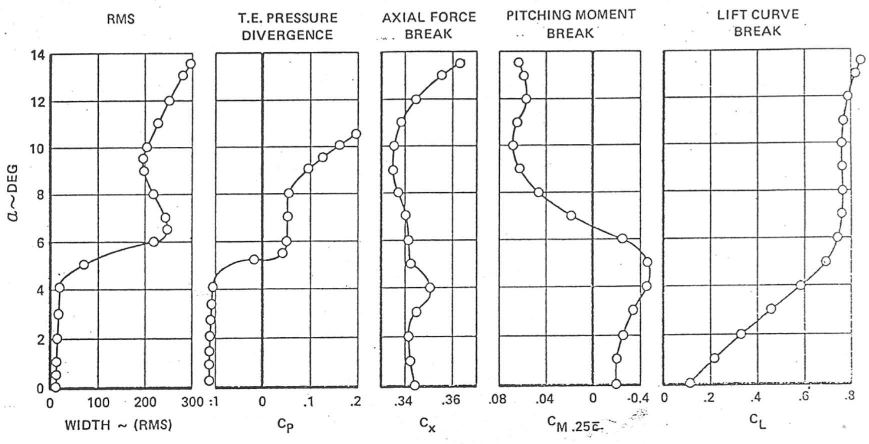


How to detect buffet onset

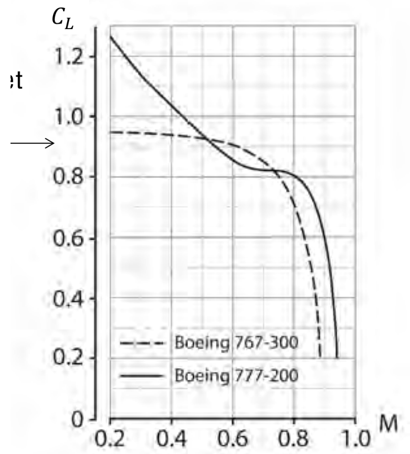
1. Breaks in $C_L-\alpha$, $C_M-\alpha$ or $C_X-\alpha$ curves

Trailing edge pressure divergence on outboard wing

Divergence of dynamic wing root strain-gauge recordings.



Supercritical airfoils improve buffet boundaries.



Boeing 767-300 and Boeing 777-200 buffet onset boundary

From MMO to MD

The selected design speeds are (EAS).

Design cruising speed, VC.

1. Minimum value of VC must be sufficiently greater than VB to provide for inadvertent speed increases likely to occur as a result of severe atmospheric turbulence.
2. VC may not be less than VB + 43 knots
3. At altitudes where VD is limited by Mach Number, VC may be limited to a selected Mach Number.

Design dive speed, VD. Selected so that VC/MC is not greater than 0.8 VD/MD. Or that the minimum speed margin between VC/MC and VD/MD is the greater of the following values.

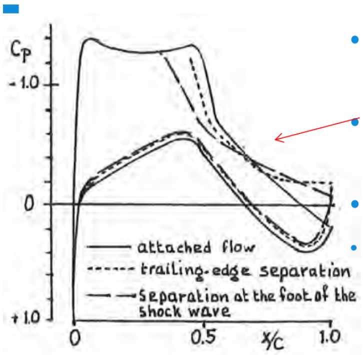
CS-25 Regulations: pg. 23 of Flight beyond buffet onset.

1. Speed at an specific maneuver.
2. ...

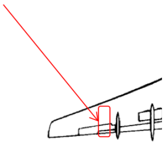
Flight Characteristics Between MMO and MD

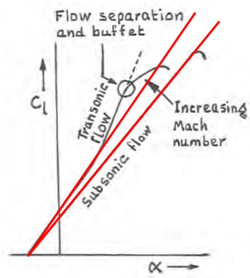
- Civil transportation aircraft do not exceed MMO, but meet the requirements to do so. Due to severe atmosphere upsets.
- Airworthiness: acceptable flight characteristics up to $M_D \rightarrow M_D = M_{MO} + 0.05$ to 0.09.
- $M_{design} = M_{MO} - 0.03$ to 0.05: design wing.

Fokker 100 Beyond MMO Example



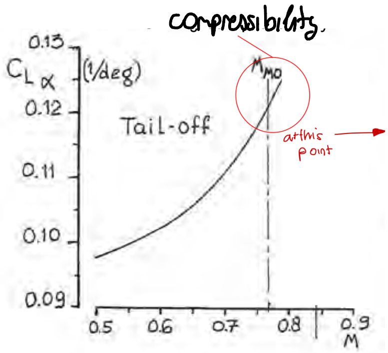
- Initial separation occurs at highest loaded section
- Large change in local pitching moment coefficient
- Little change in section c_l
- Overall $C_{L_\alpha} > 0$ due non-stalled region and compressibility effect



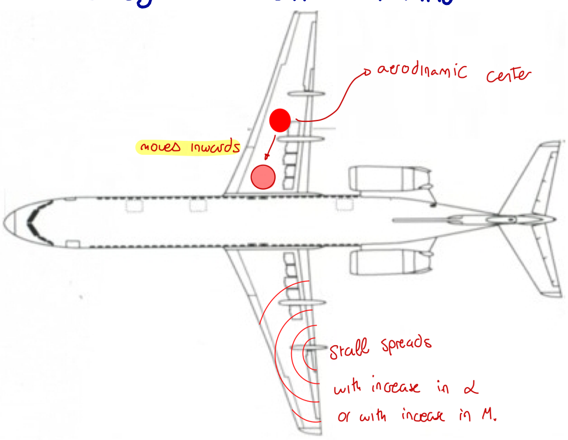


Remember this...

compressibility



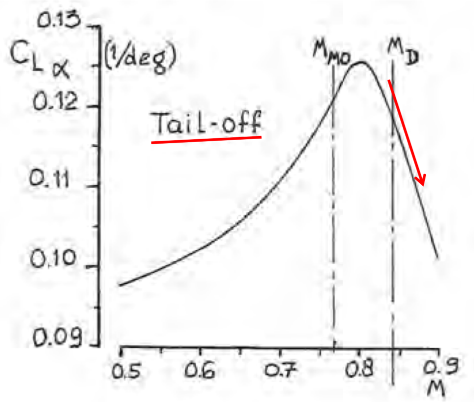
Aerodynamic center at MMO



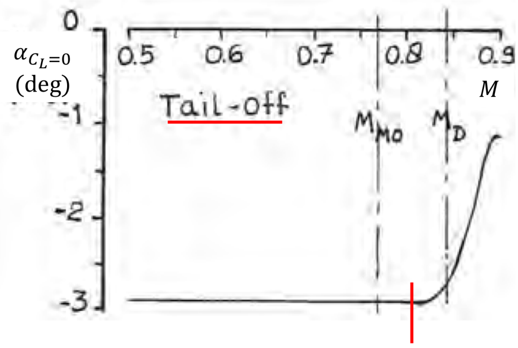
When M arrives to MD the $C_{L\alpha}$ drops:

lift decreases

lift shifts inwards



To balance pressure distributions, increase α.

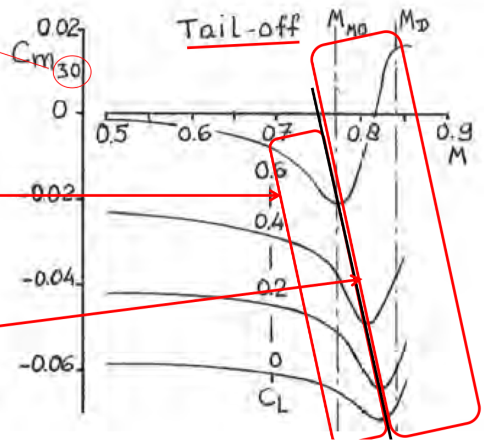


Resulting pitching moment NO TAIL

Most af cg postion

Resulting pitching moment characteristics:

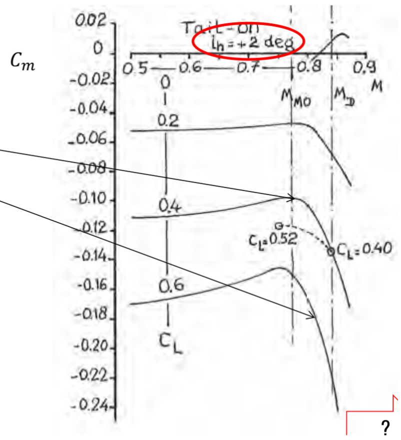
- Strong compressibility effects up to M_{MO}
- Pitch break at M_{MO}
- Unstable pitching moment beyond M_{MO}



Resulting pitching moment with tail

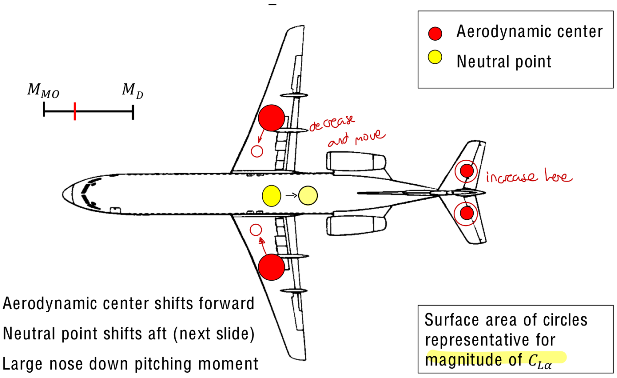
Effect of tail:

- Stable pitch break
- Strong pitch down moment



Q63: Why is there a pitch-down tendency?

Due to an aft shift in neutral point position



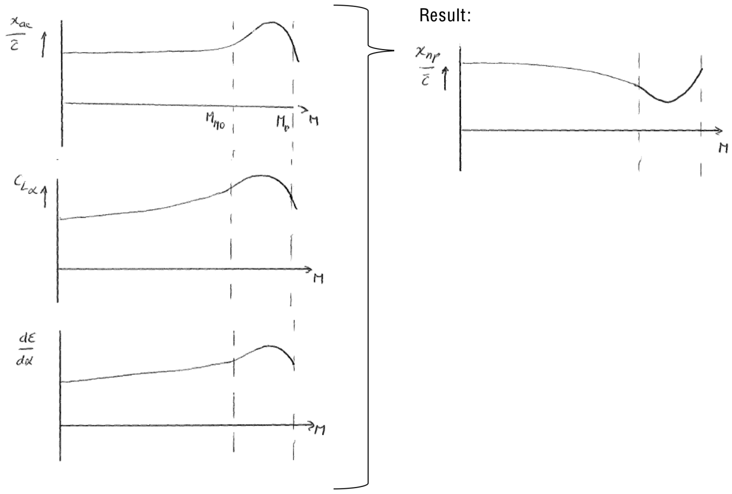
- Aerodynamic center shifts forward
- Neutral point shifts aft (next slide)
- Large nose down pitching moment

Surface area of circles representative for magnitude of $C_{L\alpha}$

Shift in Neutral Point

Stick fixed N.P.

$$X_{NP} = X_{ac_{wf}} + \frac{C_{L\alpha_h}}{C_{L\alpha_{wf}}}\eta_h \cdot \frac{S_h}{S}\left(1 - \frac{d\varepsilon}{d\alpha}\right) \qquad X_{NP} \sim X_{ac_{wf}} \qquad X_{NP} \sim \frac{1}{C_{L\alpha_{wf}}} \qquad X_{NP} \sim -\frac{d\varepsilon}{d\alpha}$$



Triming the airplane:

- Deploy trim tab on elevator
- Deploy elevator
- Change incidence angle of tail.

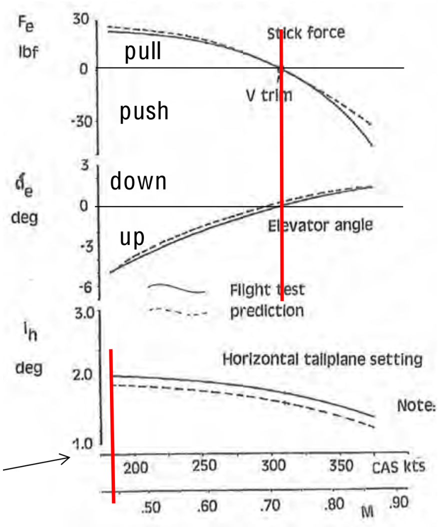
less effective

Stick Reversal:

Originally, increasing speed, push down when nose goes down push up.

Mach Trim Compensator

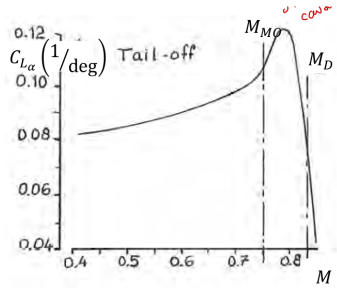
Allows for positive stick force stability up to M_D without stick reversal.



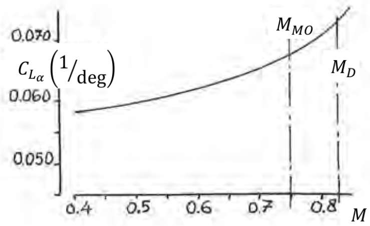
Fokker 28 Beyond M_{MO}

Shorter than F100: wings were overdesigned. so extended to F100.

Good characteristics between M_{MO}, M_D without Mach trim compensator.



Tail-off curve slope



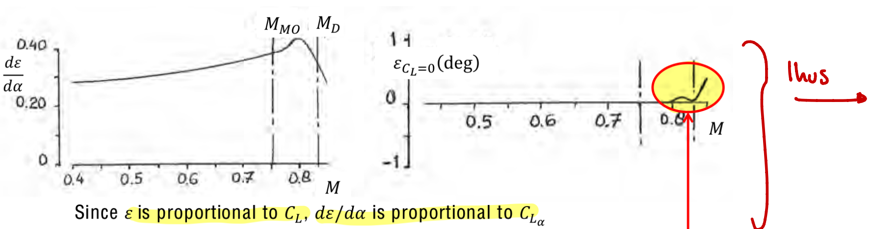
HT lift curve slope

Q64: What planform charact explains the difference between wing and HT $C_{L\alpha}$ when $M \rightarrow M_D$

The larger sweep of the horizontal tail compared to the wing.

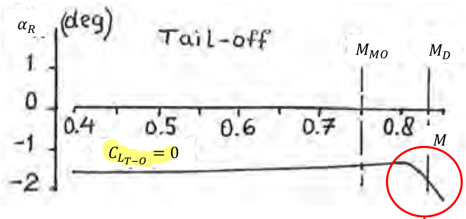
Lower α required!

Downwash angle:



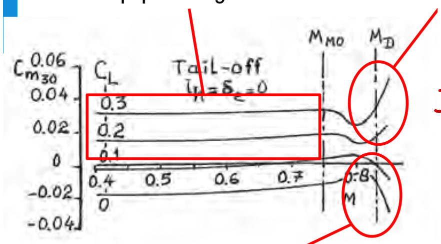
Since ε is proportional to C_L, $d\varepsilon/d\alpha$ is proportional to C_{L_α}

Action not equal to reaction...?



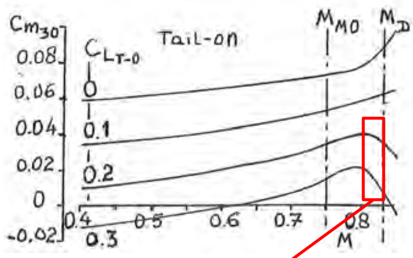
Lower α required to balance top and bottom pressure distribution when we increase the $C_{L T\text{-}off}$ we get unstable pitch break

Nose-up pitching moment



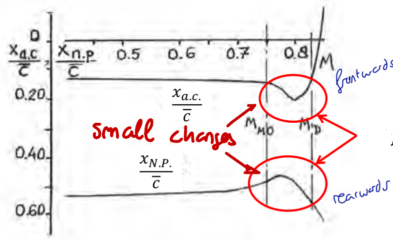
Stable pitch break with small nose-down C_{mT_0}

If we include the tail

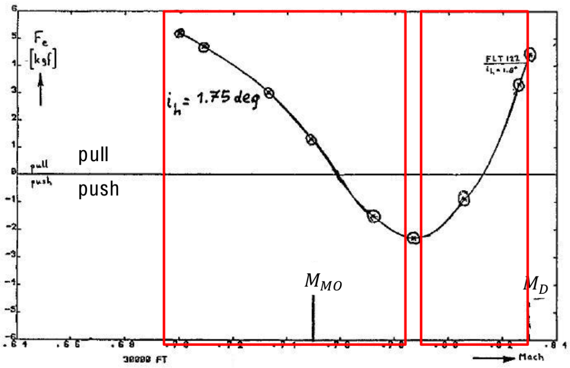


Small decrease in C_m

thus



Stick reversal on F28

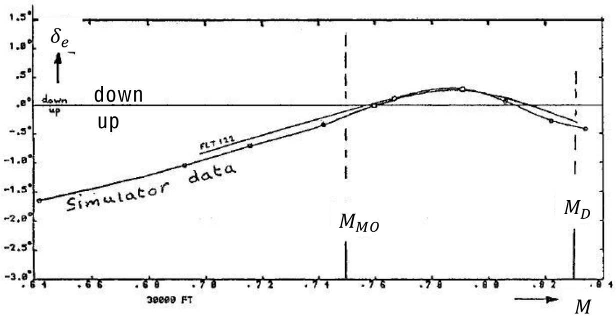


Positive stick-force stability

Negative stick-force stability

5 kgf max

but only small changes on δ_e are required to trim the airplane



Variable incidence angle stabilizers are used.

Summary

- Buffet onset effectively limits the maximum operating Mach number and service ceiling
- Airplanes need to demonstrate acceptable flying qualities between MMO and MD
- Shock induced stall is the cause for pitch deviations beyond MMO. The location of stall onset and the stall development influences the pitching moment with Mach number
- Horizontal tail planes should be designed to postpone adverse Mach effects such as shock-induced separation
- All moving stabilisers can be used to neutralized the change in pitching moment with Mach number

Vertical Tail

Functions

1. Provide stability in flight conditions. Directional.
2. Provide yaw control in all flight conditions
3. Ensure safe handling during engine failure conditions

Design drivers:

Minimum control speed with OEI (V_{MC})

- Low speed
- High thrust
- High α

} Result when 1 engine fails.

High yaw rate
Large slip angles.

Maximum cross-wind capabilities

- Low speed
- High side-slip angle

Requirements

1. Shall provide a sufficiently large contribution to static and dynamic stability (directional and lateral)
2. Shall provide sufficient directional control capability
3. Directional control shall be possible with acceptable control forces
4. Shall be able to handle high angles of sideslip
5. Shall provide sufficiently large forces to balance OEI moments and provide equilibrium
6. Shall be able to handle high Mach numbers without flow separation

QGS: To have a large contribution to the static directional stability

Aspect ratio high low sweep, mainly.

Shall provide a sufficiently large contribution to static and dynamic stability (directional and lateral)

High aspect ratio
Minimum sweep

High $\frac{dC_{L_v}}{d\beta_v} S_v$

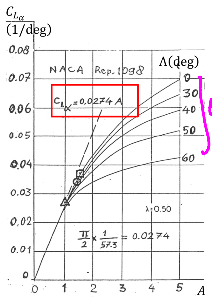
For low A the sweep dont matter.

$$C_{L_\alpha} = \frac{\pi A}{2}$$

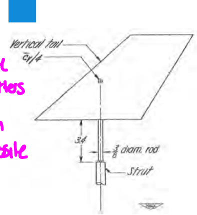
$$L = C_{L_\alpha}\alpha \cdot \rho V^2 \frac{S_v}{S}$$

$$\Bigg\} L = \frac{\pi A}{2}\alpha \cdot \rho V^2 \cdot \frac{S_v}{S}$$

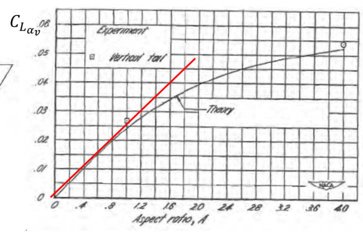
$$L = \pi \alpha \rho V^2 \frac{b v^2}{4}$$



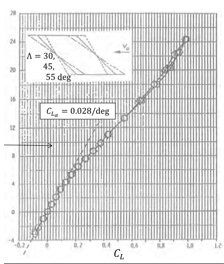
looks like it matters but then opposite



$A = 1.0,\ \lambda = 0.6,\ \Lambda = 45°$



$C_{L_\alpha} = \pi A/2$



Which means that the lift force only depends on the height for a given α.

"Shall provide sufficiently large forces to balance OEI moments and provide equilibrium"

Achieved in all flight conditions:

- All aerodynamic conditions
- All center of gravity positions
- Allowing for control surface deflections
- Including effect of ice.

Requirements on Requirement

- Sufficiently large surface — all forces scale with area
- Measures to ensure a high $C_{L_{max}}$ — high slip-angle as well, no stall, or stall resistant!

"Shall be able to handle high angles of sideslip"

Limiting conditions

- Low speed and high cross wind
- OEI condition right after take-off

Requirements on requirement

- Low aspect ratio
- High sweep of fin.

} Harder with icing.

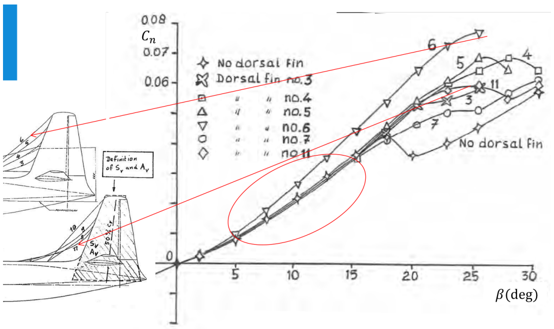
Dorsal Fins

Q66: Why does a dorsal fin increase $C_{n_{max}}$?

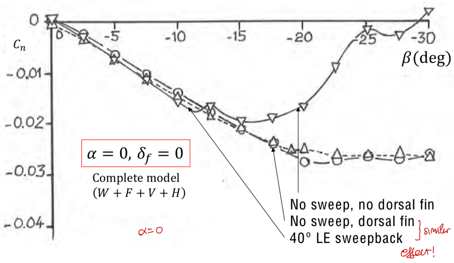
Due to vortex lift at high side-slip angles.

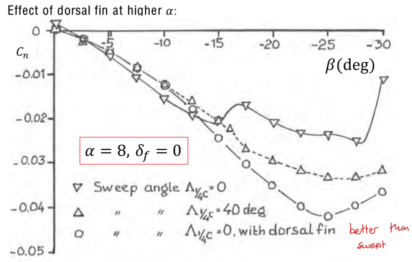
Generates a l.e. vortex which stabilizes flow and provides a low pressure region over the main surface

Works identical to strakes. F18.



No swept vertical tail, and a tail with sweep can have the same output. (Only at certain α)





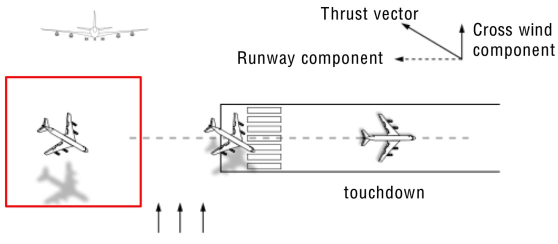
Summary High Yaw Characteristics

- To ensure safe flight characteristics at high yaw angles the vertical tailplane must have a large stalling angle
- This is obtained by a low aspect ratio and sweepback and/or a dorsal fin
- Racy swept back tails on slow propeller aircraft may well be functional

Q67: How much rudder deflection do we need ahead of a crosswind landing.

Zero in decrab landing.

De-crab landing



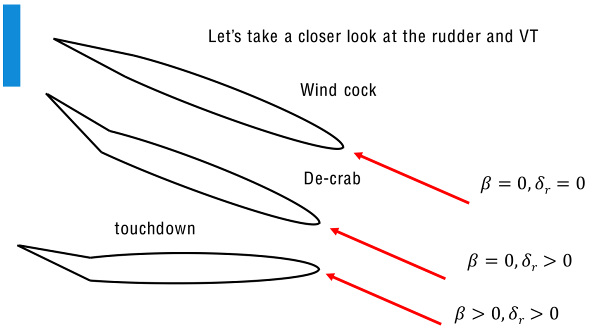
"Shall provide sufficient control capability"

High aspect ratio

Minimum sweep

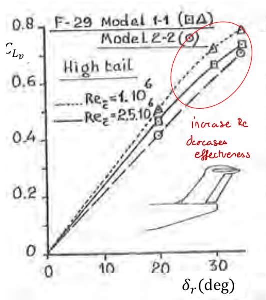
$$\text{High } \frac{dC_{L_v}}{d\delta_r} S_v$$

Rudder Design

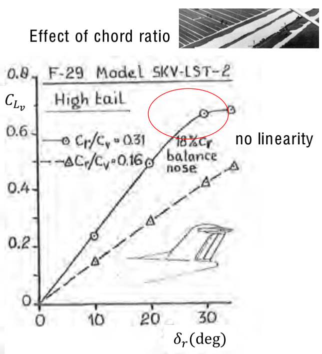


Rudder must be very powerful to provide sufficient side force

Effect of Reynolds number



Effect of chord ratio



Increasing the chord ratio increases increases the $(\Delta C_n)_\delta$ until $\boxed{30\%}$ $\frac{C_r}{C_v}$ after it has no effect

"Control shall be possible with acceptable control forces"

Note: this requirement is most severe for manual/reversible control systems

Requirement on control forces:

$$F = \boxed{G_e}\boxed{C_h}\frac{1}{2}\rho V^2\boxed{S_r \bar{c}_r}$$

proportional to:
- b
- c^2

Includes kinematics

From experience: only 30% accurate due to strong influence of boundary layer (and thus Re) on pressure distribution over control surface

High aspect ratio of the control surface.

Rudder Design (continued)

Some handling considerations

Control forces should be acceptable for reverse flight controls

The force should vary linearly with deflection and side-slip angle

$$C_h = C_{h_0} + \boxed{\frac{\partial C_h}{\partial \alpha}}\alpha + \boxed{\frac{\partial C_h}{\partial \delta}}\delta$$

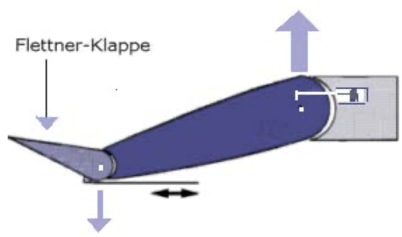
in practice: hardly ever constant

To reduce the force required, two options:

2. Horn balance:

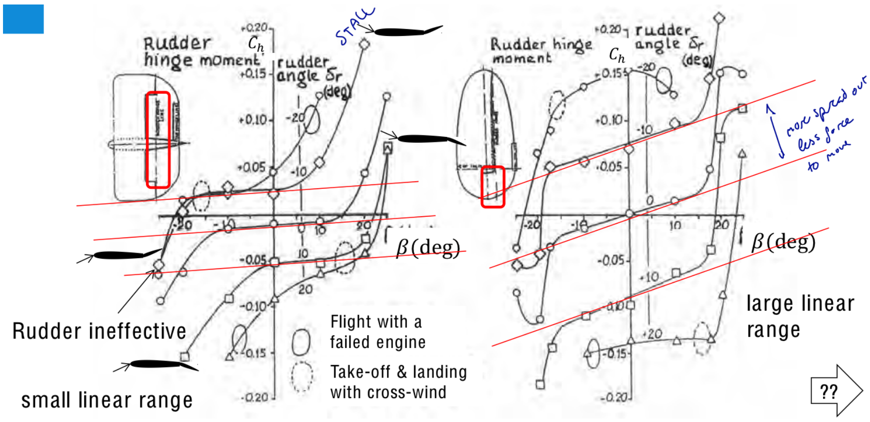
1. Balance tabs:

1



2

Hinge Moment



Q68: Why would a low hinge moment derivative be disadvantageous?

It can more easily cause overstressing of the airframe.

"They shall be able to handle high Mach numbers without flow separation"

Mach number at which extensive flow separation starts is above M_D for:

Control deflection necessary to correct for sideslip.

Common VT include:

5 deg higher ° than wing sweep

1 to 2 % less relative thickness than outward wing.

More considerations on vertical tail design:

High aspect ratio

Higher weight

For T-tails, the flutter analysis should be considered.

High taper ratio

Lower weight

Could lead to premature tip stall

aggravated with sweep unless leading edge vortex is formed

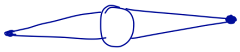
Sweep makes stall more gradual.

Rudder Design

Some <u>structural</u> considerations w.r.t. sweep angle:

- Aft spar of VT highly loaded when rudder deflected
- Thicker spar beneficial (effect on airfoil design)
- Compressibility effects at cruise Mach numbers requires higher sweep of the aft spar (and rudder!)
- Rudder effectiveness decreases with sweep (see chapter 30)
- Careful trade-off needs to be made to arrive at sweep angle

Tail surfaces



Result of analysis of requirements:

effectivity

high sideslip

- the aspect ratio should be high and low
- the sweepback should be high and low
- the taper ratio should be high and low

Summary

- The function of the vertical tail is to provide 1) a state of equilibrium, 2) stability, and 3) directional control
- The vertical tail needs to be effective and a have a high stall angle resulting in a compromise in sweep, aspect ratio, and surface area
- A dorsal fin sheds a stable vortex under large sideslip angles resulting in an increase in stall angle and a rudder that remains effective up to the stall angle
- Horn balances and servo tabs reduce control force required to deflect the rudder
- Large forces at the rudder hinge line could require the thickest point on the airfoil to be positioned more aft

---

Control Surfaces

Control Surface Design

Functions:

- Provide a mean to achieve equilibrium
- Allow for maneuvering in pitch, roll and yaw in all flight conditions
- Counteract gusts for flight path tracking.

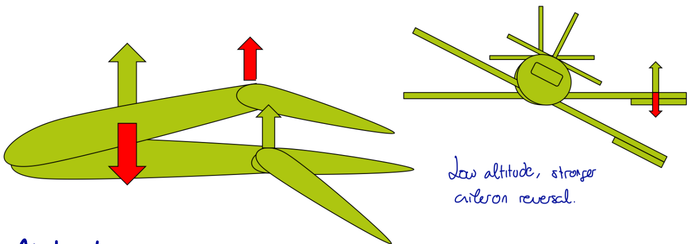
Requirements:

- High deflections without separations
- Linear behaviour over entire range of deflections

Aileron Design

Q6a: Why the aircraft roll oposite to input? AILERON REVERSAL

Due to the elastic wing structure, the aileron deflection caused an opposite local angle of attack.



More on sweep flexible wings!

Sweep back.

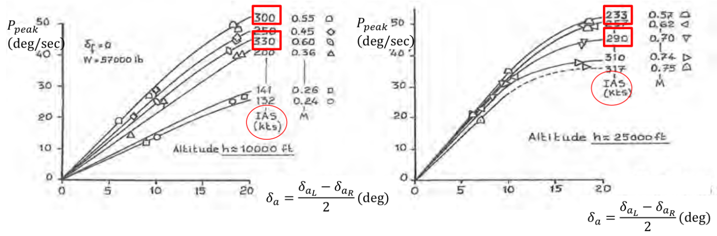
At high q, small changes in deflection cause large forces: problem!
Torsional stiffness remains the same though.
} Control reversal.

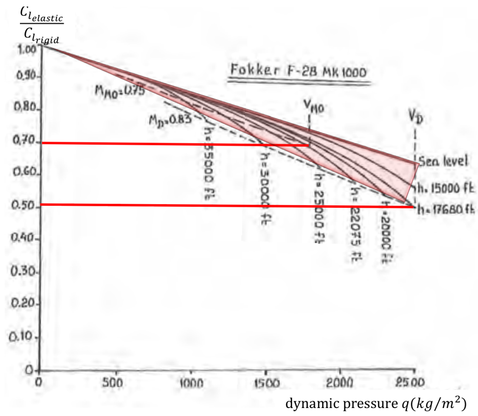
High aspect ratio wings have this problem, which means that a heavier structure will be required. Geometric twist

Sweep increases susceptibility to aileron-induced wing bending. Aerodynamic twist.

Aileron Design (continued)

Result on peak roll rates:



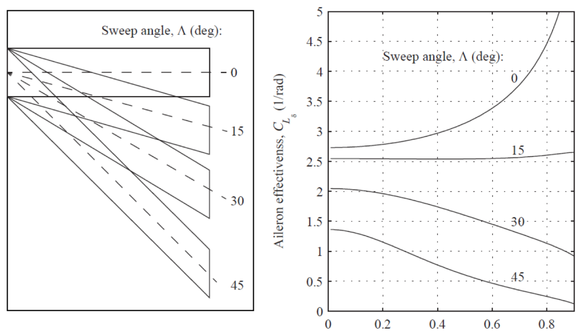


Linear effect of dynamic pressure

Increasing the Mach results in compressibility effects.

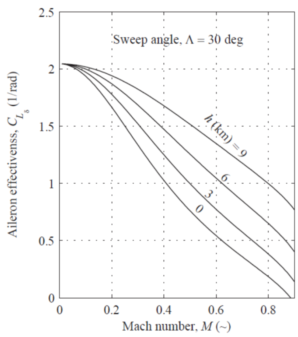
Beyond the M_{MO} shock waves in combination with flow separation.

Infinite torsional stiffness assumption:

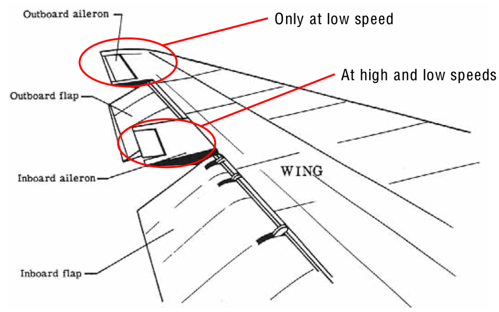


Assumption: infinite torsional stiffness

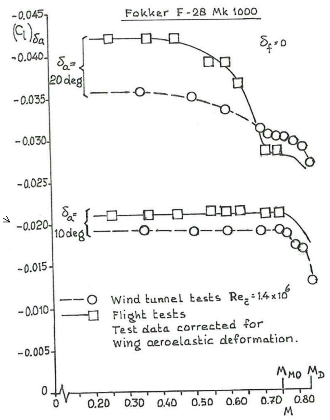
Most optimal is 0 angle sweep. Else the aileron maintains it or reduces the effectiveness.



Effectiveness is also reduced with altitude



Reynolds effect:



Higher Re the lower the effectiveness.

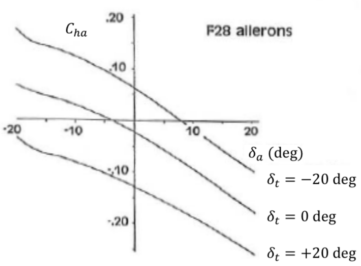
Other way to increase efficiency of ailerons is to install vortex generators. Aerodynamic fix not design.

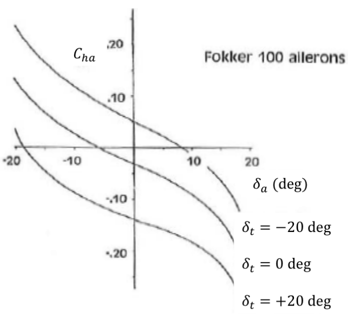
Prevents:

- L-E separation
- Separation at the foot of shock wave
- Separation at hinge line.

On the rudder, we have to make sure that no fin stall or rudder lock occurs. When the aircraft is rolling.

Hinge Moment coefficients

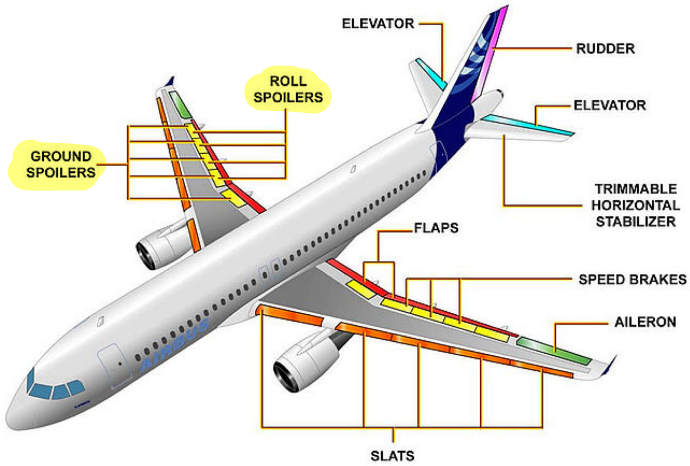




SPOILERS spoil the flow over the wing and reduces lift, increases drag, changes pitching moment

Functions:

- Roll control
- Speed brakes
- Lift dumpers
- Load alleviation



Spoilers decrease lift to ensure appropriate contact with the ground, so that the wheels can brake.

You can have closed shroud spoilers or open shroud spoilers.

Closed shroud spoilers

Fokker 100

Open shroud spoilers

Airbus 310

Open shroud spoilers show strong non-linear behavior

The control response is dependent on angle of attack and flap angle

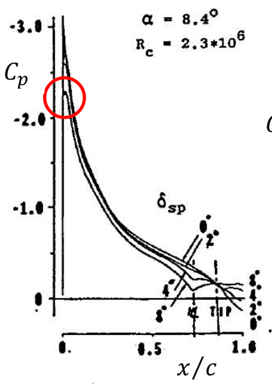
Closed shroud spoilers aim to decouple the response from flap deflection

Separated speed brakes decouple the airbrake function from the other spoiler functions and from the lift generation

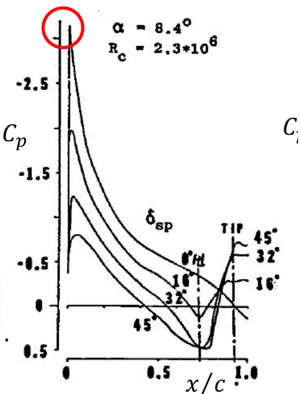
Most current transport aircraft accept the disadvantages of open shroud spoilers because of reduced hardware complexity

EFFECT OF SPOILERS

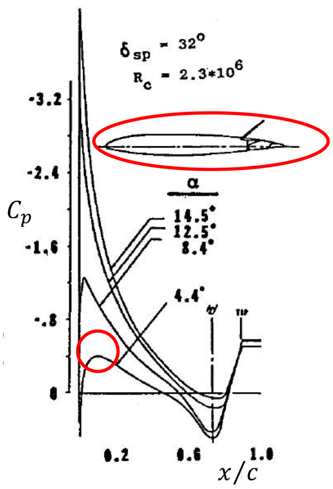
Upper surface pressure distribution // when α changes for a deflection:



Small Spoiler deflection



Large Spoiler deflection

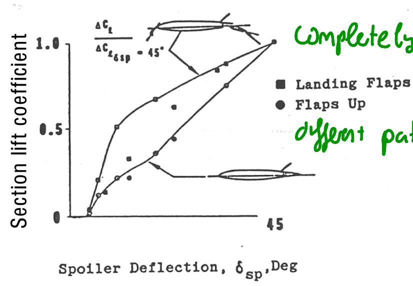


Angle of Attack

EFFECTIVENESS

Coupled to flap deflection

Highly non-linear when flap is deflected.



Completely different paths.

FUNCTIONAL INTERACTIONS

Deflection to achieve roll control also affects overall lift.

Deflection to brake also affects lift and pitching moment

Deflection to dump lift can also produce large pitching moments that increase or decrease nose wheel-load.

Complex mixing required:

Spoilers (continued)

Design Considerations:

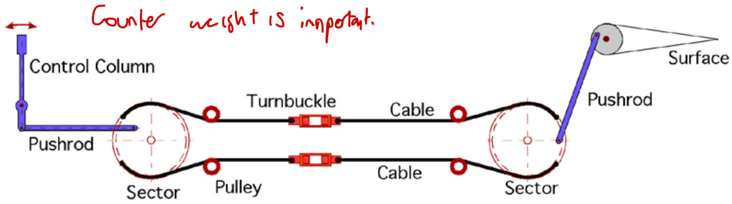
- Strong interaction btw spoiler functions
- Forces and moments are non-linear with:
  - Spoiler and flap deflection
  - Angle of attack
  - Mach number
  - Dynamic pressure
- System redundancy requires multiple spoiler panels
- Complex mixing schedules are required.

Control Surface Actuation

Until begin of WWII cable or push-pull-rod system. Advantages:

- Reliable
- Good feedback (fully reversible)
- Uncomplicated

Counter weight is important.



Disadvantages for fast or large aircraft.

- High degree of aerodynamic balancing has to be developed.
- Static aero-elastic deformation effects can introduce slack.
- To prevent flutter, large counter weights are required.

Booster systems

- Mixture of manual and hydraulic control systems.
- Pilot's control forces are multiplied by hydraulic actuators.

Advantages:

- Fully reversible
- Control forces lowered
- But variations still remain

Fully irreversible hydraulic control systems:

- Control surfaces actuated through one or more hydraulic actuators.
- Pilot controls hydraulic actuators
- The forces are delivered to the pilot by a feel unit.

  Comprises of a spring box; sees the pilot stick displacement.

  Velocity feedback through the free stream dynamic pressure.

Less reliable:

Multiplex systems for redundancy.

Fly by Wire

Electronic Signaling:

Directly relating cockpit controls with surface actuators. Not with mechanical cables but electric.

Full fly by wire:

Pilot controls a certain normal acceleration or pitch or yaw rate with the system computing the required control deflection. Allows for operational safety limits. (Airworthiness requirements on:)

- $C_{L_{max}}$
- $F_{\delta_{min}}$
- M_{MO} and M_D
- C_g range.

The deflection **rates** of primary and secondary control surfaces (slats, flaps, speed brakes) should be as follows:

- The deflection rates should be high enough to give the pilot a feeling that he is really "in control" of the aircraft.
- Typically, full control surface deflection should be achieved in 0.4 to 0.5 second for roll control surfaces and 0.6 to 0.8 second for pitch and yaw controls.
- For primary control surfaces, this means that they should have deflection rates of 50 to 60 deg/sec and 35 to 45 deg/sec respectively.

The deflection rates should be **high** enough to compensate for trim changes occurring in normal operation. This applies to elevators but more in particular to stabilisers. The latter require trim rates of about 0.5 deg/sec at low speed and 0.15 to 0.2 deg/sec at high speed.

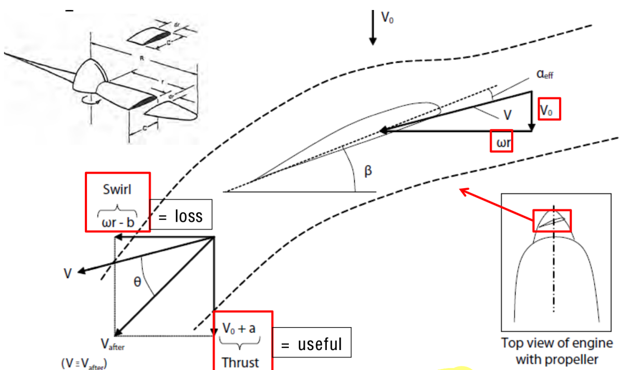
However, stabilisers and flaps should have sufficiently **low** deflection rates so that the pilot can cope with the trim changes caused by flap deflection or change in stabiliser setting. These trim changes may be deliberate (for example flap extension or retraction) or due to inadvertent operation. (for example a "run-away" on a trimmable stabiliser).

Summary

Structural flexibility reduces aileron effectiveness
Spoilers or inboard ailerons can be utilized for roll control at high q conditions
A large coupling exists between roll and yaw leading to potentially high sideslip angles in some flight conditions
Spoilers can be used for speed braking, lift dumping, roll control and load alleviation
Spoilers have a nonlinear behaviour due to the fact that they induce flow separation
Control surface actuation can be done by means of manual, boosted, hydraulic, or fly-by-wire control systems
All hydraulic systems require redundancy resulting in complex flight control svstem architectures

PROPELLER SLIPSTREAM EFFECTS

SLIPSTREAM EFFECTS

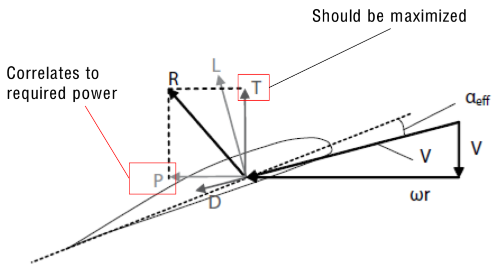


Basic propeller theory

That was the basic propeller theory, in reality it is more complex:

- Radial velocity varies with span
- Finite blade span causes induced velocities
- Multiple blades cause induced velocities

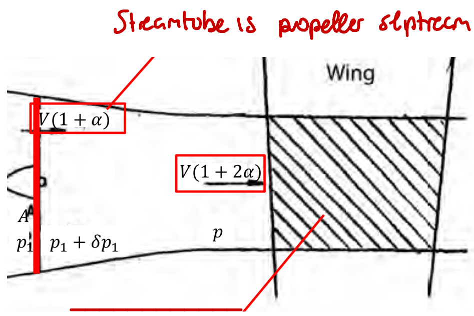
Thrust should be maximized:



After the propeller the flow is:

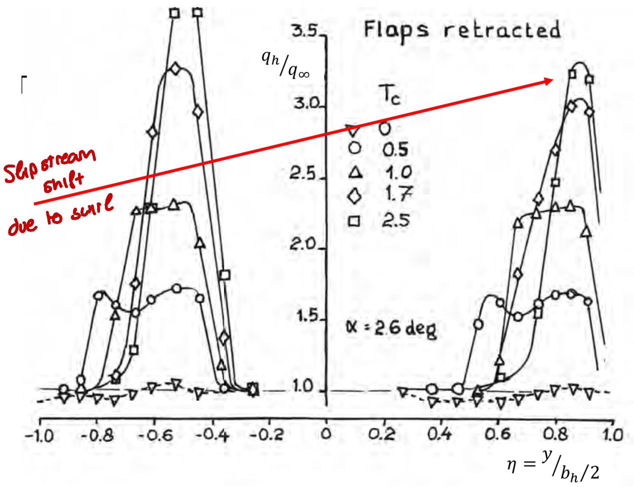
Not homogeneous
Different pressure distribution
Lift, drag and pitching moment altered
Contracted

Streamtube is propeller slipstream

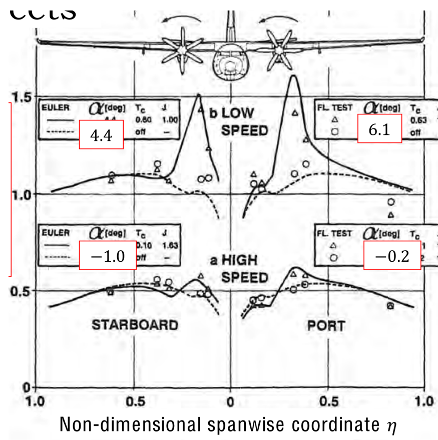


LONGITUDINAL STABILITY

Dynamic pressure at Horizontal Tail



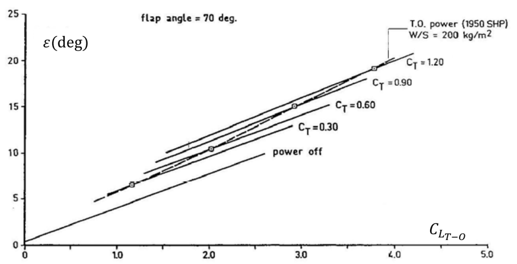
The propellers create an increase in α in the wing behind



On one side counteracts the effect on lift by q.

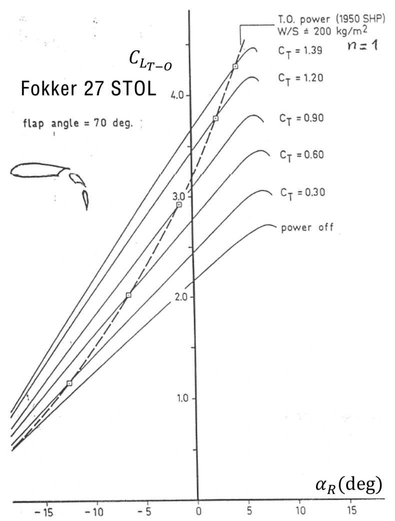
On the other side it reinforces the effect on lift by q.

Downwash increases constantly when C_T increases. Not the slope but just the offset.



Constant change of downwash with tail-off lift coefficient
Slope is independent of thrust coefficient

If the T.O. power is increased the C_L increases.
Increase in $C_{L_{max}}$ and C_{L_α}



Slipstream Effects (continued)

What is the effect of C_T on stability $dC_m/d\alpha$?

We need $d\varepsilon/d\alpha$

Observations

$$C_{L_\alpha} = \left(\frac{dC_L}{d\alpha}\right)_{C_T=0}(1 + k\cdot C_T)$$

$$\frac{dC_L}{d\varepsilon} = \text{constant}$$

$$\underbrace{\frac{d\varepsilon}{d\alpha} = \frac{d\varepsilon}{dC_L}\cdot\frac{dC_L}{d\alpha}}$$

$$\left(\frac{d\varepsilon}{d\alpha}\right)_{C_T=constant} = \frac{d\varepsilon}{dC_L}\left\{\left(\frac{dC_L}{d\alpha}\right)_{C_T=0}(1 + kC_T)\right\}$$

Q70: When kC_T becomes larger:

The tail effectiveness is reduced and the airplane becomes less stable.

NOT GOOD

$$C_{m_{\alpha_{stick-free}}} = C_{L_{\alpha_{wf}}}\left(\bar{X}_{c.g.} - \bar{X}_{ac_{wf}}\right) - C_{L_{\alpha_h}}\eta_h\frac{S_h}{S}\left(\bar{X}_{ac_h} - \bar{X}_{c.g.}\right)\left[\left(1 - \boxed{\frac{d\varepsilon}{d\alpha}}\right) + \tau_e\frac{\partial\delta_e}{\partial\alpha}\right]$$

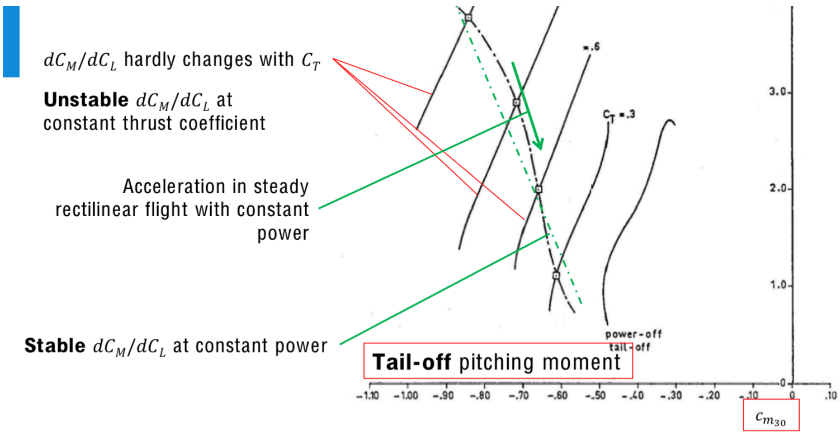
Increase in C_T has a destabilizing effect.

Two types of longitudinal stability exist.

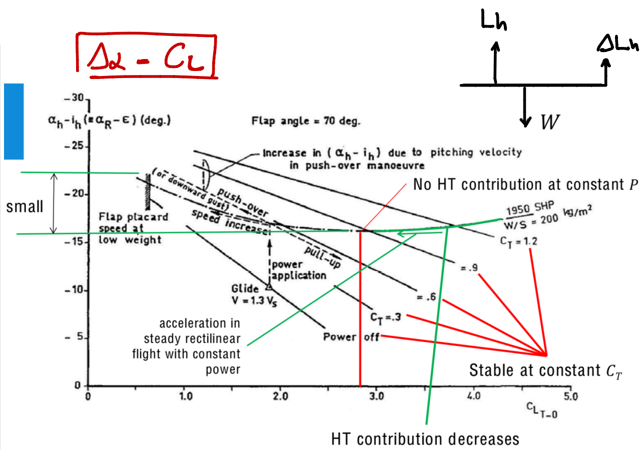
The response to $\Delta\alpha$ at constant C_T

The response to $\Delta\alpha$ due to change in speed and C_T.

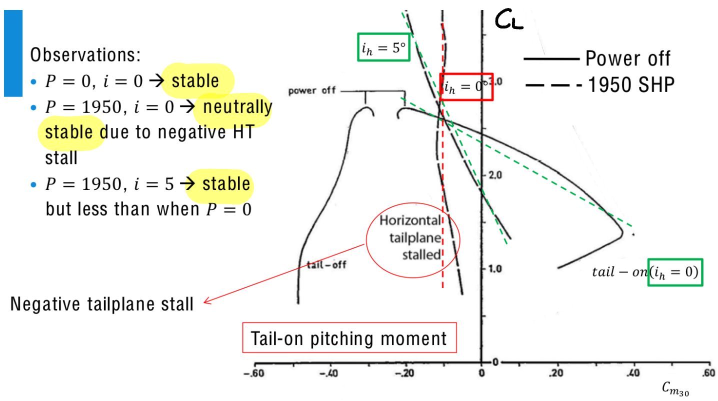
$C_L - C_m$



$\Delta\alpha - C_L$



$C_L - C_m$ for different powers and incidence of tail.



Negative tailplane stall cause and effect:

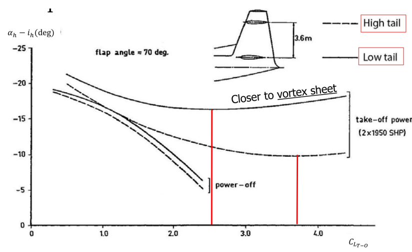
- High power, large flap deflection and low speed causes large downwash angles
- Very large negative angles of attack at HT
- Flow separation happens.

Possible solutions:

Modify HT leading edge with negative camber

Change i with flap settings.

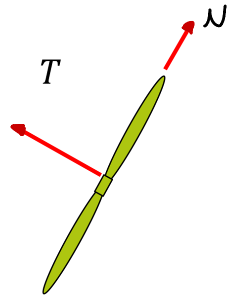
Change to T-tail configuration.



Slipstream Effects (continued)

1. Propeller Forces:

- Thrust increase might be destabilizing depending on position w.r.t the c.g. Important at low speeds when Thrust is at maximum. T
- The propeller normal forces (CNp) will become quite substantial if the propeller is at a high effective angle of attack. Since the point of application is usually ahead of the center of gravity. Destabilizing effect. N



2. Increase in wing lift, tail-off pitching moment and downwash.

The increase in local wing lift due to the slipstream causes an increase in downwash behind wing.
Increase in wing lift, increase the tail-off pitching moment in nose down.

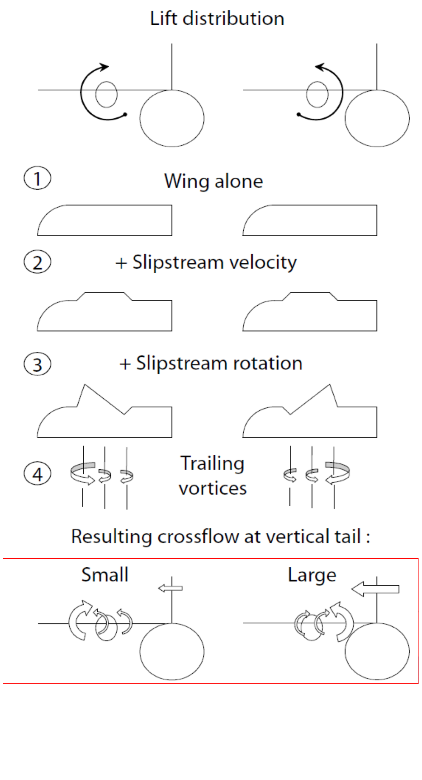
3. Change in horizontal tail lift due to the increased dynamic pressure in the slipstream.

If the horizontal tail is partly or completely immersed it will experience a higher average dynamic pressure.
This will increase the effectiveness and thus the stability.

4. Oncoming flow at HT differs from undisturbed flow due to:

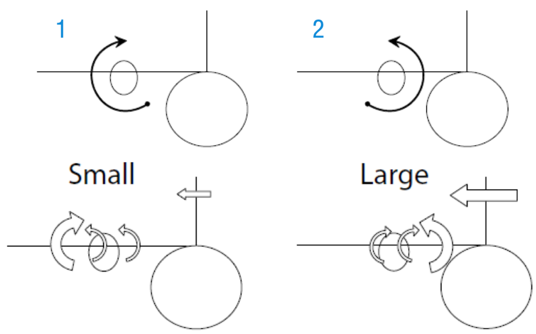
1. The wing and engine nacelle wake: lower average dynamic pressure. Lower effectiveness at high α if stabilizer is in the wake.
2. The propeller slipstream: increased dynamic pressure. Might increase effectiveness or complicate it.
3. The downwash: consequence of lift.

Directional Equilibrium



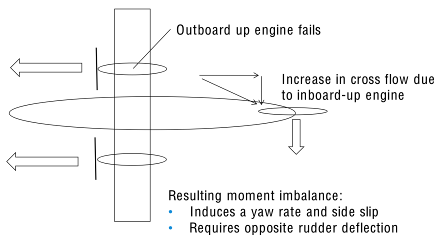
- Effect on directional equilibrium due to cross-flow.
- Cross flow introduced through assymetric lift distribution.
- Assymetric lift distribution caused by propeller swirl.

Q31: For a twin-engine prop with co-rotating props, which engine is critical wrt to fin design? Considering OEI condition.



The 2, inboard up rotation, larger slipstream on vertical Tail.

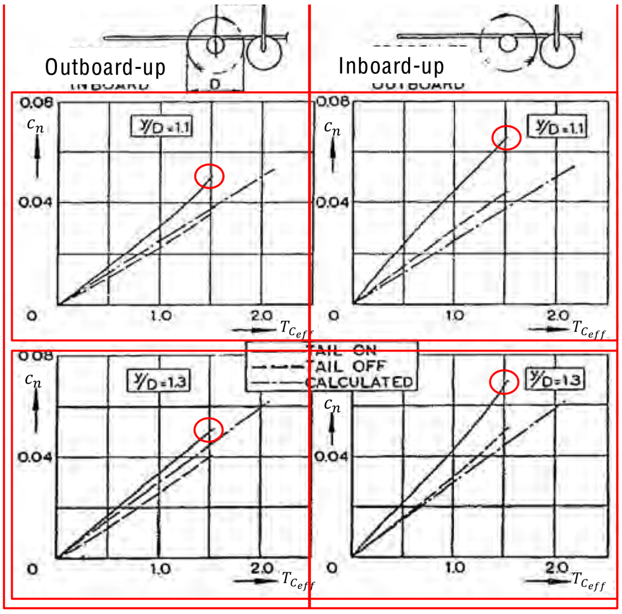
- Results in yaw rate and side slip
- Requires opposite rudder deflection.



Slipstream Effects (continued)

The effect on yawing due to propeller rotation depends on:

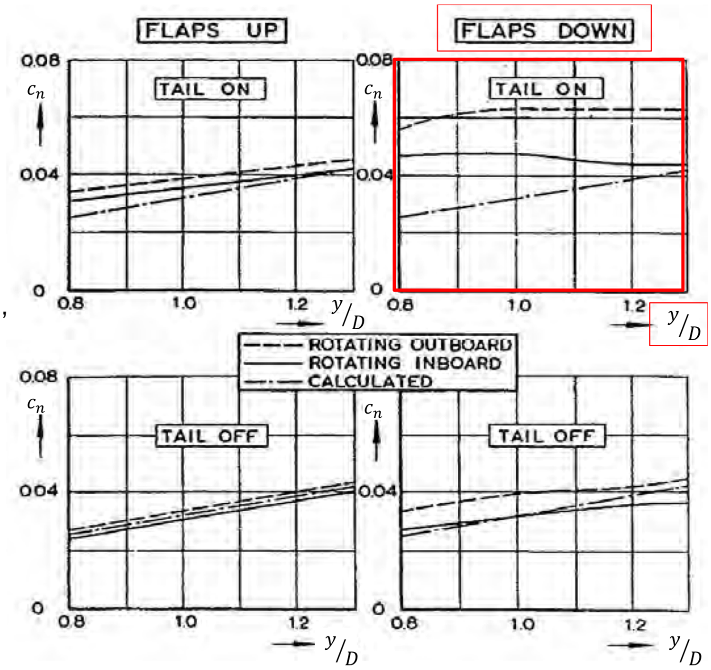
- Engine spacing, y/D: Cross-flow damps effect of spanwise engine position on C_n.
- Direction of rotation:



Flaps increase downwash vortices and cross flow

C_n is constant with y/D for flaps down and tail on

These effects are lower for low wing aircraft



Critical situation for directional equilibrium: Flaps down, outboard-up engine fails.

Large crossflows occur independent of tail size.

Larger VT causes a larger yawing moment at $\beta = 0$

Balance between: Moment from O.E. and moment by sideslip and rudder deflection.

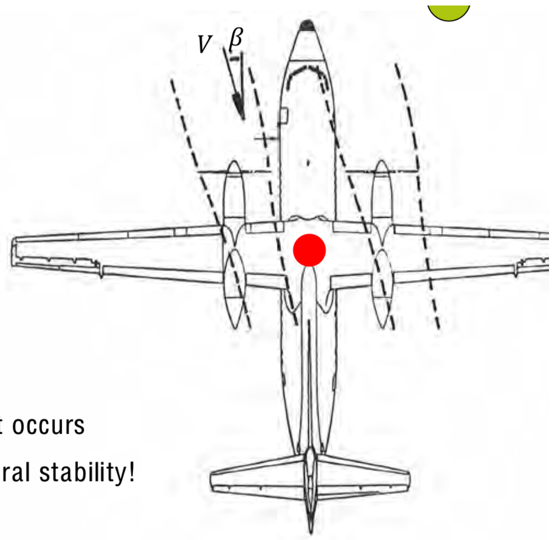
Lateral Stability

Power application results in:

- Asymmetric lift distribution
- Rolling moment
- This can be trimmed

When $\beta > 0$

- Center of lift shifts laterally
- Destabilizing rolling moment occurs
- For high P, this reduces lateral stability!



ENGINE INTAKES

FUNCTIONS OF INTAKE:

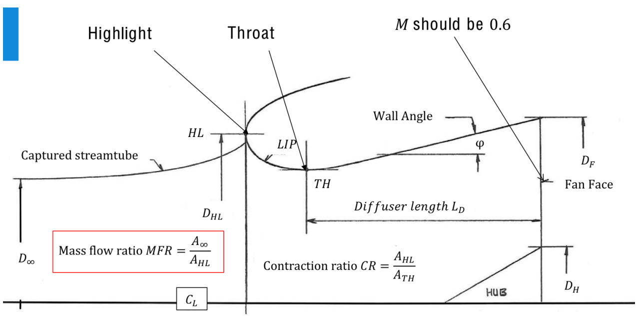
- Decelerate flow to approximately $M = 0.6$
- Raise the pressure in the flow in high speed conditions.
- Avoid shocks or separated flow.
- Minimize loss in total energy of the internal flow

INTAKE MUST DELIVER LARGE AMOUNT OF AIR TO THE ENGINE OVER A LARGE ENVELOPE OF OPERATING CONDITIONS:

- M 0 to 0.9
- α −5 to 20 degrees
- large mass flow dimensions

Q72: Why is total pressure recovery important for engine efficiency?

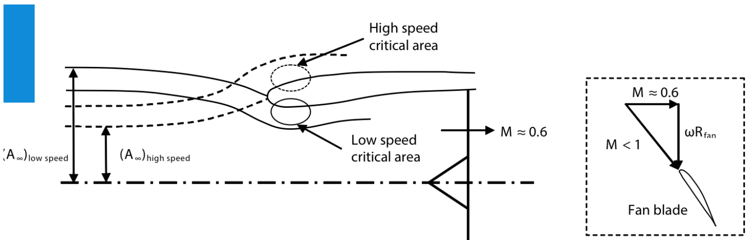
NOMENCLATURE



INTAKE DESIGN DRIVERS

- Cruise conditions
- Take-off conditions
- Wind milling condition

ENGINE INTAKES

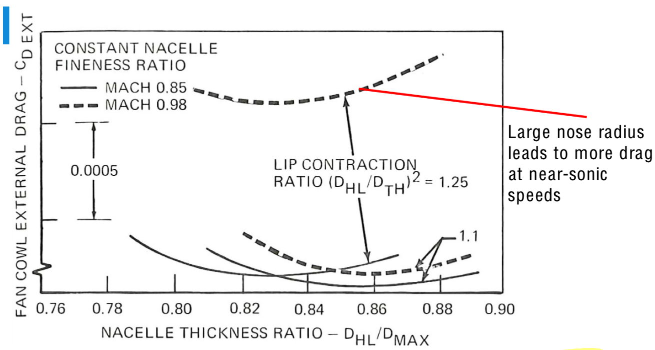


- Mass flow and speed determines streamtube diameter
- Fan RPM is compromise btwn turbine and fan
- Fan tips may be supersonic ($M_{tip} = 1.15$)
- High speed at fan increases helical tip Mach.

INTAKE DESIGN REQUIREMENTS

CRUISE:

- MFR <= 1.
- Supervelocities on the outside of intake will be critical
- Cross section of streamtube is independent of intake
- Mass flow varies greatly with engine setting, altitude and airspeed.



REQUIREMENTS ON GEOMETRY

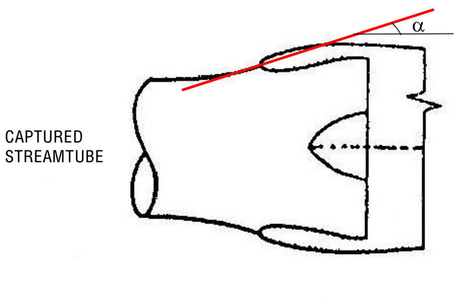
Area should be tailored to required mass flow.

External cowling should prevent strong shock waves from occurring

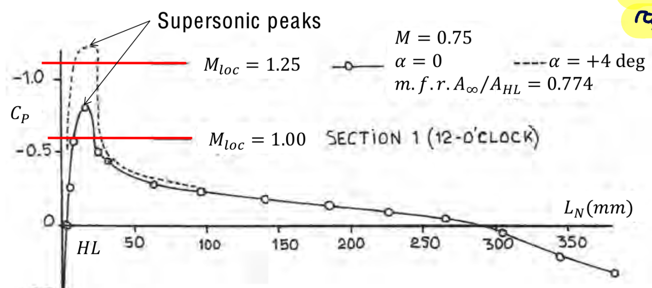
Thin lip are required!

DESIGN FOR HIGH SPEED OPERATION

Design condition: streamtube diameter ≤ throat diameter



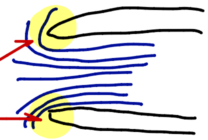
HIGH-SPEED FLIGT



Example: 767 shock on intake

AT LOW SPEEDS:

- MFR > 1.0
- Highest supervelocities occur near the throat area.
- Velocity distribution over throat not uniform, near the wall

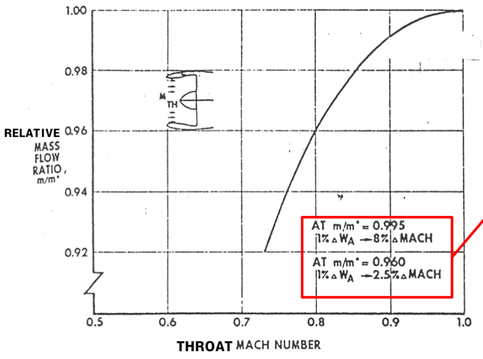


- If $M_{TH} > 0.8$ large decrease in total pressure recovery and efficiency
- Maximum M_{TH} is critical at low speed because the required engine mass flow is largest at T-O.

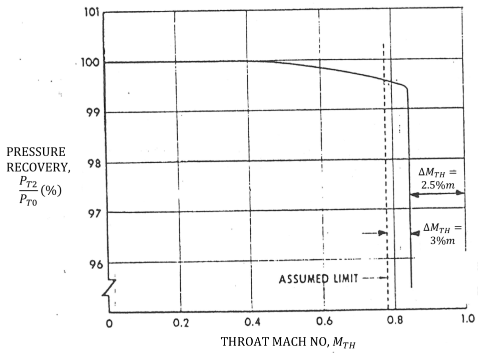
M_{TH} = Mach throat
MFR = Mass flow ratio

Requirement on interior intake geometry:

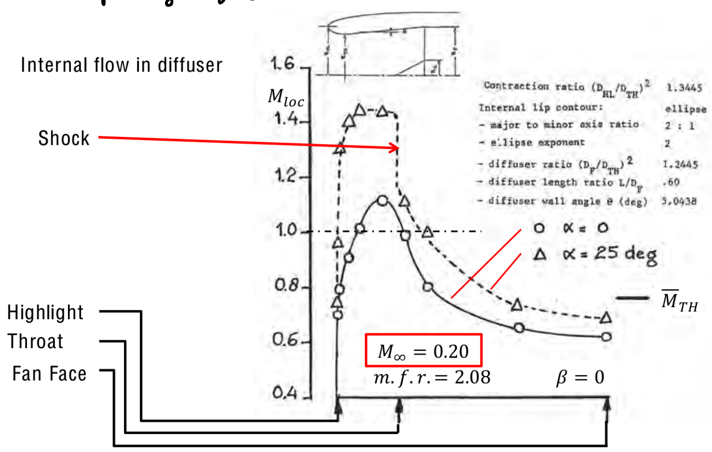
Average throat Mach number should be limited to $M_{TH} < 0.8$ to prevent shock waves.



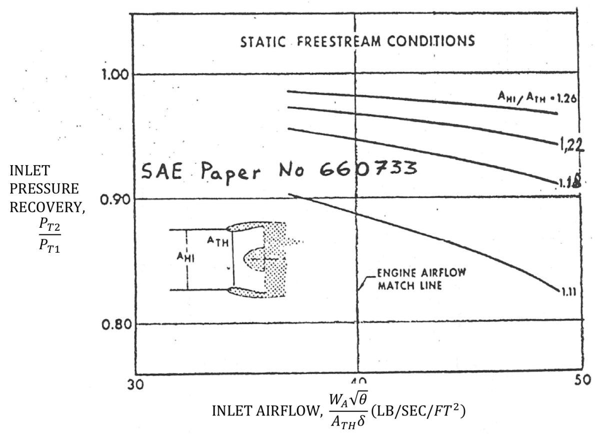
- Mass flow ratio $= A_\infty / A_{HL}$
- The relative mass flow ratio is the actual MFR divided by the MFR for $M_{TH} = 1$
- Close to $M_{TH} = 1$ the flow is very sensitive to small mass flow changes



Example of engine with and without shock



Inlet pressure recovery vs mass flow.

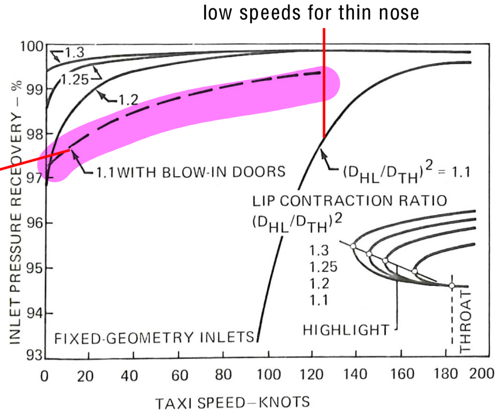


Q73: Why does the pressure recovery improve with larger contraction ratios?

LOSS OF TOTAL PRESSURE

Second cause for loss of total pressure: separation at the lip. At t-o and low speed flight.

Bad pressure recovery at low speeds for thin nose

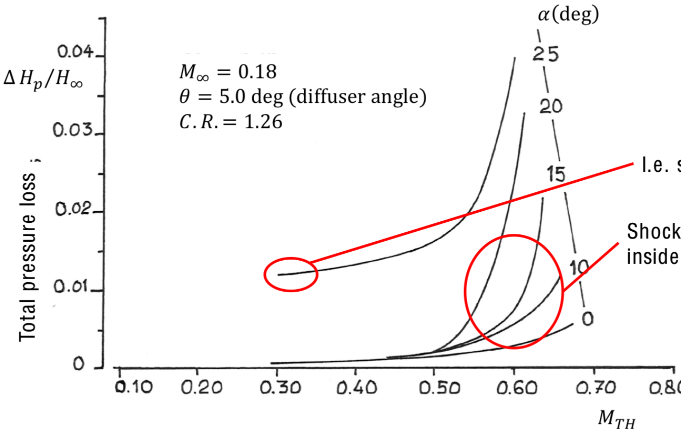


Auxiliary doors could solve.

Blow-in doors

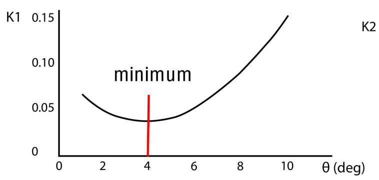
Trapdoors installed in the intake that allow for the air to flow in.

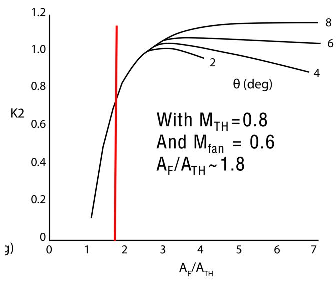
Inlet Diffuser Design



Stall generates pressure losses

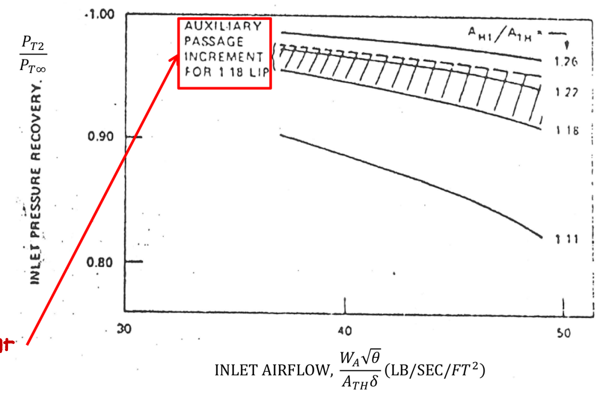
Diffuser loss $= k_1 \cdot k_2 \cdot M_{TH}^2$





Observations:

- Intake areas should be sized with a margin for variations in the maximum airflow:
  - Thrust and mass flow may increase over the engine development lifetime.
  - Mass flow req. may not be fixed when the nacelle design should be frozen.
- Result: Increase nacelle weight and drag.
- Alternative: Use blow-in doors to allow increase of mass flow. These actuate when aditional flow is required after $M_{TH} > 0.8$



Improvement

Q74: Why do rear-mounted engines have an increased incidence angle?

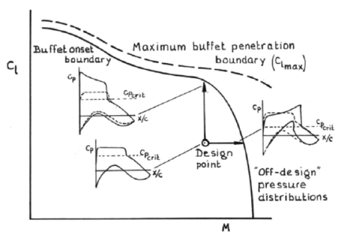
To align intake and the engine nacelle with the local flow direction.

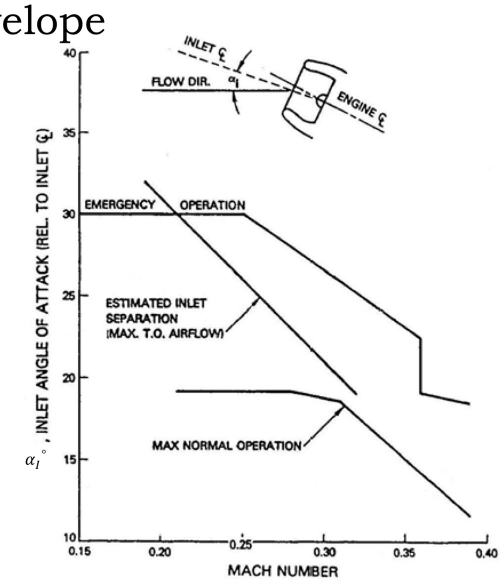
Inlet Droop

- Aligns intakes with local flow at cruise (upwash of wing)
- Maximizes intake efficiency at full thrust.
- Minimizes the cowl drag when engine fails.

Inlet design envelope

Note the similarity with the wing buffet onset boundary!



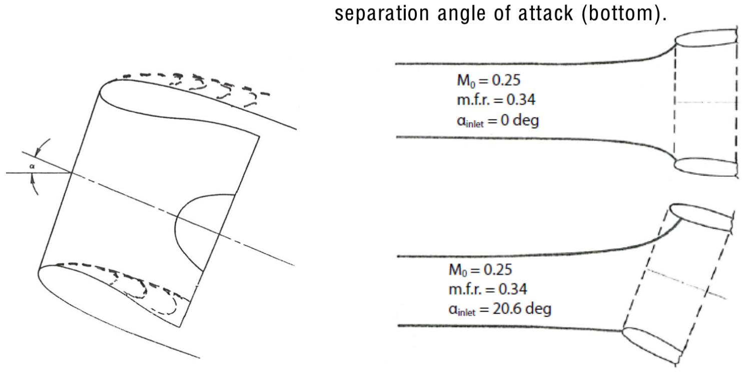


O.E.O. Flight

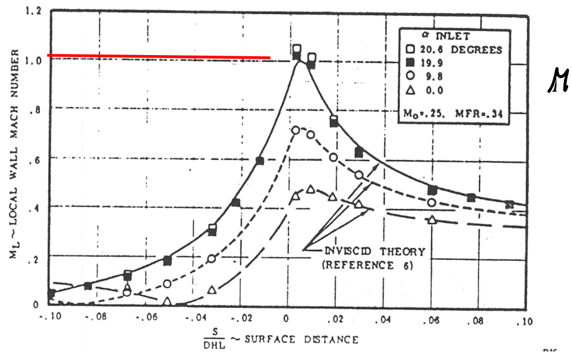
- Meet second segment climb gradient requirement
- Condition: low speed, high α, high β
- Aditional drag due to:
  - Larger rudder deflection
  - Windmill, blocked engine
  - Increased forebody drag.

Wind Mill Condition

Inlet flow field for windmill condition at zero angle of attack (top) and near separation angle of attack (bottom).

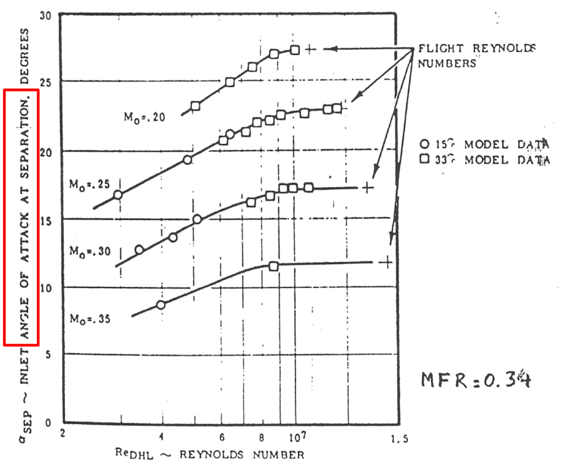


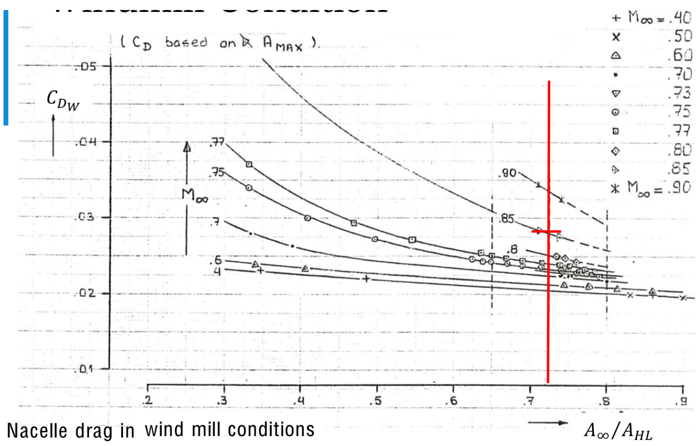
Local mach numbers around inlet lip in windmill condition.



$M = 0.25$

Separation is dependent on Re and Mach number.





Nacelle drag in wind mill conditions

Inlet Testing

Pg. 44 of Engine Intakes

Summary Inlet Design

- A turbofan inlet has to function under widely differing operating conditions
- A proper compromise results in very little cruise efficiency loss and benign low speed handling, with good tolerance to mass flow variations and angle of attack variations
- A first design loop can be done with simple design tools, providing basic geometry characteristics, based on one-dimensional flow and throat Mach number criteria
- Inlet testing can be done with test rigs based on flow-through nacelles: this provides useful info on internal and external flow
- Full CFD analysis and turbine-powered-simulation nacelle testing provide the final results

Engine Exhaust and Reversers

Engine Exhausts - Nozzle

Function:

To convert the energy supplied by the engine into kinetic energy by means of expansion.

- Decrease of static pressure
- Decrease of static temperature
- Decrease in density
- Increase in velocity
- Increase in momentum

Optimum configuration determined by:

- Boundary layer internal and external flow.
- Axial velocity over each cross-section
- Rotation in the exhaust
- Not one-dimensional flow
- Mixing at the flow boundaries between external and engine exhaust flow and between the fan and the core flow.
- Mixing may be forced (reduce noise)

Exhaust Efficiency Coefficients

To incorporate the above mentioned effects, the following coefficients are used.

Velocity flow coefficient

$$C_V = \frac{V_{actual}}{V_{ideal}}$$

Mass flow coefficient
Discharge coefficient

$$C_D = \frac{\dot{m}_{actual}}{\dot{m}_{ideal}}$$

Actual speed

$$V_{actual} = \frac{F_{actual}}{\dot{m}_{actual} \cdot \cancel{V_{ideal}}}$$

Nozzle thrust coefficient Loss of gross thrust through the core and bypass nozzles

Jet

$$C_T = \frac{F_{actual}}{F_{ideal}} = C_V \cdot C_D$$

Turbofan

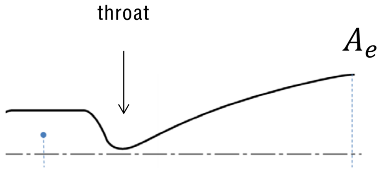
$$C_T = \frac{(F_{actual})_{fan+core}}{(F_{ideal})_{fan} + (F_{ideal})_{core}}$$

Unchoked Nozzle: $\frac{P_0}{P_T} > 0.528$ (cold flow) $\frac{P_T}{P_0} < 1.89$

$$V_{ideal} = \sqrt{\frac{2\gamma R T_T}{\gamma - 1}\left[1 - \left(\frac{p_0}{p_T}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

$$\dot{m}_{ideal} = A_e p_T \sqrt{\frac{2\gamma}{\gamma-1}\frac{1}{RT_T}\left[\left(\frac{p_0}{p_T}\right)^{\frac{2}{\gamma}} - \left(\frac{p_0}{p_T}\right)^{\frac{\gamma+1}{\gamma}}\right]}$$

A_e = exhaust area
T = total or stagnation
0 = back pressure



Choked Nozzle: $\frac{P_0}{P_T} < 0.528$ (cold flow) or $\frac{P_T}{P_0} > 1.89$

$$V_{ideal} = \sqrt{\frac{2\gamma R T_T}{\gamma - 1}}$$

$M_e = 1$
A_e = exhaust area.

$$\dot{m}_{ideal} = \left(\frac{2\gamma}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}} A_e p_T \sqrt{\frac{\gamma}{RT_T}}$$

Nozzle Losses

Ideal nozzle	Real nozzle
238 kN (53,500 lb)	233.5 kN (52,460 lb) to 43.9°C
268 kN (60,200 lb)	262 kN (58,950 lb) to 30°C
272.5 kN (61,300 lb)	267.5 kN (60,100 lb) to 30°C
262.4 kN (59,000 lb)	257.4 kN (57,860 lb) to 35°C
252 kN (56,700 lb)	247.6 kN (55,670 lb) to 30°C
257.6 kN (57,900 lb)	253.1 kN (56,900 lb) to 32.2°C
233.5 kN (52,500 lb)	229.4 kN (51,570 lb) to 32.2°C
234.5 kN (52,700 lb)	229.8 kN (51,650 lb) to 32.2°C
257.5 kN (57,900 lb)	252.9 kN (56,850 lb) to 32.2°C

NET THRUST: difference btw gross thrust and intake momentum plus a pressure component.

$$T = \dot{m}_e (V_e - V_\infty) + A_e (P_e - P_0)$$

For high BPR engines, $\dot{m}_e$ is large and $(V_e - V_\infty)$ is small, while V_e and V_∞ are large.

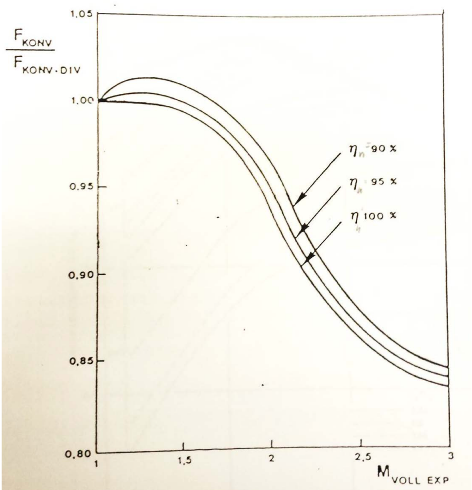
The thrust loss is much larger than the thrust coefficient suggest. Although C_T should be as high as possible.

Q75: What is the cause for non-ideal nozzle flow?

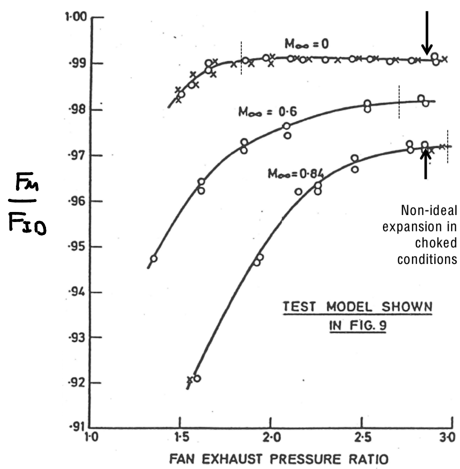
Non ideal flow due to mixing
Non uniform environmental pressure distribution behind the nozzle
The dissipation of total pressure through wall friction of nozzle
Nozzle flow deflection behind the nozzle

TESTING on page 19
ENGINE EXHAUST ...

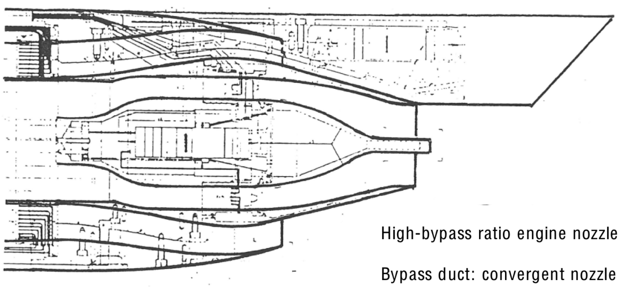
NOZZLE TYPES



FAN NOZZLE EFFECTS



FAN AND CORE FLOW INTERACTION

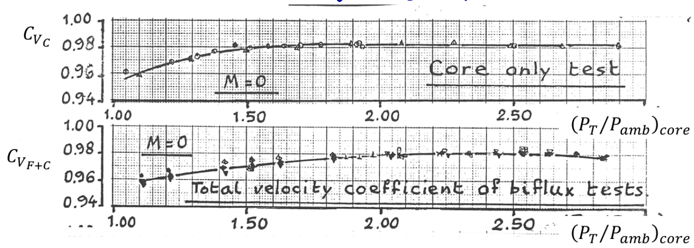


High-bypass ratio engine nozzle

Bypass duct: convergent nozzle

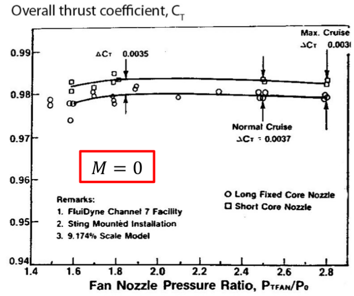
Core: con-di nozzle (1.5% div)

velocity coefficients



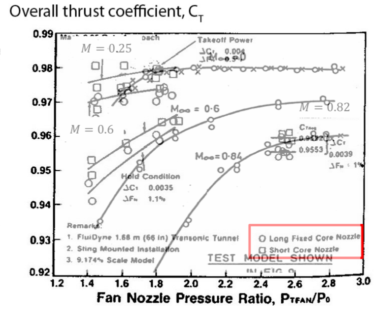
NOZZLE EXTENSION (REDUCTION)

Overall thrust coefficient, C_T



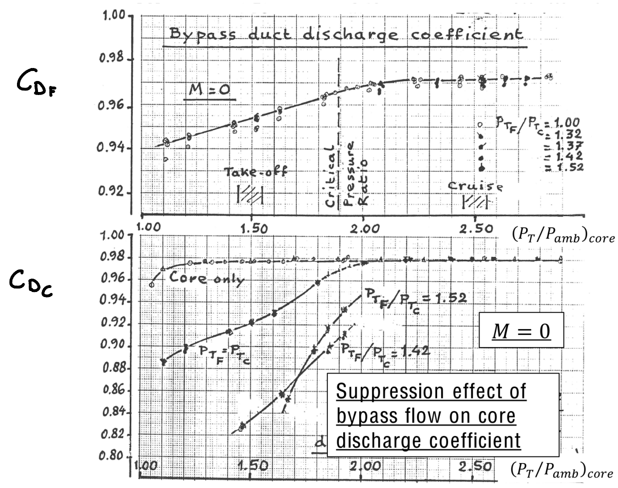
Scale model isolated nacelle static test data.

Overall thrust coefficient, C_T



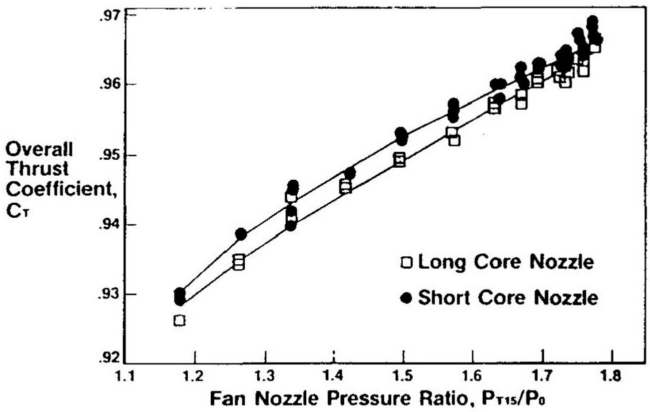
Scale model isolated nacelle wind-tunnel test data.

Mass coefficients

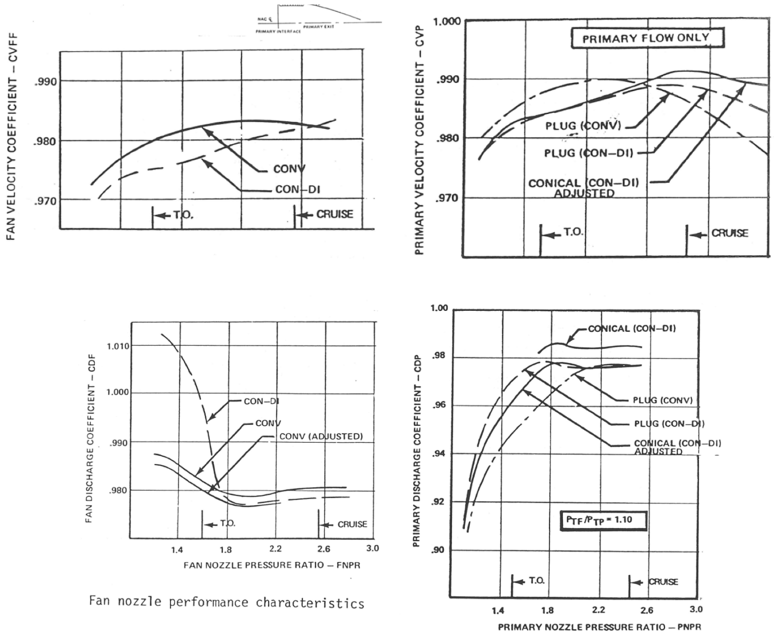


Nozzle Extension (reduction)

Unchoked conditions



Nozzle optimization



Fan nozzle performance characteristics

discharge coefficients

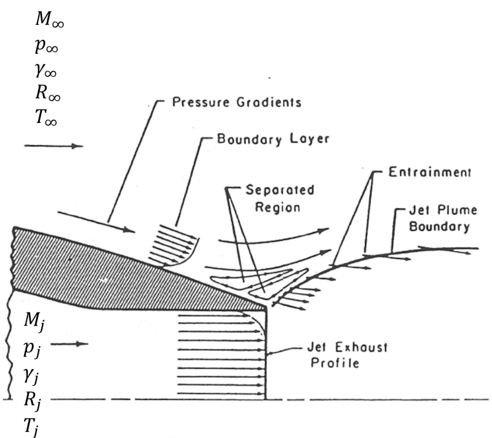
Primary nozzle flow suppression/ performance characteristics

Testing of exhausts

Nozzle performance depends on P_0

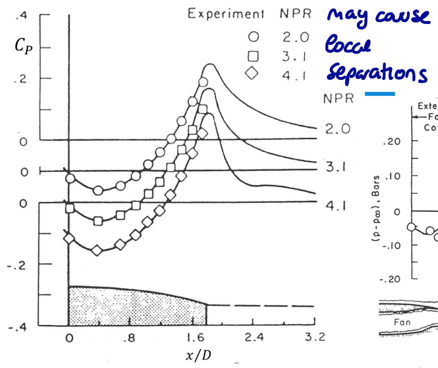
Dedicated flight test required to measure performance

Boattail Drag

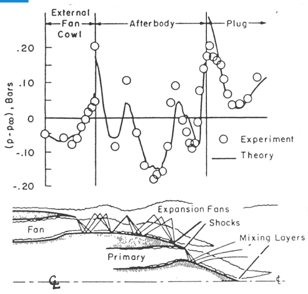


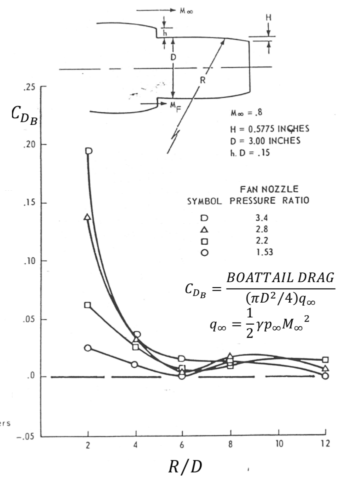
Schematic of nozzle aftbody flow.

Supercritical core exhaust pressure ratio: may cause local separations



Comparison of predictions with experiment.





Noise Damping

Achieved by mixing the core flow with the fan flow.

Convoluted or lobed mixers can be used within cowlings.

Chevrons to damp noise:

- Less thrust loss due to lack of internal mixing.
- Smaller cowlings required
- Also mixing of fan with external flow.

Summary

- Turbofan exhaust design involves fan flow and core (primary) flow, which may interact
- Nozzles may be choked or unchoked
- Takeoff and cruise give different optimized shapes
- Applying slight converging-diverging may improve matching
- Nozzle losses in % of gross thrust lead to larger % loss on net thrust (may be factor 3)
- Nozzle external drag ("boat-tail drag") is sensitive to the nozzle external shape
- Much effort required to limit losses as far as practical

Thrust Reversers

Function:

- Decrease ground roll distance.
- Also for taxiing backwards

Types:

- Bucket- or target-type thrust reversers
- Petal type thrust reversers
- Cascade thrust reversers

Performance effects

Use of thrust reversers is not allowed to reduce the certified accelerate stop or landing distance on a dry runway. Because is not reliable enough. Possible engine failure and cross wind conditions.

↳ on wet conditions, allowed for certified runway.

Benefit: reduce brake wear and decrease ground roll distance on wet and icy or snow runway.

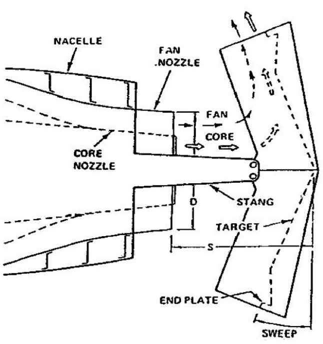
Disadvantages: heavy, expensive and maintenance prone.

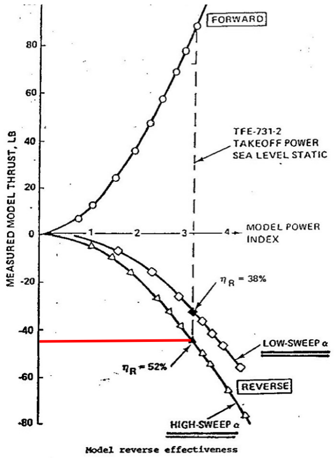
Design Goals

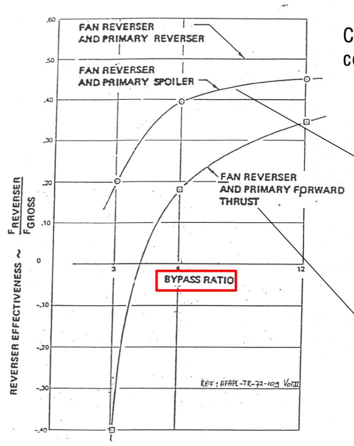
1. The maximization of reverse thrust
2. Minimizing of risk of ingestion of the hot exhaust gas and foreign objects.
3. The minimization of adverse effects on stability and control

Fan vs total flow reverse thrust

Target-type reverser for core and fan flow

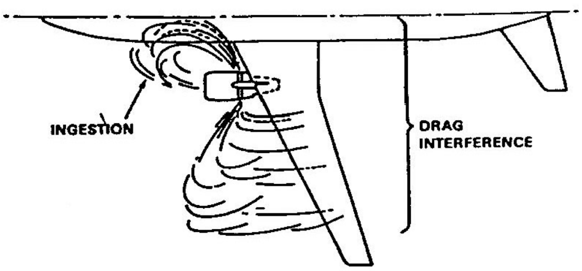




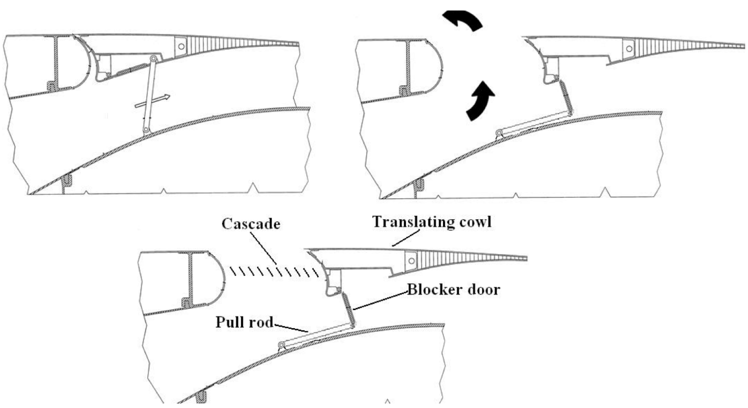


Cascade-type reverser for fan and/or core flow

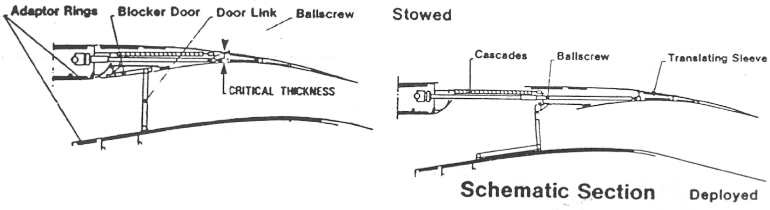
Reverser plume effects

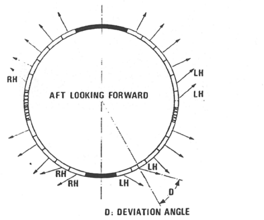


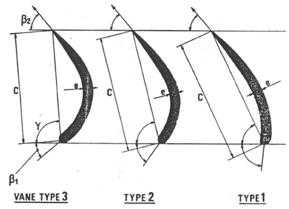
Cascade reverser principle

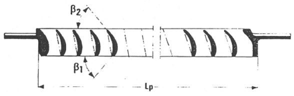


Fan Thrust Reverser



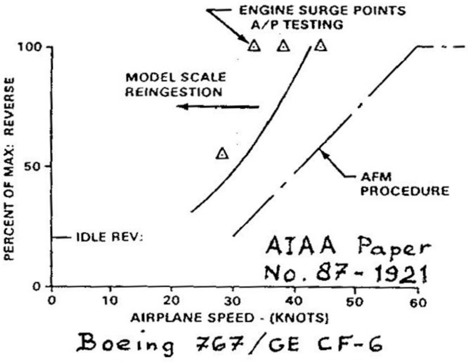






In the cascades, more spacing at the back than at front

Ingestion / Surge Limit



Comparison of Model to Full-Scale Ingestion/Surge Data

Target Type Thrust Reversers

- Less complex than cascade
- Only used for full flow and primary flow reverse
- Form part of the exhaust nozzle
- Less control over exhaust plume

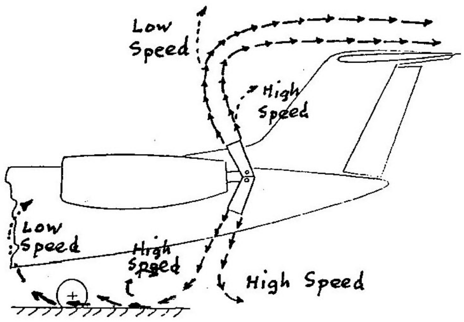
Rear-fuselage reversers:

- Lower rudder effectiveness
- Lower nose-wheel load, steering
- Effect on directional stability.

Clocking Thrust Reversers:

Q36: Why would one "clock" the thrust reverses?

To prevent ingestion of runway debris



Summary

Thrust reversers have no benefit in certified performance, but provide a secondary deceleration means: operational/safety benefit

Total-flow and fan-only-flow reversers are applied

Total-flow reversers are usually of the “target” type

Fan-flow reversers usually apply cascade type reversers: complex, but useful to direct the plume

Fan-flow reversers are only useful for bypass ratio 5+

- Less than 20% of thrust available for reverse
- But spoiling of idle thrust is also beneficial

Design effort required to minimize re-ingestion/FOD effects, and maintain directional stability

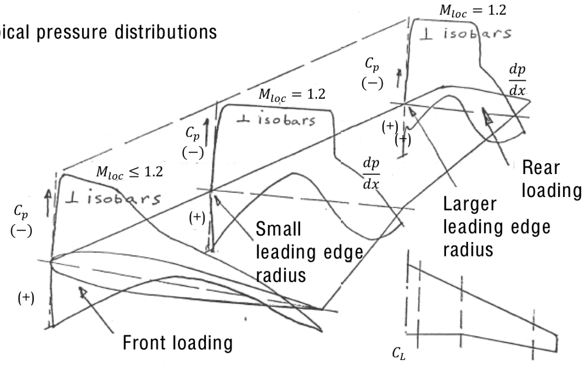
Target type reversers are part of the exhaust system, leading to extra constraints

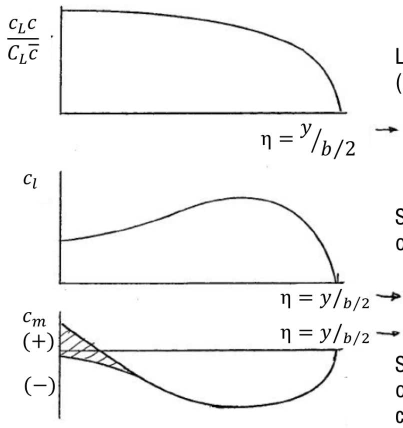
Last slides:

Examples of Modern Wing Design for High-Speed Transport Aircraft

Swept Wing Design

Typical pressure distributions





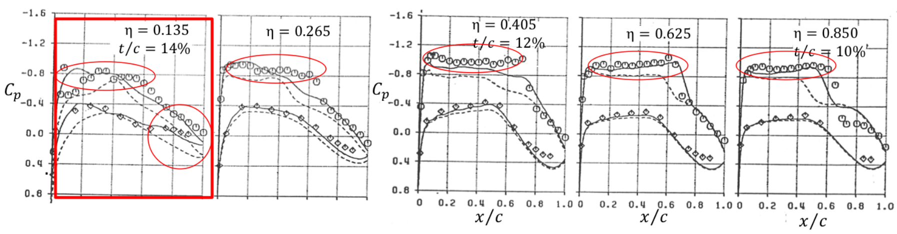
Lift distribution (circulation)

Spanwise distribution of lift coefficient

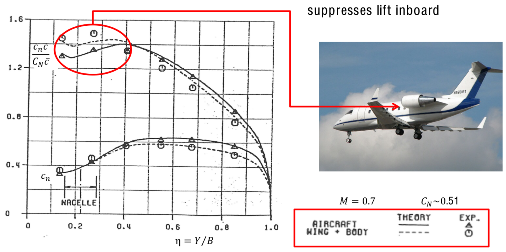
Spanwise distribution of pitching moment coefficient

Canadair Bombardier "Challenger"

inboard → outboard

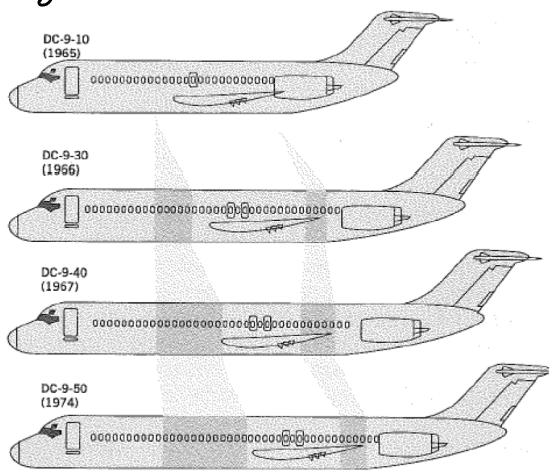


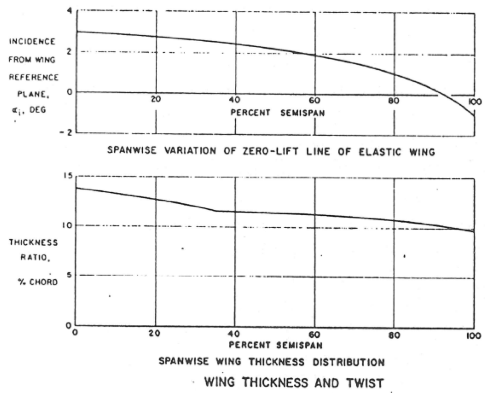
Nacelle interference suppresses lift inboard



- near constant upper-surface pressure distribution along the span
- Less rear loading inboard
- Incorporating the fuselage in the computations clearly improves the comparison between theory and experiment especially near the fuselage

Douglas DC-9



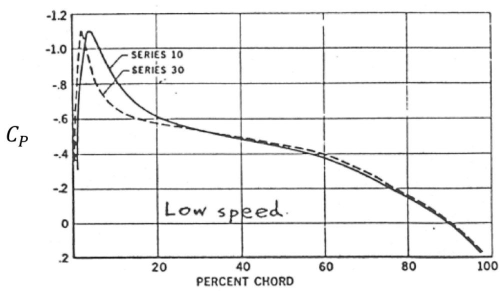


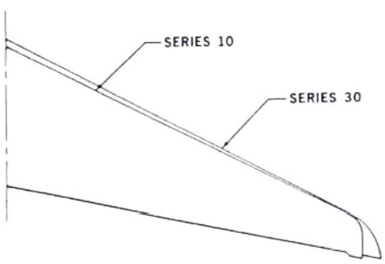
Incidence distribution

Thickness distribution

Q77: Why would the designers want a sharper suction peak in low-speed conditions?

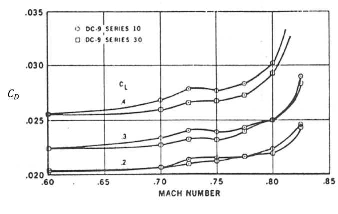
Reduces the pressure drag on the front part of the airfoil



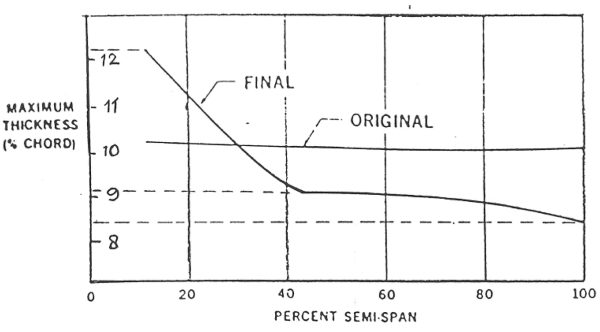


Low speed C_P distribution for new airfoil

Drag creep significantly reduces



Douglas DC-10



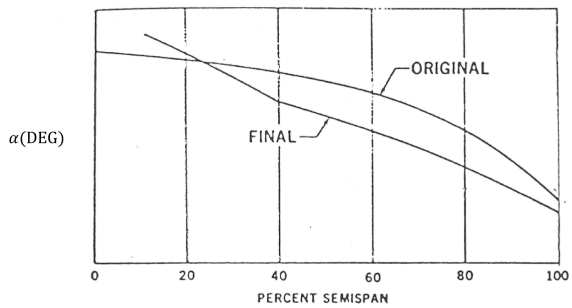
THICKNESS DISTRIBUTION

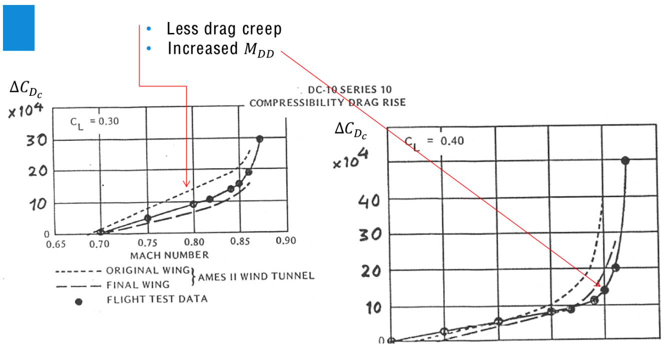
Q78: Why did the designers choose to increase the t/c ratio near the root?

To obtain a similar chordwise thickness-induced upper-surface velocity distributions along the span.

Q79: Why did the designers choose to increase incidence near the root?

To obtain a similar spanwise lift-induced upper-surface velocity distribution.

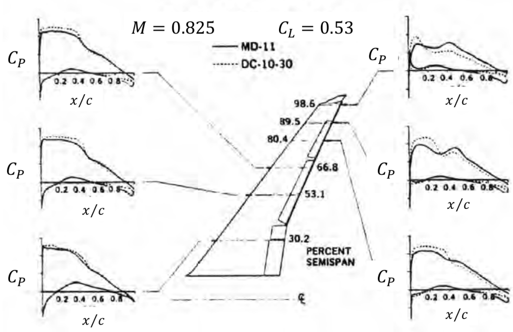




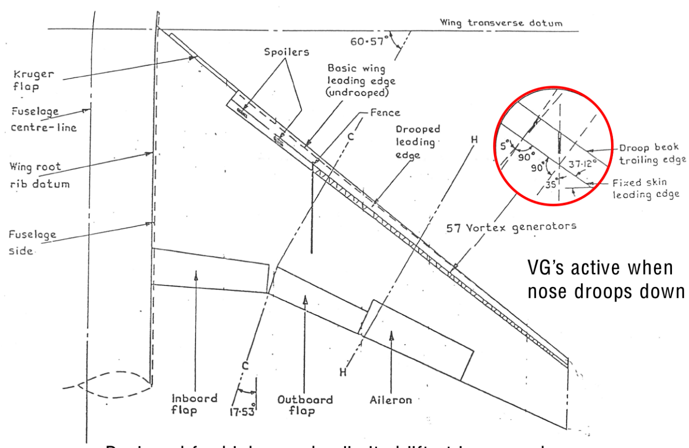
Q80: How can one reduce drag creep on a wing with a fixed planform shape?

Add more aft loading to reduce the overspeeds at the top surface for a given C_L.

De Havilland Trident



Chordwise pressure distribution on the DC-10-30 and MD-11 wing

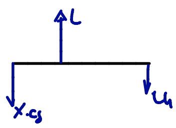


Designed for high speed > limited lift at low speed

Aeroelastic deformation at the tip.

Q81: Due to aeroelastic deformation of an aft swept wing under 1g loading

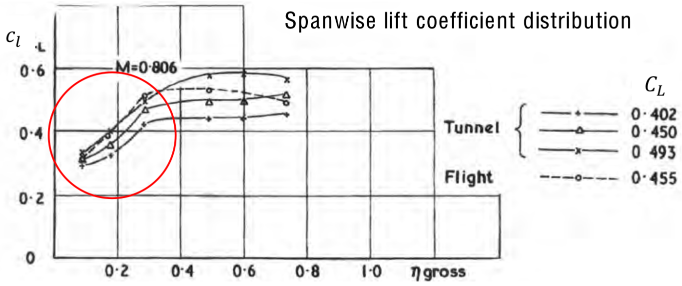
Loss of lift on wing tips. Less lift



Nose up pitching moment due to bending of wings.

Vickers VC-10

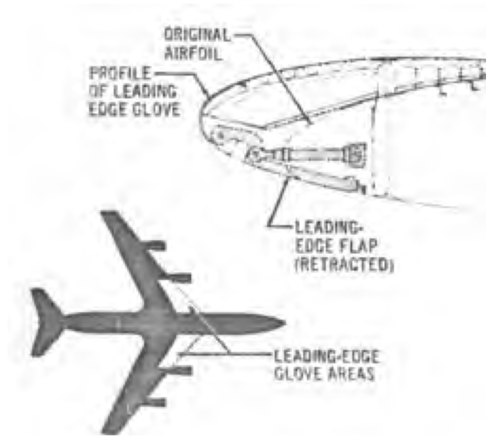
Long range, larger than trident, $M_c = 0.81$, $\Lambda_{c/4} = 32.5°$



Q82: Why does the local lift coefficient decrease near the root?

To ensure that $C_l * C$ varies elliptically along the span.

Boeing 720



Q83: What is the function of the leading-edge glove?

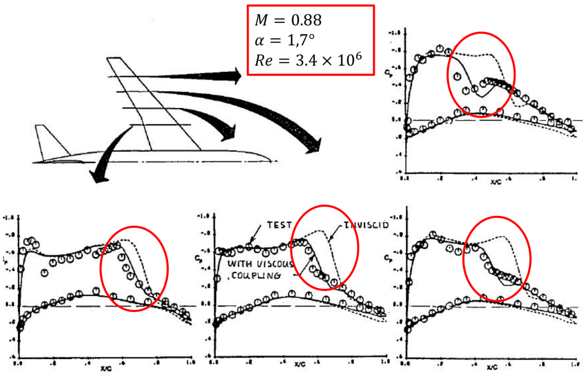
Align the isobars at the root.

727:

Q84: Why is the fence curved inboard?

To align it with the local streamlines and reduce interference drag.

Boeing 747



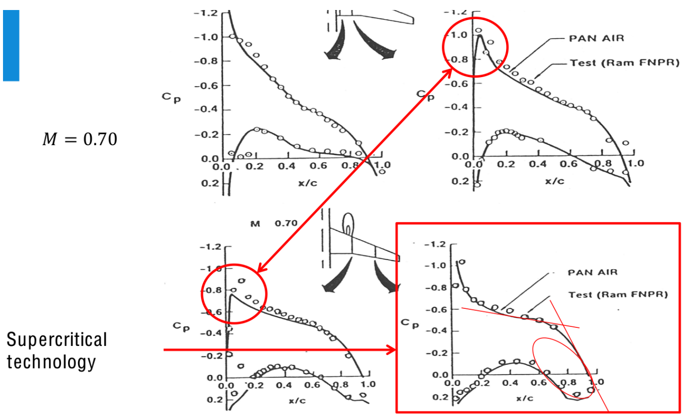
Q85: Why does the inviscid misplace the position of the shock?

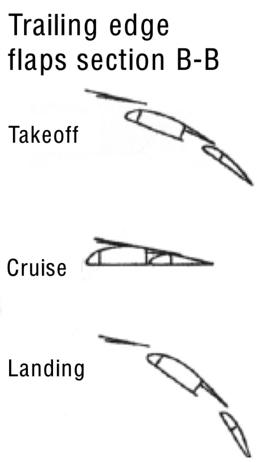
Because it does not include the effect of the b-l.

Q89: Front loading at the root is used to...

Offset the nose-down pitching moment of the outboard wing

Boeing 757:

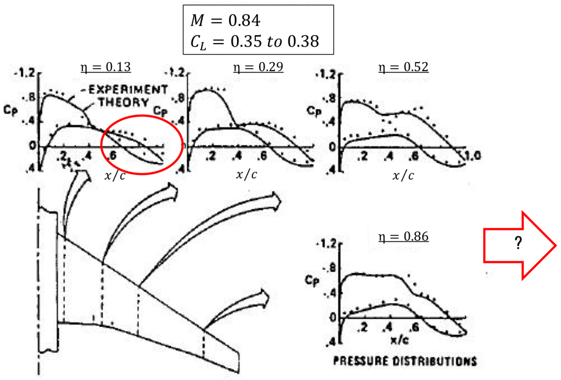




Q90: Why less gaps in take off configuration?

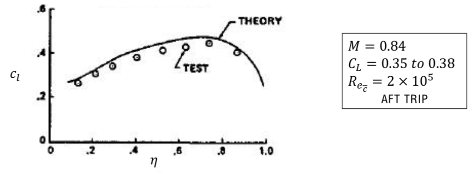
Gaps increase the drag coefficient of the wing.

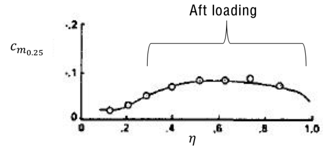
B767:



Q91: Why does the 767 root have reduced aft loading?

To offset the pitch up moment coefficient of the outboard wing.

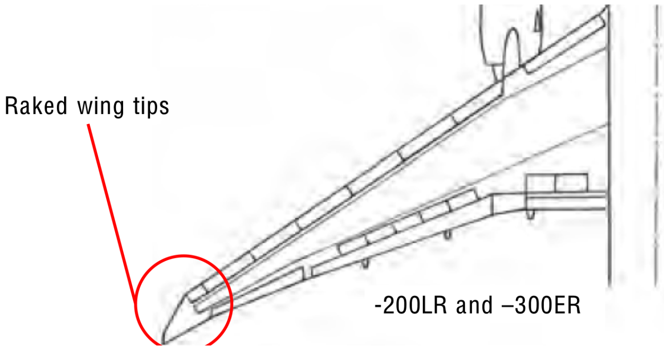


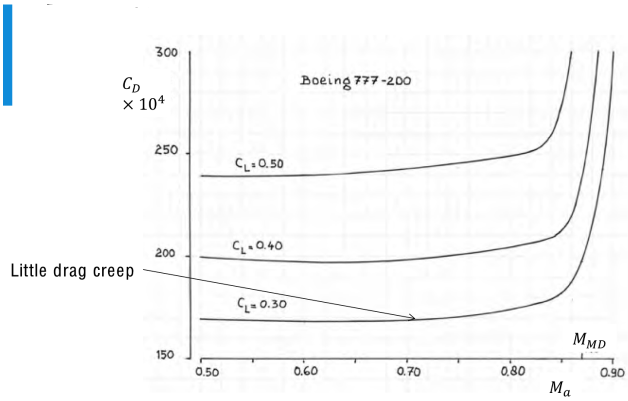


B777

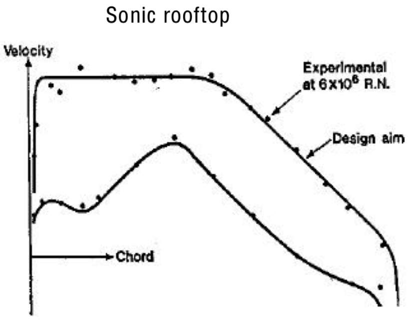
Q92 What is the function of raked wing tips?

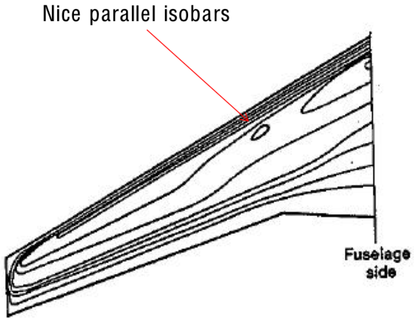
Reduce lift-induced drag.

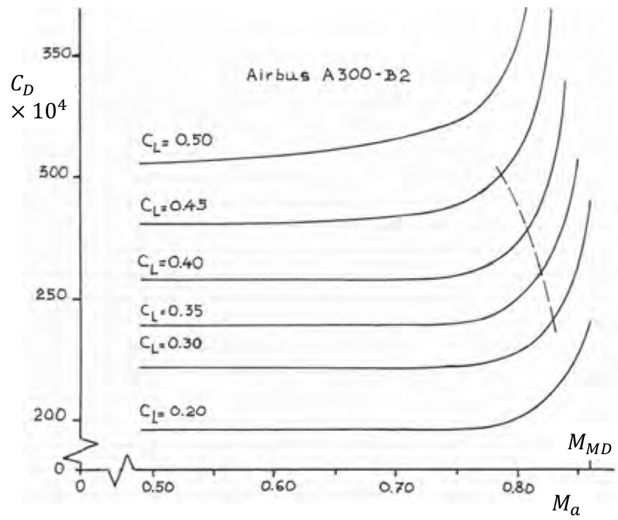


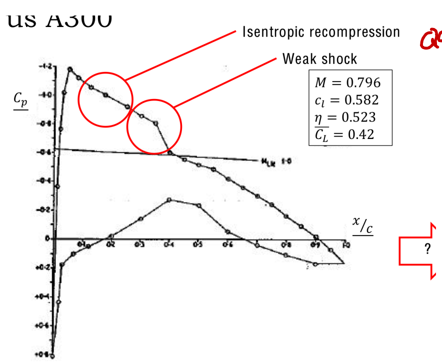


Airbus A300





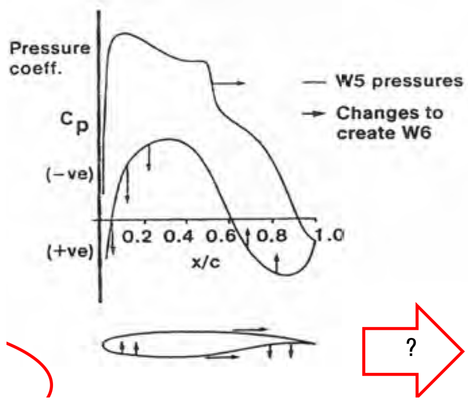




Q93: When would you expect this pressure distribution?

A320:

Designed for lower speeds, minimizing rear loading and maximizing front loading.

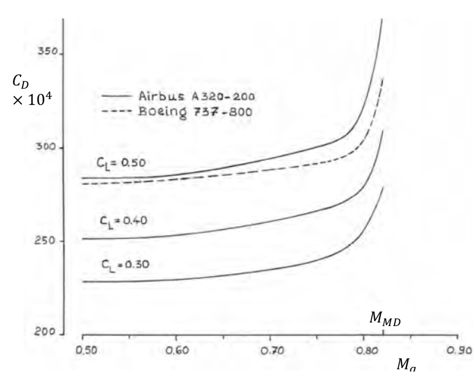


This allowed for lighter wing flaps, lowered trim drag.

Q94: Why does limited aft loading contribute to lighter flaps?

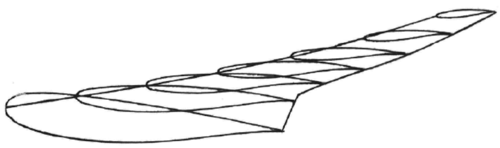
Because it concentrates the lift on the flap's elastic axis reducing its required torsional stiffness.

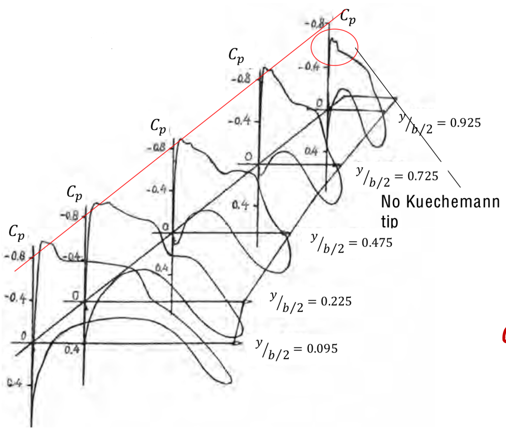
Q95: What do you conclude based on the following graph:



B737 has larger commercial potential.

A340:





A380:

The Airbus A380 has the following design characteristics (A380-800):

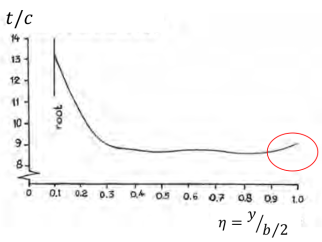
MTOW	=	560 *tonnes*
Maximum cruise altitude	=	43,000 *ft*
Wing reference area S_W	=	845 m^2
Maximum operating Mach no. M_{MO}	=	0.89
Cruise Mach number M	=	0.85

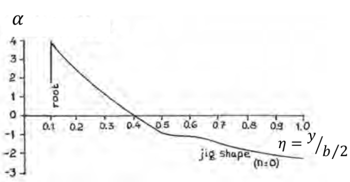
These very demanding design requirements produced a wing with the following characteristics:

Wing sweep angle $\Lambda_{1/4c}$	=	33.5°
Aspect ratio A	=	7.67 (Airbus definition)
Relative root thickness t/c	=	0.132
Relative outer wing thickness t/c	=	0.087

Q96: Why does A380 have a low A?

To comply with regulations





Q97: Why does the tip airfoil have a higher t/c?

To increase the nose radius of the airfoil and prevent an early onset of tip stall

FOKKER INFO IN LAST SLIDE:

Hope you have enjoyed my summary