10AE81: FLIGHT VEHICLE DESIGN

Text Books:

1. Tomas C Corke., “Design of Aircraft,” Person Education, LPE, 2003.
2. John P Fielding, “Introduction to Aircraft Design” Cambridge University Press, 1999

Reference:

1. Darrol Stinton D.,” The Design of the Aeroplane”, Black Well Science, 2nd Edition, 2001
2. Daniel P. Raymer, “Aircraft Design: A Conceptual Approach”, AIAA Education Services, 1992.

Unit 5 - Performance Estimation

- Take-off phases, minimum take-off specification, climb gradients. Balanced field length.
- Landing approach. Free roll and braking. Spread sheet for take-off and landing distance.
- Enhance lift considerations - passive lift enhancement, trailing edge flap configuration, lift and drag determination. Active lift enhancement,
- Drag polar.
- Power to climb and maneuver.

10AE81-FVD-UNIT 5: VTU Question Bank

Take-Off

1. Define clearly the term ground roll, rotation, transition and climb phases in take-off condition. (10)
2. Derive relationship for ground roll distance for take-off. (10)
3. Describe the balance field length for takeoff. Also mention the formula used. (10)

Landing

1. Enlist all phases of flight landing with schematic sketch and mention all the expression related to each phase. (10)
2. Write the equation of motion for landing ground roll and obtain an expression for landing ground roll distance. (10)

Spreadsheet

1. Draw spread sheet layout for take-off and landing distance. (10)

Lift Enhancement Devices

1. Write a short note on “Passive Lift Enhancement” and “Active Lift Enhancement”
2. What are the common approaches used for active left enhancement. Explain in detail with appropriate figures and graph. (10)
3. Draw and explain drag polar for active lift enhancement. (10)

Take-Off

- The take-off flight phase consists of accelerating from rest to a take-off velocity, V_{TO} , and climbing to an altitude which is greater than a reference obstacle altitude, $H_{obstacle}$.
- The take-off flight phase can be divided into four parts, as shown in Fig., and, consists of:

1. Ground roll, 2. Rotation, 3.Transition and 4. Climb

❑ Ground Roll

- The ground roll is the portion in which the aircraft accelerates from rest to the take-off velocity. The distance of ground roll is designated S_G .

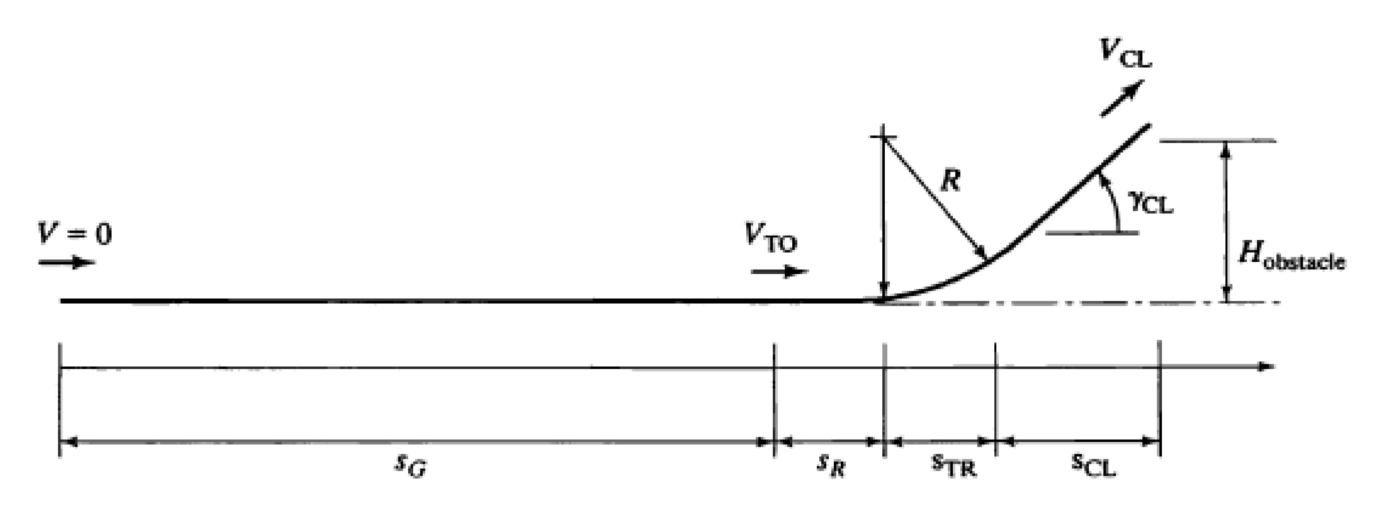
$$V_{TO} = 1.2V_s = 1.2\left[\left(\frac{W}{S}\right)_{TO}\frac{2}{\rho C_{L_{max}}}\right]^{0.5}$$

❑ Rotation

- The rotation portion consists of a rotation maneuver in which the aircraft is pitched up to increase the angle of attack.
- The lift coefficient in the rotation portion is defined as: $C_{L_R} = 0.8\,C_{L_{max}}$
- The distance for rotation is designated as S_R.

❑ Transition

- The transition portion of take-off is where the aircraft first leaves the ground and flies at constant velocity along a circular arc of radius *R.*
- The ground distance for the transition portion is designated as S_{TR} .



Take-Off (contd)

Climb

- The climb portion begins where the aircraft first reaches its climb angle and ends when an altitude of a reference altitude is reached.
- The ground distance for the climb portion is s_{CL}.
- The total take-off distance is given by the sum,

$$s_{TO} = s_G + s_R + s_{TR} + s_{CL}$$

- Aircraft with low wing loading may reach $H_{obstacle}$ in the transition portion of take-off itself. In such cases S_{CL} is not included in the sum for s_{TO}.
- Table shown below, lists the minimum take-off parameters for three classes of aircraft, where AEO = all engines operating, and OEI = one engine inoperative.

Minimum take-off specifications.

	MIL-C5011A Military	FAR Part 23 Civil	FAR Part 25 Commercial
Velocities:			
	$V_{TO} \geq 1.1V_s$ $V_{CL} \geq 1.2V_s$	$V_{TO} \geq 1.1V_s$ $V_{CL} \geq 1.1V_s$	$V_{TO} \geq 1.1V_s$ $V_{CL} \geq 1.2V_s$
Climb Gradient:			
Gear Up, AEO	500 fpm at SL	300 fpm at SL	—
Gear Up, OEI	100 fpm at SL	—	3% at V_{CL}
Gear Down, OEI	—	—	0.5% at V_{CL}
Rolling Friction Coefficient:			
	0.025	—	—
Field Length Definition:			
	Distance needed to clear 50-f obstacle	Distance needed to clear 50-f obstacle	115% of distance needed to clear 35-f obstacle

Take-Off (contd)

❑ GROUND ROLL

- In the ground roll portion of take-off, the aircraft accelerates from rest, until it reaches the take-off velocity given by,

$$V_{TO} = 1.2V_s = 1.2\left[\left(\frac{W}{S}\right)_{TO}\frac{2}{\rho C_{L_{max}}}\right]^{0.5} \qquad (1)$$

- The ground distance required for this portion of take-off is

$$s_G = \int_0^{V_{TO}}\left(\frac{V}{a}\right)dV = \frac{1}{2}\int_0^{V_{TO}}\frac{dV^2}{a} \qquad (2)$$

- The acceleration, a , is found from

$$a = \frac{g}{W_{TO}}\sum F_x = \frac{g}{W_{TO}}[T - D - F_f] \qquad (3)$$

where, F_f , is the rolling friction force given by,

$$F_f = \mu\,[W_{TO} - L_G] \qquad (4)$$

- A schematic that indicates the forces acting on an aircraft during ground roll is shown in Fig.
- The rolling friction coefficient, μ , varies with the runway conditions. Examples are given in Table 1.

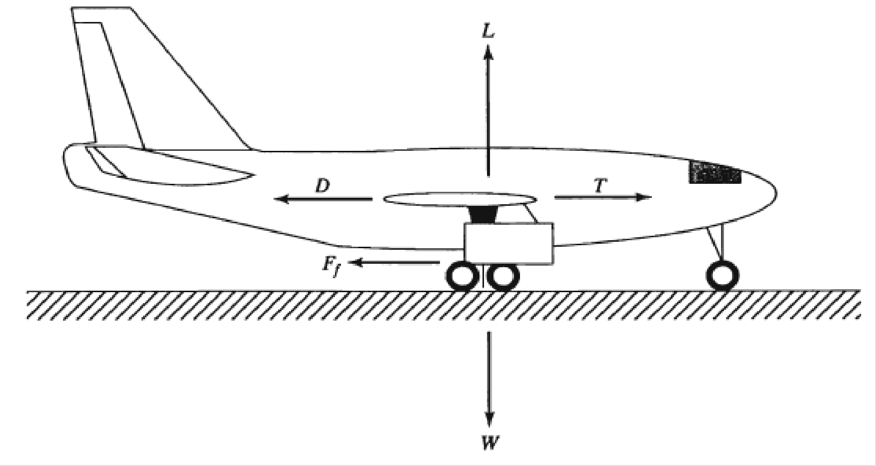


Table 1. Rolling friction coefficients for different runway surfaces.

Surface Type	μ
Concrete (wet or dry)	0.03–0.05
Hard Turf	0.05
Firm & Dry Dirt	0.04
Soft Turf	0.07
Wet Grass	0.10
Snow or Ice-Covered	0.02

Take Off (contd)

GROUND ROLL (contd)

- The lift generated during ground roll, L_G is based on an enhanced lift configuration for the wing and the AoA produced when the aircraft is on the ground.

$$L_G = qSC_{L_G} \tag{5}$$

- The drag force consists of the base drag and lift-induced drag, plus additional base drag produced by extended flaps and landing gear.

$$D = qS\left[C_{D_0} + kC_{L_G}^2 + \Delta C_{D_{0_{\text{flap}}}} + \Delta C_{D_{0_{LG}}}\right] \tag{6}$$

- For the flaps, the added base drag depends on the type of flap and deflection angle, δ_f .
- Empirical data for the added base drag due to flaps is give in Table 2.

Table 2. Added base drag due to flaps.

Flap Type (60% span, 25% chord)	δ_f	$\Delta C_{D_{0_{\text{flap}}}}$
Fowler	30	0.032
Fowler	50	0.083
Split or Plain	30	0.05
Split or Plain	50	0.10
Slotted	30	0.02
Slotted	50	0.05

- The base drag due to extended landing gear can be estimated from the following empirical relation,

$$\Delta C_{D_{0_{LG}}} = f_{LG}\frac{A_{LG}}{S} \tag{7}$$

where, A_{LG} , is the frontal (projected) area of the landing gear, f_{LG} , is a correlation function that is based on the take-off weight of the aircraft.

$$f_{LG} = 3.23\sqrt{\frac{W_{TO}}{1000}} \tag{8}$$

- For take-off and landing, where the aircraft is in close proximity to the ground, the effective aspect ratio of the wing is larger by an amount

$$\frac{A}{A_{\text{effective}}} = \sqrt{\frac{2H}{b}} \tag{9}$$

where, *H* is the altitude and *b* is the wing span.

Take Off (contd)

GROUND ROLL (contd)

Evaluation of Ground Roll Distance:

- The acceleration, a , occuring in the integral for the ground roll distance is a complex function of velocity and thrust.
- The maximum thrust is also a function of velocity.
- Therefore, two possible approaches for evaluating the integral were developed.

Method 1:

- Assume that *T/W* is constant, then

$$a = f_1 + f_2 V^2$$ where, $$f_1 = g\left(\frac{T}{W} - \mu\right)$$

$$f_2 = \frac{g\rho}{2(W/S)}\left(\mu C_{L_G} - C_{D_0} - kC_{L_G} - \Delta C_{D_{0_{\text{flap}}}} - \Delta C_{D_{0_{LG}}}\right)$$

- Then the integral for the landing distance can be rewritten as,

$$s_G = \int_0^{V_{TO}} \frac{dV^2}{f_1 + f_2 V^2} = \frac{1}{2f_2} \ln\left[\frac{f_1 + f_2 V_{TO}^2}{f_1}\right]$$

- A good estimate for T/W is $\frac{T}{W} = \left(\frac{T}{W}\right)_{\text{max}}$ at $0.7V_{TO}$

Method 2:

- Integrate numerically taking small velocity time steps, over which *T/W* is constant and equal to the maximum thrust at each upper time-step value of velocity.

NOTE:

- Method 1 is implemented in the spreadsheet for take-off and landing calculations.

Take Off (contd)

❑ ROTATION:

- In the rotation part of the take-off, the aircraft AoA is increased until $C_L = 0.8\,C_{L_{max}}$.
- As a convention, rotation is assumed to take three seconds, and during this maneuver the aircraft velocity is V_{TO}.
- Therefore, the ground distance for roll is given by,

$$s_R = 3V_{TO}$$

❑ TRANSITION:

- In the transition portion of the take-off, the aircraft leaves the ground and flies at a constant velocity along a circular arc of radius R_{TR}.
- During transition, the load factor is given by,

$$n_{TR} = \left(\frac{L}{W}\right)_{TR} = 1 + \frac{V_{TO}^2}{R_{TR}\,g} \qquad (1)$$

and the lift-to-weight ratio is given by,

$$\left(\frac{L}{W}\right)_{TR} = \frac{C_{L_{TO}}\rho V_{TO}^2}{2(W/S)} = \frac{0.8C_{L_{max}}\rho\,(1.2V_s)^2}{2(W/S)} \qquad (2)$$

- Substituting for the stall velocity V_S, the lift-to-weight ratio reduces to,

$$\left(\frac{L}{W}\right)_{TR} = 1.15 \qquad (3)$$

- Now, Eq.(1) can be written as,

$$1 + \frac{V_{TO}^2}{R_{TR}\,g} = 1.15 \quad \text{or} \quad R_{TR} = \frac{V_{TO}^2}{0.15g} \qquad (4)$$

- The rate of climb of the aircraft is given by,

$$\frac{dH}{dt} = V_{TO}\sin\gamma \qquad (5)$$

- At a constant climb velocity,

$$V_{TO}\sin\gamma = \frac{V_{TO}(T-D)}{W} \qquad (6)$$

- The transition portion ends when $\gamma = \gamma_{CL}$.
- At the end point of transition, the radial vector has turned by an angle equal to γ_{CL}.
- The horizontal (ground) distance subtended by the arc is,

$$s_{TR} = R_{TR}\sin\gamma_{CL} \qquad (7)$$

and, the altitude at the end of the transition portion is,

$$H_{TR} = R_{TR}\,(1-\cos\gamma_{CL}) \qquad (8)$$

Take Off (contd)

❑ CLIMB

- The climb portion starts at the end of transition and ends when the aircraft reaches a prescribed altitude, $H_{obstacle}$.
- Throughout this portion, the climb angle is γ_{CL} .
- From geometry, the horizontal (ground) distance is

$$s_{CL} = \frac{H_{obstacle} - H_{TR}}{\tan\gamma_{CL}}$$

- The prescribed obstacle height is 50 ft for military and small civil aircraft, and 35 ft for commercial aircraft.
- In the aircraft designs with low wing loading at take-off, it is possible to reach the obstacle altitude during the transition portion itself. In this case

$$s_{CL} = 0$$

Take Off (contd)

❑ BALANCED FIELD LENGTH

- The total take-off distance specifies the minimum airfield length that is required for the aircraft to take-off.
- From practical point of view, another airfield length known as "Balanced Field Length" is specified.
- The balanced field length corresponds to the total air field length, which is required for safety in the event that one engine of a multiengine aircraft fails.
- In the engine failure event, there is a reference velocity called the "decision speed".
- If the engine fails when the take-off velocity is below the decision speed, the field length needs to be sufficient to allow the aircraft to break to a stop.
- If the engine fails above the decision speed, the field length has to be long enough to allow the aircraft to take-off and clear the necessary obstacle height.
- A schematic illustration of the balanced field length for an emergency aborted take-off, compared to standard take-off is shown in Fig.

➢ The Balanced field length can be estimated from the following fairly detailed empirical formula:

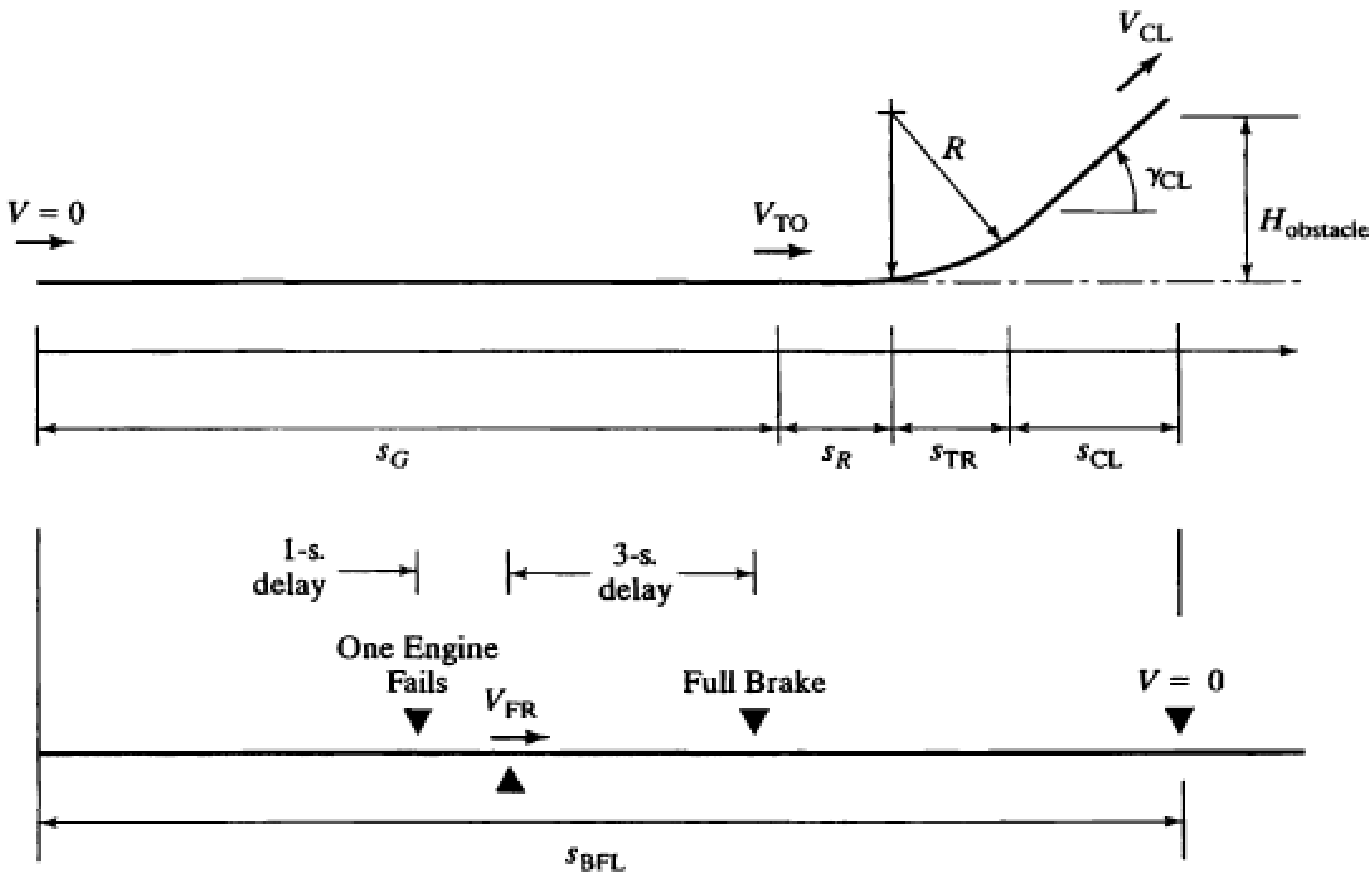
$$s_{\mathrm{BFL}} = \frac{0.863}{1+2.3G}\left[\frac{W/S}{\rho g\left(0.8C_{L_{\max}}\right)} + H_{\mathrm{obstacle}}\right]\left[\frac{1}{\frac{T_{av}}{W} - U} + 2.7\right] + \frac{655}{\sqrt{\rho/\rho_{\mathrm{SL}}}}$$

Jet Engine: $T_{av} = 0.75T_{\mathrm{static}}\left[\frac{5+B}{4+B}\right]$

Propeller Engine: $T_{av} = 5.75P\left[\frac{(\rho/\rho_{\mathrm{SL}})N_e D_p^2}{P}\right]^{1/3}$

$G = \gamma_{\mathrm{CL}} - \gamma_{\min}$ $\quad\left[\gamma_{min} = 0.024(\ for\ N_e = 2\ ); = 0.027(\ for\ N_e = 3\ ); = 0.030(\ for\ N_e = 4\ )\right]$

- The drag produced by extended flaps (U) is given by $U = 0.01C_{L_{\max}} + 0.02$
- B is the jet engine bypass ratio, and P is the shaft horsepower for the reciprocating engine.
- N_e is the number of engines, and D_p is the propeller diameter.



Schematic illustration of the balanced field length for an emergency aborted take-off, compared to standard take-off.

Landing

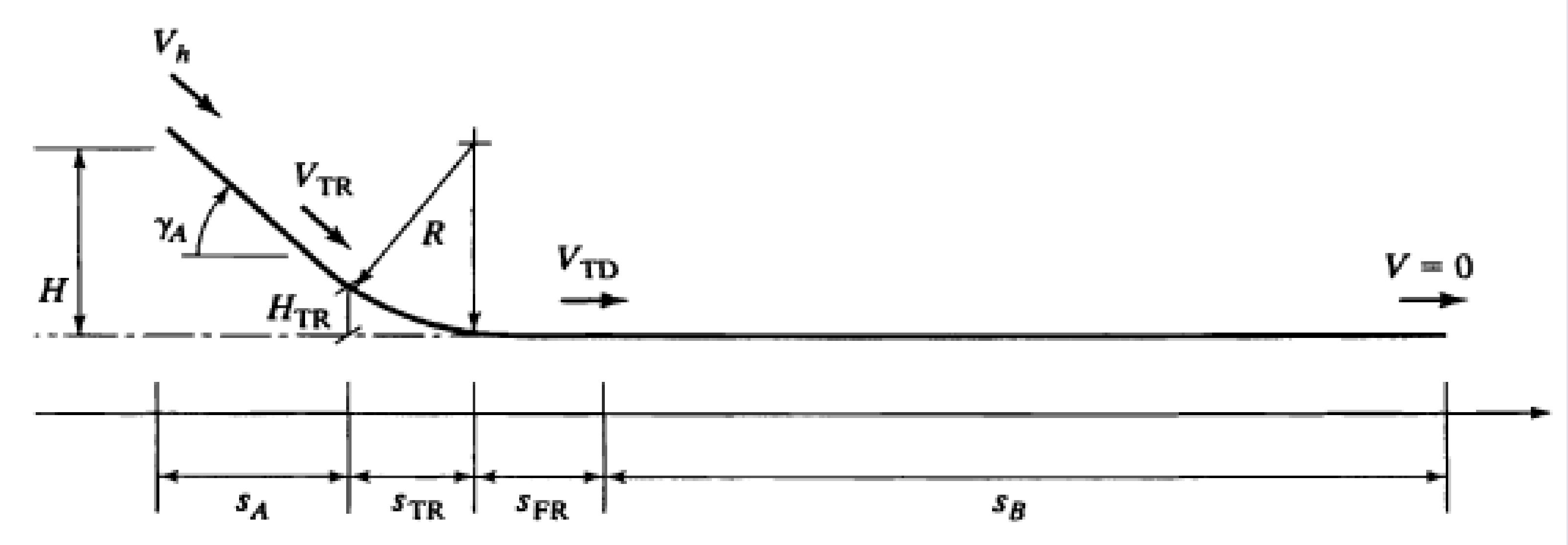
- The landing flight phase consists of an approach starting at an altitude of 50 ft, a touch-down at a velocity of V_{TD}, a free-roll at constant velocity, and a braking deceleration until the aircraft comes to rest.
- The distance required to accomplish this is the landing distance, S_L.
- A schematic representation of the landing phase is shown in Fig.
- In the first portion of the landing phase, the aircraft starts descent at an elevation of 50 ft and a velocity of $V_{50} = 1.3V_s$. For military aircraft $V_{50} = 1.2V_s$
- The aircraft descends at a fixed angle γ_A and velocity V_{50} until it reaches a transition height H_{TR}

- The horizontal distance for approach is S_A
- In the second portion of the landing, the aircraft flies along a constant radius circular arc. At the bottom of the circular arc, the aircraft touches down at the velocity $V_{TD} = 1.15V_s$
- Just prior to touchdown, the aircraft will flare to produce a positive AoA such that

$$C_{L_{TD}} = 0.8\, C_{L_{max}}$$

where, $C_{L_{TD}}$ is based on an enhanced lift (flap) configuration.

- The horizontal distance for this portion of the landing is designated S_{TR}



Landing

- In the third portion of the landing, the aircraft rolls freely at a constant velocity of V_{TD} .
- The distance for this portion of the landing is s_{FR}
- In the fourth and final portion of the landing, the aircraft breaks to a stop. This distance is designated as s_B .
- The total landing distance is given by,

$$s_L = s_A + s_{TR} + s_{FR} + s_B$$

- For landing, the worst case scenario is assumed in which the weight of the aircraft at landing is taken to be $W_L = W_{TO} - 0.5\,W_{fuel}$

That is, it is still carrying 50% of its take-off fuel.

- The minimum values of various landing parameters for three classes of aircraft are shown in the Table.

	MIL-C5011A Military	FAR Part 23 Civil	FAR Part 25 Commercial
Velocities:			
	$V_{TO} \geq 1.2V_s$ $V_{CL} \geq 1.1V_s$	$V_{TO} \geq 1.3V_s$ $V_{CL} \geq 1.15V_s$	$V_{TO} \geq 1.3V_s$ $V_{CL} \geq 1.15V_s$
Breaking Friction Coefficient:			
	0.30	—	—
Field Length Definition:			
	Distance needed starting above 50-f obstacle	Distance needed starting above 50-f obstacle	160% of distance starting above 35-f obstacle

Landing (contd)

❑ APPROACH

- The approach is a constant velocity descent from a height of 50 ft to a height of H_{TR}.
- The descent angle can be determined from eqn.,

$$V_{50} \sin \gamma_{\text{approach}} = \frac{V_{50}(T - D)}{W}$$

- Most typically, the engines will be idle so that T=0 then,

$$\gamma_{\text{approach}} = \sin^{-1} \frac{-D}{W}$$

- As a reference, a transport aircraft descent angle would be no larger than 3 deg.
- The drag (D) in the above equation can be determined from the eqn.,

$$D = qS\left[C_{D_0} + kC_{L_G}^2 + \Delta C_{D_{0_{\text{flap}}}} + \Delta C_{D_{0_{LG}}}\right]$$

for full flaps and extended landing gear.

- The approach distance can be found from eqn.

$$s_A = \frac{H_{TR} - 50}{\tan \gamma_A}$$

where, H_{TR}, is obtained from the transition portion of the landing.

❑ TRANSITION

- In the transition portion of the landing, the aircraft flies along a circular arc with radius R_{TR}.
- The velocity decelerates slightly from V_{50} to V_{TD} which is from $1.3V_s$ to $1.5V_s$
- Using an average velocity of $V_{TR} = 1.23V_s$, which can be assumed to be constant, it can be shown that the load-factor and radius during the transition portion of landing are given by

$$n_{TR} = \left(\frac{L}{W}\right)_{TR} = 1.19 \quad \text{and} \quad R_{TR} = \frac{(1.23V_s)^2}{0.19g}$$

- H_{TR} for landing is given by,

$$H_{TR} = R_{TR}\left(1 - \cos \gamma_{approach}\right)$$

- The horizontal (ground) distance is given by,

$$s_{TR} = -R_{TR} \sin \gamma_{approach}$$

❑FREE-ROLL

- During the free-roll portion of the landing, the aircraft maintains a constant velocity of V_{TD}.
- The free-roll lasts for about 3 s, and the distance covered is $s_{FR} = 3V_{TD}$

Landing (contd)

❑ BRAKING (Landing Ground Roll)

- The deceleration during the breaking portion of landing is given by the following equation,

$$a = \frac{g}{W_{TO}} \sum F_x = \frac{g}{W_{TO}} [T - D - F_f]$$

with the option that,

1. The engines will be at idle so that T = 0, or
2. The engines are equipped with thrust reversers, in which case $-0.57\,T_{max} \le T \le -0.4\,T_{max}$

- The drag includes all of the quantities given in eqn.,

$$D = qS\left[C_{D_0} + kC_{L_G}^2 + \Delta C_{D_{0_{flap}}} + \Delta C_{D_{0_{LG}}}\right]$$

- For the rolling friction, the friction coefficients are larger because of braking. These are given in the Table.
- Assuming that any reverse thrust is not a function of velocity, the braking distance is given by,

$$s_B = \int_{V_{TD}}^{0} \frac{dV^2}{f_1 + f_2 V^2} = \frac{1}{2f_2} \ln\left[\frac{f_1}{f_1 + f_2 V_{TD}^2}\right]$$

where,

$$f_1 = g\left(\frac{T}{W} - \mu\right)$$

$$f_2 = \frac{g\rho}{2(W/S)}\left(\mu C_{L_G} - C_{D_0} - kC_{L_G} - \Delta C_{D_{0_{flap}}} - \Delta C_{D_{0_{LG}}}\right)$$

with, $T = 0$ or $T = -0.4 T_{Max}$ to $-0.5 T_{Max}$

- The total landing distance is given by

$$s_L = 1.6\,[s_A + s_{TR} + s_{FR} + s_B]$$

where, 1.6 is the safety factor imposed by FAR-25.

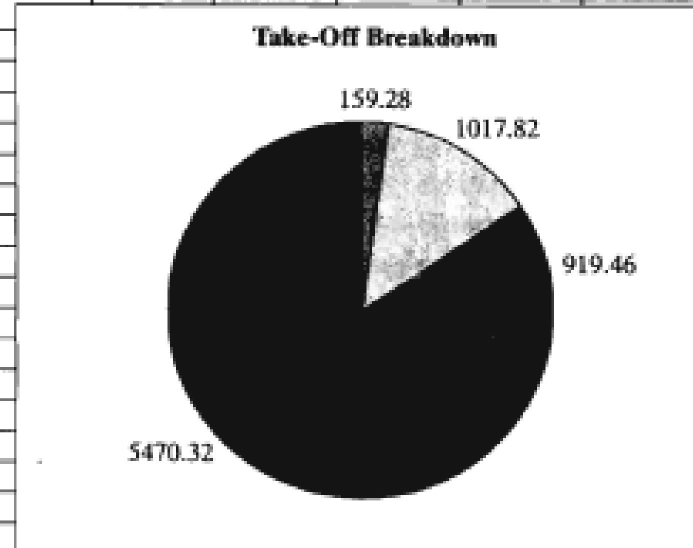
TABLE : Rolling friction coefficients with brakes applied, for different runway surfaces.

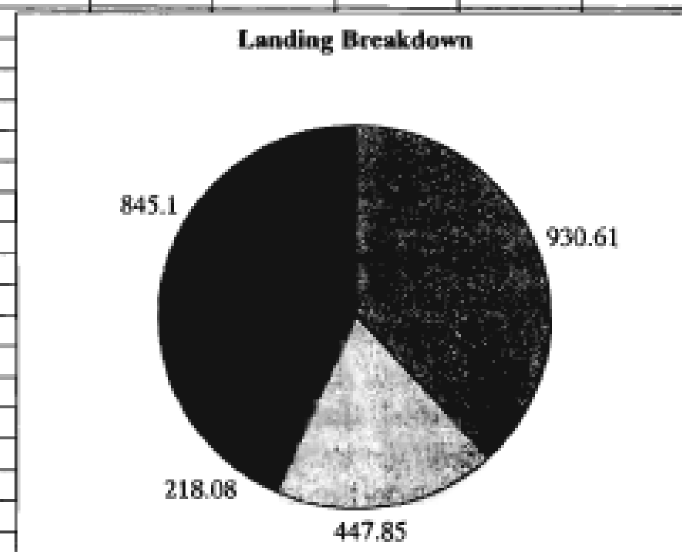
Surface Type	μ
Concrete (wet or dry)	0.4–0.6
Hard Turf	0.4
Firm & Dry Dirt	0.3
Soft Turf	0.0
Wet Grass	0.3
Snow or Ice-Covered	0.07–0.10

Spreadsheet Approach for Take-Off and Landing Analysis

- **A typical spreadsheet used to estimate take-off and landing distances for conceptual design of aircraft is shown in Fig.**
- **The spreadsheet is divided into two parts corresponding to take-off or landing analysis.**
- **In each of these, the input parameters are grouped at the top.**

Take-Off				
CD_0	0.04		mu_TO	0.05
A	2		T_max (lb)	49026
H (f)	1,000		f_LG	30.73
CL_G	2		A_LG (f^2)	2.5
W_TO (lb)	90,523		deltCD_0_flap	0.05
S (f^2)	600		gamma_CL (deg)	3
			H_obstacle (f)	35
k	0.2		T/W	0.54
rho (lbm/f^3)	0.07		f1 (f/s^2)	15.83
W/S (lb/f^2)	150.87		deltCD_0_LG	0.13
S (f^2)	600		f2 (f^−1)	−126.1E−6
V_T-O (f/s)	306.49		R_TR (f)	19447.91
q_T_O (lb/f^2)	108.63		H_TR (f)	26.65
			S_G (f)	5470.32
			S_R (f)	919.46
			S_TR (f)	1017.82
			S_CL (f)	159.28
			S_T-O (f)	**7566.88**
Landing				
W_L (lb)	23384		D_50 (lb)	19933.81
W/S (lb/f^2)	38.97		gamma_A (deg)	−58.48
V_50 (f/s)	168.75		gamma_A _act	−3
V_TD (f/s)	149.28		R_TR (f)	4166.95
q_50 (lb/f^2)	32.93		H_TR (f)	5.71
q_TD (lb/f^2)	25.77		f1 (f/s^2)	−19.32
mu _L	0.6		f2 (f^−1)	562.8E−6
T_L (lb)	0			
			S_A (f)	845.1
			S_TR (f)	218.08
			S_FR (f)	447.85
			S_B (f)	930.61
			S_L (f)	2441.63
			1.6(S_L) (f)	**3906.61**





Case Study: Take-Off and Landing (SSBJ)

Enhanced Lift Design

❑ INTRODUCTION

- The value of the maximum lift coefficient $C_{L_{max}}$ affects the take-off and landing distances.
- In aircraft designs, lift enhancing devices are used to achieve the necessary $C_{L_{max}}$ values in order to satisfy the maximum lift requirements that are imposed by such flight phases as take-off and landing, and combat (maximum maneuverability)
- The lift-enhancing devices fall in two categories: passive and active.
- The passive devices further fall into two sub-categories:

  i) trailing-edge devices, which primarily act to increase the camber of the airfoil section, and

  ii) leading-edge devices, which primarily act to prevent leading-edge separation.
- Passive lift enhancement is relevant to most of the aircraft designs, except STOL and ultra-STOL.
- STOL and ultra-STOL must make use of active lift enhancement.
- Active lift enhancement consists of using air streams that are directed over the upper surface of wing in order to energize the boundary layer and prevent flow separation.

Enhanced Lift Design (contd)

❑ PASSIVE LIFT ENHANCEMENT

Trailing-Edge (TE) Lift Enhancement Devices

- The most common types of trailing-edge lift enhancement devices are plane flaps, spilt flaps, slotted flaps, and Fowler flaps.
- Further, slotted flaps include single, double, and triple segments.
- Schematic illustration of different trailing-edge flap configurations are shown in Fig. 1.
- The effectiveness of any of these devices depends on :
  - the flap deflection angle, δ_f;
  - the wing thickness-to-chord ratio (t/c);
  - the ratio of the flap chord to wing chord, c/c_f;
  - the wing sweep angle, and
  - the aspect ratio.
- In most cases, $c/c_f \cong 0.3$, and the maximum lift occurs at $\delta_f \approx 40^o$

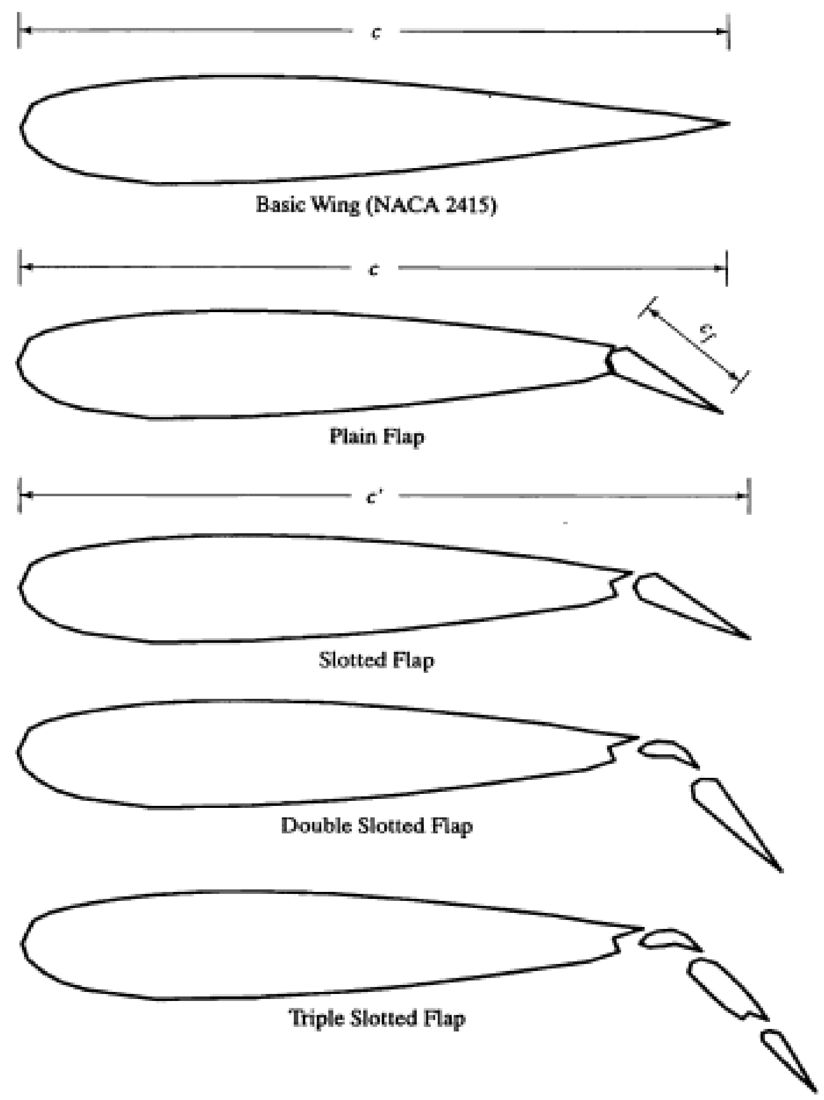


FIGURE 1 : Schematic illustration of different trailing-edge flap configurations.

Enhanced Lift Design (contd)

❑ Trailing-Edge (TE) Lift Enhancement Devices

▪ **Plain Flap:**

- The plain flap is simply a deflection of the trailing edge of the airfoil section.
- This type is most widely used on smaller aircraft.

▪ **Split Flap:**

- The split flap is similar to the plain flap except that only the bottom half of the airfoil section deflects.
- The lift produced by the split flap is virtually the same as a plain flap, but the drag is larger.
- Therefore, the split flaps are rarely used now, but were popular on aircraft built during World War II.

▪ **Slotted Flap:**

- A Slotted Flap is essentially a plain flap with the addition of a slot at the hinge point to allow high-pressure air from the lower side of the airfoil to pass over the upper surface of the flap.
- This has the effect of adding momentum to the boundary layer on the upper flap surface to allow larger flap deflections before the flow separates.

▪ **Fowler Flap:**

- A Fowler flap is a slotted flap that translates rearward, away from the wing.
- This has the benefit of increasing the slot width and increasing the effective wing area.
- A fowler flap is used on the C5-A aircraft.

▪ **Multiple Slotted Flaps:**

- These are refined slotted (Fowler) flap designs using two or three flap segments.
- These designs can lead to extremely high lift coefficients ($C_{L_{max}} \geq 3.0$), but are complex and require extra volume inside the wing to be stored during cruise.

▪ Single slotted flaps are most common on mid-size aircraft.

▪ Most larger commercial and transport aircraft use a multiple slotted flap arrangement.

❑ Disadvantages of Trailing Edge Flaps

- Although trailing-edge flaps increase lift at a given AoA, they do not increase the angle of stall, α_s, but actually cause it to decrease.
- This is the result of changes in the location of the stagnation line and local pressure gradient near the leading-edge, which causes a leading-edge flow separation. Sharper LEs are more sensitive to this.
- One solution to leading-edge separation is to increase the leading-edge radius. This is the principle effect of a leading-edge flap.

Enhanced Lift Design (contd)

❑ **PASSIVE LIFT ENHANCEMENT (contd)**

Leading-Edge (LE) Lift Enhancement Devices

- **Increasing the leading-edge radius of an airfoil section prevents flow separation at the leading-edge.**
- **This is the principle of the leading-edge lift enhancement devices.**
- **These devices consist of a hinged portion of the leading-edge, which deflects downward to effectively increase the leading-edge curvature.**
- **A variation of this is a Kruger flap, which consists of a hinged flap on the lower side of the wing leading-edge, which extends out into the flow.**

  This approach is lighter in weight and, as a result, popular on large aircraft with large wing spans.
- **The most common types of leading-edge lift enhancement devices are a fixed slot, leading-edge flap, Kruger flap, and plain slats (slotted leading-edge flap) . These are shown in Fig. 2.**

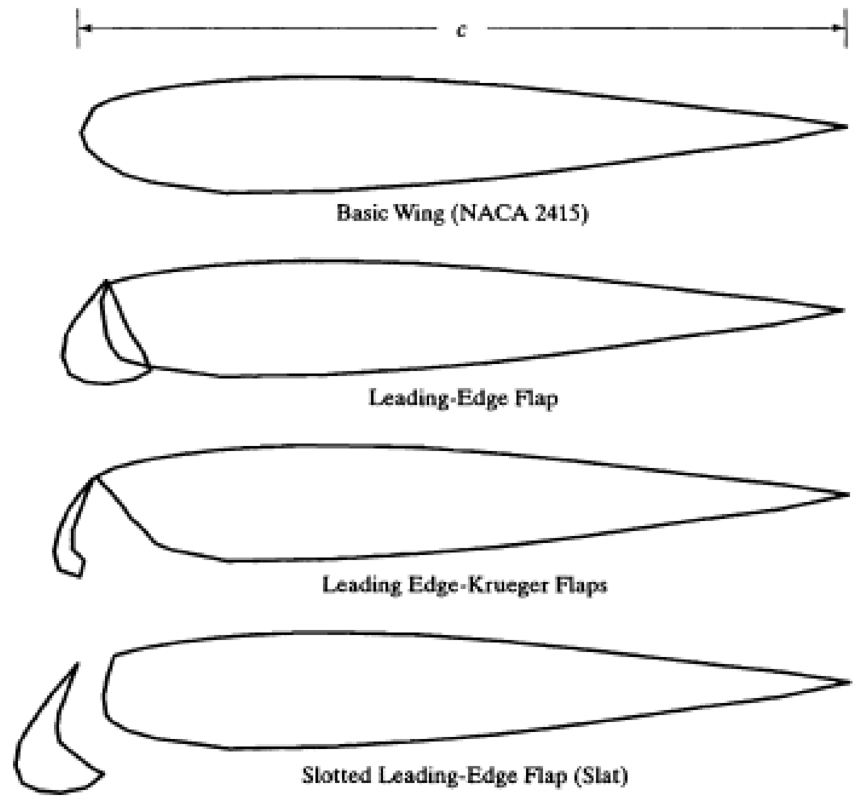


FIGURE 2 : Schematic illustration of different leading-edge flap configurations.

Enhanced Lift Design (contd)

Leading-Edge Lift Enhancement Devices (contd):

- A leading-edge slot works the same way as a slotted flap by allowing air from the high-pressure lower surface to flow to the upper surface to add momentum to the boundary layer and prevent flow separation.
- A slotted leading-edge flap (slat) is the leading-edge equivalent of the trailing-edge slotted flap.
- In this, the leading edge is extended forward and downward to open the slot and simultaneously increase the wing section camber and area.
- As a result of the change in camber, there is also a small change in α_{0_L} . This is the arrangement used on C5-A aircraft.

- Of these lift enhancement devices, leading-edge flaps are more effective than slotted flaps on highly swept wings.
- They are also usually located over the outboard half-span of the wing in order to reduce the potential for wing-tip stall.
- The optimum leading-edge flap deflection is approximately 30 – 40 deg.

Enhanced Lift Design (contd)

❑ LIFT DETERMINATION

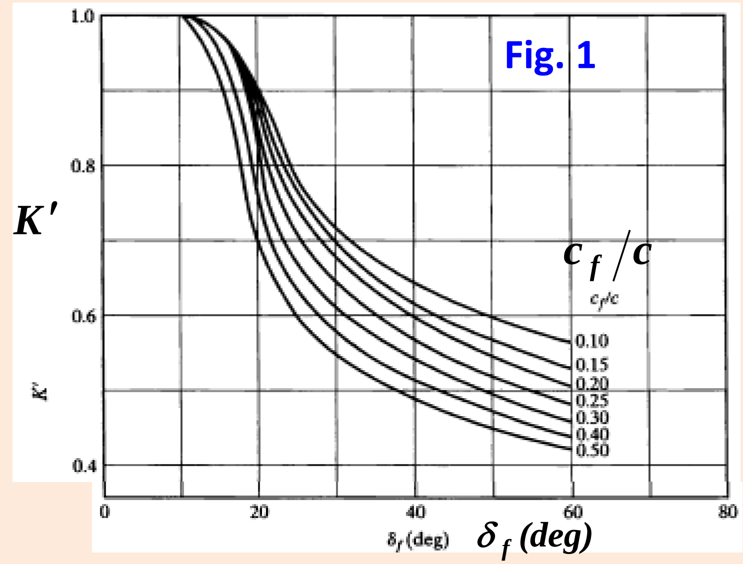
- Lift determination deals with constructing the 3-D lift coefficient versus AoA for the main wing with flaps and slats.
- Starting with the 3-D lift coefficient Vs AoA for the basic wing, the first step is to find the change in the AoA at zero lift, $\Delta\alpha_{0_L}$, produced by the addition of a trailing-edge flap.
- The formula to determine the AoA at zero lift depends on the type of the trailing-edge flap, as shown below:

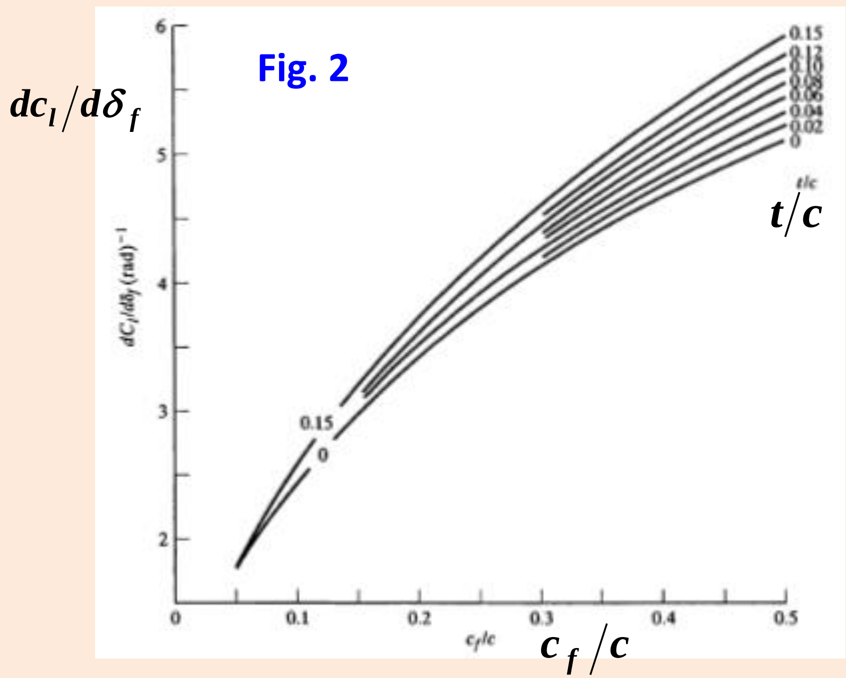
▪ **For Plain Flaps:**

$$\Delta_{\alpha_{0_L}} = -\frac{dC_l}{d\delta_f}\frac{K'}{C_{l_\alpha}}\delta_f$$

where C_{l_a} is the 2D section lift coefficient, which from linear theory should be $2\pi/rad$

- K' is a correction for nonlinear effects, and can be found from Fig. 1.
- The term $dc_l/d\delta_f$ is the change in the 2-D section lift coefficient with flap deflection. This can be found from Fig. 2., and it is a function of c_f/c and t/c .





Enhanced Lift Design (contd)

LIFT DETERMINATION (contd)

- **For Single Slotted and Fowler Flaps:**

$$\Delta\alpha_{0_L} = -\frac{d\alpha}{d\delta_f}\delta_f$$

where, $d\alpha/d\delta_f$, can be read from Fig. 3 as a function of c_f/c.

- **For Split Flaps:**

$$\Delta\alpha_{0_L} = -\frac{k}{C_{l_\alpha}}(\Delta C_l)_{\frac{c_f}{c}=0.2}$$

where, k and $(\Delta C_l)_{\frac{c_f}{c}=0.2}$ are found from Figs. 4 and 5.

- As a result of the flap deflection, the C_L vs α curve for the wing is translated along the α axis by an amount $\Delta\alpha_{0_L}$.
- To complete the construction of the lift curve requires determining $C_{L_{max}}$ with flaps.
- To do this first requires finding $C_{L_{max}}$ for the basic (unflapped) 3-D wing, as discussed below.

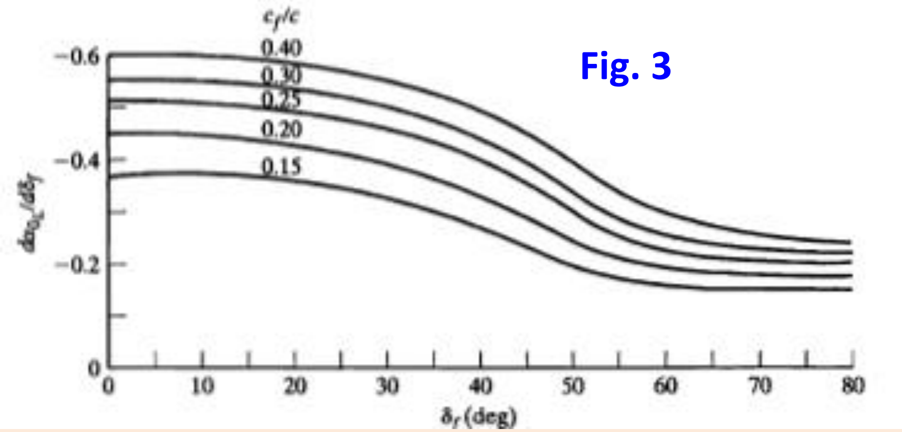


Fig. 3

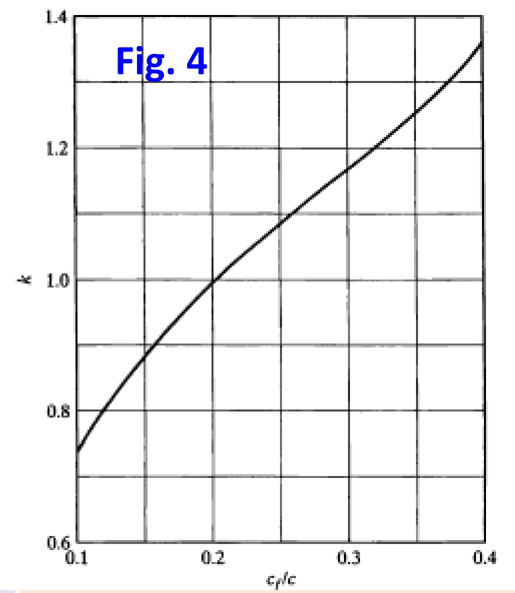


Fig. 4

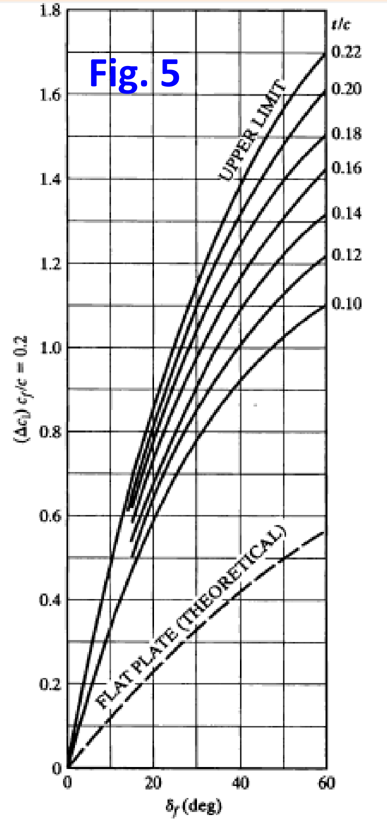


Fig. 5

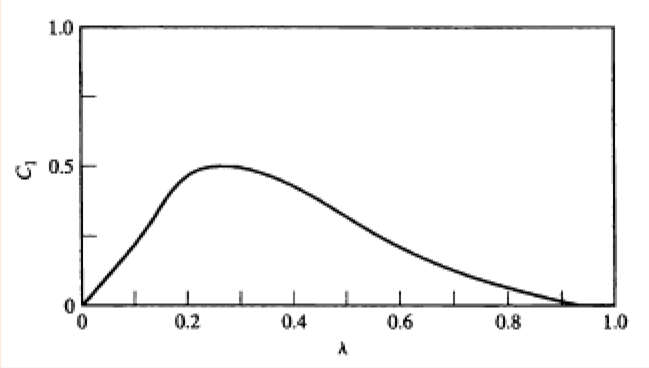
Enhanced Lift Design (contd)

❑ Finding $C_{L_{max}}$ for the basic (unflapped) 3-D Wing

- The value of $C_{L_{max}}$ is affected by the aspect ratio of the wing.
- With high aspect ratio wings, $C_{L_{max}}$ is primarily determined by the airfoil section shape.
- For a low aspect ratio wing, $C_{L_{max}}$ is primarily determined by the wing planform shape.
- A wing is considered to have high aspect ratio when

$$A > \frac{4}{(C_1 + 1)\cos(\gamma_{LE})}$$

where, the coefficient is a function of the taper ratio and can be found from Fig. 7.



Enhanced Lift Design (contd)

Enhanced Lift Design (contd)

❑ ACTIVE LIFT ENHANCEMENT

- Passive lift enhancement approaches will not provide sufficient $C_{L_{max}}$ for the STOL aircraft.
- Assuming sea-level conditions $\left(\sigma = \rho_{TO} / \rho_{SL} = 1\right)$ the take-off distance is given by,

$$s_{TO} = 20.9 \frac{W}{S} \frac{W}{T} \frac{1}{C_{L_{max}}} + 87 \sqrt{\frac{W}{S} \frac{1}{C_{L_{max}}}}$$

- For STOL aircraft, $s_{TO} < 1000 \;\; ft$
- For medium-size aircraft that would be designed to carry passengers or cargo, efficient cruise would dictate

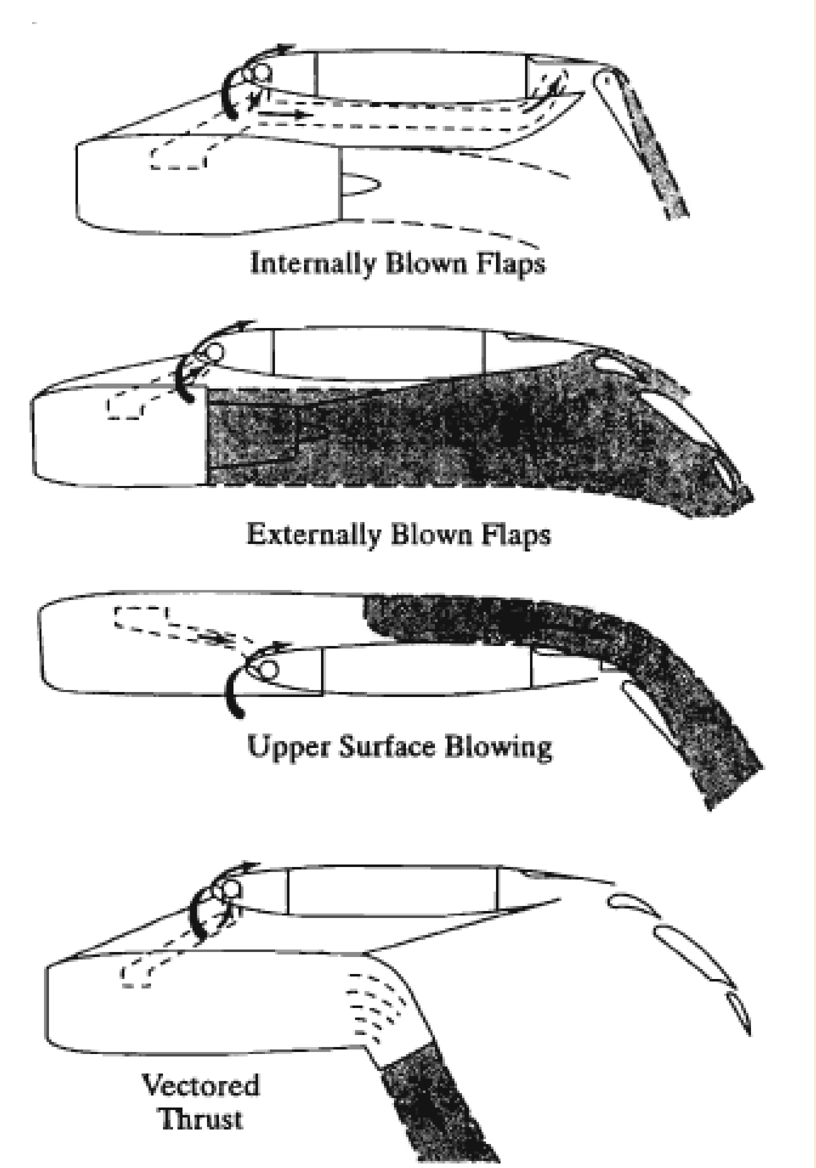
$$W/S \cong 40\, lb/f^2 \quad \text{and} \quad T/W \cong 0.2$$

- Using these values, the conditions on $C_{L_{max}}$ for STOL are:

$$\frac{4180}{C_{L_{max}}} + \frac{550}{\sqrt{C_{L_{max}}}} < 1000$$

- In order to satisfy the above equation, $C_{L_{max}} > 5.47$
- The largest $C_{L_{max}}$ that is attainable by passive approaches is approximately 4.0.
- Thus, active approaches are needed for STOL A/C

- Some of the common approaches used for active lift enhancement are shown in Fig. 1.



Enhanced Lift Design (contd)

- The active lift enhancement approaches generally fall into 3 categories:

  i) Upper Surface Blowing (USB),
  ii) Blown Flaps, where air is supplied either externally (EBF) or internally (IBF) , and
  iii) Vectored Thrust.

❑ **USB:**

- With USB, a high velocity air stream is directed over upper surface of the main wing.
  This requires placing the engines above and forward of the wing.

❑ **Blown Flaps:**

- With blown flaps, high-velocity air is directed specifically at the trailing-edge flaps.

▪ **EBF:**

- For externally blown flaps (EBF), the air is supplied by the engine exhaust, and the engine is located below the wing.
- The flaps are slotted in this case so that high-momentum air can reach the upper surface and energize the boundary layer over the flaps.
- A portion of the air in this arrangement is also deflected downward.
- The YC-15 aircraft used this arrangement.

▪ **IBF:**

- Internally blown flaps (IBF) duct a portion of the engine exhaust air only to the upper side of the trailing-edge flaps.

▪ **Generation of Downward Thrust**

- In addition to the enhanced aerodynamic lift that these 3 approaches provide, they also generate a component of downward thrust.
- This results because of the "Coanda Effect", which is the ability of an air stream to follow a curved surface.
- When properly designed, the air stream on the upper surface leaves the trailing edge at the angle of the flaps.

❑ **Vectored Thrust:**

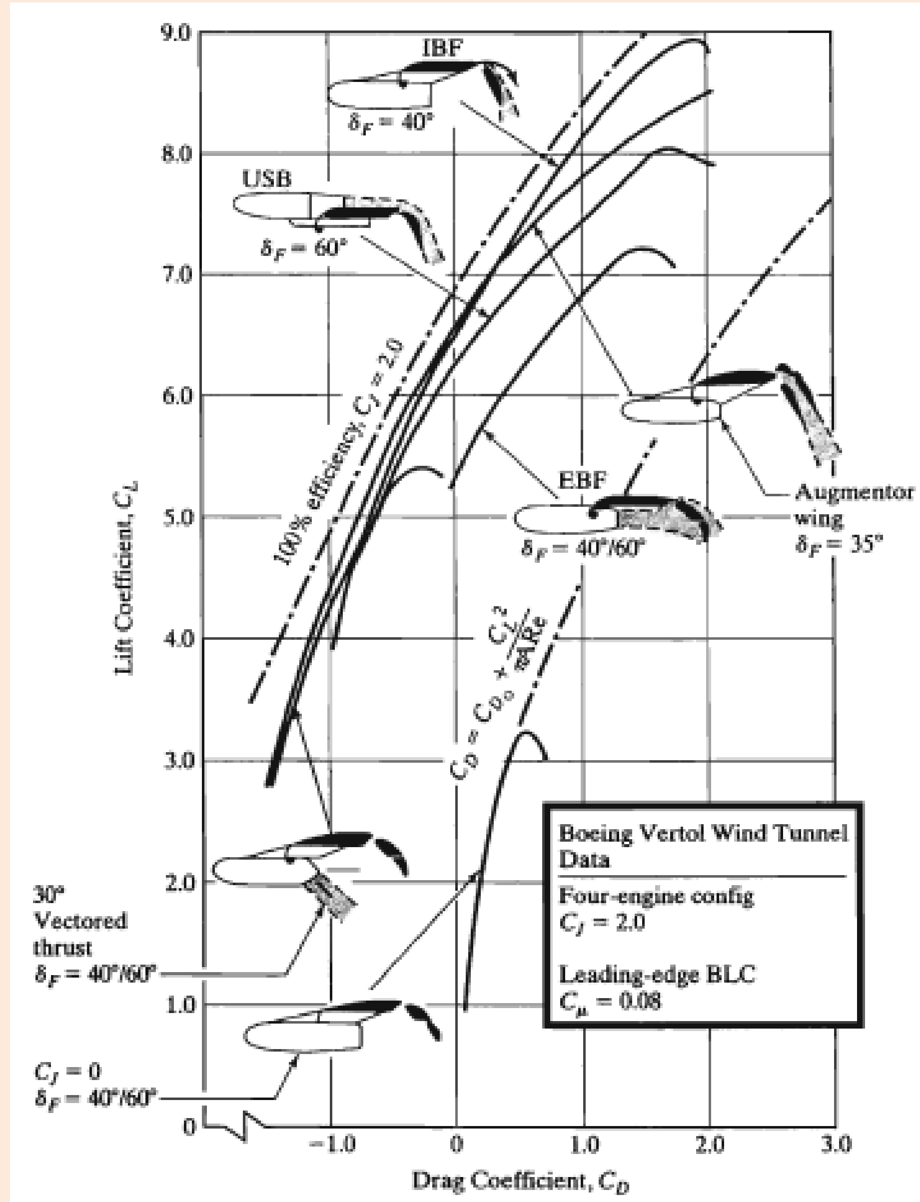
- Vectored thrust uses an articulated exit nozzle to direct the jet exhaust air downward.
- This gives a downward component of thrust, which is independent of any aerodynamic lift enhancement on the wing.

Enhanced Lift Design (contd)

- The effectiveness of these active approaches is summarized in Fig. 2., in terms of the drag polar C_L versus C_D .
- Any of these are capable of providing lift coefficients in excess of 7.0.
- The Vectored thrust, USB, and IBF have lower drag coefficients than EBF.
- Also, the effectiveness of USB is a function of the jet coefficient defined as, $C_j = \frac{\text{Thrust}}{\text{qSw}}$
- The value of C_j in Fig. 2 is 2.0.

❑ **Disadvantages:**

- In all the active lift enhancement approaches, there are additional factors that affect the selection of one over another.
- The IBF requires internal ducting that can be heavy and result in internal momentum losses.
- The USB blows hot exhaust air over the wing surface. This generally requires that portion of the wing to be covered with a heat-resistant material (stainless steel), which adds weight.



Enhanced Lift Design (contd)

- The EBF approach only directs the hot exhaust over the flaps, so that the area of heat-resistant material that has to be covered is less than with the USB. This makes the weight penalty less.
- This, and its relative simplicity, may be the reason that the USB approach appears to be the most popular means for active lift enhancement used by aircraft manufacturers.

Spreadsheet for Enhanced Lift Calculations

Enhanced Lift Design

$$\Delta\alpha_{0_L} = -\frac{d\alpha}{d\delta_f}\delta_f$$

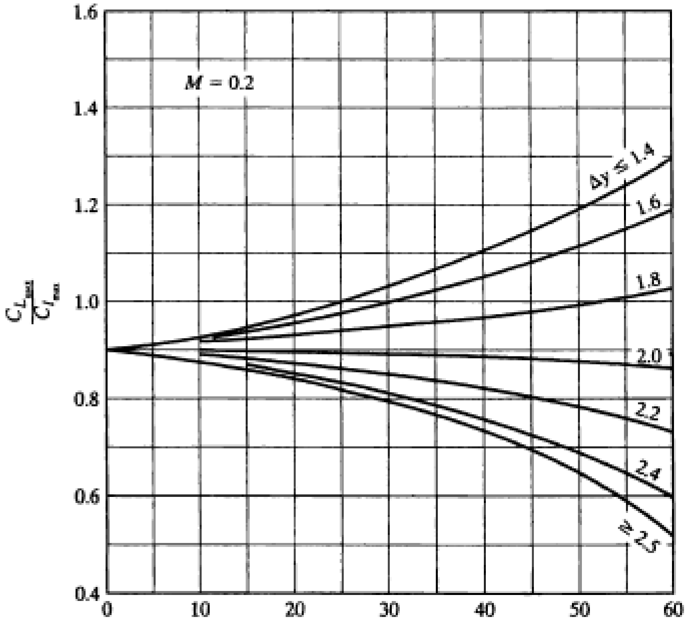
$$\Delta_{\alpha_{0_L}} = -\frac{dC_l}{d\delta_f}\frac{K'}{C_{l_\alpha}}\delta_f$$

$$\Delta\alpha_{0_L} = -\frac{k}{C_{l_\alpha}}(\Delta C_l)_{\frac{c_f}{c}=0.2}$$

$$\alpha_s = \frac{C_{L_{\max}}}{C_{L_\alpha}} + \alpha_{0_L} + \Delta\alpha_{C_{L_{\max}}}$$

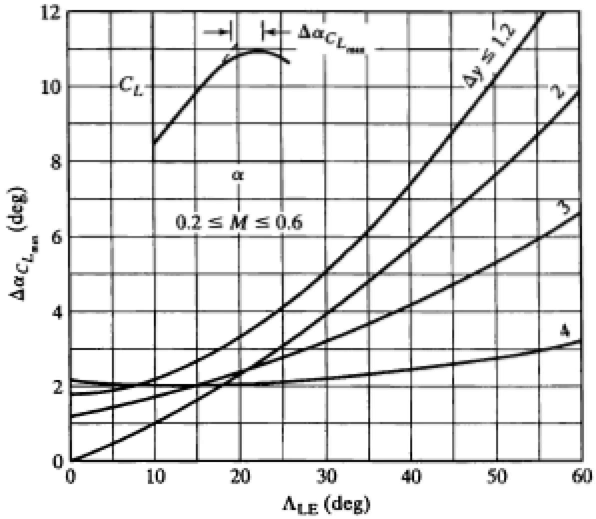
$$C_{L_{\max}} = \left[\frac{C_{L_{\max}}}{c_{l_{\max}}}\right]C_{l_{\max}}$$

Enhanced Lift Design

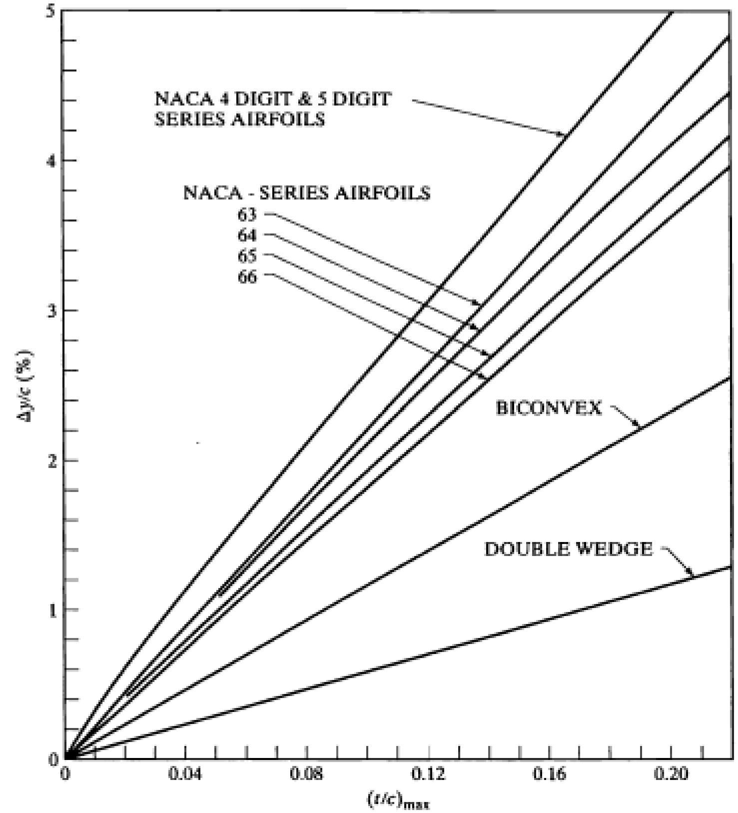


$$\Delta C_{L_{max}} = \Delta C_{l_{max}} \frac{\cdots}{S_W} K_\Delta$$

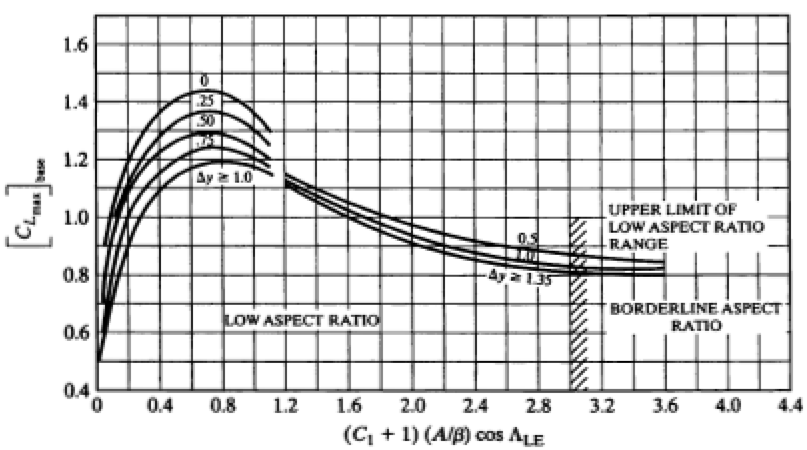
Enhanced Lift Design



$\alpha_{s_{\text{basic}}} + \Delta\alpha_s$

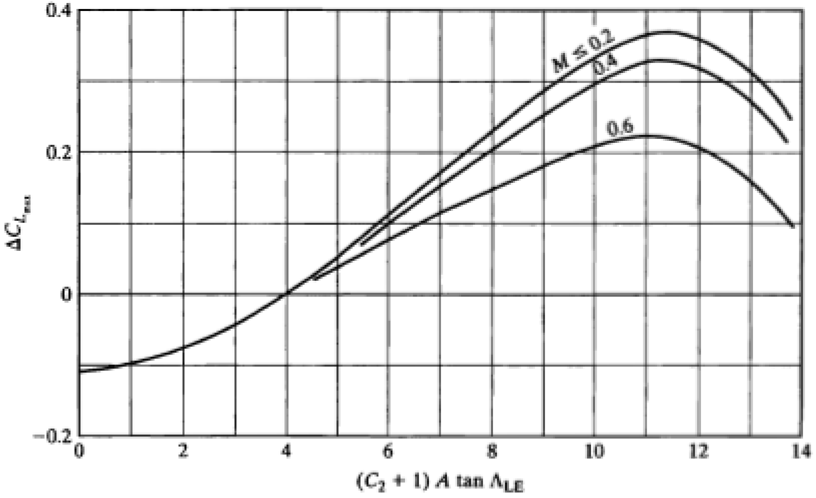


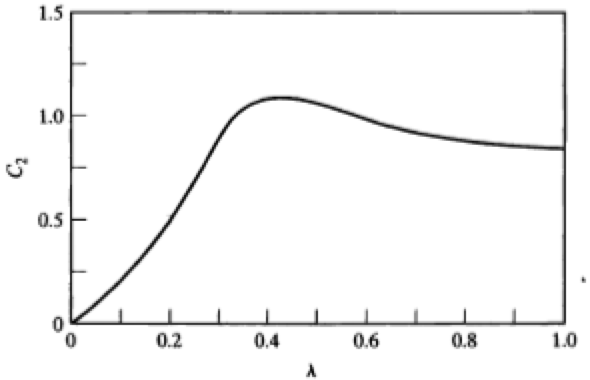
$$\Delta C_{l_{\max}} = (C_{l_{\max}})_{\text{flapped}} - (C_{l_{\max}})_{\text{basic}}$$



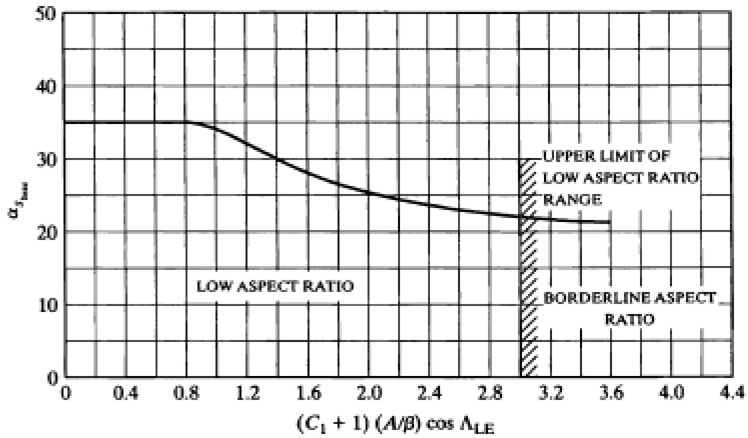
$$K_\Delta = \left[1 - 0.08\cos^2(\Lambda_{c/4})\right]\cos^{3/4}(\Lambda_{c/4})$$

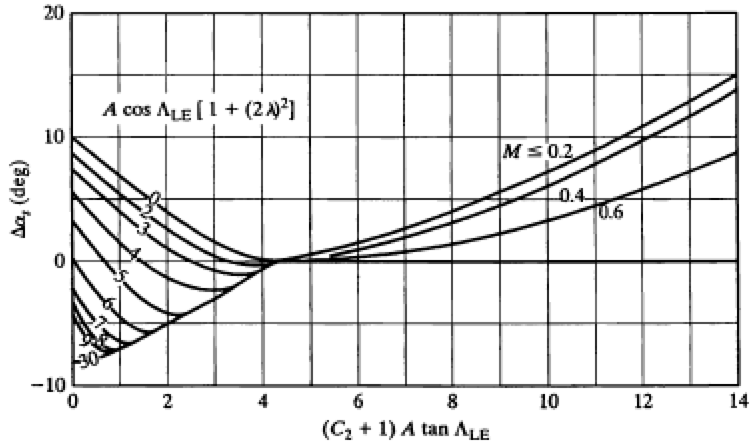
Enhanced Lift Design



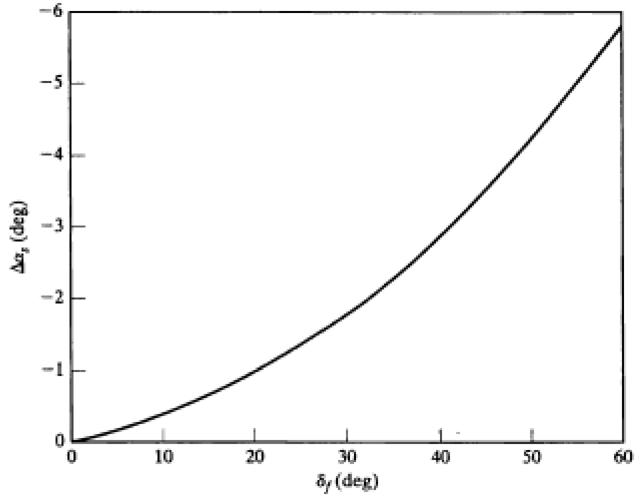


$$(C_{L_{\max}})_{\text{flapped}} = (C_{L_{\max}})_{\text{basic}} + \Delta C_{L_{\max}}$$



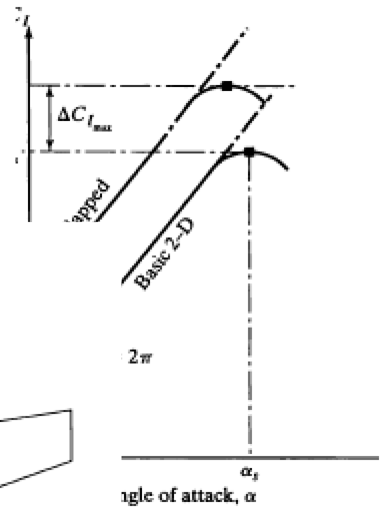


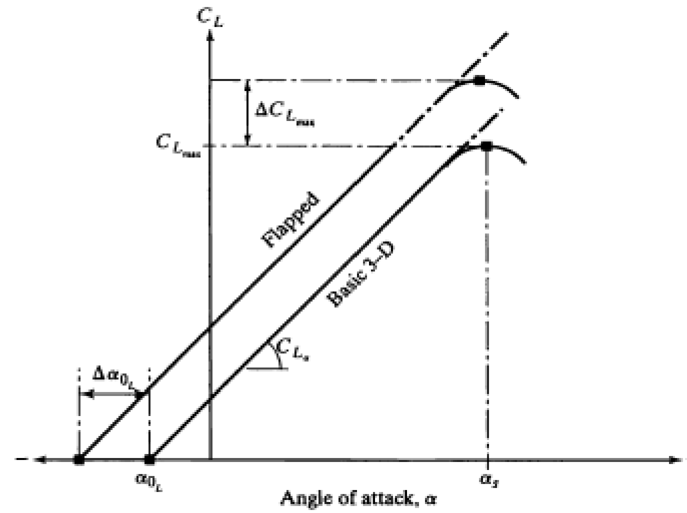
Enhanced Lift Design

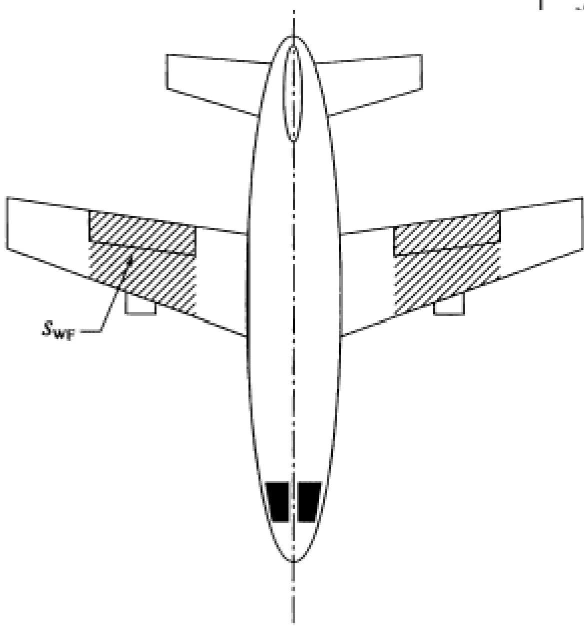


$$\Delta C_{D_0} = k_1 k_2 \frac{S_{WF}}{S_W}$$

$$s_{TO} = 20.9 \frac{W}{S} \frac{W}{T} \frac{1}{C_{L_{max}}} + 87 \sqrt{\frac{W}{S} \frac{1}{C_{L_{max}}}}$$







$$\frac{4180}{C_{L_{max}}} + \frac{550}{\sqrt{C_{L_{max}}}} < 1000$$

Enhanced Lift Design

TABLE : 2-D lift coefficient increment for different leading-edge flap designs.

Type	$\Delta C_{l_{max}}$
Fixed Slot	0.2
Leading-Edge Flap	0.3
Kruger Flap	0.3
Slat	0.4

$$s_G = \int_0^{V_{\mathrm{TO}}} \left(\frac{V}{a}\right) dV = \frac{1}{2}\int_0^{V_{\mathrm{TO}}} \frac{dV^2}{da}$$

$$V = \frac{ds}{dt}, \quad a = \frac{dV}{dt}$$

$$\frac{V}{a} = \frac{ds}{dt}\frac{dt}{dV} = \frac{ds}{dV}$$

$$ds = \left(\frac{V}{a}\right) dV$$

$$s = \int \left(\frac{V}{a}\right) dV$$