Chapter 3

Lecture 12

Drag polar – 7

Topics

3.7 High lift devices

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3.7 High lift devices

3.7.1 Need for increasing maximum lift coefficient (C_{Lmax})

An airplane, by definition, is a fixed wing aircraft. Its wings can produce lift only when there is a relative velocity between the airplane and the air. The lift (L) produced can be expressed as :

$$L=\frac{1}{2}\rho V^2 S C_L \tag{3.57}$$

In order that an airplane is airborne, the lift produced by the airplane must be atleast equal to the weight of the airplane i.e.

$$L = W = \frac{1}{2}\rho\, V^2\, S\, C_L \tag{3.58}$$

Or $$V = \sqrt{\frac{2W}{\rho S C_L}} \tag{3.59}$$

However, C_L has a maximum value, called C_{Lmax}, and a speed called 'Stalling speed (V_s)' is defined as :

$$V_s=\sqrt{\frac{2W}{\rho S C_{Lmax}}} \tag{3.59a}$$

The speed at which the airplane takes-off (V_{T0}) is actually higher than the stalling speed.

It is easy to imagine that the take-off distance would be proportional V_{T0}^2 and in turn to V_S^2. From Eq.(3.59a) it is observed that to reduce the take-off distance (a) the wing loading (W/S) should be low or (b) the C_{Lmax} should be high. Generally, the wing loading of the airplane is decided by considerations like minimum fuel consumed during cruise. Hence, it is desirable that C_{Lmax} should be as high as possible to reduce the take-off and landing distances. The devices to increase the C_{Lmax} are called high lift devices.

3.7.2 Factors limiting maximum lift coefficient

Consider an airfoil at low angle of attack (α). Figure 3.36a shows a flow visualization picture of the flow field. Boundary layers are seen on the upper and lower surfaces. As the pressure gradients on the upper and lower surfaces of the airfoil are low at the angle of attack under consideration, the boundary layers on these surfaces are attached. The lift coefficient is nearly zero. Now consider the same airfoil at slightly higher angle of attack (Fig.3.36b). The velocity on the upper surface is higher than that on the lower surface and consequently the pressure is lower on the upper surface as compared to that on the lower surface. The airfoil develops higher lift coefficient as compared to that in Fig.3.36a. However the pressure gradient is also higher on the upper surface and the boundary layer separates ahead of the trailing edge (Fig.3.36b). As the angle of attack approaches about 15^o the separation point approaches the leading edge of the airfoil (Fig.3.36c). Subsequently, the lift coefficient begins to decrease (Fig.3.36d) and the airfoil is said to be stalled. The value of α for which C_l equals C_{lmax} is called stalling angle (α_{stall}). Based on the above observations, the stalling should be delayed to increase C_{lmax} .

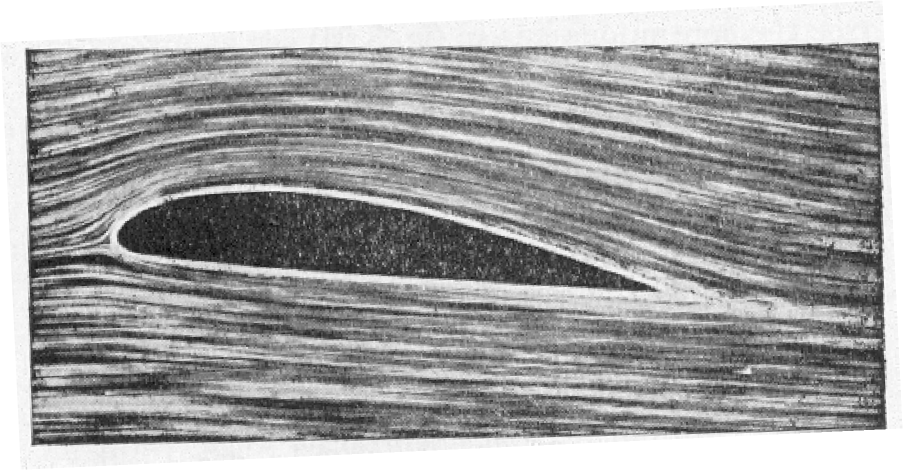


Fig.3.36a Flow past an airfoil at low angle of attack. Note: The flow is from left to right (Adapted from Ref.3.20, chapter 6 with permission of editor)

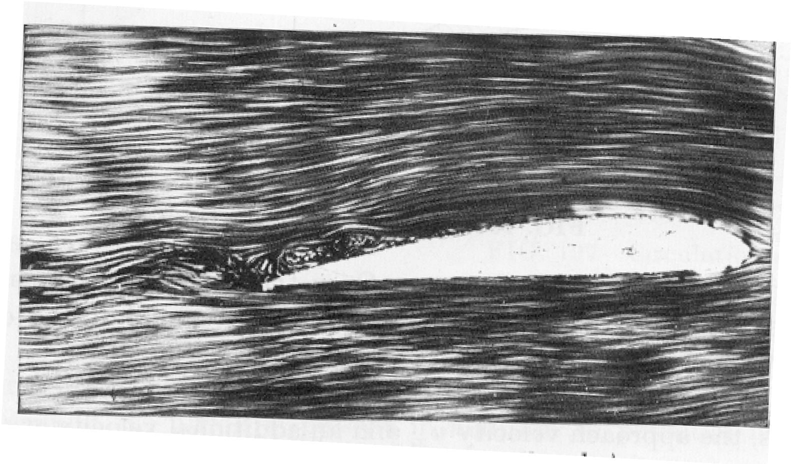


Fig.3.36b Flow past an airfoil at moderate angle of attack.
Note: The flow is from right to left
(Adapted from Ref. 3.21, part 3 section II B Fig.200 with permission from McGraw-Hill book company)

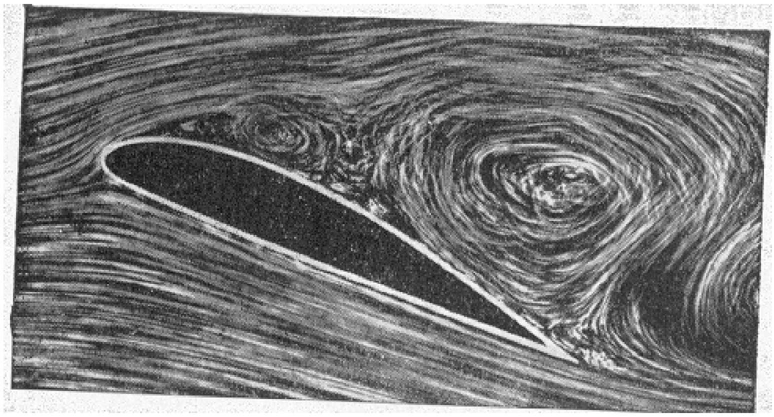


Fig.3.36c Flow past an airfoil at angle of attack near stall. Note: The flow is from left to right (Adapted from Ref.3.12, chapter 6 with permission of editor)

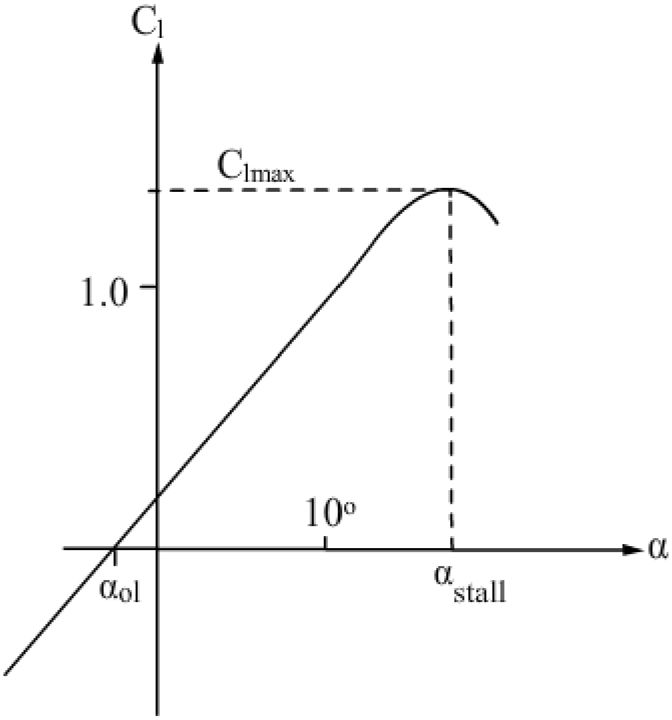
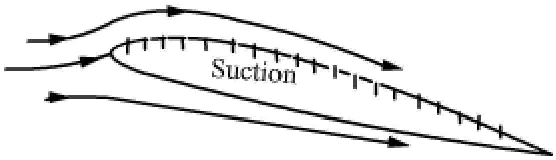


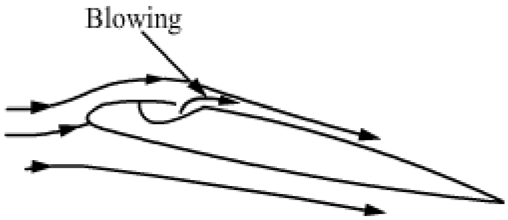
Fig.3.36d Typical C_l vrs α curve

Remark:

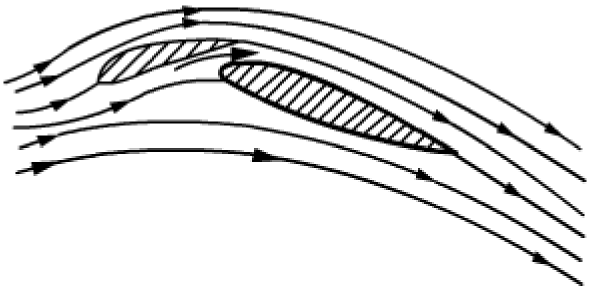
Since stalling is due to separation of boundary layer, many methods have been suggested for boundary layer control. In the suction method, the airfoil surface is made porous and boundary layer is sucked (Fig.3.37a). In the blowing method, fluid is blown tangential to the surface and the low energy fluid in the boundary layer is energized (Fig.3.37b). Blowing and suction require supply of energy and are referred to as active methods of control. The energizing of the boundary layer can be achieved in a passive manner by a leading edge slot (Fig.3.37c) and a slotted flap which are described in section 3.7.3. Reference 3.11, chapter 11 may be referred for other methods of boundary layer control and for further details.



a. Suction



b. Blowing



c. Blowing achieved in a passive manner

Fig.3.37 Boundary layer control with suction and blowing

3.7.3. Ways to increase maximum lift coefficient viz. increase in camber, boundary layer control and increase in area

Beside the boundary layer control, there are two other ways to increase the maximum lift coefficient of an airfoil ($C_{l\max}$) viz. increase of camber and increase of wing area. These methods are briefly described below.

I) Increase in maximum lift coefficient due to change of camber

It may be recalled that when camber of an airfoil increases, the zero lift angle (α_{0l}) decreases and the C_l vs α curve shifts to the left (Fig.3.38). It is observed that α_{stall} does not decrease significantly due to the increase of camber and a higher $C_{l\max}$ is realized (Fig.3.38). However, the camber of the airfoil used on the wing is chosen from the consideration that the minimum drag coefficient occurs near the lift coefficient corresponding to the lift coefficient during cruise. One of the ways to achieve a temporary increase in the camber during take-off and landing is to use flaps. Some configurations of flaps are shown in Fig.3.39. In a plain flap the rear portion of the airfoil is hinged and is deflected when $C_{l\max}$ is required to be increased (Fig.3.39a). In a split flap only the lower half of the airfoil is moved down (Fig.3.39b). To observe the change in camber brought about by a flap deflection, draw a line in-between the upper and lower surfaces of the airfoil with flap deflected. This line is approximately the camber line of the flapped airfoil. The line joining the ends of the camber line is the new chord line. The difference between the ordinates of the camber line and the chord line is a measure of the camber.

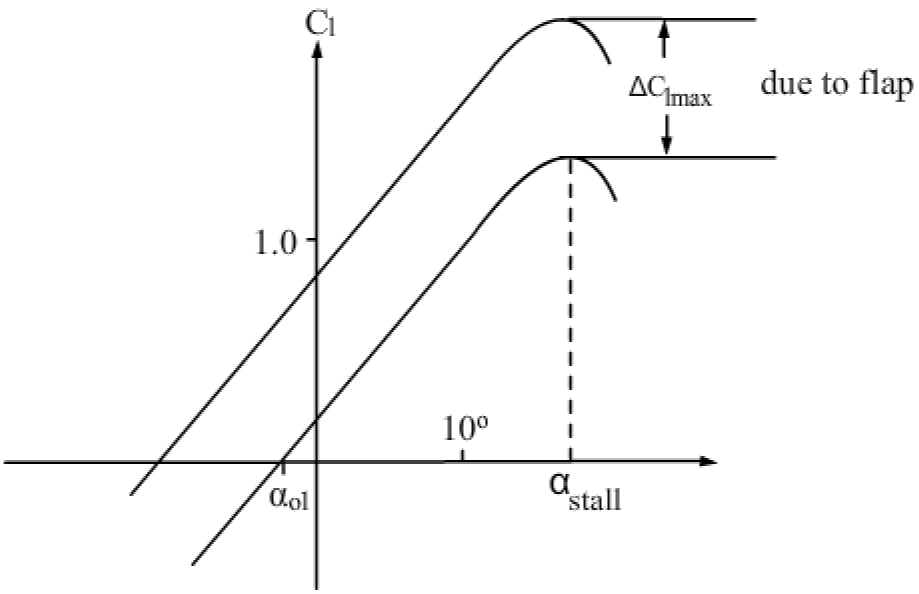


Fig.3.38 Increase in C_{lmax} due to increase of camber

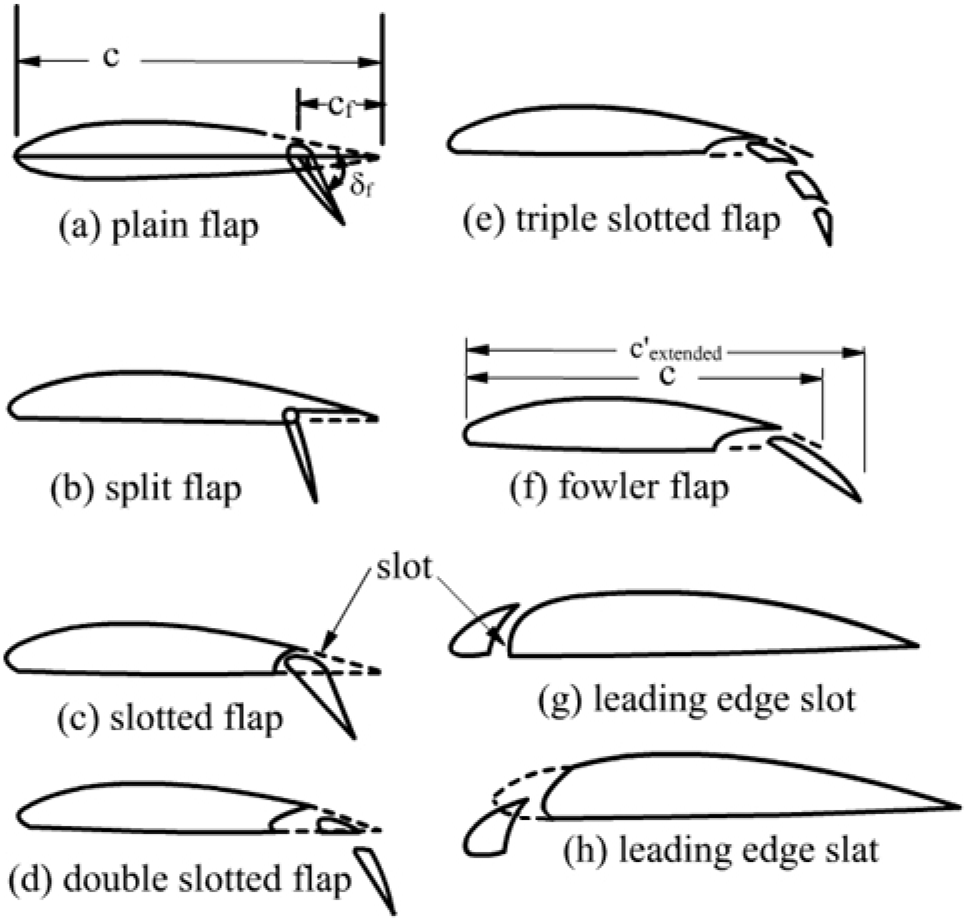


Fig.3.39 Flaps, slot and slat

II) Increase in maximum lift coefficient due to boundary layer control

In a slotted flap (Fig.3.39c) the effects of camber change and the boundary layer control (see remark at the end of section 3.7.2) are brought together. In this case, the deflection of flap creates a gap between the main surface and the flap (Fig.3.39c). As the pressure on the lower side of airfoil is more than that on the upper side, the air from the lower side of the airfoil rushes to the upper side and energizes the boundary layer on the upper surface. This way, the separation is delayed and C_{lmax} increases (Fig.3.40). The slot is referred to as a passive boundary layer control, as no blowing by external source is involved in this device. After the success of single slotted flap, the double slotted and triple slotted flaps were developed (Figs.3.39d and e).

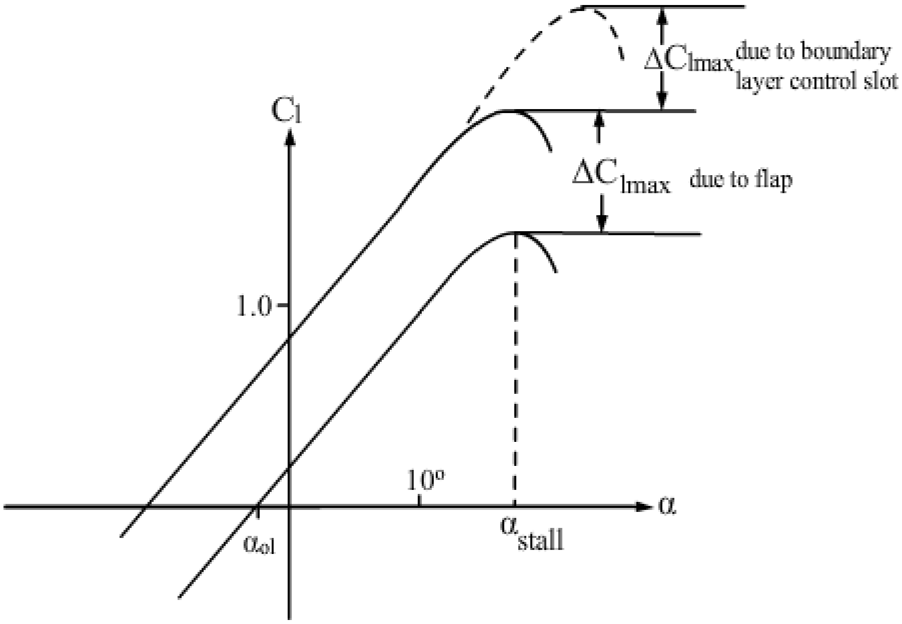


Fig.3.40 Effects of camber change and boundary layer control on C_{lmax}

III) Increase in C_{lmax} due to change in wing area

Equation (3.57) shows that the lift can be increased when the wing area (S) is increased. An increase in wing area can be achieved if the flap, in addition to being deflected, also moves outwards and effectively increases the wing area. This is achieved in a Fowler flap (Fig.3.39f). Thus a Fowler flap incorporates three methods to increase C_{lmax} viz. change of camber, boundary layer control and increase of wing area. It may be added that while defining the C_{lmax}, in case of Fowler flap, the reference area is the original area of the wing and not that of the extended wing.

A zap flap is a split flap where the lower portion also moves outwards as the flap is deflected.

IV) Leading edge devices

High lift devices are also used near the leading edge of the wing. A slot near the leading edge (Fig.3.39g) also permits passive way of energizing the boundary layer. However, a permanent slot, in addition to increasing the lift, also increases the drag and consequently has adverse effects during cruise. Hence, a deployable leading edge device called ‘Slat’ as shown in Fig.3.39h is used. When a slat is deployed it produces a slot and increases $C_{l\max}$ by delaying separation.

On high subsonic speed airplanes, both leading edge and trailing edge devices are used to increase $C_{l\max}$ (Fig.1.2c).

Remarks:

i) References 1.9, 1.10, 1.12 and 3.9 may be referred for other types of high lift devices like Kruger flap, leading edge extension, blown flap etc.

ii) Reference1.10, chapter 1 may be referred for historical development of flaps.

3.7.4 Guide lines for values of maximum lift coefficients of wings with various high lift devices

An estimate of the maximum lift coefficient of a wing is needed to calculate the stalling speed of the airplane. It may be added that the maximum lift coefficient of an airplane depends on (a) wing parameters (aspect ratio, taper ratio and sweep) (b) airfoil shape, (c) type of high lift device(s), (d) Reynolds number , (e) surface finish , (f) the ratio of the area of the flap to the area of wing and (g) interference from nacelle and fuselage.

Table 3.6 presents the values of $C_{L\max}$ which are based on (a) Ref.1.10, chapter 5, (b) Ref.3.9 chapter 5 and (c) Ref.3.15 chapter 5. These values can be used for initial estimate of $C_{L\max}$ for subsonic airplanes with unswept wings of aspect ratio greater than 5.

The quarter chord sweep($\Lambda_{1/4}$) has a predominant effect on $C_{L\max}$. This effect, can be roughly accounted for by the following, cosine relationship:

$$(C_{L\max})_{\Lambda} = (C_{L\max})_{\Lambda=o} \cos \Lambda_{1/4}$$

For example, when the unswept wing without flap has $C_{L\max}$ of 1.5, the same wing with 30^{o} sweep would have a $C_{L\max}$ of 1.5 x cos 30^{o} or 1.3. Similarly, an unswept wing with Fowler flap has $C_{L\max}$ of 2.5. The same wing with 30^{o} sweep would have C_{Lmax} of 2.5 x cos 30^{O} or 2.17. With addition of leading edge slat, this can go upto 2.43.

Type of flap	**Guideline for C_{Lmax} in landing configuration**
No flap	1.5
Plain flap	1.8
Single slotted flap	2.2
Double slotted flap	2.7
Double slotted flap with slat	3.0
Triple slotted flap	3.1
Triple slotted flap with slat	3.4
Fowler flap	2.5
Fowler flap with slat	2.8

Table 3.6 Guidelines for C_{Lmax} of subsonic airplanes with unswept wings of moderate aspect ratio

Figure 3.41 shows C_{Lmax} for some passenger airplanes. The solid lines correspond to the cosine relation given above.

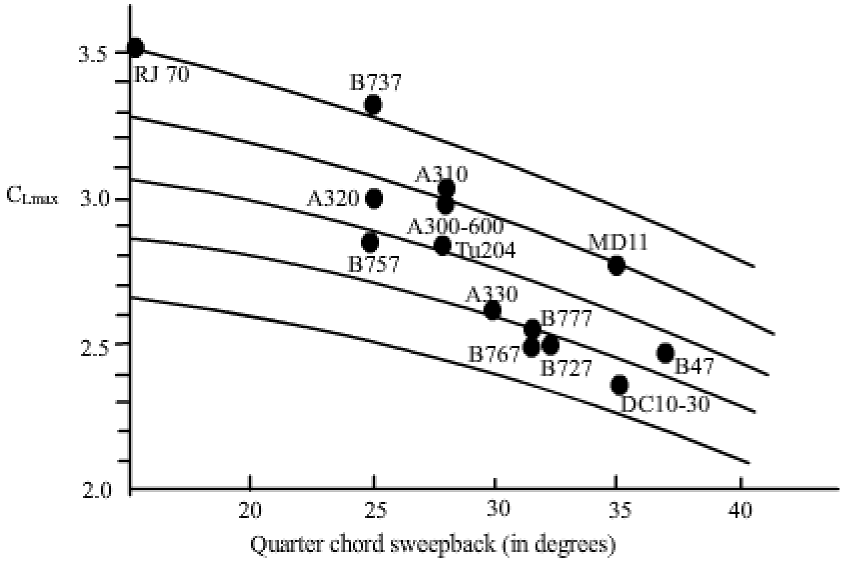


Fig.3.41 Maximum lift coefficient of passenger airplanes operating at high subsonic Mach numbers

(Adapted from Ref.3.22, Chapter 8 with permission of authors)

Remarks:

i) The value of C_{Lmax} shown in Table 3.6 can be used in landing configuration. The flap setting during take-off is lower than that while landing. The maximum lift coefficient during take-off can be taken approximately as 80% of that during landing.

ii) The values given in Table 3.6 should not be used for supersonic airplanes which have low aspect ratio wings and airfoil sections of small thickness ratio. Reference 3.5, section 4.1.3.4 may be referred to for estimating C_{Lmax} in these cases.

iii) As the Mach number (M) increases beyond 0.5, the C_{lmax} of the airfoil section decreases due to the phenomena of shock stall (see item IV in section 3.3.3). Hence C_{Lmax} of the wing also decreases for M > 0.5. The following relationship between C_{Lmax} at M between 0.5 to 0.9, in terms of C_{Lmax} at M = 0.5, can be derived based on the plots of C_{Lmax} vs M in Ref.3.23, chapter 9, and Ref.3.9 chapter 12.

$$\frac{(C_{L\max})_M}{(C_{L\max})_{M=0.5}} = -0.418M + 1.209\,,\ 0.5 \le M \le 0.9$$

For example at M = 0.9, $C_{L\max}$ would be about 0.833 of $C_{L\max}$ at M = 0.5.

Note: The maximum lift coefficient ($C_{L\max}$) in transonic Mach number range is not likely to be monotonic as seen in Fig.3.27a. At transonic and supersonic Mach numbers, $C_{L\max}$ must be estimated at each Mach number. Reference 3.5, section 4.1.3.4 may be consulted for this estimation.