Design, Build, Test: Aerodynamics

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Aero objectives (reminder)

Design a wing with droop/flap settings to give:

1) Shortest takeoff distance from concrete/asphalt (rolling friction coefficient =0.025) – 'takeoff'. Allows convenient operation in confined spaces. At zero incidence minimise
2) Highest top speed – 'dash' (min Cd0). Can make a getaway if needed, or follow a misbehaving motorist
3) Best endurance – 'loiter' (min Cd @ Cl=0.5). Spend as long as possible over a particular area taking souvenir photos, or waiting for the burglar to leave the bushes
4) Slowest landing speed – 'land' (max Clmax). Safer and easier if done slowly

…approximately a complete UAV mission. The requirements conflict – this is life!

Today's Objectives

Your wings are being built; there's not much you can change!

1) Decide on the flap setting for the takeoff
2) Predict drag vs. lift polars for your wing at the 3 different configurations (takeoff, land, dash/cruise) (a polar is a curve showing Cd vs. Cl)

A couple of hints – it's likely (but by no means certain...) that the highest Clmax will be for the maximum deflection of both the droop and flap.

The minimum Cd0 will 'almost certainly' be for the clean wing.

The minimum drag for Cl=0.5 will again be likely to be for the clean wing. So, the only condition not fixed is takeoff.

Learn from this process!

Tunnel tests

- Tunnel testing will be a case of sweeping in incidence and measuring Cl and Cd. The tunnel will be run at a constant speed (this will involve tweaking the motor as the wing drag changes)

- You will have noticed the takeoff condition was at zero incidence. So, we shall adjust the angle until the wing produces zero lift, then set your takeoff flap angle, and then measure Cd and Cl. This is the fairest way; geometric incidence is difficult to define as it will depend on how your spars are set within the structure

Aero Tools

- Analytical

Provides good understanding, but limited in applicability

- Experimental

Fairly accurate but slow and sometimes expensive

- Computational

Accurate and fast in some areas, but still inaccurate for separated flow

- Semi-empirical

Combines analytical and experimental approaches. Provides understanding and moderate accuracy across most areas

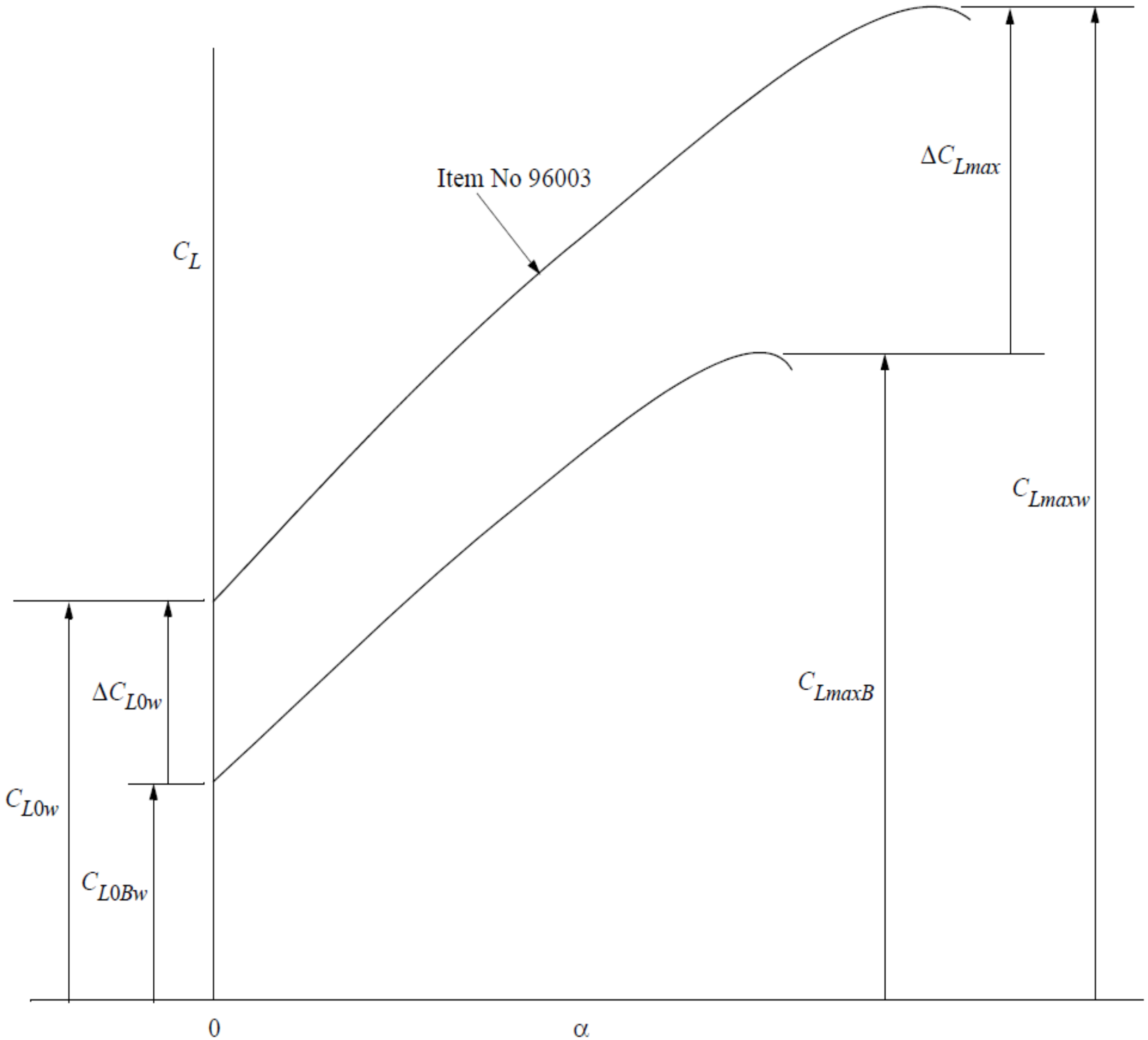
ESDU - Engineering Sciences Data Unit

- Created during WW2 when many designers needed to switch from peacetime to wartime manufacturing.
- The sheets work reasonably well for conventional configurations. Their inability to predict behaviour of unusual designs is one driver for development of CFD
- Unfortunately, CFD remains inaccurate for separation in most cases
- ESDU is a huge resource that is free for you to use. Make the most of it!
- I've given you some inputs (eg 3D lift slope) to reduce the number of sheets you will need

Steps

- 3D lift increment from flap/droop – reqiures 2D lift increments
- 3D max lift increment from flap/droop – requires 2D max lift increments
- 3D induced drag and profile drag increments – the profile drag increase is more important here. You can ignore the flap effect on induced drag initially

- We're going to start at the end and work back to the beginning. So the 3D results we want look like...



Item No 96003
C_L
ΔC_{Lmax}
C_{Lmaxw}
C_{LmaxB}
ΔC_{L0w}
C_{L0w}
C_{L0Bw}
0
α

Lift and Drag Below Stall

$$C_L = \frac{dC_L}{d\alpha}(\alpha - \alpha_{0_{2D}}) + \Delta C_{L_{0_l}} + \Delta C_{L_{0_t}}$$

96032/97011 only

From vortex lattice or
from ESDU ≈ 4.2

From section data
Or Xfoil

Wing induced Drag
74035 (use total Cl).
Can use delta=0
initially

$$C_D = C_{D_0} + \Delta C_{D_{0_t}} + \frac{(1+\delta)C_L^2}{\pi A_R} + K^2 \Delta C_{L_{0_t}}^2$$

Flap profile drag correction
06014, Aero F.02.01.07.
Could also use Xfoil **at low flap angles**

Flap induced drag
correction
Aero F.02.01.08
Use K=0 initially

3D Wing Lift Increments

- 96032/97011

Wing lift gradient, ~4.2

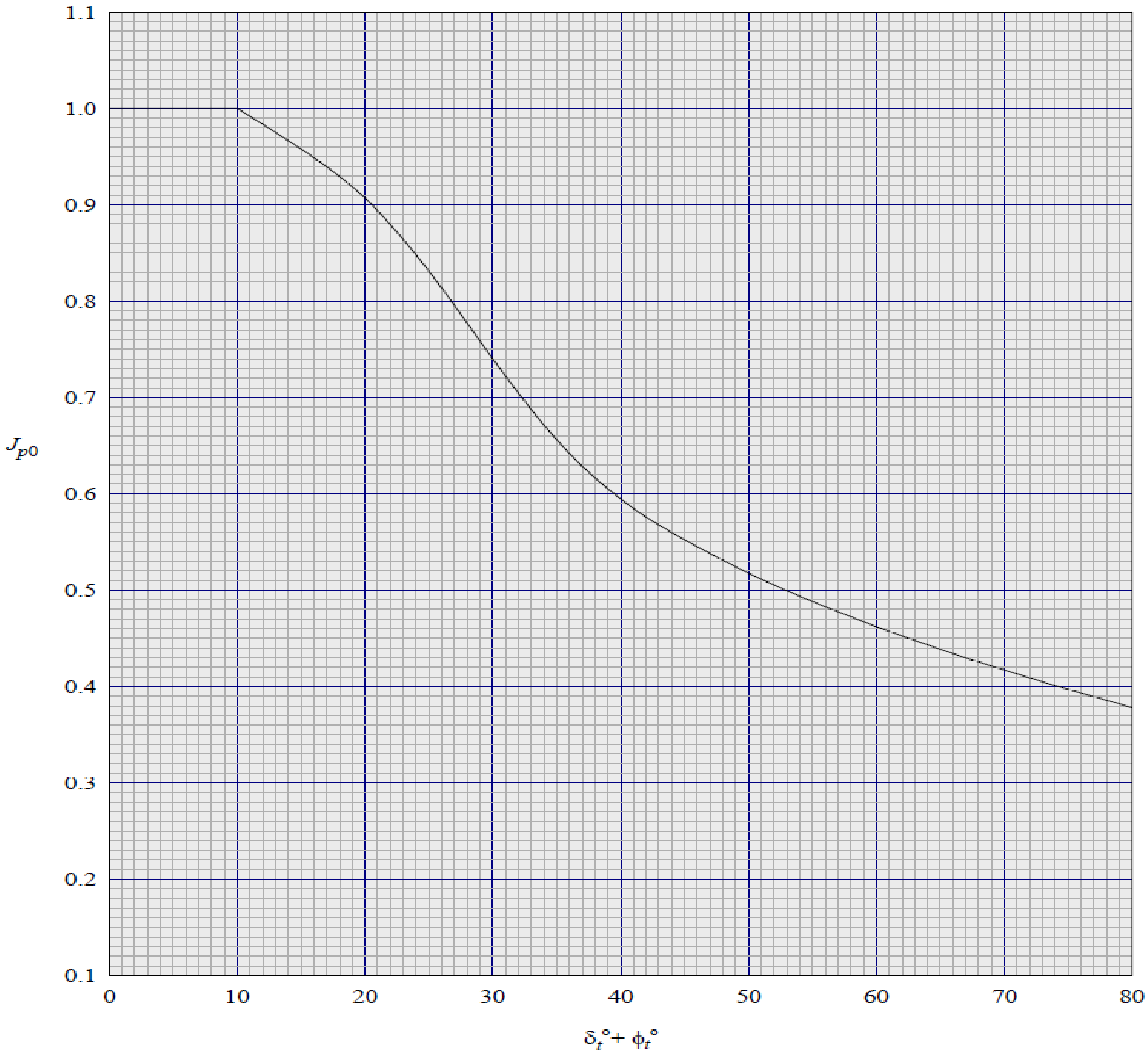
$$\Delta C_{L0lw} = \Delta C_{L0l}(a_1/2\pi)(\psi_o - \psi_i)$$

$$\Delta C_{L0tw} = K_{f0}\Delta C_{L0t}J_p(a_1/2\pi)(\Phi_o - \Phi_i)$$

Jp depends on
Deflection
Kf0=1.02
Jp=Jp0

2D values

Part-span factors
Only flap is part span
here



1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
J_{p0}
0
10
20
30
40
50
60
70
80
$\delta_t^\circ + \phi_t^\circ$

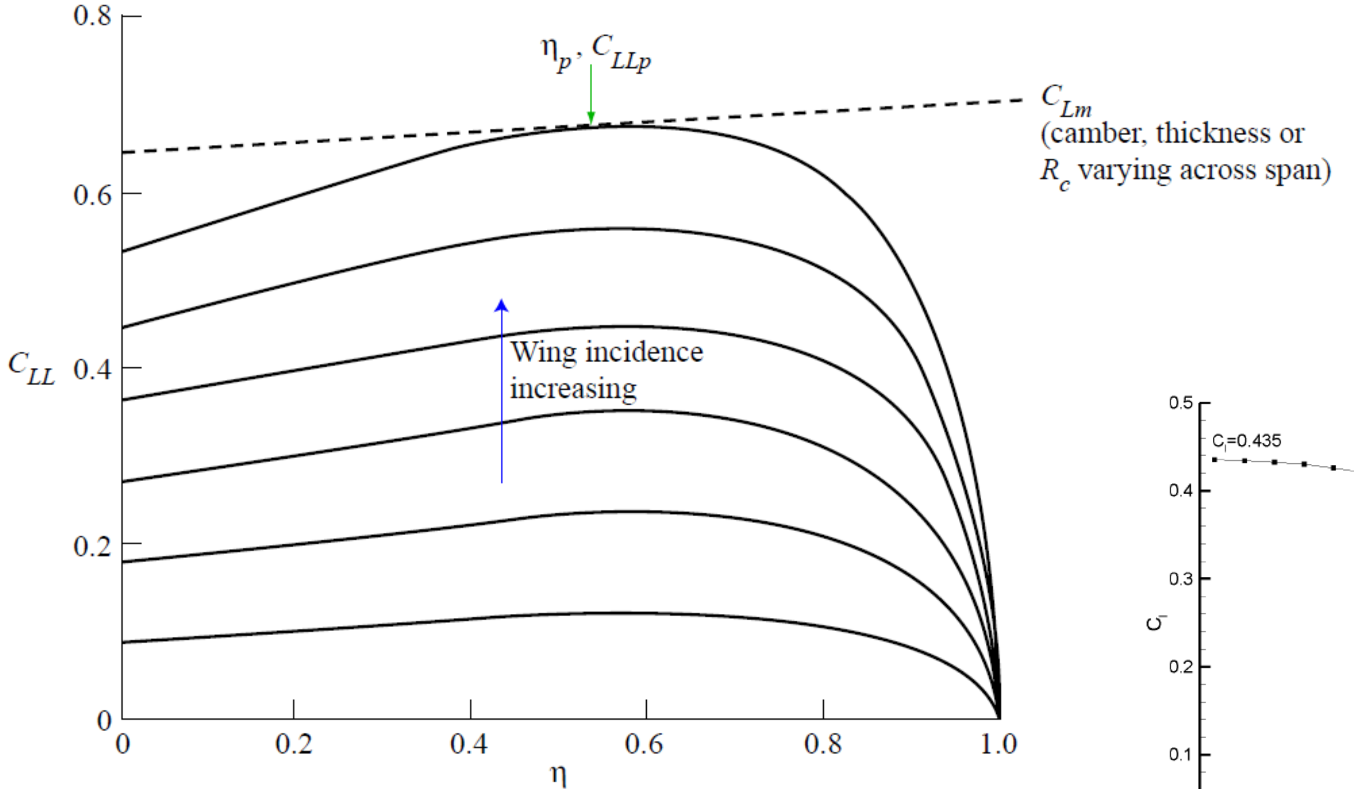
Lift at stall

- Sum up contributions from the clean wing, for the droop and for the flap

$$C_{Lm} = C_{LmB} + \Delta C_{Lm} = \underbrace{C_{LmB}}_{\text{Basic}} + \underbrace{\Delta C_{Lml}}_{\text{Droop}} + \underbrace{\Delta C_{Lmt}}_{\text{Trailing}}$$

Don't use Xfoil for increments in maximum lift!

3D Wing Max Lift



Sketch 6.1

$$C_{Lmax} = C_{Lm}/\mu_p$$

Vortex lattice gives:

$$\mu = \frac{0.435}{0.367} = 1.185$$

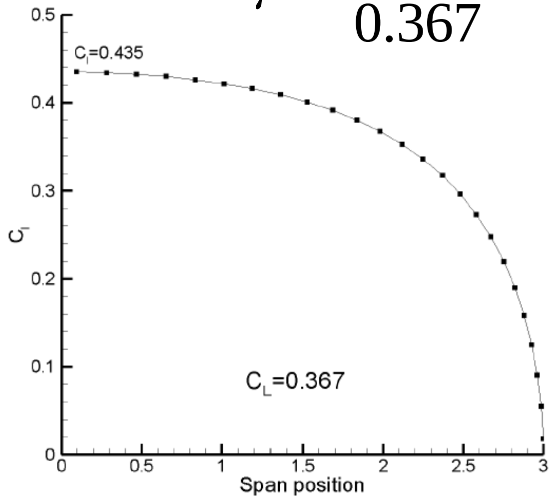


Figure 1: $A_R = 6$ spanload at $\alpha = 5^o$ for a rectangular untwisted uncambered wing

3D droop/flap max lift

- Correct for 3D droop/flap for max lift

1

Span weighting
From fig 3a on
91014 for curve
labelled -8

$$\Delta C_{Lmaxl} = F_R(\Delta C_{Lml} / \mu_p)\psi_i$$

$$\Delta C_{Lmaxt} = K_f F_R(\Delta C_{Lmt} / \mu_p)(\Phi_o - \Phi_i)$$

1 for
plain flap

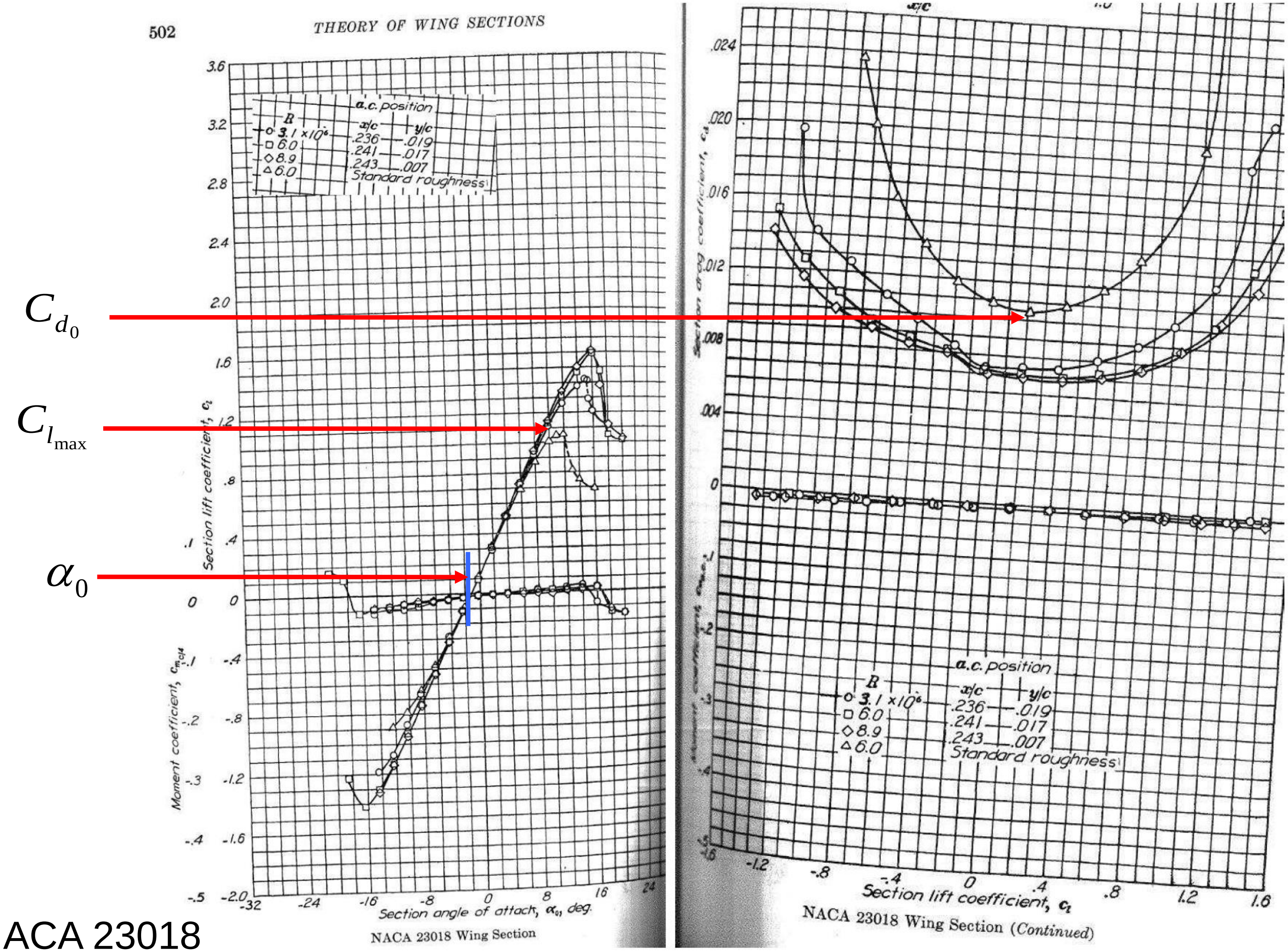
Reynolds no effect

2D values

FR=0.153log10(Re)

2D Inputs

- So far all the 3D results have required 2D results. Time to look at these!
- Initial section data needs to be max lift, zero lift incidence and zero lift drag. This should come from an experimental source – eg *Theory of Wing Sections.* This sets Clmax and Cd0 of the clean wing.

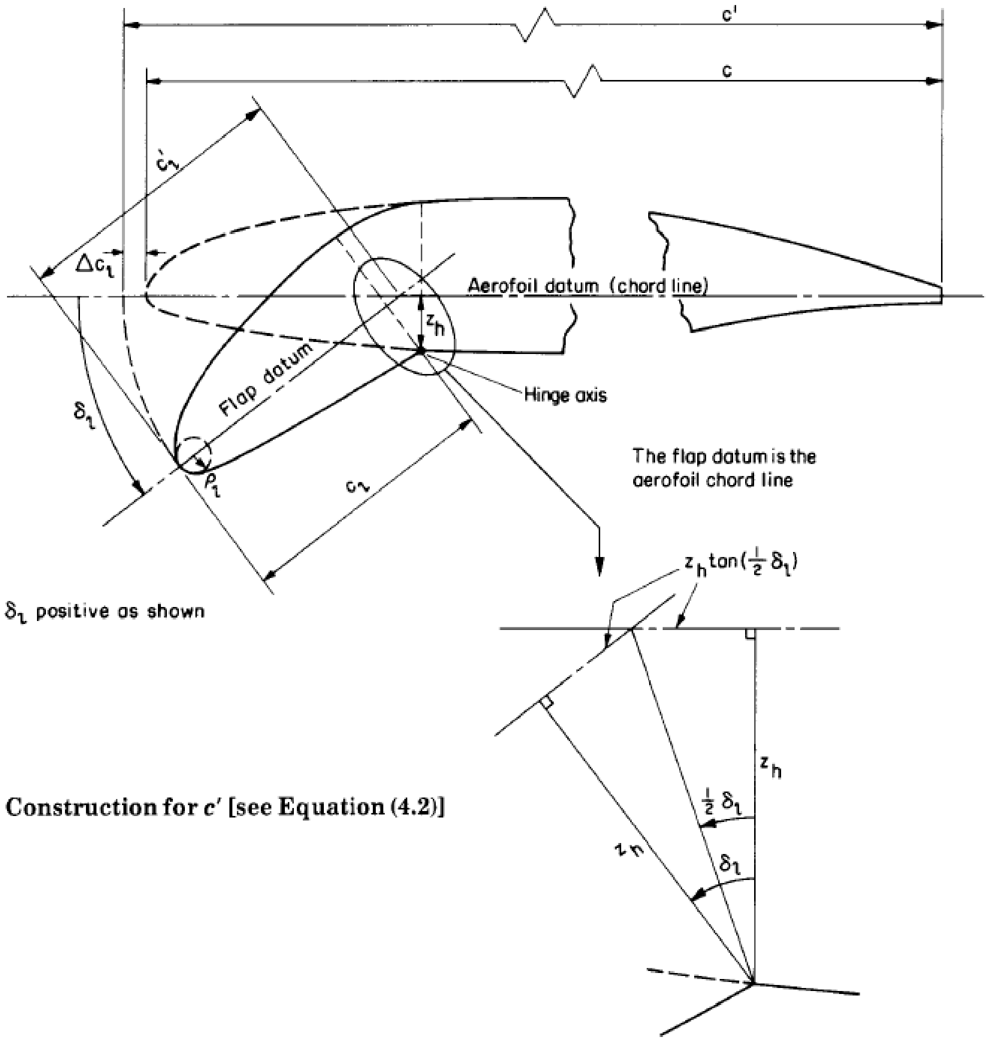


NACA 23018

(a) Lift

(b) Pitching moment and Drag

Geometry



Construction for c' [see Equation (4.2)]

$$\Delta C_{L0l} = (c'/c)\Delta C'_{L0l}$$

$$c'_l = c_l + z_h \tan(\delta_l/2)$$

$$c' = c + 2z_h \tan(\delta_l/2)\,.$$

Coefficients defined on c' need scaling on to c

2D droop lift increments

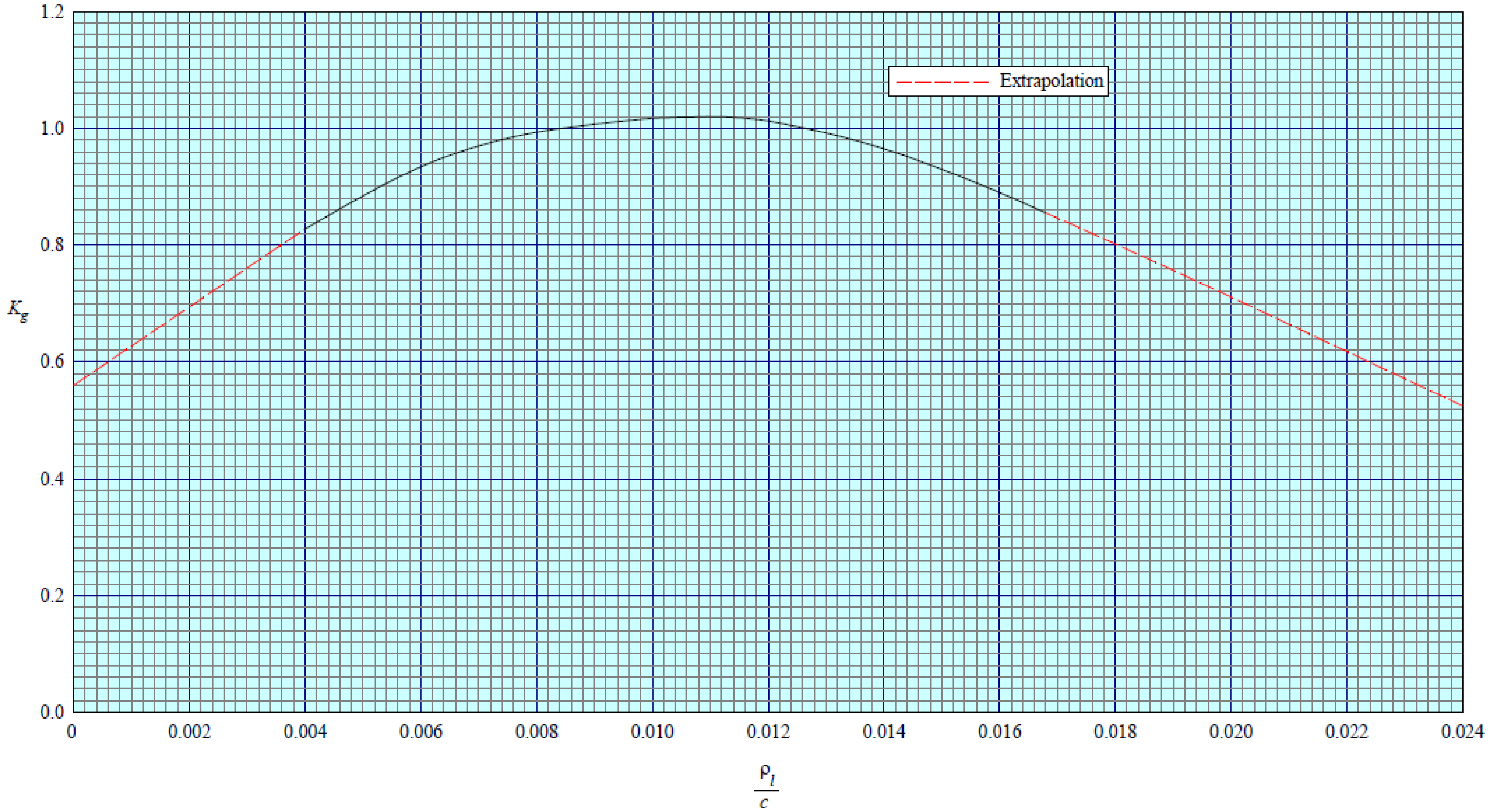
- Droop 94027

$$\Delta C'_{L0l} = -2K_0\delta_l \{ \cos^{-1}(1-2c_{el}/c') - [1-(1-2c_{el}/c')^2]^{½} \}$$

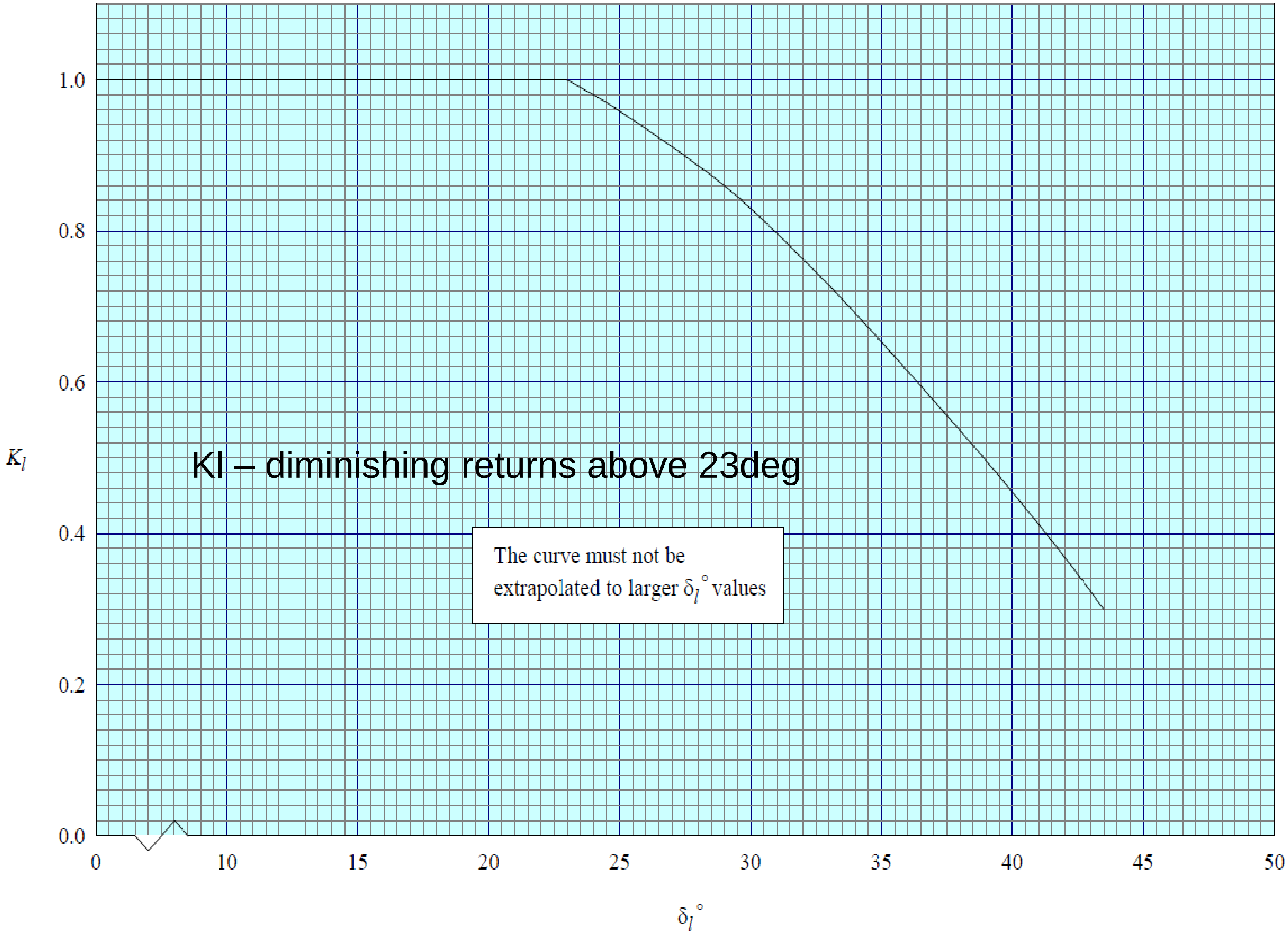
Positive (nose down) droop lowers lift at fixed incidence
cel=cl' here
K0=1/Kl
Kl comes from fig 1a on 94027

$$\Delta C'_{Lml} = 2K_e K_g K_l(\delta_l - \delta_0)[1-(1-2c_{el}/c')^2]^{½}$$

Positive droop raises max lift (lift at stall)
Ke=1
Kg from fig 2a on 94027
Delta_0=0


Extrapolation
1.2
1.0
0.8
0.6
0.4
0.2
0.0
K_g
0
0.002
0.004
0.006
0.008
0.010
0.012
0.014
0.016
0.018
0.020
0.022
0.024
$\frac{\rho_l}{c}$

Kl – diminishing returns above 23deg



2D flap lift increments

- Flap 94028

$$\Delta C'_{L0t} = 2J_p\delta_t\{\pi - \cos^{-1}(2c_t/c' - 1) + [1 - (2c_t/c' - 1)^2]^{1/2}\}$$

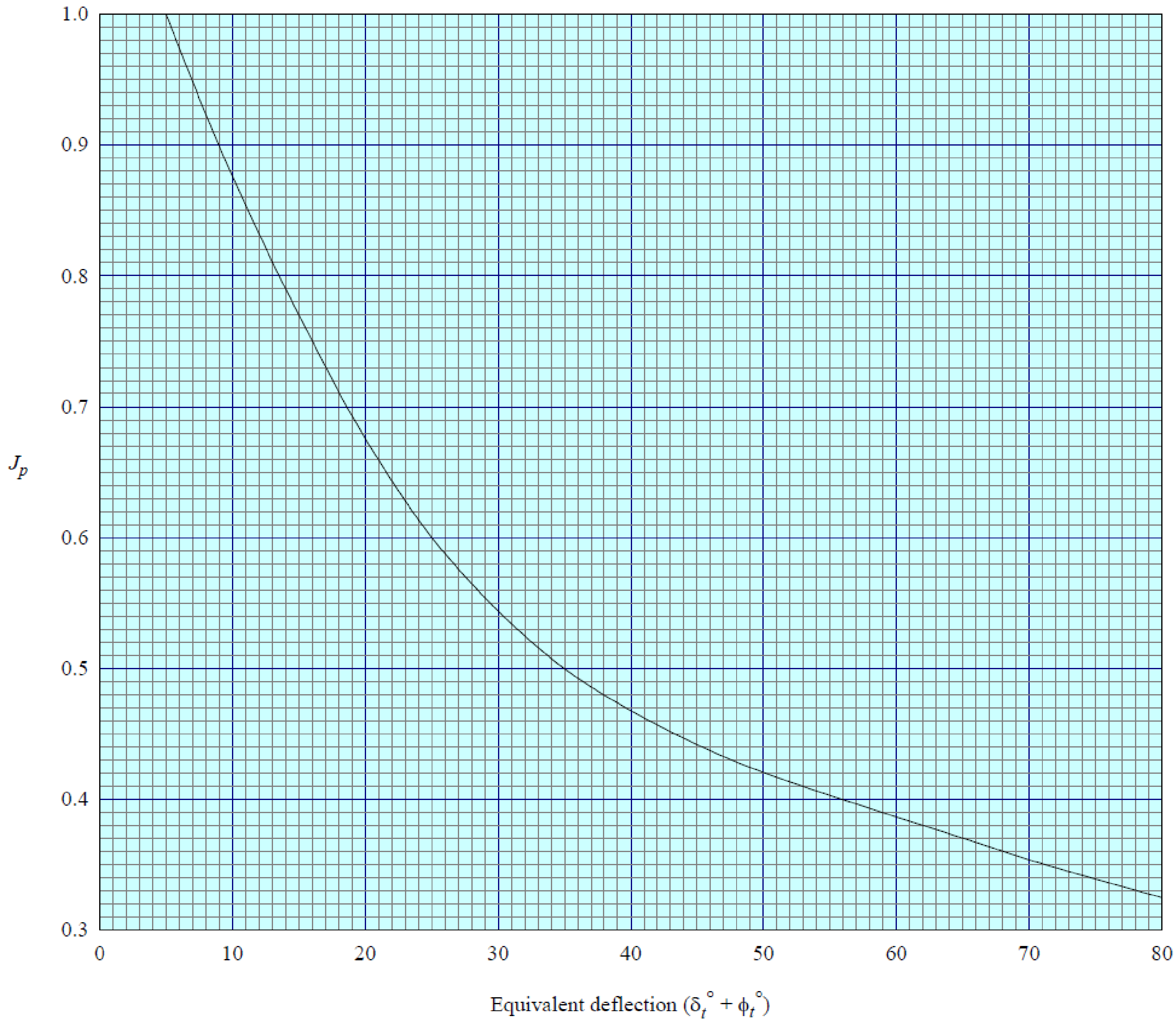
$$\Delta C'_{Lmt} = K_G K_t T \Delta C'_{L0t}$$

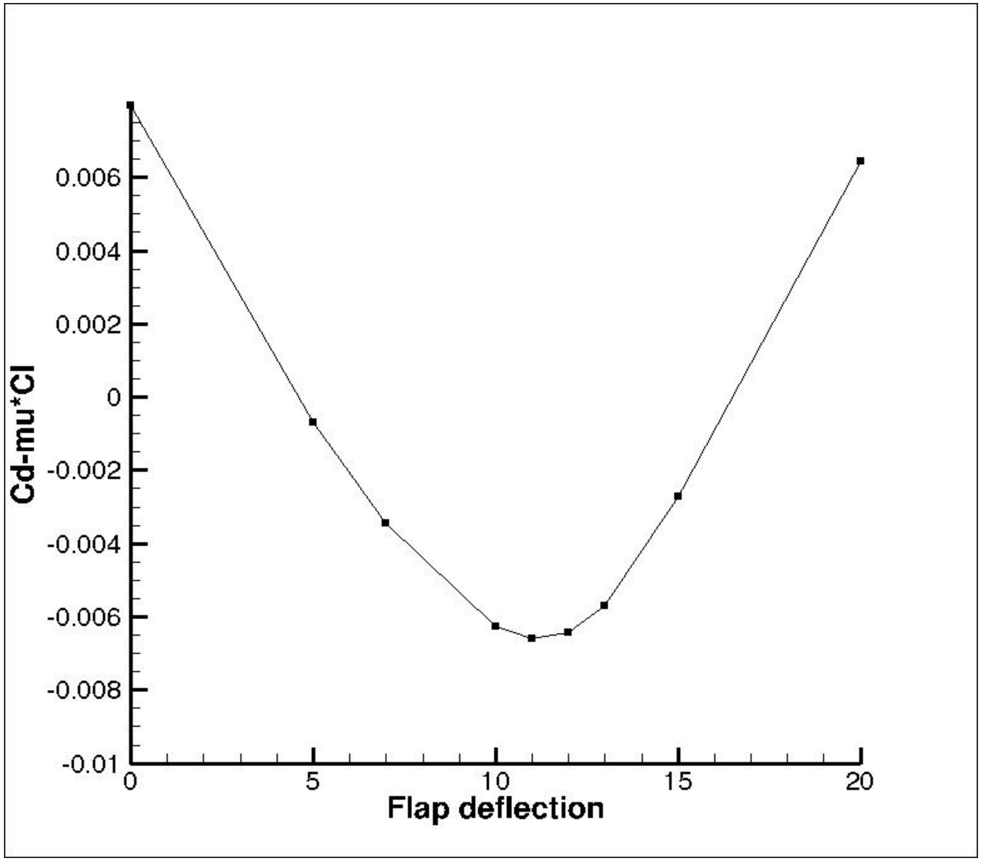
A flap **raises** the maximum lift and gives a positive lift increment at fixed incidence. Jp depends on flap delfection and trailing edge shape by fig 1 on 94028. Kt=0.8 here. T comes from fig 2 on 94028 – you can use xs'=one half of the chord fraction of the droop, or zero

$$K_G = 1.225 + 4.525\rho_l/t$$

Thicker section better!

For NACA 4/5 series have
(from Theory Wing Sections)
rho_l/t=1.1019*(t/c)


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
J_p
0
10
20
30
40
50
60
70
80
Equivalent deflection ($\delta_t^\circ + \phi_t^\circ$)



This is a result for 23015 from Xfoil. You could consider it to be correct for an infinite wing.

When selecting your TO flap setting, you should compute the full 3D drag as accurately as you can using the Cd result on slide 10, although a 2D Xfoil calculation is a reasonable place to start. Induced drag will probably shift the optimum slightly to the left.