Some High Lift Aerodynamics

Part 1
Mechanical High Lift Systems

W.H. Mason
Configuration Aerodynamics Class
Why High Lift is Important

• Wings sized for efficient cruise are too small to takeoff and land in “reasonable” distances.

• From Boeing:
  – “A 0.10 increase in lift coefficient at constant angle of attack is equivalent to reducing the approach attitude by one degree. For a given aft body-to-ground clearance angle, the landing gear may be shortened for a savings of airplane empty weight of 1400 lb.
  – “A 1.5% increase in maximum lift coefficient is equivalent to a 6600 lb increase in payload at a fixed approach speed”
  – “A 1% increase in take-off $L/D$ is equivalent to a 2800 lb increase in payload or a 150 nm increase in range.”

• For fighters:
  – Devices move continuously for minimum drag during maneuvering.

• Powered Lift concepts hold out the hope for STOL operation
CLMAX with Reynolds number and Mach number

From a presentation by Dick Kita
To the new members of the Grumman aerodynamics section
McCroskey’s Study of NACA 0012 Data
Reynolds number effects

W.J. McCroskey, “A Critical Assessment of Wind Tunnel Results for the NACA 0012 Airfoil”
NASA TM-100019, October, 1987
McCroskey’s Study of NACA 0012 Data
Mach number effects

W.J. McCroskey, “A Critical Assessment of Wind Tunnel Results for the NACA 0012 Airfoil”
NASA TM-100019, October, 1987
XFOIL Predictions - Mach Effects

Mach Number effects for XFOIL CLmax Estimates

calculations by Elizabeth Eaton
Part 1: Mainly Dick Kita’s Charts

MECHANICAL HIGH LIFT SYSTEMS

DICK KITA
FEB. 1985
Some Trailing Edge Devices

TRAILING EDGE DEVICES

BASIC AIRFOIL

PLAIN FLAP

SPLIT FLAP

SLOTTED FLAP

FOWLER FLAP
Split Flap

Fleet Aircraft Ltd. Of Canada  PT-26 Cornell
(Fairchild PT-26) At the Pima Air Museum, out
side Tucson, AZ
More Trailing Edge Devices
Leading Edge Devices
The Handley Page Fixed Slot

For slow airplanes, a fixed slot is often used. It’s always in this position. This is a picture of a Grumman S-2A Tracker at the Pima Air Museum, outside Tucson, AZ.
Passive slats” for military fighter/attack aircraft

They deployed automatically, using the aerodynamic suction – eventually abandoned in favor of hydraulics. In use they hung up – one side deploying, one not!

North American Aviation F-100, at the US Air Force Museum, Dayton, OH
F-4 Maneuver Slat

Fixed position slat seen in the San Diego Aerospace Museum in Balboa Park.

Note fixed slat on horizontal stabilator,
Picture from the Pima Air Museum
F-14 High Lift System

(remember Irv Waaland?)
Trailing Edge Flap Effects
Flap Extension Effect

\[ C_{\alpha_{\text{EXT.}}} = C_{\alpha_{\text{CLEAN}}} \left( \frac{s_{\text{REF.}} + \Delta s_{\text{EXT.}}}{s_{\text{REF.}}} \right) \]
Effect of Slats

Typical Effect of Slats on $C_{L \text{ max}}$. 

Graph showing the effect of slats on lift coefficient ($C_L$) with different slat angles ($\delta_s$).
Different LE Devices

Typical effect of LE Devices on $C_{L_{\text{MAX}}}$

1. NO LE DEVICE
2. INCREASED LE RAD.
3. NOSE FLAP
4. KRUEGER
5. SLAT OR SLOTTED KRUEGER
Kita’s $C_{L_{\text{max}}}$ Projections

“Advanced” may be unobtainium
From Civil Jet Aircraft Design, by Lloyd Jenkinson, Paul Simpkin and Darren Rhodes
Shevell’s $C_{L_{\text{max}}}$ Chart


<table>
<thead>
<tr>
<th>$\frac{S_{W_{f}}}{S_{W}}$</th>
<th>Type of flap</th>
<th>Flap chord (% chord)</th>
<th>$\Lambda_{C/4}$</th>
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<tbody>
<tr>
<td>DC-3S</td>
<td>Split</td>
<td>0.174</td>
<td>$\sim 10^\circ$</td>
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<tr>
<td>DC-4</td>
<td>Single slotted</td>
<td>0.257</td>
<td>$0^\circ$</td>
</tr>
<tr>
<td>DC-6</td>
<td>Double slotted</td>
<td>0.266</td>
<td>$0^\circ$</td>
</tr>
<tr>
<td>DC-7C</td>
<td>Double slotted</td>
<td>0.266</td>
<td>$0^\circ$</td>
</tr>
<tr>
<td>DC-8</td>
<td>Double slotted</td>
<td>0.288</td>
<td>$30.5^\circ$</td>
</tr>
<tr>
<td>DC-9-30</td>
<td>Double slotted</td>
<td>0.360</td>
<td>$25^\circ$ (Slats)</td>
</tr>
<tr>
<td>DC-10-10</td>
<td>Double slotted</td>
<td>0.320</td>
<td>$35^\circ$</td>
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</table>

Flap deflection, degrees

Airplane $C_{L_{\text{max}}}$

DC-9-30, Slats extended
DC-7C
DC-10, slats extended
DC-6
DC-4
DC-3S
DC-8
DC-9-30, slats retracted
DC-10, slats retracted
### Clark Y High Lift “Build Up”

Chart from Perkins and Hage, page 80.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Diagram</th>
<th>$C_{L_{\text{max}}}$</th>
<th>$\alpha$ at $C_{L_{\text{max}}}$ (degrees)</th>
<th>$L/D$ at $C_{\text{L_{max}}}$</th>
<th>$C_{m_{ae}}$</th>
<th>Reference NACA</th>
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<tr>
<td>Basic airfoil</td>
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<td>1.29</td>
<td>15</td>
<td>7.5</td>
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<td>Clark Y</td>
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<tr>
<td>.30c Plain flap deflected 45°</td>
<td></td>
<td>1.95</td>
<td>12</td>
<td>4.0</td>
<td>-</td>
<td>TR 427</td>
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<tr>
<td>.30c Slotted flap deflected 46°</td>
<td></td>
<td>1.98</td>
<td>12</td>
<td>4.0</td>
<td>-</td>
<td>TR 427</td>
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<td>.30c Split flap deflected 45°</td>
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<td>2.16</td>
<td>14</td>
<td>4.3</td>
<td>-0.250</td>
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<td>.30c hinged at .80c Split flap (Zap) deflected 45°</td>
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<td>2.26</td>
<td>13</td>
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<td>-0.300</td>
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<td>.30c hinged at .90c Split flap (Zap) deflected 45°</td>
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<td>12.5</td>
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<td>.30c Fowler flap deflected 40°</td>
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<td>2.82</td>
<td>13</td>
<td>4.55</td>
<td>-0.660</td>
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<td>.40c Fowler flap deflected 40°</td>
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<td>3.09</td>
<td>14</td>
<td>4.1</td>
<td>-0.860</td>
<td>TR 534</td>
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<td>Fixed slot</td>
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<td>1.77</td>
<td>24</td>
<td>5.35</td>
<td>-</td>
<td>TR 427</td>
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<td>Handley Page automatic slot</td>
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<td>1.84</td>
<td>28</td>
<td>4.1</td>
<td>-</td>
<td>TN 459</td>
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<td>Fixed slot and .30c plain flap deflected 45°</td>
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<td>2.18</td>
<td>19</td>
<td>3.7</td>
<td>-</td>
<td>TR 427</td>
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<td>2.26</td>
<td>18</td>
<td>3.77</td>
<td>-</td>
<td>TR 427</td>
</tr>
<tr>
<td>Handley Page slot and .40c Fowler flap deflected 40°</td>
<td></td>
<td>3.36</td>
<td>16</td>
<td>3.7</td>
<td>-0.740</td>
<td>TN 459</td>
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### Boeing Transports

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<tr>
<th>Type</th>
<th>B-47/B-52</th>
<th>367-80/KC-135</th>
<th>707-320/E-3A</th>
<th>727</th>
<th>747/E-4A</th>
<th>767</th>
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<tbody>
<tr>
<td>Plantform</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Typical airfoil</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Single-slotted Fowler flap</td>
<td>Single-slotted flap</td>
<td>Double-slotted flap</td>
<td>Slat and triple-slotted flap</td>
<td>Variable camber Krueger and triple-slotted flap</td>
<td>Slat and single-slotted flap</td>
<td></td>
</tr>
<tr>
<td>$C_{L,\text{max}}$</td>
<td>1.8</td>
<td>1.78</td>
<td>2.2</td>
<td>2.79</td>
<td>2.45</td>
<td>2.45</td>
</tr>
</tbody>
</table>

**Fig. 1** Trends in Boeing transport high-lift system development.

From *Applied Computational Aerodynamics*, AIAA Progress in Aeronautics Series, edited by Preston Henne
Device Effects on Drag

Typical Variation of Flap Drag

$C_L$ vs. $C_D$
Device Effect on Pitching Moment

Typical Variation of Flap Pitching Moment $C_L$ vs. $C_m$
Critical Parameters for High Lift System Development – Gap and Overlap

**FOWLER TYPE FLAP LAYOUT**

NOTE: AT HIGHER FLAP DEFLECTIONS, 25° TO 40°, FLAP TANGENCY TO LINE IS SECONDARY TO GAP AND OVERLAP CRITERIA. FLAP TYPE AND SHAPE MAY PRECLUDE THIS OCCURRENCE.

This is for a GAW(1) airfoil

Note that the maximum lift is very sensitive to the high-lift element placement, thus emphasizing the importance of accurately maintaining the correct rigging in operation and maintenance.
A-380 Trailing Edge Flap System

A photo taken during the March 2007 tour of US airports, unknown photographer
Andy Parker’ s XFOIL results: Lift

Note: Andy Parker did this as a freshman
Andy Parker’s XFOIL Results: Drag
Andy Parker’s XFOIL results: pitching moment
XFOIL - comparison with data: David Lurie

Re = 6 million, M = 0.17, calculation by David Lurie
Physics of High Lift: AMO Smith’s Classic Paper

- He “wrote the book” with his Wright Brothers Lecture
  - *It is assumed that every configuration aerodynamicist has read this paper.*
- He showed how to get the boundary layer to carry the maximum “load” (lift)
- Example: Liebeck’s Maximum Lift Single Element Airfoil
- The five effects for multielement airfoils
  - The Slat effect
  - The Circulation effect
  - The Dumping effect
  - The Off-the-surface pressure recovery effect
  - The Fresh boundary layer effect
- Etc. (mainly meaning blowing and or sucking)
How to most effectively apply load to the BL

- AMO used a “Canonical” $Cp$ to be able to equate different cases, where 0 represents the start of the pressure rise, and 1 means the max possible $Cp$, $u_e = 0$.
- He studied various shapes of pressure recoveries.
- Concave pressure distributions allowed the greatest pressure recovery.
- Stratford provided the best shape.
The “best” pressure distribution for recovery

Stratford: The pressure distribution that puts the *bl* everywhere on the verge of separation

\[
\frac{\bar{C}_p \sqrt{x \left( \frac{d \bar{C}_p}{dx} \right)}}{\left( 10^{-6} R_e \right)^{1/10}} = S
\]

Starting the recovery early (thin *bl*), allows more recovery

See AMO’s paper for details (S)

**Messages**

- thin *bl*’s can withstand extreme pressure gradients
- as the *bl* thickens, the gradient must be relaxed
- conversely, thick *bl*’s separate more easily
- you can recover to near zero edge velocity if done right, but it takes a very long distance
Liebeck’s High Lift Single Element Airfoil

- Knowing the shape of the pressure distribution required:
  - Identify the maximum lift upper surface target distribution pressure distribution
  - Use an inverse method to find the airfoil

Made to seem way easier than it really was! Scans from A.M.O. Smith’s paper. Note the the axis is the airfoil arc length
Liebeck’s Hi-Lift Airfoil: it works!

From R.T. Jones, *Wing Theory*

Liebeck’s Hi-Lift Airfoil: Including Drag

From Bertin, 
Aerodynamics for Engineers
Now consider multielement airfoils

- **1. The Slat Effect**

Contrary to old wives tales, the slat is in effect a point vortex that reduces the speed on the main element, thus reducing the chance of separation: the slat “protects” the leading edge.

Figure from AMO Smith’s paper
2. The Circulation Effect

The downstream element causes the trailing edge of the upstream element to be in a high velocity region inclined to the mean line. To achieve the Kutta condition, the circulation has to be increased.
3. The Dumping Effect

The TE of the forward element is in a region of velocity appreciably higher than the freestream. Thus, the BL can come off the fwd. element at a higher velocity. You don’t have to recover to $C_p = +0.2$ for attached flow, relieving the pressure rise on the BL, and alleviating sep’ n problems. The suction lift can be increased in proportion to the TE velocity squared for the same margin against separation.
4. The Off-the-Surface Pressure Recovery Effect

The BL leaves the TE faster than the freestream, and becomes a wake. The recovery back to freestream velocity can be more efficient away from contact with the wall. Wakes withstand more adverse pressure gradient than BLs.

Note: for well designed high lift systems the local BLs and wakes remain separate.

Multielement airfoils

5. The Fresh Boundary Layer Effect

Simply put: because thin boundary layers can sustain greater pressure gradients than thick boundary layers, three thin boundary layers are better than one thick boundary layer.
Fixes: Vortex Generators

Photos taken at the Pima Air Museum, outside Tucson, AZ

AV-8A Harrier

A-4 Skyhawk

Lear Jet
Fixes: the F-111 Eyelid Flap

It is very hard to get photos of the eyelid flap deployed. These are scans from a British magazine no longer published, the *World Air Power Journal*.
Last, but not least: The Gurney Flap

Invented to add downforce in racing, named after Dan Gurney, but eventually done by Bob Liebeck

Called a Wickerbill in NASCAR

Pictures taken outside Shelor’s QuickLane, Fall 2008
Liebeck’s Description of the Gurney Flap


To Conclude

• These are the high points of mechanical high-lift systems
• It is difficult to get more than a $C_{L_{max}}$ of 3 or a little more for practical aircraft
• There are many, many NACA/NASA Reports

Note: the most recent major survey is by C.P. van Dam, “The aerodynamic design of multi-element high-lift systems for transport airplanes,” in *Progress in Aerospace Sciences*, Vol. 38, 2002. -electronic version available through the library


And the *Journal of Aircraft*, July-August 2015: Special Section: Second High-Lift Prediction Workshop