13

OPERATIONAL ENVELOPE AND ESTIMATED AIRCRAFT BUFFET BOUNDARY

OPERATIONAL ENVELOPE CONCEPT

All aircraft are constrained to operate within altitude - airspeed boundaries called the *operational envelope*. This operational envelope, described on a plot of pressure altitude versus true airspeed, is usually defined as the level flight (1 g) operational envelope, at a specific gross weight, and consists of the following boundaries:

Minimum speed/stall speed boundary
Minimum rate of climb/absolute ceiling boundary
Maximum speed/thrust equals drag boundary

For low speed designs, such as personal/utility aircraft and turboprop commuters, the operational envelope is usually well defined by these boundaries, as shown in Fig. 13-1. For higher performance aircraft, such as transonic jet transports and business jets, and for supersonic military aircraft, the operational envelope boundaries can be a bit more complicated, as shown in Fig. 13-2. The stall speed boundary is the primary operational limit, but there is a minimum speed called the engine relight or restart speed, the minimum speed for which sufficient windmilling RPMs can be generated to allow an engine to be restarted following a flameout or voluntary shutdown. The minimum rate of climb/ absolute ceiling boundary and the maximum speed boundary also have two limits for supersonic military aircraft equipped with afterburners. The boundaries are defined for maximum (afterburner) thrust and military (non-afterburner) thrust. Also for most jet

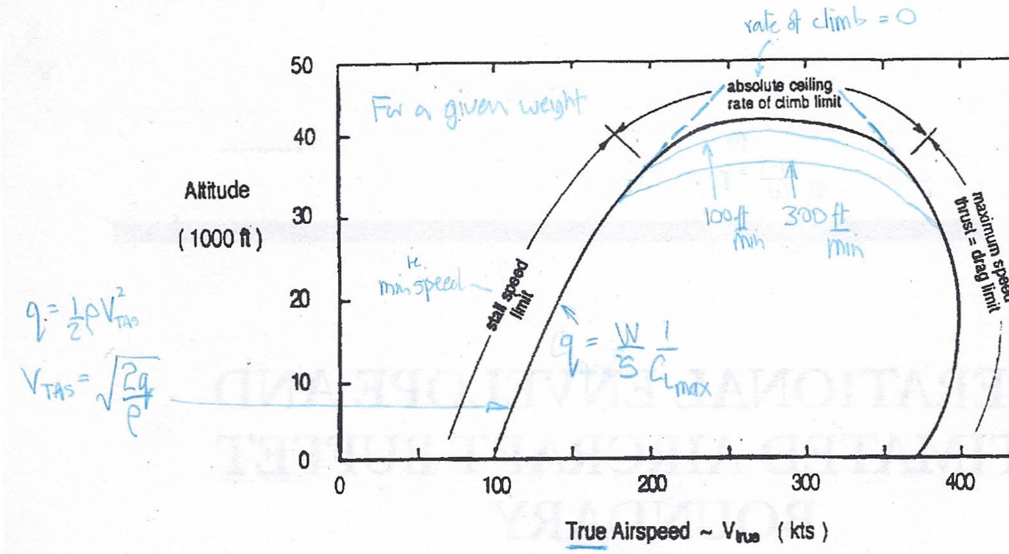

Fig. 13-1 Typical Aircraft Operational Flight Envelope ~ Subsonic Aircraft

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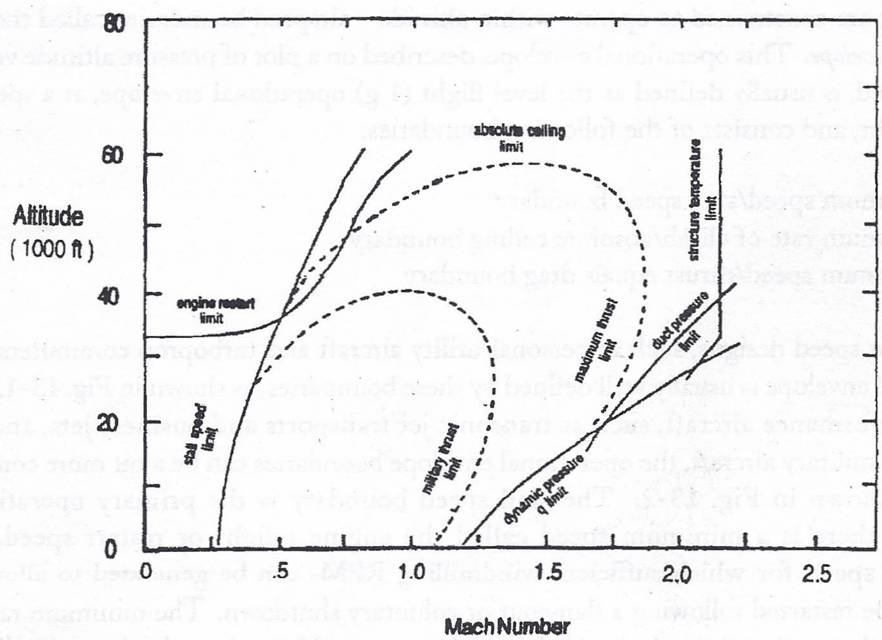

Fig. 13-2 Typical Aircraft Operational Flight Envelope ~ Supersonic Aircraft

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aircraft, the maximum speed boundary at low altitudes is defined by an arbitrary equivalent airspeed or q limit to save on structural weight. Beyond the operational envelope, supersonic military aircraft also have limits associated with the maximum dynamic pressure that can be tolerated within the engine inlet ducts, and a structure temperature limit, a maximum Mach number beyond which the aircraft structure will overheat and lose the structural strength required to withstand the design loads.

PROCEDURE FOR ESTIMATING THE OPERATIONAL ENVELOPE

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The minimum speed boundary may be estimated from Eq. 1-24, using the clean configuration C_{Lmax} and the gross weight appropriate for the operational envelope. The resulting q and corresponding V_{EAS} may be converted into a proper true airspeed at several altitudes from Eq. 1-16. The minimum rate of climb/operational ceiling boundary may be estimated from Eq. 1-22. 23 At a few appropriate Mach numbers, derive the maximum climb thrust from the data of Figs. 8-7 through 8-13 and calculate the variation of R/C versus altitude at the selected Mach numbers. From this data, the operational envelope for any one of three definitions of operational ceiling may be found. The three definitions are:

Rate of Climb

$R/C = \frac{(T-D)V_{TAS}}{W}$

Absolute ceiling	R/C = 0
Service ceiling	R/C = 100 ft/min
Operational ceiling	R/C = 300 ft/min

The maximum speed/thrust drag boundary may be estimated by the following. At several appropriate altitudes, calculate the aircraft drag versus speed using the idea that in level flight,

$$D = \frac{W}{(L/D)} \tag{13-1}$$

At each airspeed, the C_L may be determined and the corresponding (L/D) may be found from the (L/D) charts prepared in Chapter 12. Plot the drag versus airspeed at each altitude, and compare with the thrust at that altitude obtained from the data of Chapter 8. The intersection of the thrust required and the thrust available at each altitude will define the high speed portion of the operational envelope. The three sectors of the envelope should be joined with a smooth curve. An example problem has been included to illustrate the procedure for determining the operational envelope.

Example Problem

Determine the operational envelope for the aircraft shown in Fig. 12-1. Additional pertinent data is as follows.

$\frac{W}{S} = \frac{98,000}{1000.7} = 97.93 \frac{lb}{ft^2}$

Gross Weight is 98,000 lbs.
Engines are BPR 1.0 turbofans with a SLSTO thrust of 14,000 lbs each
Clean configuration C_{Lmax} = 1.42
Assumed weight at all conditions

1. **Determine the stall speed boundary**

The stall speed in ft/sec (EAS) is

$$V_{stall} = \sqrt{\frac{2(W/S)}{\rho_{SL} C_{Lmax}}}$$

At sea level, ρ_{SL} = .0023769 slugs/cu ft (Fig. 1-9)

Fig 12.1

$$V_{stall} = \sqrt{\frac{2\,(98{,}000/1000.7)}{.0023769 \times 1.42}} = 241 \text{ ft/sec} = 143 \text{ kts}$$ B EAS

clean C_{Lmax} (given)   Plot these on Fig 13-5

V_{stall} in true airspeed is V_{stall} (EAS) $\div \sqrt{\sigma}$

Altitude	σ	$\sqrt{\sigma}$	V_{stall} (EAS)	V_{stall} (TAS)
10,000ft	.7385	.859	143	166 C
20,000ft	.5328	.729	143	196 E
30,000ft	.3741	.612	143	234 D

2. **Determine the R/C boundary**

Select at least two Mach numbers to calculate R/C at two of the higher altitudes where you expect the operational envelope to be. The approach is to determine from a plot of R/C vs altitude at a specific Mach number, at what altitude does the R/C diminish to the defining value for the operational envelope. For this example, the defining value is 300 ft/min, the minimum operational R/C.

Calculate R/C at M = 0.60 and M = 0.75 at 30,000 ft and 35,000 ft.

$R/C = \left(\frac{T-D}{W}\right) \times V \times$ K.E. Factor, $(T-D)/W = (T/W) - (D/W)$, $(D/W) = 1/(L/D)$

$$R/C = \left(\frac{T}{W} - \frac{1}{\frac{L}{D}}\right) V \times KE\ factor$$

	30,000 ft		35,000 ft		
q/M^2	439.9 psf		348.6 psf		← Fig. 1-9 } p 11
a (speed of sound)	994.9 fps		973.1 fps		← Fig. 1-9
M	0.60	0.75	0.60	0.75	
q ~ psf	158.4	247.4	125.5	196.1	
C_L	0.62	0.40	0.78	0.50	← W/Sq
(L/D)	16.1	13.8	16.0	15.0	← Fig. 12-12
Max Cr Thrust / SLSTO Thrust	0.29	0.29	0.24	0.24	← Fig. 8-9 p186
Max Cl Thrust / Max Cr Thrust	1.071	1.071	1.068	1.068	← Fig. 8-8 p185
Max Cl Thrust per engine lbs	4348	4348	3588	3588	
Total Cl Thrust lbs	×2 8696	8696	7177	7177	
(T/W)	.0887	.0887	.0732	.0732	
(D/W) = 1/(L/D)	.0621	.0725	.0625	.0667	
① (T/W) - (D/W)	.0266	.0162	.0107	.0065	
V ~ fps	596.9	746.1	583.8	729.8	
② V ~ fpm	35,813	44,766	35.028	43,789	
③ K.E. Factor	1.05	1.05 8	1.08 5	1.08	← Fig. 8-6
①×②×③ R/C ~ fpm	1000 Ⓐ	✓ 783 Ⓑ	✓ 394 Ⓒ	307 Ⓓ	→ Fig 13-3

bottom of p256

From Fig. 13-3, At M = 0.60, 300 fpm reached at 35,800 ft Ⓔ
At M = 0.75, 300 fpm reached at 35,000 ft Ⓕ
Ⓔ At 35,800 ft, M = 0.60 = 0.60 x a = 0.60 x 574.3 kts = 344.6 kts
Ⓕ At 35,000 ft, M = 0.75 = 0.75 x a = 0.75 x 576.4 kts = 432.3 kts

3. Determine the Thrust equals Drag boundary

At three altitudes. calculate thrust and drag vs Mach number and find graphically the point where drag in level flight equals the maximum cruise thrust.

At 30,000 ft, q/M^2 = 439.9 psf, a = 589.3 kts

M	0.70	0.80	0.84	
q ~ psf	215.6	281.6	310.0	← $(q/M^2) \times M^2$
C_L	0.454	0.348	0.316	W/Sq — $\frac{1}{q}\frac{W}{S}$
(L/D)	14.8	11.9	8.4	← Fig. 12-12
D-lbs	6621 Ⓥ	8235 Ⓦ	11,667 Ⓧ	← W/(L/D)
T-lbs	8120 Ⓨ	8120 Ⓩ	8120 Ⓖ	← Total SLSTO Thrust x (Max Cr Thrust)/(SLSTO Thrust)

Calc in Ch 8   Fig 8-9 & 8-11

From Fig. 13-4, thrust and drag are equal at M = 0.795, V_{TRUE} = 468.4 kts

At 20,000ft, q/M^2 = 680.8psf, a = 614.3kts ← Fig 1.9

M	0.60	0.75	0.80	0.84
q ~ psf	245.0	382.9	435.7	480.4
C_L	0.400	0.256	0.225	0.204
(L/D)	14.3	10.8	9.3	6.9
D-lbs	6853 M	9074 N	10,538 O	14,202 P
T ~ lbs	10,370 Q	10,370 R	10,370 S	10,370 T

← $C_L = \frac{1}{q}\left(\frac{W}{S}\right)$

Fig 12-12 (p241)

To Fig 13-4.2

Thrust and drag are equal at M = 0.795, V_{TRUE} = 488.4 kts U

At sea level, q/M^2 = 1481 psf, a = 661.5 kts ← Fig 1.9

M	0.60	0.70
q ~ psf	533.1	833.1
C_L	0.182	0.118
(L/D)	8.2	5.7
D ~ lbs	11,951 I	17,192 J
T ~ lbs	15,680 K	14,840 L

To Fig 13-4.1

Thrust and drag are equal at M = ~~0.709~~ 0.675 V_{TRUE} = ~~469.0~~ 446.5 kts H

2. Determining the R/C boundary

see table at top of p 257

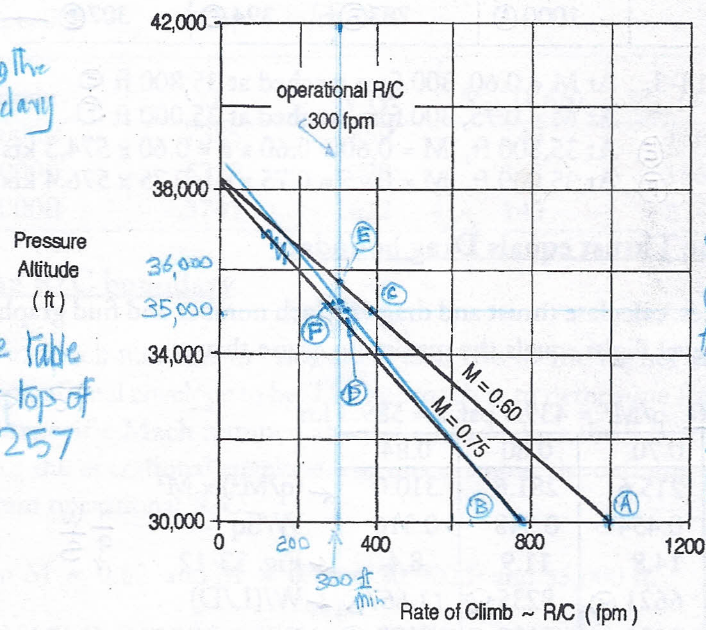

Fig. 13-3 Rate of Climb Plots ~ Example Problem

Plot A B C D from Table on p 257 then construct lines for M = 0.60 + M = 0.75, then identify points E + F. Plot these on Fig 13-5

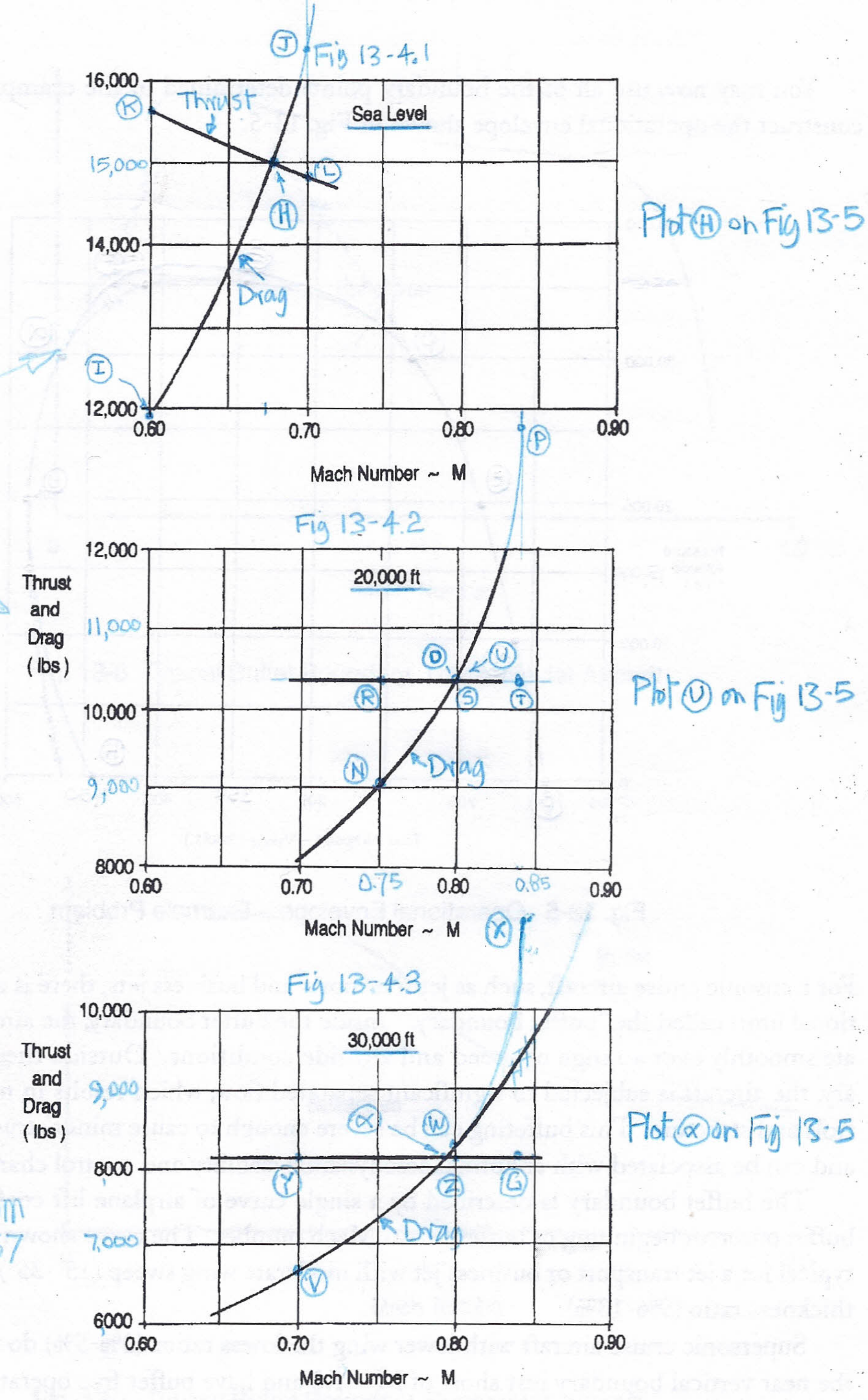

Fig. 13-4 Thrust - Drag Plots ~ Example Problem

You may now use all of the boundary points determined in the example problem to construct the operational envelope shown in Fig. 13-5.

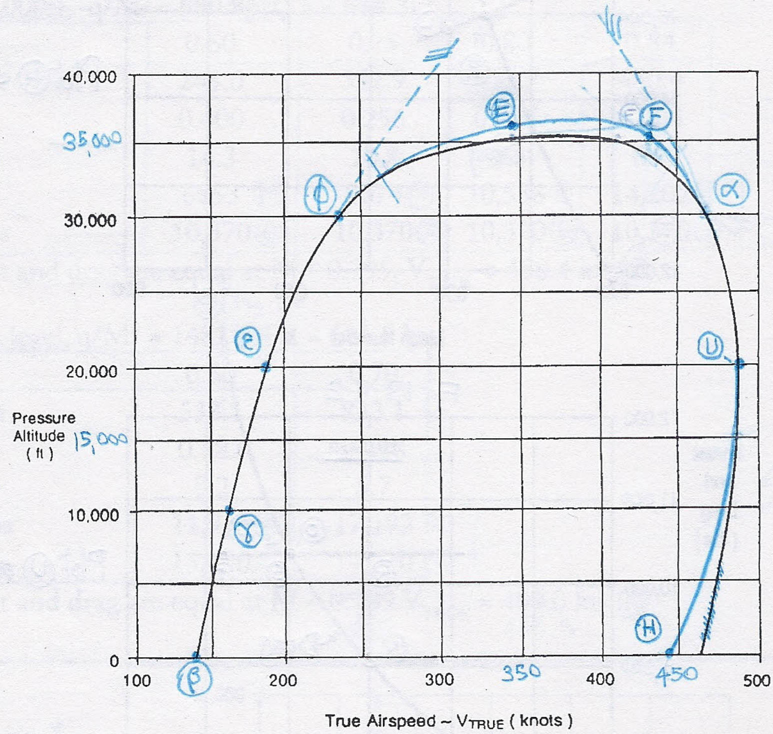

Fig. 13-5 Operational Envelope ~ Example Problem

For transonic cruise aircraft, such as jet transports and business jets, there is another operational limit called the "buffet boundary." Inside the buffet boundary, the aircraft can operate smoothly over a range of speed and altitude conditions. Outside the buffet boundary, the aircraft is subjected to significant separated flow, which results in noticeable controls and structure. This buffeting can be severe enough to cause minor structural damage, and can be associated with abnormal aerodynamic stability and control characteristics.

The buffet boundary is described by a single curve of airplane lift coefficient, C_L for buffet onset, or beginning of buffet versus Mach number. The curve shown in Fig. 13-6 is typical for a jet transport or business jet with moderate wing sweep (15°-35°) and moderate thickness ratio (9%-13%).

Supersonic cruise aircraft with lower wing thickness ratios (3%-5%) do not experience the near vertical boundary just short of M = 1.0 and have buffet free operation supersonically, as shown in Fig. 13-7.

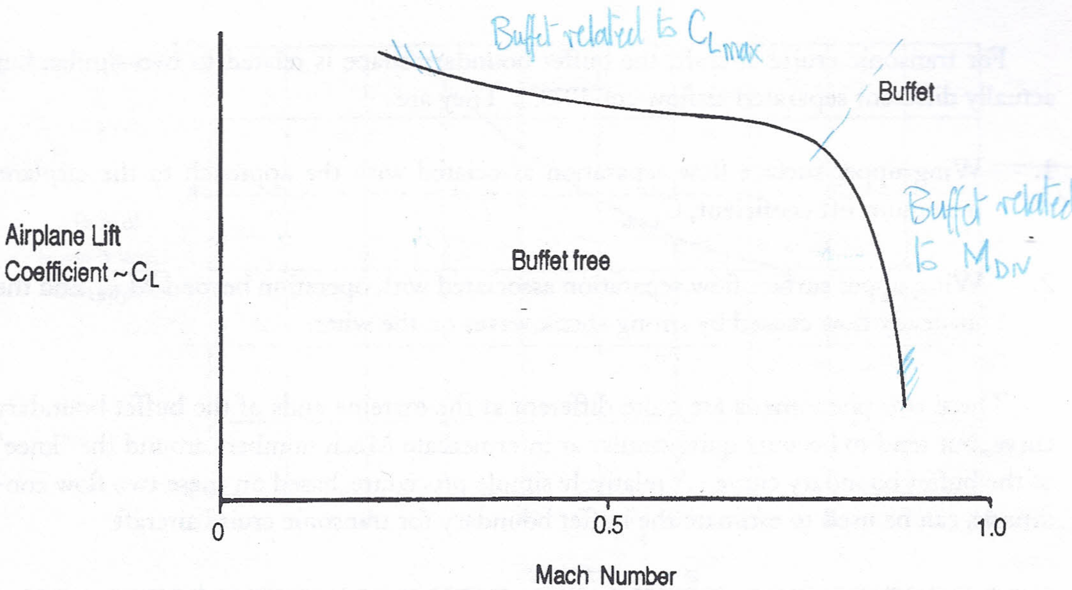

Fig. 13-6 Typical Buffet Boundary, Transonic Jet Aircraft

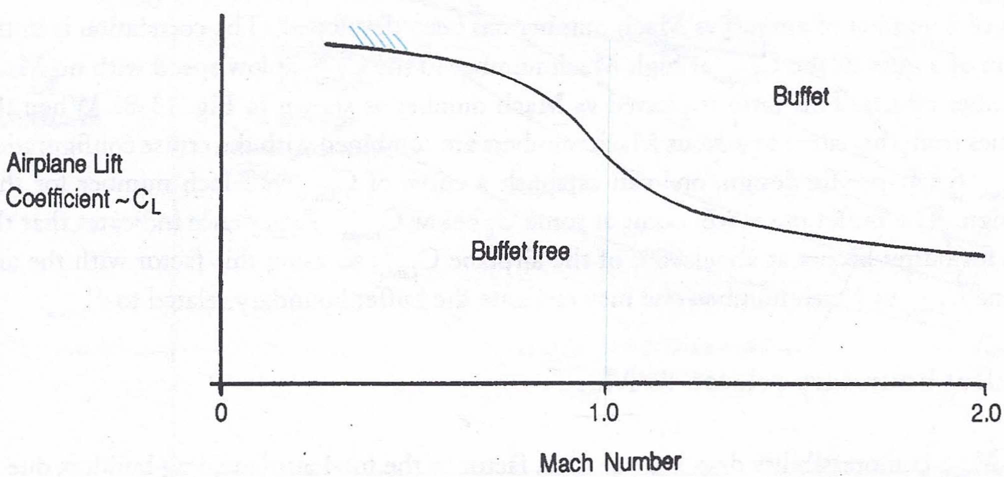

Fig. 13-7 Typical Buffet Boundary, Supersonic Aircraft.

For transonic cruise aircraft, the buffet boundary shape is related to two similar, but actually different separated airflow conditions. They are

1. Wing upper surface flow separation associated with the approach to the airplane maximum lift coeficient, C_{Lmax}

2. Wing upper surface flow separation associated with operation beyond M_{DIV}, and the unsteady flow caused by strong shock waves on the wing.

These two phenomena are quite different at the extreme ends of the buffet boundary curve, but tend to become quite similar at intermediate Mach numbers around the "knee" of the buffet boundary curve. A relatively simple procedure, based on these two flow conditions, can be used to estimate the buffet boundary for transonic cruise aircraft.

PROCEDURE FOR ESTIMATING THE BUFFET BOUNDARY

Buffet boundary related to C_{Lmax}

As noted in Fig. 1-21, the C_{Lmax} is reduced as the flight Mach number increases. Since buffet onset occurs prior to reaching C_{Lmax} a first step is to estimate the variation of airplane C_{Lmax} with Mach number. Fortunately, a trend curve which correlates the C_{Lmax} characteristics of a number of aircraft vs Mach number has been developed. The correlation is in the form of a ratio of the C_{Lmax} at high Mach number to the C_{Lmax} at low speed with no Mach number effects. This ratio is plotted vs Mach number as shown in Fig. 13-8. When the values from this curve at various Mach numbers are combined with the cruise configuration C_{Lmax} for a specific design, one can establish a curve of C_{Lmax} vs Mach number for that design. The buffet onset will occur at some C_L below C_{Lmax}. Experience indicates that the C_L for buffet occurs at about 90% of the airplane C_{Lmax}, so using this factor with the airplane C_{Lmax} vs Mach number, one may estimate the buffet boundary related to C_{Lmax}.

Buffet boundary related to M_{DIV}

At M_{DIV} compressibility drag is a already a factor in the total airplane drag buildup, due to the existence of shock waves on the wing, but the airfow is steady and there is no buffet. However, at slightly higher Mach numbers, the shock waves become stronger, which leads to separation, unsteady flow and buffet. As noted in Fig. 12-11, M_{DIV} is a function of C_L

From Fig 11-5 Step 5
Eg. $C_{L_{max\,ls}} = 1.6$

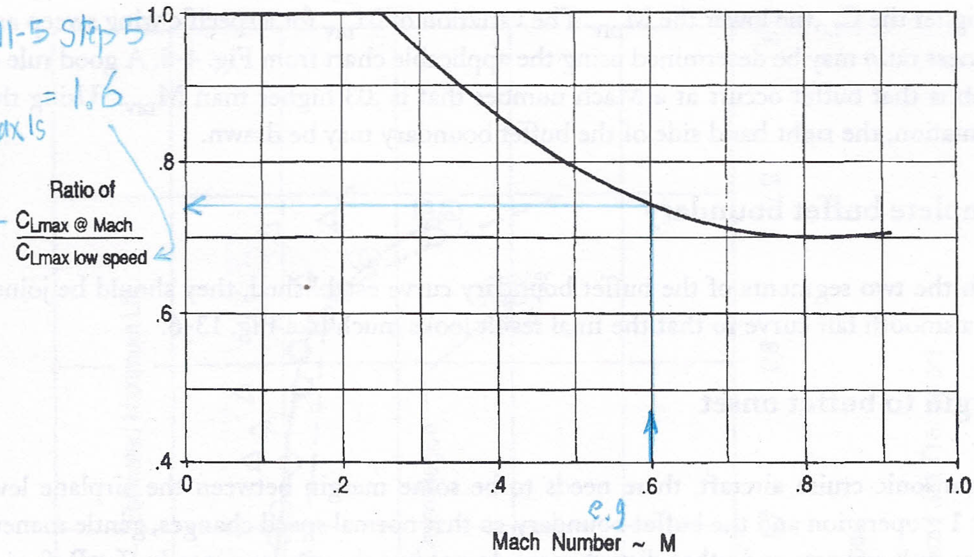

Fig. 13-8 Typical Maximum Lift Coefficient Ratios for Transonic Aircraft

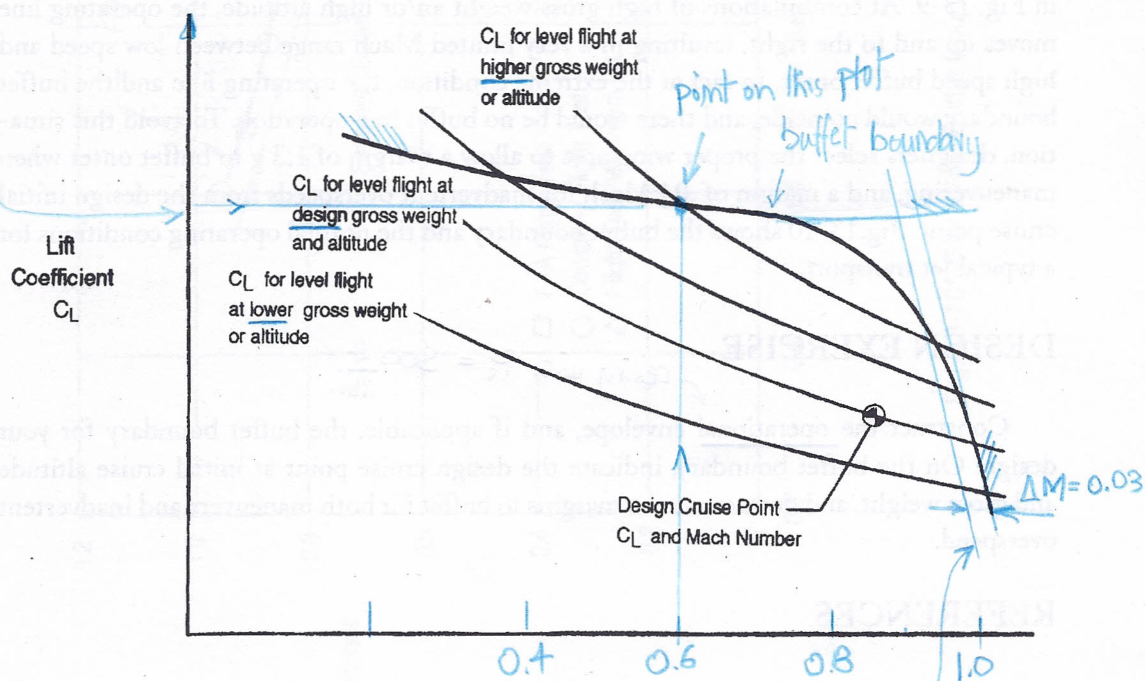

Fig. 13-9 Design Cruise Point Relative to the Buffet Boundary

plot of C_L vs M_{DIV}
from Fig 4-8
for given Λ + t/c

the higher the C_L ,the lower the M_{DIV}. The variation of M_{DIV} for a specific wing sweep and thickness ratio may be determined using the applicable chart from Fig. 4-8. A good rule of thumb is that buffet occurs at a Mach number that is .03 higher than M_{DIV}. Using this information, the right hand side of the buffet boundary may be drawn.

Complete buffet boundary

With the two segments of the buffet boundary curve established, they should be joined with a smooth fair curve so that the final result looks much like Fig. 13-6.

Margin to buffet onset

For transonic cruise aircraft, there needs to be some margin between the airplane level flight 1 g operation and the buffet boundary, so that normal speed changes, gentle maneuvers, as well as gusts and other disturbances do not put the airplane into buffet Referring back to Fig. 1-16, any number of 1g operating lines may be superimposed on the buffet boundary, representing different combinations of gross weight and cruise altitude as shown in Fig. 13-9. At combinations of high gross weight an/or high altitude, the operating line moves up and to the right, resulting in a very limited Mach range between low speed and high speed buffet onset. In fact at the extreme condition, the operating line and the buffet boundary would coincide, and there would be no buffet free operation. To avoid this situation, designers select the proper wing area to allow a margin of 1.3 g to buffet onset when maneuvering, and a margin of .04 Mach for inadvertent overspeeds from the design initial cruise point. Fig.13-10 shows the buffet boundary and the normal operating conditions for a typical jet transport.

DESIGN EXERCISE

ceiling with $P_s = 300 \frac{ft}{min}$

Construct the operational envelope, and if applicable, the buffet boundary for your design. On the buffet boundary, indicate the design cruise point at initial cruise altitude and gross weight, and determune the margins to buffet for both maneuvers and inadvertent overspeed.

REFERENCES

13.1 Nicolai, Leland M., Fundamentals of Aircraft Design, METS, San Jose, CA 1984

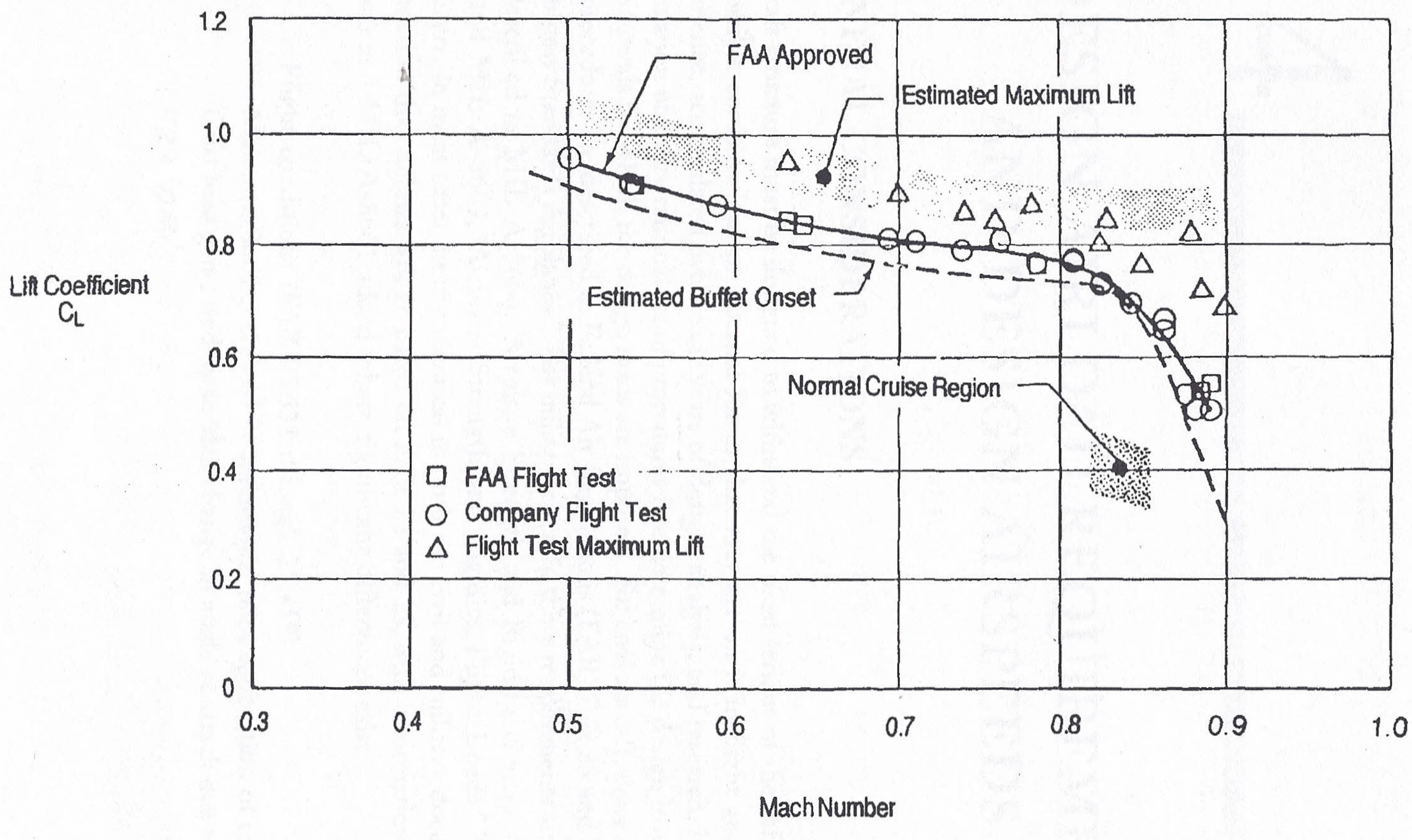

Fig. 13-10 Flight Test Buffet Boundary~Typical Jet Transport