Aerospace Vehicle Design And System Integration 3 AENG30013 (AVDASI3)

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Aerodynamic Wing Design

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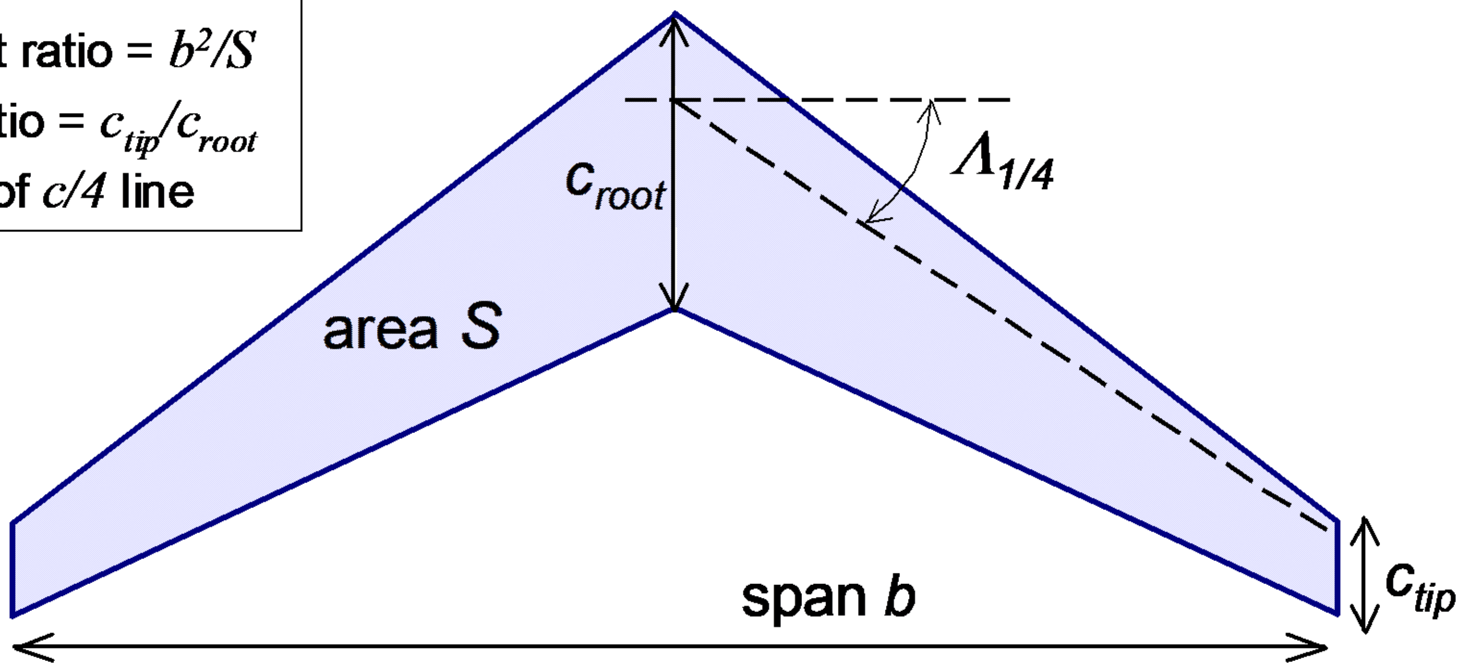
Content

- review of basic wing sizing
  - wing area, aspect ratio and sweep
  - taper ratio and twist
  - wing height
- aerofoil choice and design
- optimisation

The Wing

- review basic wing sizing constraints
  - wing area
  - aspect ratio
  - sweep angle

S = wing area
AR = aspect ratio = b^2/S
λ = taper ratio = c_{tip}/c_{root}
Λ = sweep of $c/4$ line



Wing Area

- three classes of constraint/requirement :

1. ‘wetted area’
   - cruise drag
2. ‘available lift’
   - landing (and take-off)
   - manoeuvre
   - transonic cruise buffet
   - gust response
   - ceiling
3. ‘physical size’
   - fuel volume
   - wing weight
   - span (in relation to AR)

Aspect Ratio

- three classes of constraint/requirement :

1. induced drag
   - Important at high lift
   - T-O, climb where thrust limited

$$C_{Di} = KC_L^2 = \frac{k}{\pi AR} C_L^2$$

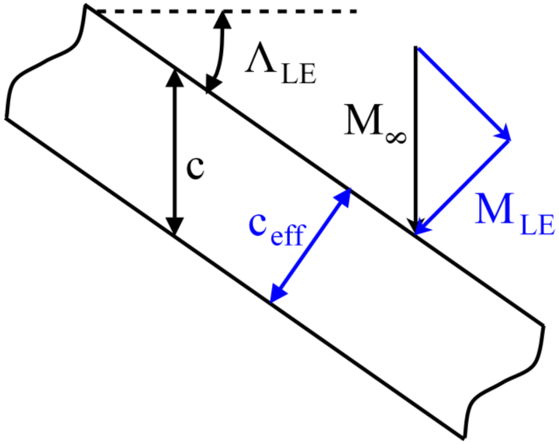
2. lift curve slope (a→a_0 as AR →∞)
   - good gust response
   - but wide variation in fuselage incidence between cruise and landing

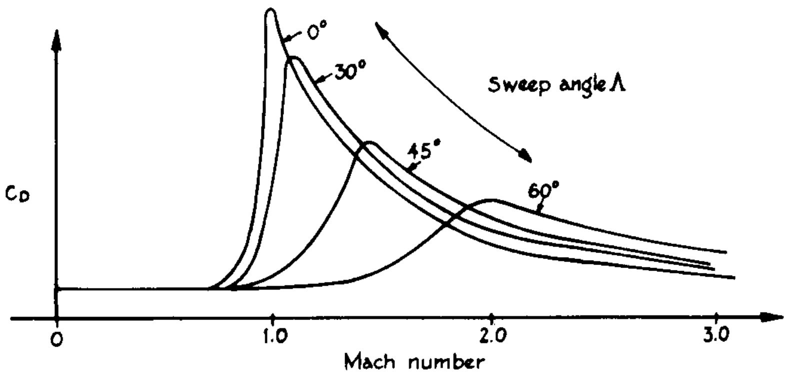
$$a = \frac{a_0}{1 + a_0 / \pi AR}$$

3. 'physical size'
   - fuel volume
   - wing weight
   - span limits
   - flutter

Wing Sweep

- most effective way of increasing critical Mach Number



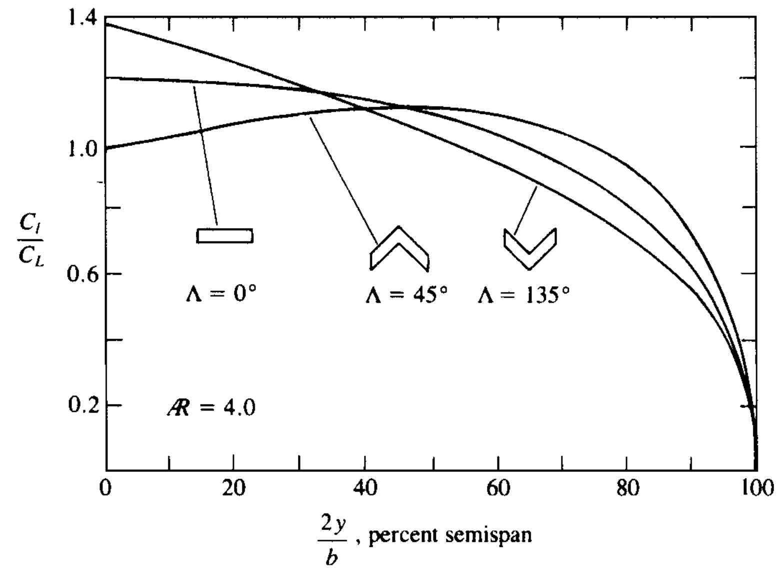


- sweep reduces Mach Number perpendicular to LE
- also increases C_L and *t/c*
  - reduced Mach Number outweighs above two effects

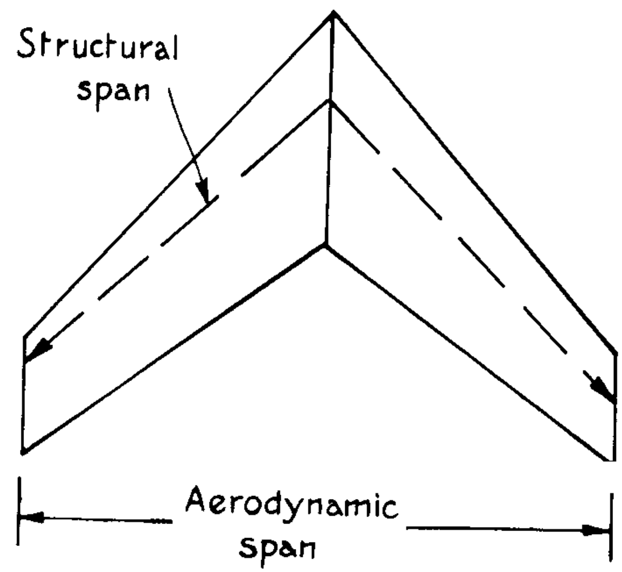
- use to increase cruise speed
  - or to increase wing thickness for a given cruise speed

Wing Sweep

- generally an adverse effect …
- outboard shift in loading
  - increased induced drag
  - reduced maximum lift
- reduced lift curve slope
  - poor visibility on approach
  - but improved gust response



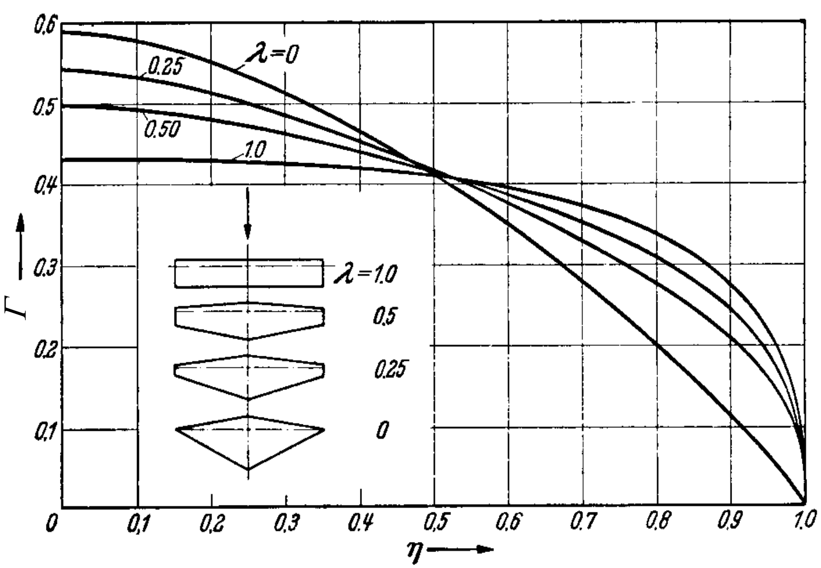
- sweep increases ‘structural span’
  - increased wing weight
- increased torsion at wing root
  - plus bending due to lift distribution
  - increased wing weight

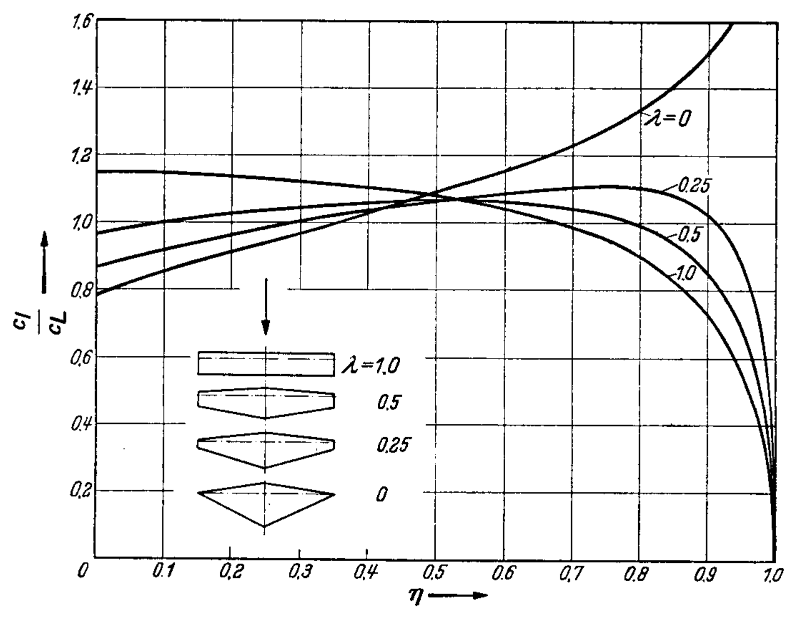


Taper Ratio

- chosen (together with twist) to :

1. maximise aerodynamic efficiency
   - adjust spanwise lift distribution to near-elliptical
2. minimise structural weight
   - drives to small taper ratio with inboard load





Wing Twist

- chosen to :

1. maximise aerodynamic efficiency at *cruise*
   - compensate for effects of sweep and taper ratio on lift distribution
   - only effective at one (design) incidence, because *increment* in lift due to twist is fixed
   - *shape* of final lift distribution will therefore depend on magnitude of initial distribution and hence on geometric incidence
2. improve stall characteristics
   - *washout* (tips twisted nose-down) prevents tip-stall
3. reduce wing weight
   - centre of pressure shifted inboard $\rightarrow$ trade-off against increased drag due to triangular lift distribution

Twist vs Camber ?

- for a given planform:

1. **twist** sets basic spanwise *load* distribution
   - governs overall wing aerodynamic efficiency
2. **camber** modifies local *pressure* distribution
   - adjusts isobar pattern to avoid (for example) shock formation or flow separation

- *rather simplistic statement - effects are coupled* …

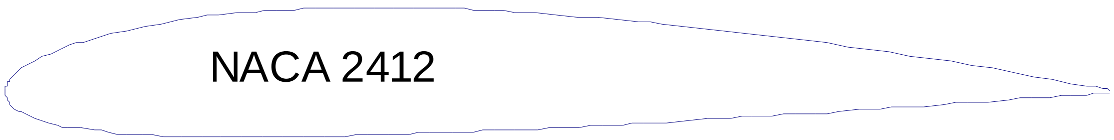
Wing Height

- wing can be positioned high mid or low relative to fuselage
- choice is mostly based on configuration requirements (e.g. props, gravel runways, ease of inspection etc.) and not aerodynamic reasons

AEROFOILS

4-Digit Aerofoils – NACA CXTT

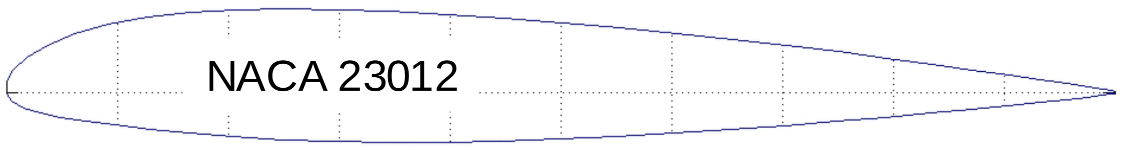
- eg NACA 2412 has 2% camber at 0.4*c* and is 12% thick
  - still found on many light aircraft – eg Cessna 152



- high drag, but relatively little variation with lift
  - insensitive to surface condition
  - popular for light training aircraft with wide operating range
- cambered sections have relatively high maximum lift and docile stalling characteristics
  - eg 2412 and 4412

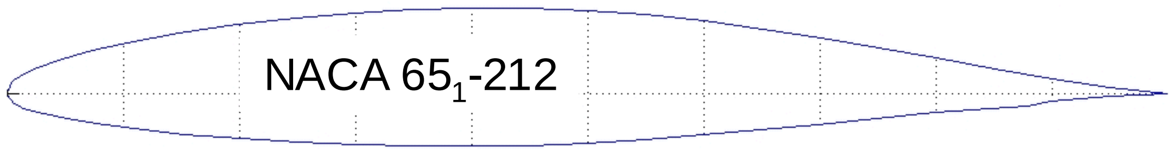
5-Digit Aerofoils – NACA LXXTT

- eg NACA 23012 has a design C_L of 0.3, maximum camber at 0.15c and is 12% thick

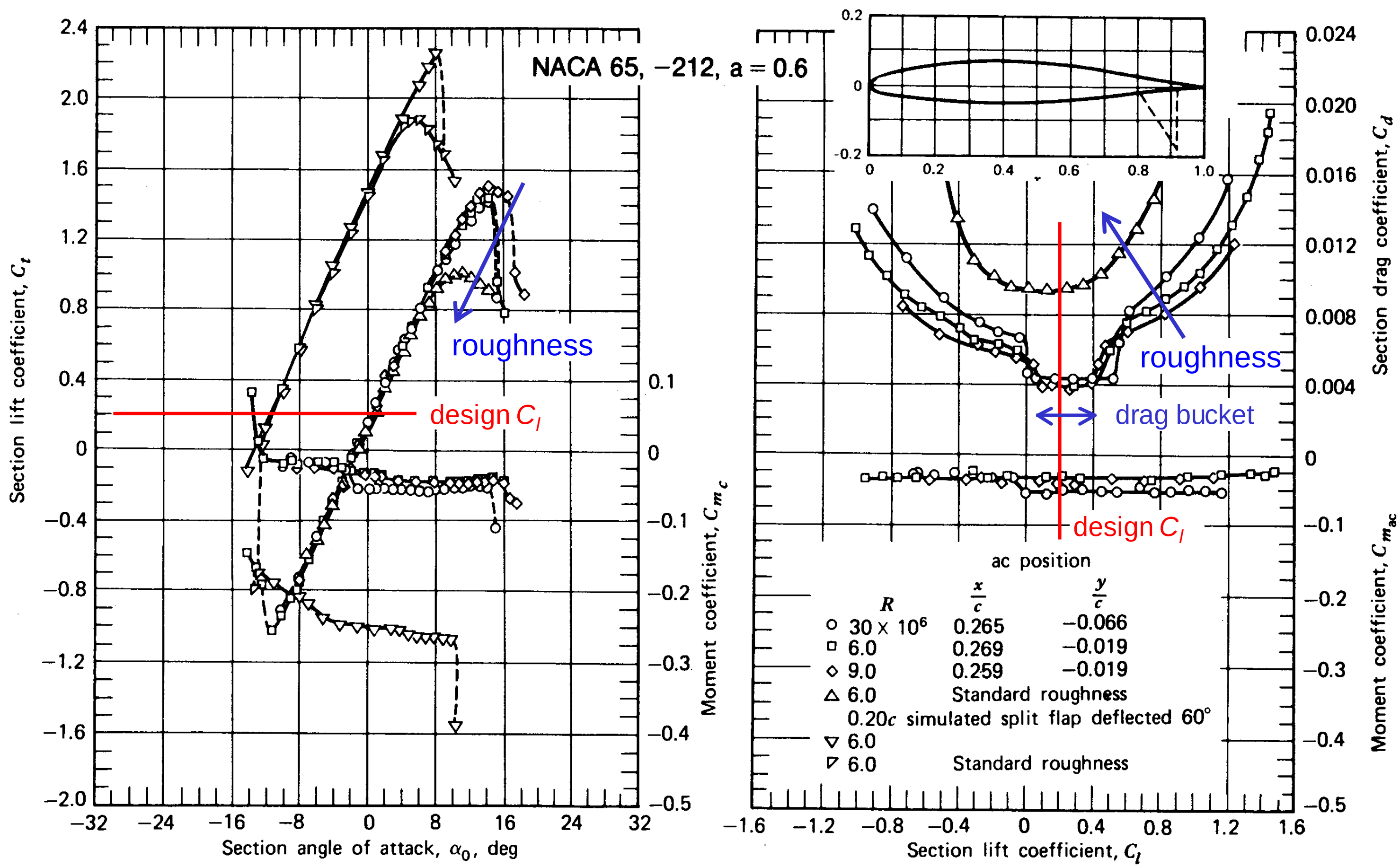


- minimise profile drag at operating conditions
- increased maximum lift
- reduced pitching moment
- poorer stall behaviour

6-Digit Aerofoils – NACA LXXTT

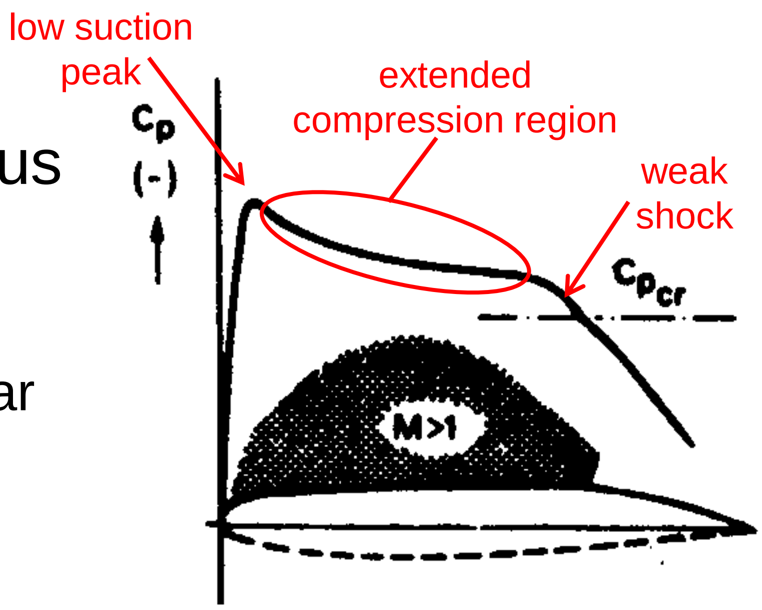


- Try to promote laminar flow – drag bucket!



Modern Supercritical Sections

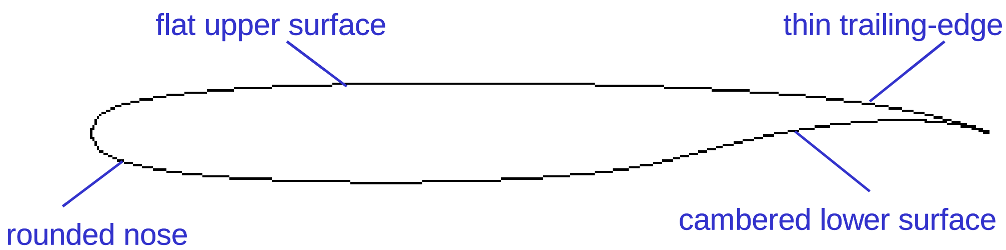
- developed by Whitcomb in the US
  - also responsible for area rule and winglets ..!
- designed to have substantial regions of supersonic flow
  - smaller initial peak followed by longer compression



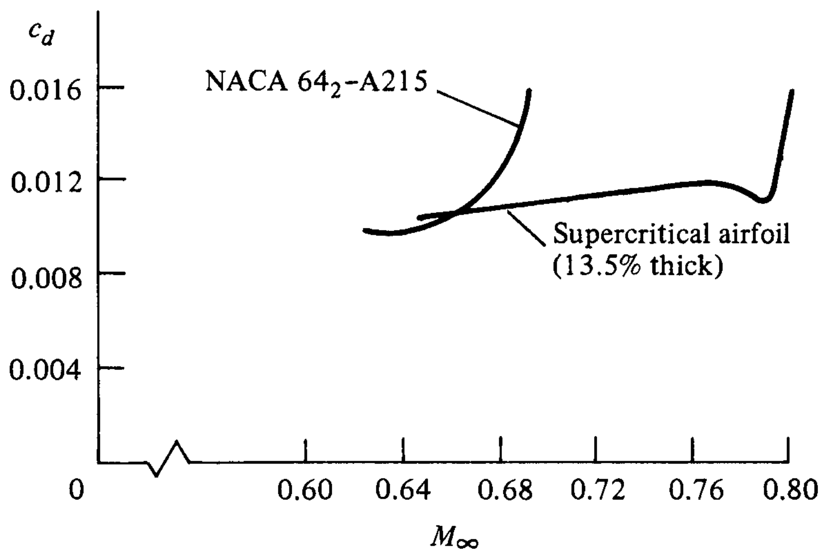
- relatively large leading-edge radius
- very small curvature over much of upper surface
  - reduce drag penalty of suction at rear
- aft portion cambered
  - aft loading reducing peak velocity for given lift

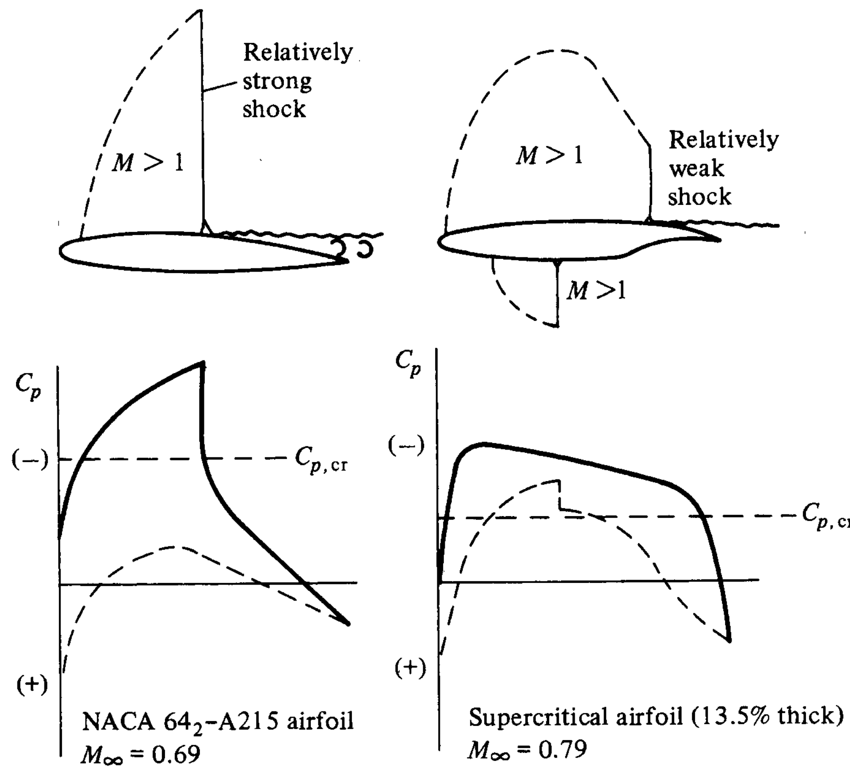
Supercritical Design Features

- significant lower surface curvature



- rather similar to modern laminar flow sections
  - good structural shape!

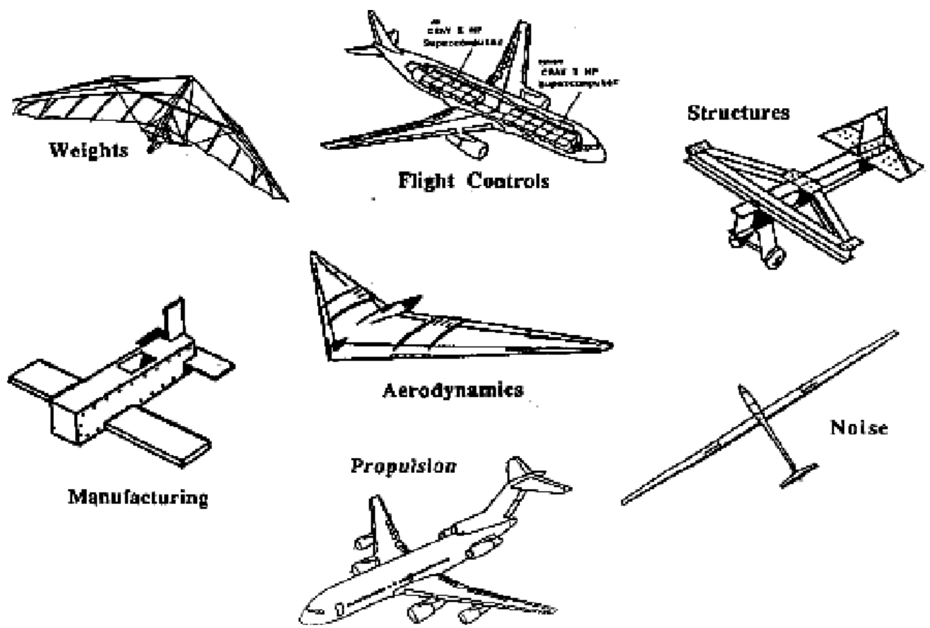




OPTIMISATION

Optimisation

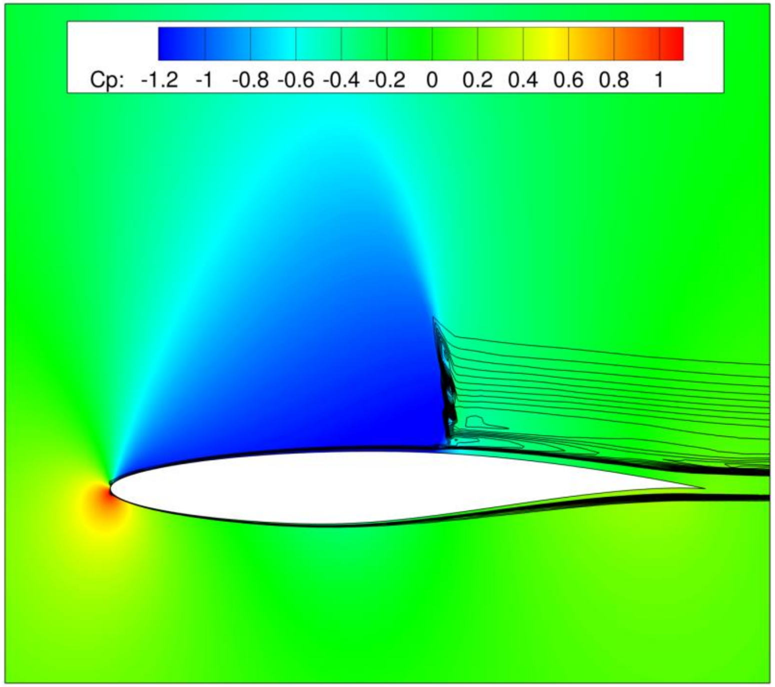
- Traditionally, experienced designers use combination of intuition, numerical analysis (CFD), and experimental data to design wings
- Decisions coupled between different disciplines

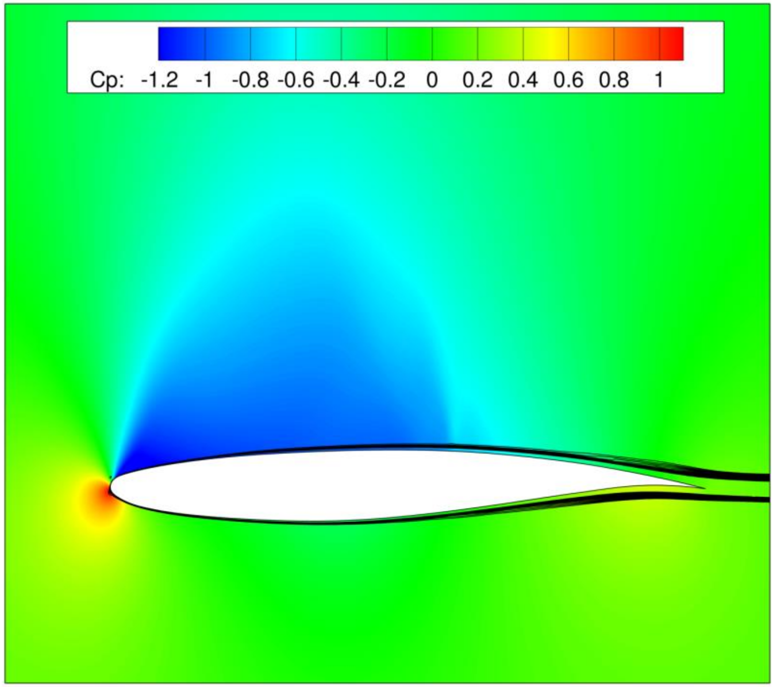


- Couple numerical analysis to “*clever*” optimiser
  – Helps designer make more informed decisions

Optimisation: Aerofoils

- Use nature-inspired optimiser with mathematically-derived design deformation
- RANS equations – compressible, viscous
- 35% drag reduction – eliminate wave drag

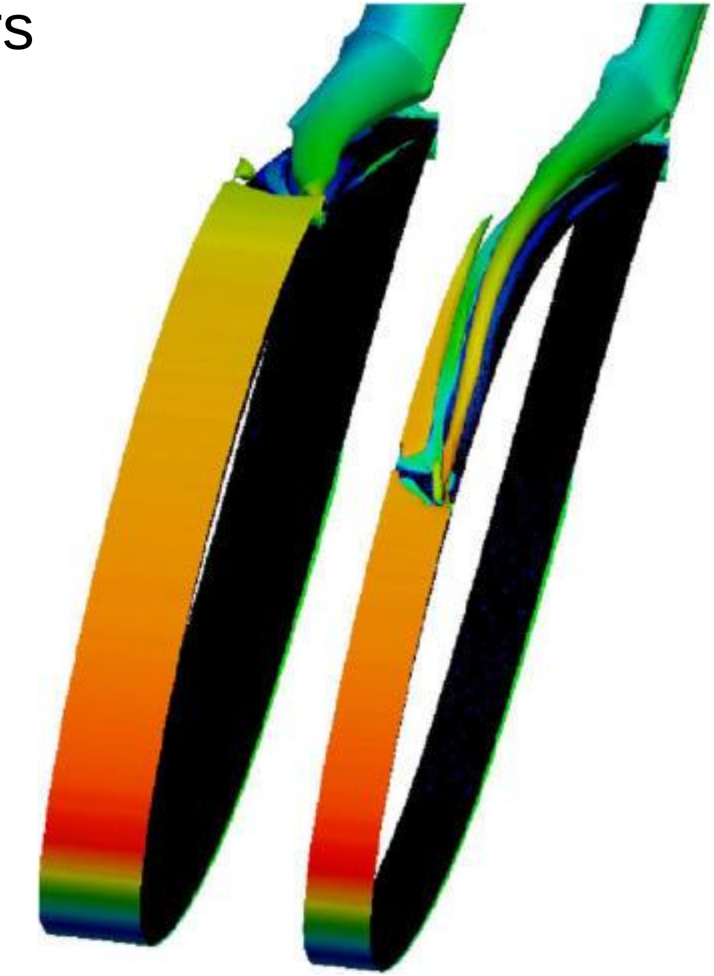




D Poole "Efficient Optimisation Methods for Generic Aerodynamic Shape Optimisation," PhD thesis, University of Bristol, 2017.

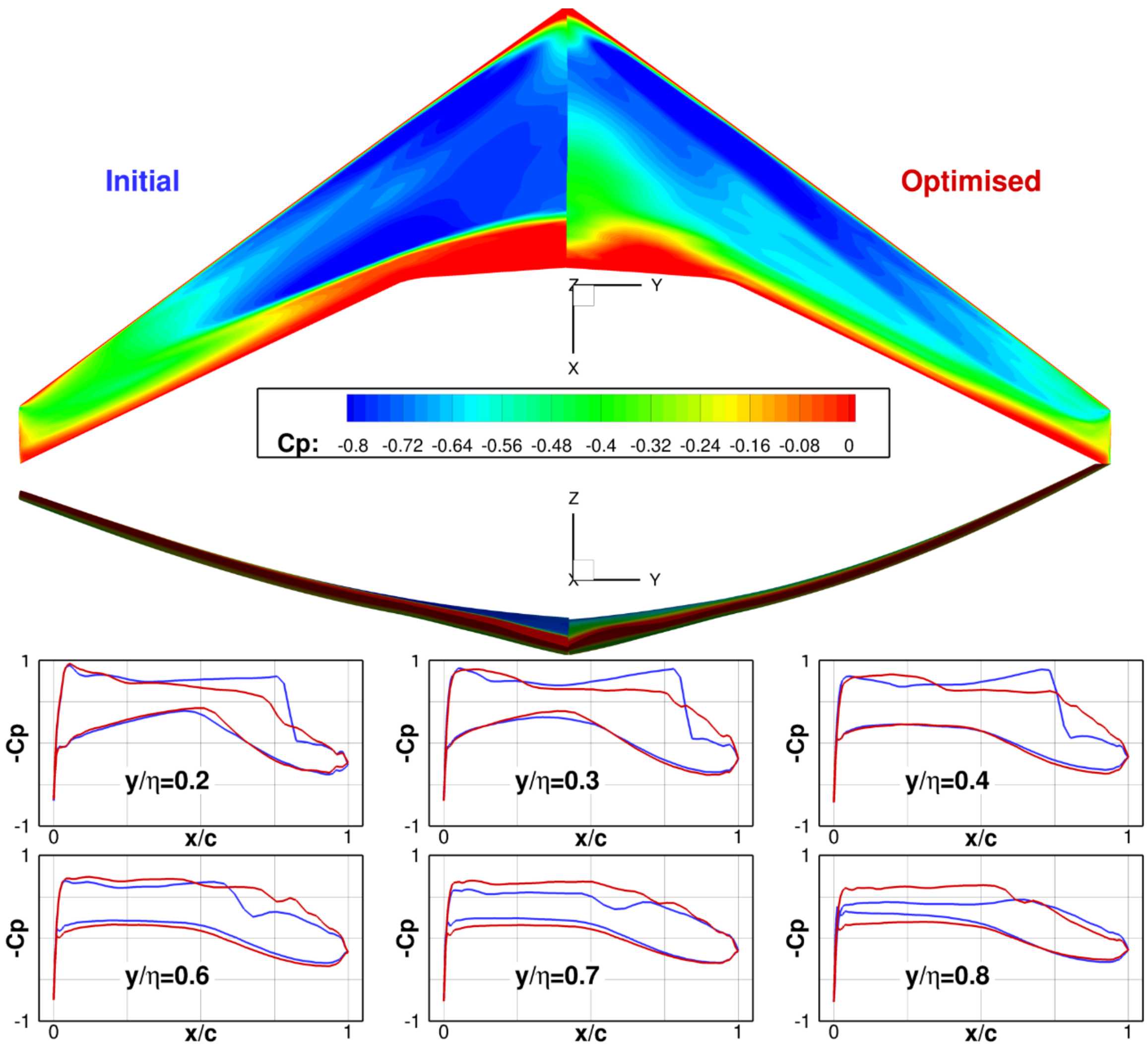
Optimisation: Aerofoils

- Can also optimise vortex generators
- Work done in collaboration with Leonardo for AW609
- Optimise VG shape and location to minimise buffet



R Bevan, D Poole, C Allen & T Rendall, “Adaptive Surrogate-Based Optimization of Vortex Generators for Tiltrotor Geometry,” Journal of Aircraft, 2017.

Optimisation: Multi-disciplinary



- Optimise drag subject to fixed lift & volume
- Aero-structure coupled high fidelity solver

	Initial	Optimized
C_L	0.4	0.4
C_D	0.0179	0.0126
C_{M_x}	0.144	0.174
C_{M_y}	-0.386	-0.429
Δz_{tip}	6.16m	8.44m
ΔC_D	-	**-29.7%**

D Poole, C Allen & T Rendall, "Efficient Aero-Structural Wing Optimization Using Compact Aerofoil Decomposition," AIAA Scitech Forum 2019, San Diego, CA, Jan 2019.

Conclusions

- Wing parameters chosen based on number of trade-offs
  - Cruise performance/aerodynamic efficiency
  - Stability
  - Edge-of-envelope
  - Structural

- Aerofoil design for specific conditions
  - Supercritcal typical of modern transonic passenger aircraft

- Optimisation can be used to help inform design