14.3 Air Loads

Although detailed quantification of air loads is not normally required during the conceptual design process, it is useful to know what the limiting air loads are, and the conditions at which they occur. Air loads that exceed the 1-g loading condition are the result of

- Aircraft maneuvers (usually in pitch)
- Vertical gusts

These loads are normally expressed as graphical envelopes with a horizontal axis of equivalent airspeed and vertical axis as the ratio, n, of actual load to a 1-g load. This is known as the V-n diagram. These plots do not necessarily define the maximum loads that may be experienced by the aircraft structure and components. Other conditions, such as taxi, takeoff, and landing may result in loads exceed the air loads.

In order to calculate the maneuver and gust envelopes, the following information about the aircraft must be known:

- Aircraft gross weight at which loads are to be calculated
- Flap setting
- Design cruise speed
- $C_{L_{max}}$ for the given flap setting
- Gradient of the lift curve slope, C_{L_α}
- Wing geometry (area and m.a.c.)

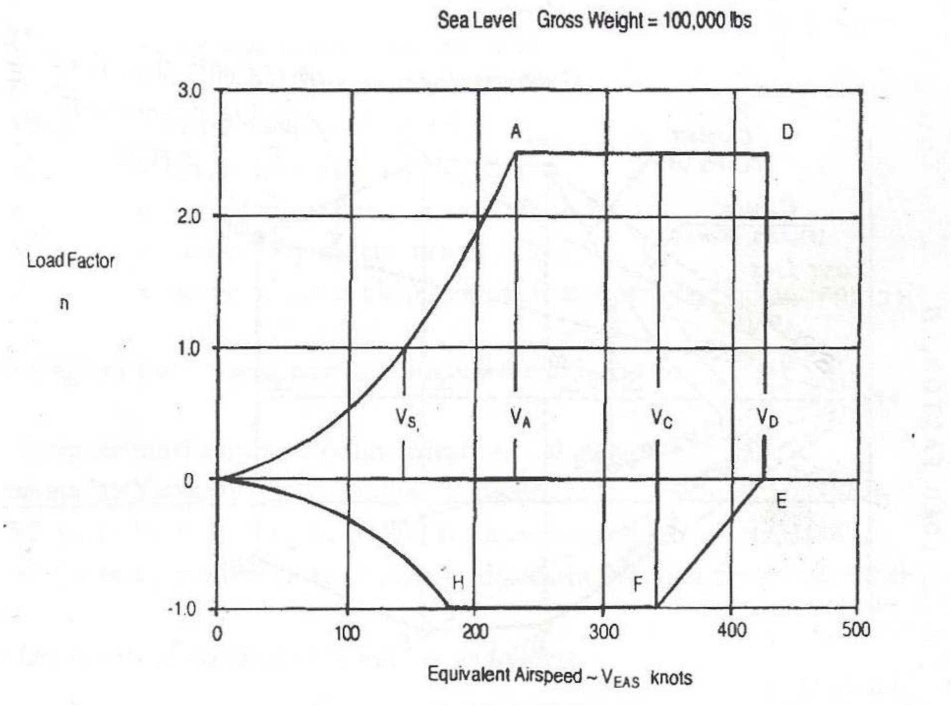
Design Airspeeds

FAA designated design airspeeds (commonly, but somewhat redundantly, called V-speeds), are illustrated in Figs. 14.3.1 and 14.3.2.

V_S	Stalling speed or minimum steady flight speed
V_{S_1}	Stalling speed under 1-g loading
V_A	Maneuver speed or full control deflection speed
V_B	Design speed for maximum gust intensity
V_{FE} nn	Design flap extended speed (nn is the flap deflection in degrees)
V_{LE}	Design landing gear extended speed
V_{LO}	Design landing gear operating speed (if different from V_{LE})
V_C	Design cruising speed ($\geq V_B + 43$ KEAS)
V_{MO}	Maximum operating limited speed (“barber pole” speed)
V_{FC}	Maximum speed at which flight characteristics requirement must be met
V_D	Design dive speed, $\geq 1.25\ V_C$, or speed reached in a 7.5 degree dive for 20 seconds from V_C, followed by a 1.5-g recovery.

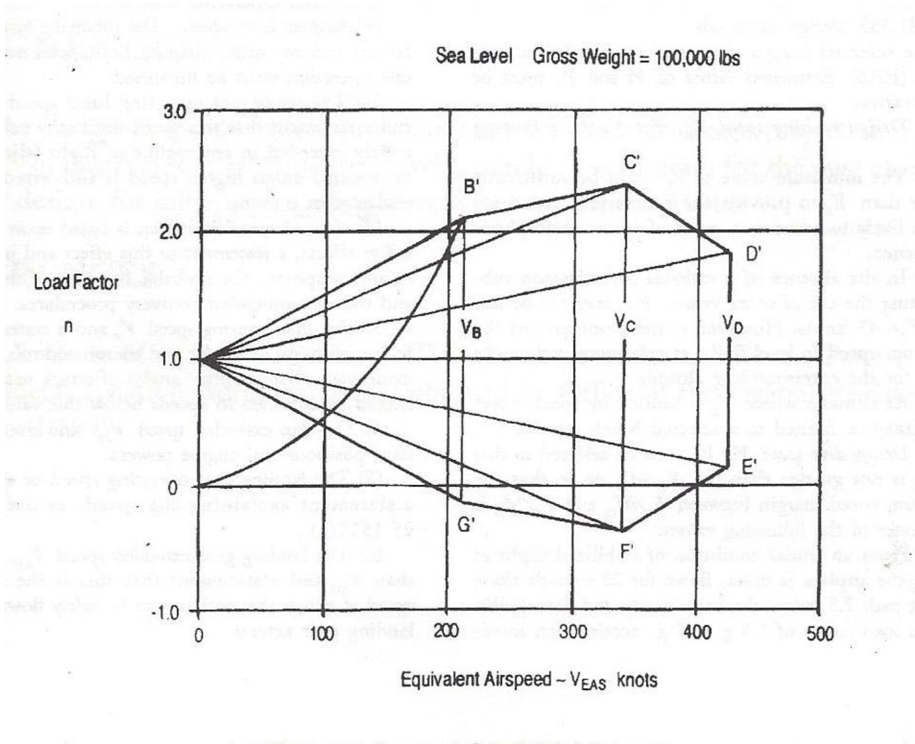
The “barber pole” refers to the marking on the airspeed indicator (ASI), similar to the red line on a car tachometer.

A complete set of designated airspeed definitions may be found in FAR Part 1.2, Definitions and Abbreviations. Note that FAR Part 1.2 defines V_{S_1} more generically as "the stalling speed or minimum steady flight speed obtained in a specific configuration", so this speed depends on the particular circumstances (defined above for this case).



Source: Schaufele

Fig. 14.3.1 Design Airspeeds for Maneuver Envelope



Source: Schaufele

Fig.14.3.2 Design Airspeeds for Gust Envelope

Maneuver Load Envelope

Generation of the maneuver envelope, shown in Fig. 14.3.3, is relatively straightforward.

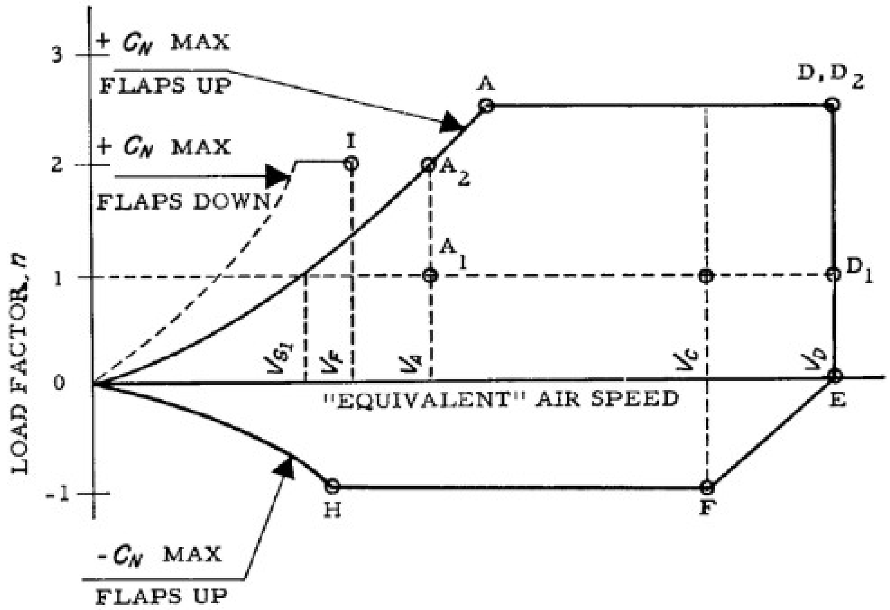


Fig. 14.3.3 Maneuver Envelope

Some additional assumptions must be made, and values calculated. The coefficient C_N is the normal force coefficient, and its direction is perpendicular to the horizontal axis of the aircraft. This vector is not the same as the lift coefficient, which is perpendicular to the airflow. The normal force coefficient may include some component of drag, as illustrated in the top half of Raymer Fig. 14.4.

Line O-A The curve from the origin to point A is defined by

$$n = \frac{L}{W} = \frac{C_{L_{\max}}\, q}{\frac{W}{S}} = \frac{0.5\, C_{L_{\max}}\, \rho_0 \left(V_{EAS}\right)^2}{\frac{W}{S}} \tag{14.3.1}$$

Point A This is the intersection of the line for pull-up at $C_{N_{\max}}$ with the maximum positive maneuver load.

For FAR Part 23 aircraft, the maximum value of *n* is a function of aircraft category (Table 14.3.1). Categories are defined in Table 14.3.2

Aircraft category	$n_{\max}$ positive	$n_{\max}$ negative
Normal	3.8	-1.52
Utility	4.4	-1.76
Acrobatic	6.0	-3.00
Commuter	3.8	-1.52

Table 14.3.1 FAR Part 23 $n_{\max}$ as a function of aircraft category

Aircraft category	MTOGW [lb]	Passenger Seats	Max bank angle
Normal	≤ 12,500	≤ 9	$\varphi \leq 60^o$
Utility	≤ 12,500	≤ 9	$60^o \leq \varphi \leq 90^o$
Acrobatic	≤ 12,500	≤ 9	No restriction
Commuter	≤ 19,000	≤ 19	$\varphi \leq 60^o$

Table 14.3.2 Definition of FAR Part 23 categories

For FAR Part 25 aircraft, the maximum value of *n* is a function of MTOGW (Table 14.3.3)

MTOGW [lb]	$n_{\max}$ positive	$n_{\max}$ negative
≤ 4,100	3.8	-1.0
> 4,100 and ≤ 50,000	$2.1 + \left[\frac{24{,}000}{MTOGW + 10{,}000}\right]$	-1.0
> 50,000	2.5	-1.0

Table 14.3.3 FAR Part 25 $n_{\max}$ as a function of MTOGW

Line A – D This line represents the value of n_{max} positive as defined above. The point D is at the maximum dive speed, V_D.

Line 0 – H This line represents the maximum negative load factor. Most aircraft (except acrobatic designs) have asymmetric airfoil sections, for which the maximum positive lift coefficient is greater than the maximum negative value. It can be approximated that $C_{N_{max}}$ (negative) = 0.7 $C_{N_{max}}$ (positive).

Line H – F This line lies on the maximum negative load factor, and point F is at the design cruise speed, V_C.

Gust Envelope

Raymer points out that the method described here has been superseded by more accurate methods. These methods rely on a power-spectral-density approach in which the gusts are described by a cosine function and the actual aircraft dynamics are modeled. FAR Part 25 now requires that these methods be used in the certification process. Nevertheless, the method described illustrates the general process of generating a gust envelope.

In Fig. 14.3.4 the corner points for the gust envelope (B', C', D', etc.) are at the intersection of the diagonal gust response lines for a given speed and the vertical line from the value of that speed on the horizontal axis.

The gust response line is defined by the empirical equation

$$n = 1 + \frac{K_g U_{gE} V_E a}{498\left(\frac{W}{S}\right)} \tag{14.3.2}$$

where

$$K_g \;(\text{gust alleviation factor}) = \frac{0.88\,\mu_g}{5.3 + \mu_g}$$

$$\mu_g \;(\text{mass ratio}) = \frac{2\left(\frac{W}{S}\right)}{\rho\,\bar{c}\,a\,g}$$

$$U_{gE} = \text{equivalent gust velocity (see Table 14.3.4)}\left[\frac{\text{ft}}{\text{sec}}\right]$$

$$\rho = \text{air density}\left[\frac{\text{slugs}}{\text{ft}^3}\right]$$

$$\left(\frac{W}{S}\right) = \text{wing loading}\left[\frac{\text{lb}}{\text{ft}^2}\right]$$

$$\bar{c} = \text{mean geometric chord}\;[\text{ft}]$$

g = acceleration due to gravity $\left[\frac{\text{ft}}{\text{sec}^2}\right]$

V_E = aircraft equivalent airspeed [KEAS]

a = slope of the airplane normal force curve [radians]

V-speed	Alt [ft]	Speed [ft/sec]	Alt [ft]	Speed [ft/sec]	Alt [ft]	Speed [ft/sec]
V_B	SL	66	20,000	66	50.000	38
V_C	SL	50	20,000	50	50,000	25
V_D	SL	25	20,000	25	50.000	12.5

Table 14.3.4 Values of U_{gE} for different V-speeds (use linear interpolation)

Wing loading selection was described in Raymer Section 5.3 and 5.4, and accompanying annotations. Air density is for the altitude for which the envelope is being calculated. It can be assumed that the mean geometric chord is the same as the mean aerodynamic chord (Raymer Section 4.3), and that the slope of the airplane normal force coefficient is C_{L_α} (Raymer Section 12.4).

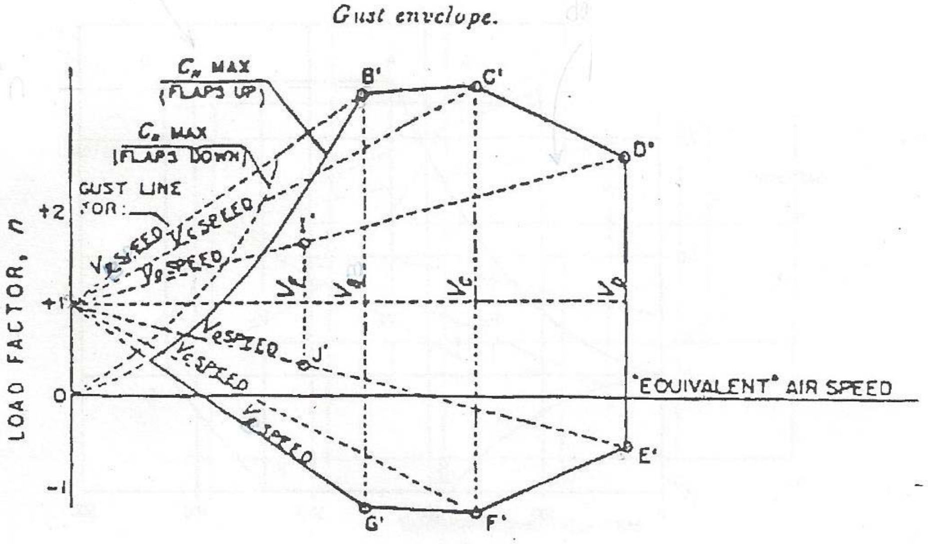


Fig 14.3.4 Gust Envelope

Line 0 – B' As in the maneuver envelope, this line describes the maximum load factor that can be generated by a gust which causes the airplane to reach its $C_{N_{max}}$

Point B' This point is the intersection of the load factor for $C_{N_{max}}$ (solid curve) and the load factor for a 66 ft/sec gust (dashed line for Eq. 14.3.2). This point determines V_B, the design speed for maximum gust intensity. In addition

$$V_B \geq \sqrt{n}\, V_{S_1} \tag{14.3.3}$$

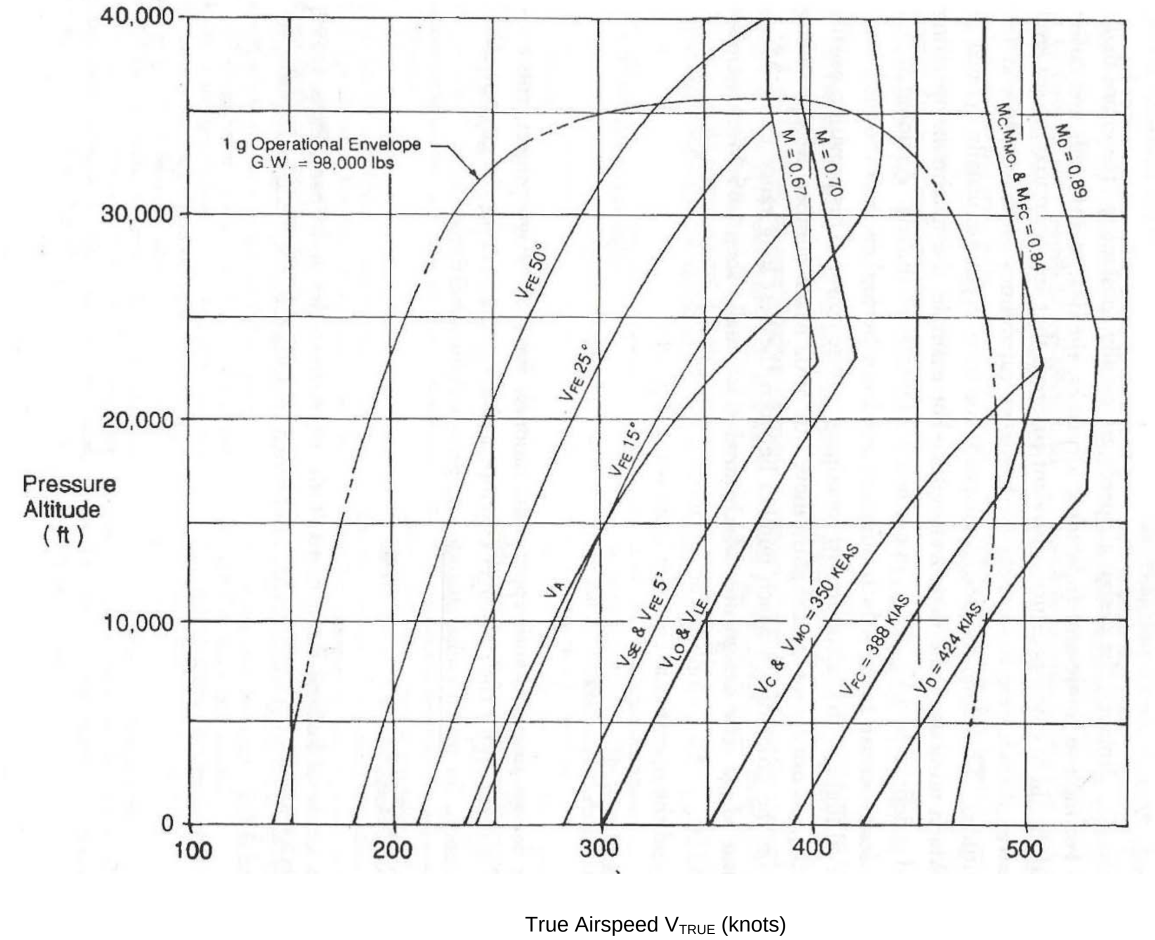
Point C' This point is the intersection of the load factor due to a 50 ft/sec gust (diagonal dashed line for Eq. 14.3.2) and V_C, the design cruise speed (dashed vertical line).

Point D' This point is the intersection of the load factor due to a 25 ft/sec gust (diagonal dashed line for Eq. 14.3.2) and V_D, the design dive speed (solid vertical line).

Point E', F', and G' These are the corresponding intersections for negative gusts at the designated speeds.

The two envelopes may be combined into a single envelope.

Fig. 14.3.5, taken from Schaufele (Ref 14.3.1), shows the relationship between design airspeeds and the operational envelope, which represents the operational capability of the aircraft. This figure represents the DC9-20. Note that the design cruise Mach number is outside the operational envelope. In the Annotation to Raymer Section 17.2.5, it can be seen that the optimum value of ML/D for this aircraft occurs at Mach 0.75. For this aircraft V_C/M_C and V_{MO}/M_{MO} have the same values all altitudes, although typically M_{MO} is set at Mach 0.01 or 0.02 above M_C, giving a margin of about M 0.08 above the optimum long range cruise Mach number. The design dive Mach number, M_D, is usually set at about Mach 0.05 above M_{MO}.



Source: Schaufele

Fig 14.3.5 Relationship between Design Airspeeds and Operational Envelope

References

14.3.1 Schaufele, R.D., "The Elements of Aircraft Preliminary Design" Aries Publications, 2007