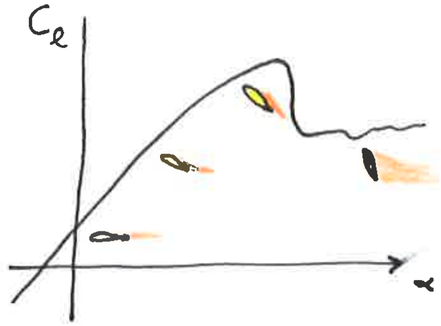
Lesson 28
High Lift

Read ADTA Chapters 25, 26

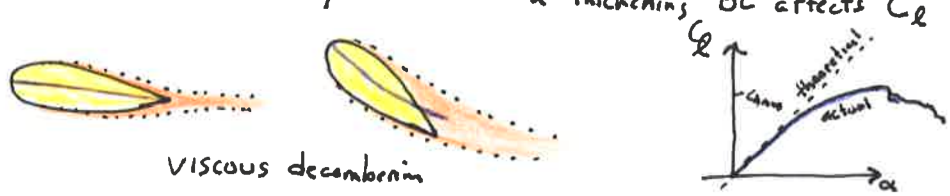
Read A.O. Smith High Lift Aerodynamics paper

High Lift combines many of the concepts that we have discussed. What is common among all high lift applications? <u>Separation.</u>



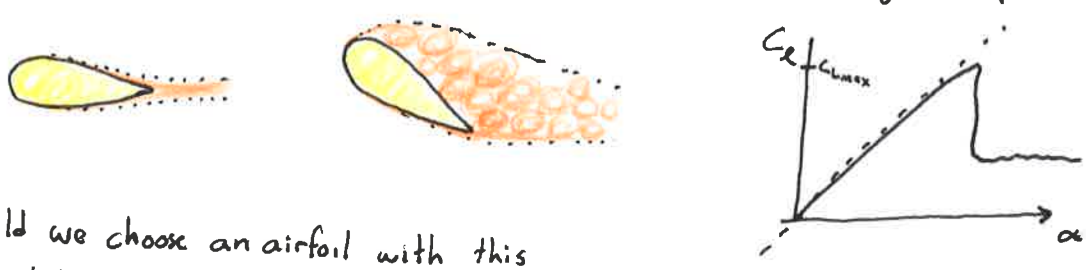
> The art of high lift is the art of delaying, mitigating or eliminating separation while maximizing circulation.

When studying the BL topics, we briefly saw how a thickening BL affects C_ℓ



We can call the point when viscous decambering leads to reduced C_ℓ from the max C_ℓ as <u>trailing edge stall</u>

Stall also has another dominant mode, the <u>leading edge stall</u> where the separation begins at the LE. This mode is typically sharper and of more magnitude. (and more unsteady).

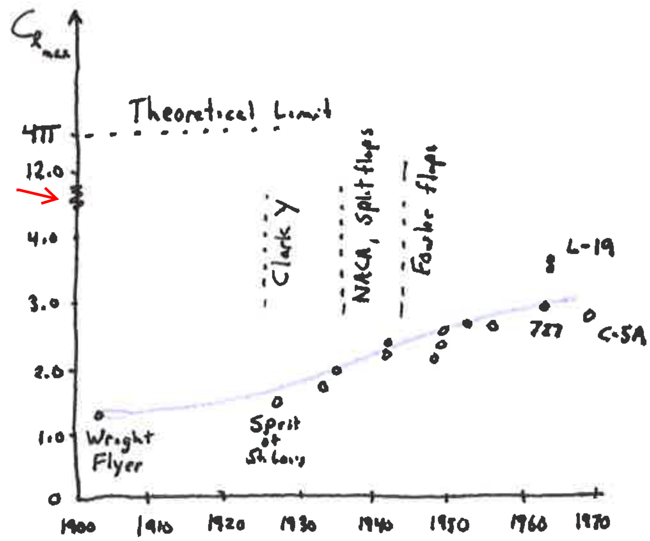


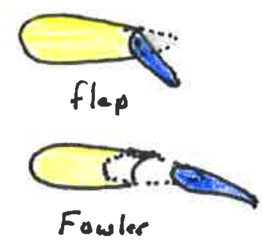
Why would we choose an airfoil with this abrupt stall behavior? <u>Performance</u>

The Piper PA38 Tomahawk was designed for spin training and uses the sharper GAW 1 airfoil. tiny.cc/PA38Stall

Both TE and LE stall can occur,

What are the limits of $C_{L_{max}}$?



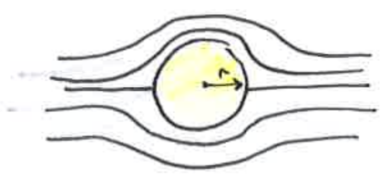


From Smith's HighLift Aerodynamics

Where does the theoretical limit come from?

- Passive surface, no active suction or blowing
- Incompressible Inviscid flow over a circle

Zero C_ℓ



$$V_\theta = \underbrace{-U\left(1+\frac{R^2}{r^2}\right)\sin\theta}_{\text{doublet}} + \underbrace{\frac{\Gamma}{2\pi r}}_{\text{vortex}}$$

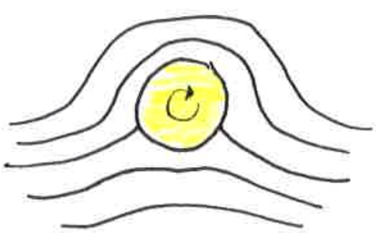
at $r=1$ and $\theta=+90°$

$$V_\theta = -U(1+1)\sin\theta + \frac{\Gamma}{2\pi r} = 0 \quad (\sin\theta = +1)$$

$$\Gamma = 2\pi \cdot 2U$$

$$C_\ell = \frac{L}{qc} = \frac{\rho V \Gamma}{q\,2} = \frac{\rho V 4\pi U}{\frac{1}{2}\rho V^2 2} = \boxed{4\pi}$$

Clmax~12.5



$C_\ell > 0$

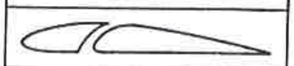
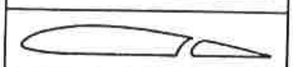
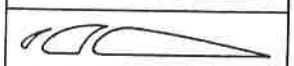
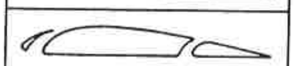
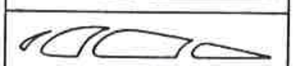
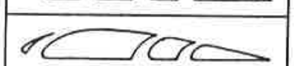
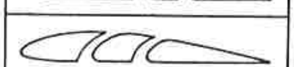
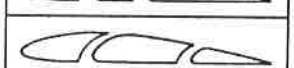
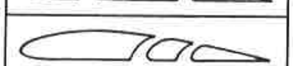
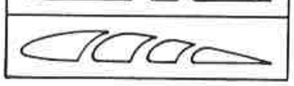
$C_{\ell_{max}}$

Multielements (slats, slots, flaps)

Again, flaps shift ΔC_L, slats and slots shift $\Delta\alpha_{stall}$

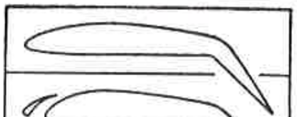
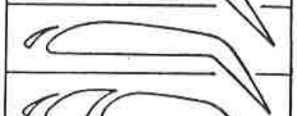
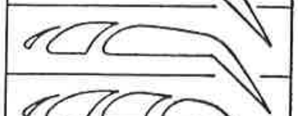
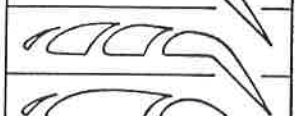
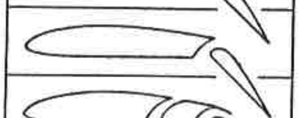
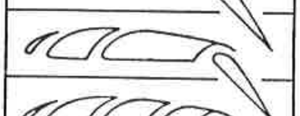
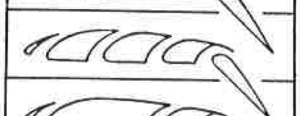
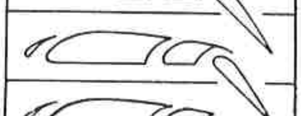
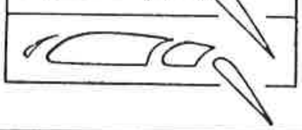
Auto-slats on commercial aircraft mitigate stall (tiny.cc/AutoSlotTestFlight)

Fowler flaps also increase wing area.

Slot combination	$C_{L_{max}}$	$C_{D_{min}}$	$\frac{C_{L_{max}}}{C_{D_{min}}}$	$\alpha_{C_{L_{max}}}$ degrees
	1.291	0.0152	85.0	15
	1.772	0.0240	73.8	24
	1.596	0.0199	80.3	21
	1.548	0.0188	82.3	19
	1.440	0.0164	87.8	17
	1.902	0.0278	68.3	24
	1.881	0.0270	69.7	24
	1.813	0.0243	74.6	23
	1.930	0.0340	56.8	25
	1.885	0.0319	59.2	24
	1.885	0.0363	51.9	25
	1.850	0.0298	62.1	24
	1.692	0.0228	74.2	22
	1.672	0.0214	78.2	22
	1.510	0.0208	72.6	19
	1.662	0.0258	64.4	22

(*a*) Multiple fixed slots.

Fig. 134. Aerodynamic characteristics of a Clark Y wing with slots and flaps.

Slot combination	$C_{L_{max}}$	$C_{D_{min}}$*	$\frac{C_{L_{max}}}{C_{D_{min}}}$	$\alpha_{C_{L_{max}}}$ degrees
	1.950	0.0152	128.2	12
	2.182	0.0240	91.0	19
	2.235	0.0278	80.3	20
	2.200	0.0340	64.7	21
	2.210	0.0270	81.8	20
	1.980	0.0164	120.5	12
	1.770	0.0164	108.0	14
	2.442	0.0208	117.5	16
	2.500	0.0258	96.8	18
	2.185	0.0214	102.0	18
	2.261	0.0243	93.2	19
	2.320	0.0319	72.7	20
	2.535	0.0363	69.8	20
	2.600	0.0298	87.3	20
	2.035	0.0298	68.3	21

* $C_{D_{min}}$ with flap neutral.

(*b*) Multiple fixed slots and a slotted flap deflected 45 degrees.

FIG. 134. (*Concluded*)

Wing Stall

Demonstration: tiny.cc/StallVGs

Clean			
	clean	1:00	60 kts
	TO flaps	140	60 kts
	Full flaps	210	58 kts
VGs outer		245	
		335	
	clean	415	
	flaps	445	
100 VGs		800	

$60^{kts} \rightarrow 45^{kts}$

$$W = L = \frac{1}{2}\rho V_o^2 C_{L_{max}} = \frac{1}{2}\rho V_{vg}^2 C'_{L_{max_{vg}}}$$

or

$$C'_{L_{max_{vg}}} = \frac{V_o^2}{V_{vg}^2} C_{L_{max_o}} = \frac{60^2}{45^2} C_{L_{max_o}}$$

$$\approx 1.78\, C_{L_{max_o}}$$

Adding VGs improved $C_{L_{max}}$ by **78%**!

Early NACA flow visualization (1938)

tiny.cc/AirfoilCLNACA

Planes, Clouds, and Vortices

tiny.cc/PlanesCloudsVortex

Watch ground effect and vortex density variations at 4:00!!
(especially at 4:15)

Prop vortex cores at 5:13 (but only on the upper surface!)

Compressible Limits.

Given $C_p = \dfrac{p - p_\infty}{q}$

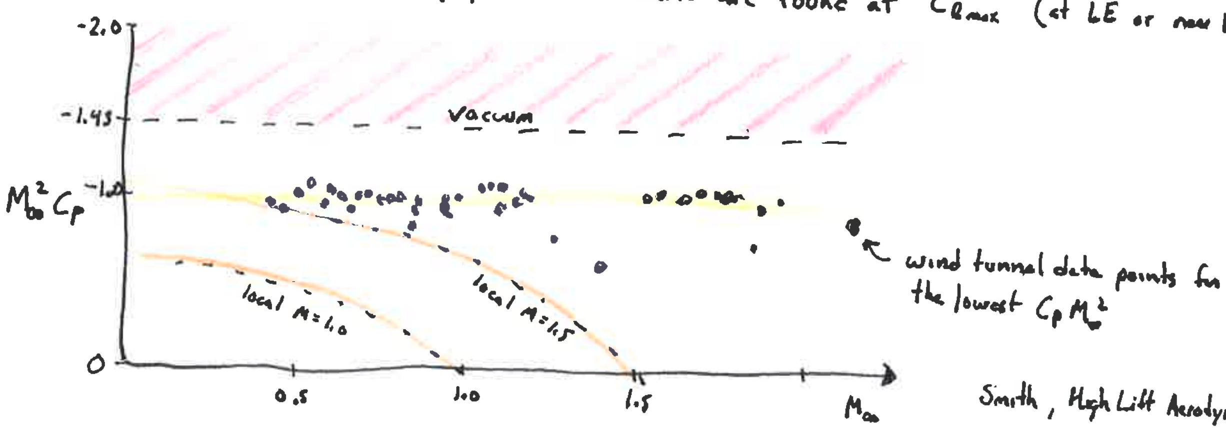
$$C_p = \frac{p - p_\infty}{\frac{1}{2}\gamma M_\infty^2 p_\infty}$$

For a vacuum, $p = 0 \Rightarrow C_p = \dfrac{-p_\infty}{\frac{1}{2}\gamma M_\infty^2 p_\infty} = \dfrac{-2}{\gamma M_\infty^2}$

Or, $M_\infty^2 C_p = \dfrac{-2}{\gamma} \approx -1.43$ for air (typo in ADTA p. 308)

This is how XFOIL provides a limit for C_p (- - - - dashed lines) when specifying a Mach #

From many experiments, the following pressure coefficients are found at $C_{\ell_{max}}$ (at LE or near LE)



Smith, High Lift Aerodynamics

Mayer found an almost universal limit to $M_\infty^2 C_p$ of 1.0 or 70% of vacuum.

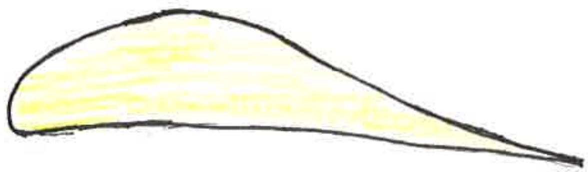
You can estimate $C_{L_{max}}$ from inviscid tools (for LE stall)

See Valarezo and Chin, Method for the Prediction of Wing Maximum Lift
J. Aircraft V31 N.1 1994

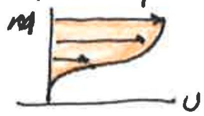
Paper suggests $C_{p_{peak}} - C_{p_{TE}} \lesssim 14$ and dependent on Re when $Re < 10 \times 10^6$ or so.

Useful for correcting LSWT subscale $C_{L_{max}}$ results to full scale.

Liebeck Family of flow separation optimized airfoils.



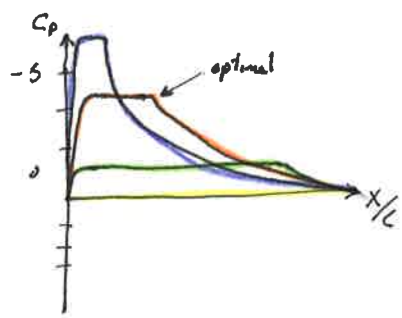
Recall the discussion of incipient separation in Falkner Skan flows. The boundary layer profile is self similar



. Liebeck through a crafty insight created a high performance and high lift airfoil section. Two characteristics define this family.

1) Rapid LE acceleration up to a rooftop C_p value

2) Pressure recovery to the TE such that incipient separation is maintained from the rooftop to the TE.



But, the question remains, <u>which</u> rooftop Mach # should be picked for max $C_{L_{max}}$?

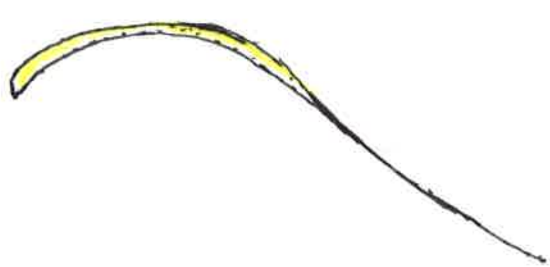
In other words, which has the most area under the curve?

The upper surface $C_{\ell_{max_{upper}}} = 2.03$ for laminar flow rooftop

$C_{\ell_{max_{upper}}} = 1.0$ for turbulent flow rooftop.

laminar flow helps lift in this application. But, not always in other applications

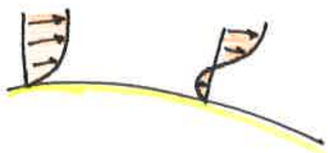
The bottom surface can also use inverse techniques to give $C_{\ell_{max}} = 3.06$ at $C_D = 51$ counts

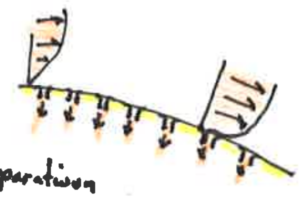


Suction, Blown Flaps, and Jets. (Active Flow Control)

Browse through Hoerner's Fluid Dynamic Lift for experimental results

Suction: Remove incipient separation by removing "bad" portion of BL.

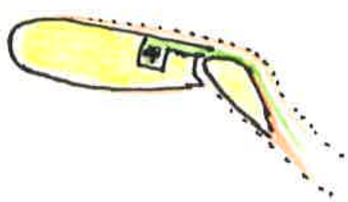




$C_Q = \frac{Q}{VS}$

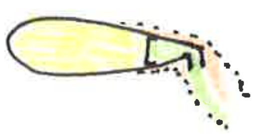
Higher C_f but lower separation

Blown Flaps: Displace or remove defect in wake



See YC-14 $\bar{w}$ $C_{L_{max}} \approx 3.5$ with powered jet

Jets:



Think AV8 Harrier

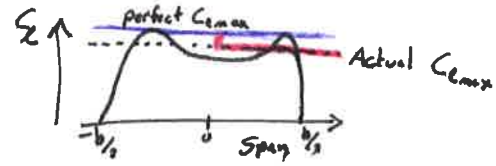
No limit to $C_{L_{max}}$

Practical considerations of $C_{L_{max}}$.

- Stall velocity scales with square root of $C_{L_{max}}$.

  At some point, increasing S or active flow control is less trouble

- As-built wings are <u>never</u> perfect. Left and Right panels will have slightly different $C_{L_{max}}$



  e.g. Right stalls prior to left. Rolls right on stall. Pilot is grumpy....

- Active Flow Control increases drag + weight.

- Reynolds' # dependent.
  - Wind tunnel $C_{L_{max}}$ is conservative (almost always).
  - Specialty airfoils for low Re are required (see: Selig 1223 or Eppler 423)

- Slat and Flap brackets and associated hardware must be considered.
  - weight
  - decreases $C_{L_{max}}$ over "clean" wing.

- 3D effects are important. $C_{l_{max}} \neq C_{L_{max}}$

- Non linear behavior

  The flow preserves history. Thus $C_L \neq C_L(\alpha)$ but $C_L = C_L(\alpha, \dot{\alpha}, \ddot{\alpha}, \dots)$