

AIRCRAFT STRUCTURAL DESIGN

SESA3026

3. Aircraft Loads

V-n Diagram

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https://www.youtube.com/watch?v=mQ1ZozXp2tw&feature=emb_logo&ab_channel=BloombergQuicktake

Maximum Load Factor

Load factor

$$L + P = nW$$

$n = 1$: level and straight flight

$$n = \frac{L + P}{W}$$

$n = 0$: zero-g (parabolic flight)

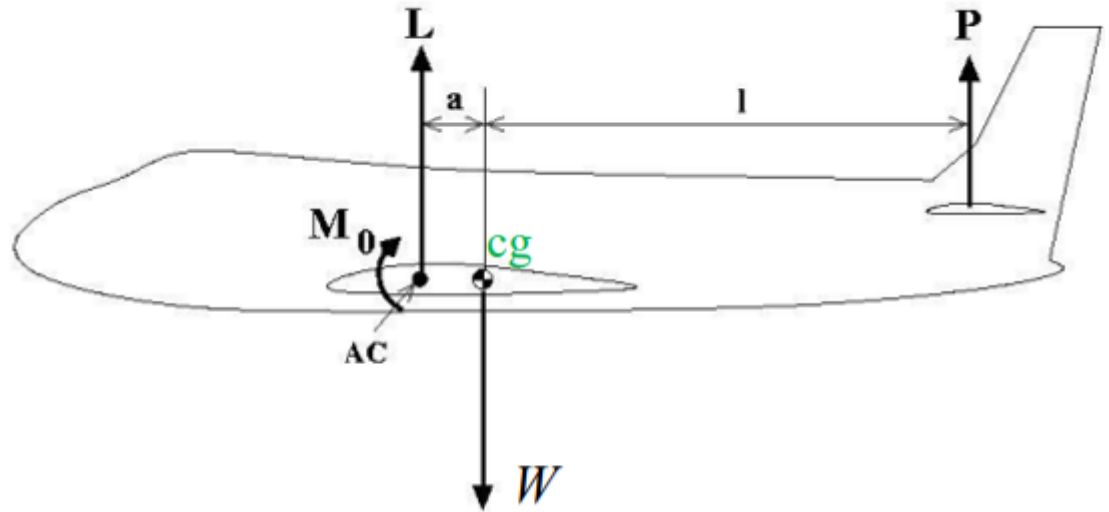
Maximum value of n just before stall

$$n_{MAX} = \frac{0.5\rho V^2 S C_L^{MAX}}{W}$$

determined by **total aircraft lift coefficient, C_L^{MAX}**



Total aircraft lift coefficient



Equilibrium rotation around cg:

$$Pl = La + M_0$$

$$P = \frac{L}{l}a + \frac{1}{l}M_0$$

$$P + L = L\left(1 + \frac{a}{l}\right) + \frac{1}{l}M_0$$

Note that the symbol a has been used previously to indicate an acceleration and now a distance. Its meaning, however, should be clear from the expression in which it is used.

Divide by the reference load

$$(C_L^{MAX})_{aircraft} = (C_L^{MAX})_{wing} \left(1 + \frac{a}{l}\right) + \frac{\bar{c}}{l} C_{m0}$$

V-n Diagram: Flight Envelope (EASA)

<https://www.easa.europa.eu/sites/default/files/dfu/CS-23%20Initial%20issue.pdf>

Easy Access Rules for Normal, Utility, Aerobatic and Commut... 76 / 505 84% + [] []

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CS 23.335 Design airspeeds

Except as provided in sub-paragraph (a)(4), the selected design airspeeds are equivalent airspeeds (EAS).

(a) Design cruising speed, VC. For VC the following apply:

- (1) VC (in knots) may not be less than –
 - (i) $33 \sqrt{W/5}$ (for normal, utility and commuter category aeroplanes); and
 - (ii) $36 \sqrt{W/5}$ (for aerobatic category aeroplanes);where $W/5$ = wing loading at design maximum take-off weight $W_0/5$.
- (2) For values of $W/5$ more than 30, the multiplying factors may be decreased linearly with $W/5$ to a value of 20% where $W/5 = 100$.
- (3) VC need not be more than 0.9 V_{hi} at sea level.
- (4) At altitudes where an MD is established, a cruising speed MC limited by compressibility may be selected.

(b) Design dive speed, VD. For VD the following apply:

- (1) VD/MD may not be less than 1.25 VC/MC; and
- (2) With VC _{min}, the required minimum design cruising speed, VD may not be less than –
 - (i) 1.40 VC _{min} for normal and commuter category aeroplanes; and
 - (ii) 1.50 VC _{min} for utility category aeroplanes; and

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EASA Easy Access Rules for Normal, Utility, Aerobatic and Commuter Category Aeroplanes (CS-23) (Initial Issue) SUBPART C – STRUCTURE WEIGHT LOADS

(b) 1.55 VC _{min} for aerobatic category aeroplanes.

(3) For values of $W/5$ more than 30, the multiplying factors in sub-paragraph (2) may be decreased linearly with $W/5$ to a value of 1.35 where $W/5 = 100$.

(4) Compliance with sub-paragraphs (1) and (2) need not be shown if VD/MD is selected so that the minimum speed margin between VC/MC and VD/MD is the greater of the following:

- (i) The speed increase resulting when, from the initial condition of stabilised flight at VC/MC, the aeroplane is assumed to be upset, flies for 20 seconds along a flight path 7.5° below the initial path and then pulled up with a load factor of 1.5 (0.5 g acceleration increment); at least 75% maximum continuous power for reciprocating engines and maximum cruising power for turbines; or, if less, the power required for VC/MC for both kinds of engines, must be assumed until the pull-up is initiated, at which point power reduction and pilot-controlled drag device may be used; and
- (ii) Mach 0.05 for normal, utility, and aerobatic category aeroplanes (at altitudes where MD is established);

(b) Mach 0.07 for commuter category aeroplanes (at altitudes where MD is established) unless a rational analysis, including the effects of automatic systems, is used to determine a lower margin. If a rational analysis is used, the minimum speed margin must be enough to provide for atmospheric variations (such as horizontal gusts, and the penetration of jet streams or cold fronts), instrument errors, airframe production variations, and must not be less than Mach 0.05.

(c) Design manoeuvring speed KA. For VA the following apply:

- (1) VA may not be less than $V_S \sqrt{C}$ where –
 - (i) V_S is a computed stalling speed with flaps retracted at the design weight, normally

V-n Diagram: Flight Envelope (EASA)

Annex to ED Decision 2015/018/R

CS-23 BOOK 1

European Aviation Safety Agency

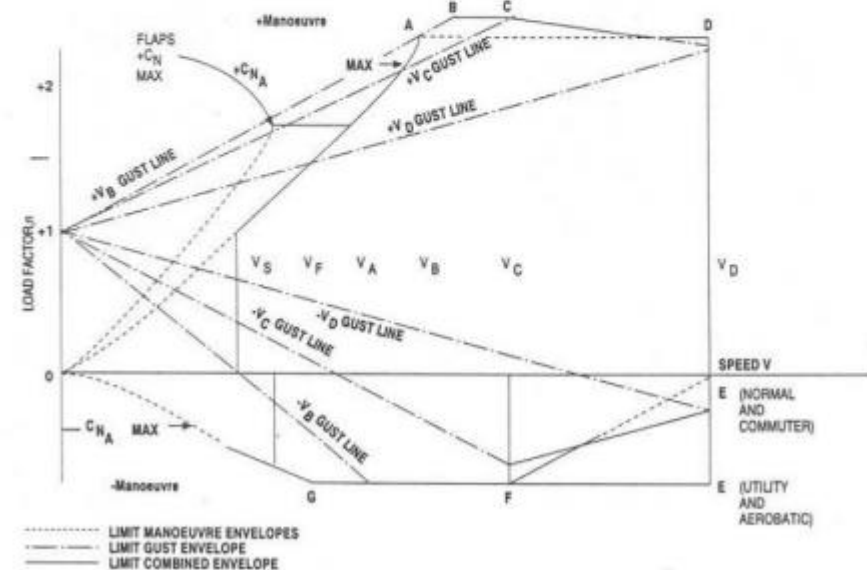
**Certification Specifications
and
Acceptable Means of Compliance
for
Normal, Utility, Aerobatic, and
Commuter Category Aeroplanes
CS-23**

Amendment 4
15 July 2015¹

¹ For the date of entry into force of this Amendment, kindly refer to Decision 2015/018/R in the [Official Publication](#) of the Agency.

Amendment 4

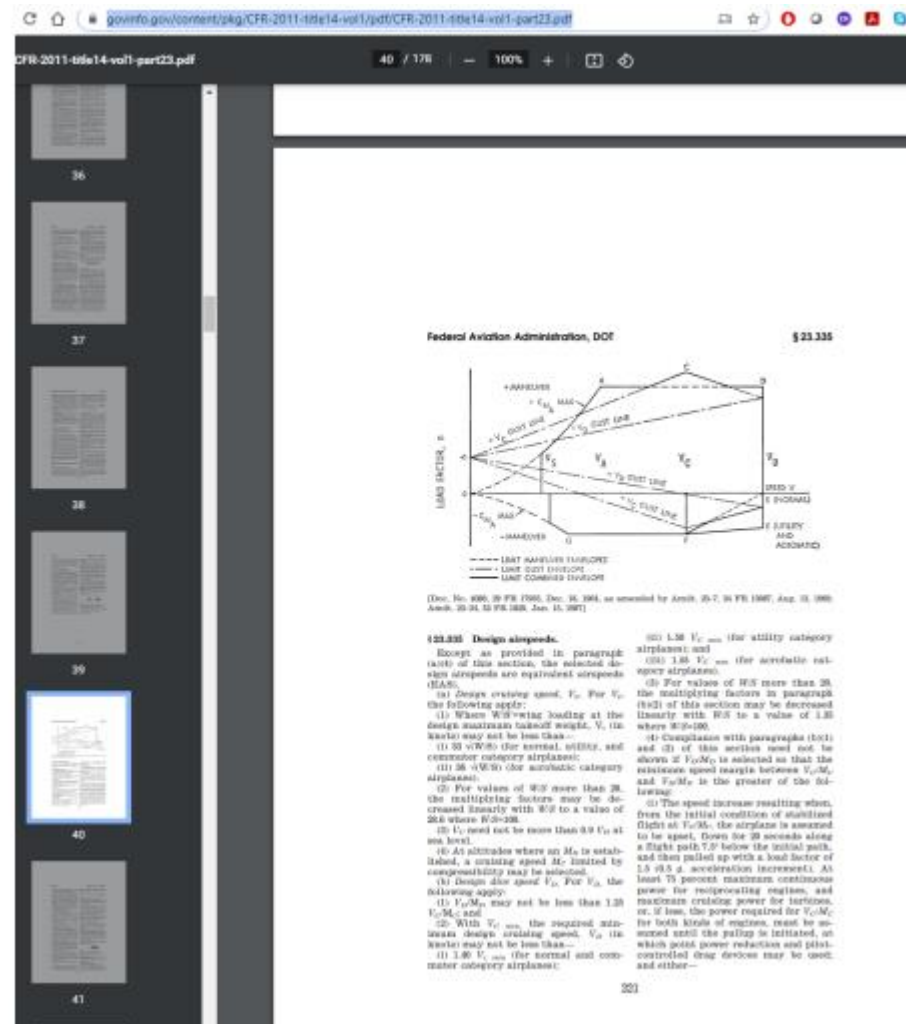
(d) *Flight envelope*



<https://www.easa.europa.eu/sites/default/files/dfu/CS-23%20Amendment%204.pdf>

V-n Diagram: Flight Envelope (FAA)

<https://www.govinfo.gov/content/pkg/CFR-2011-title14-vol1/pdf/CFR-2011-title14-vol1-part23.pdf>



V-n Diagram: Flight Envelope

At low speeds

$$(C_L^{MAX})_{aircraft} = (C_L^{MAX})_{wing} \left(1 + \frac{a}{l}\right) + \frac{\bar{c}}{l} C_{m0}$$

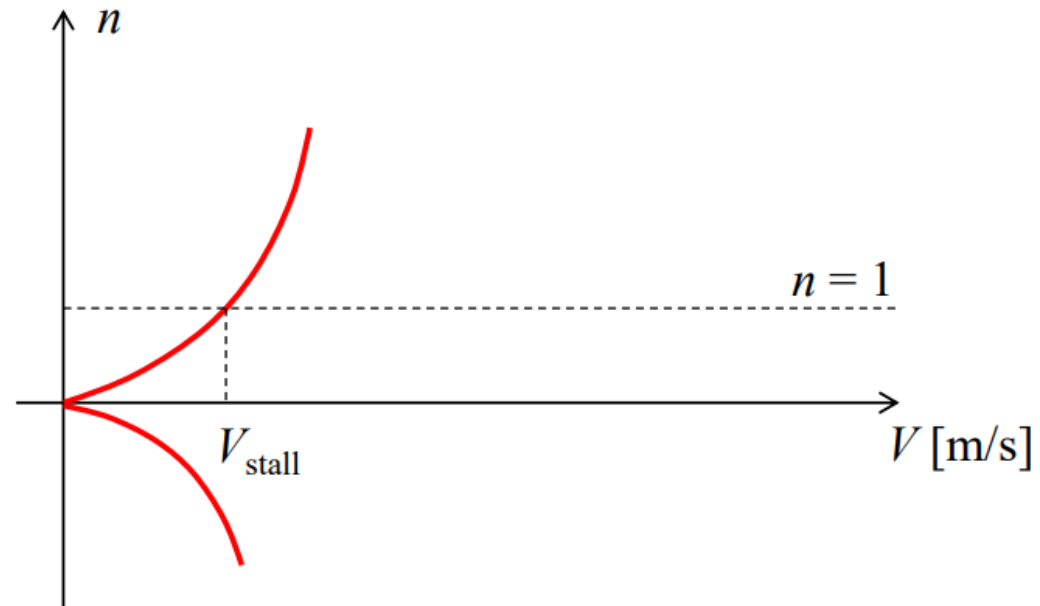
function of velocity, altitude, ...

n can be positive or negative

$$n_{MAX} = \frac{0.5\rho V^2 S C_L^{MAX}}{W}$$

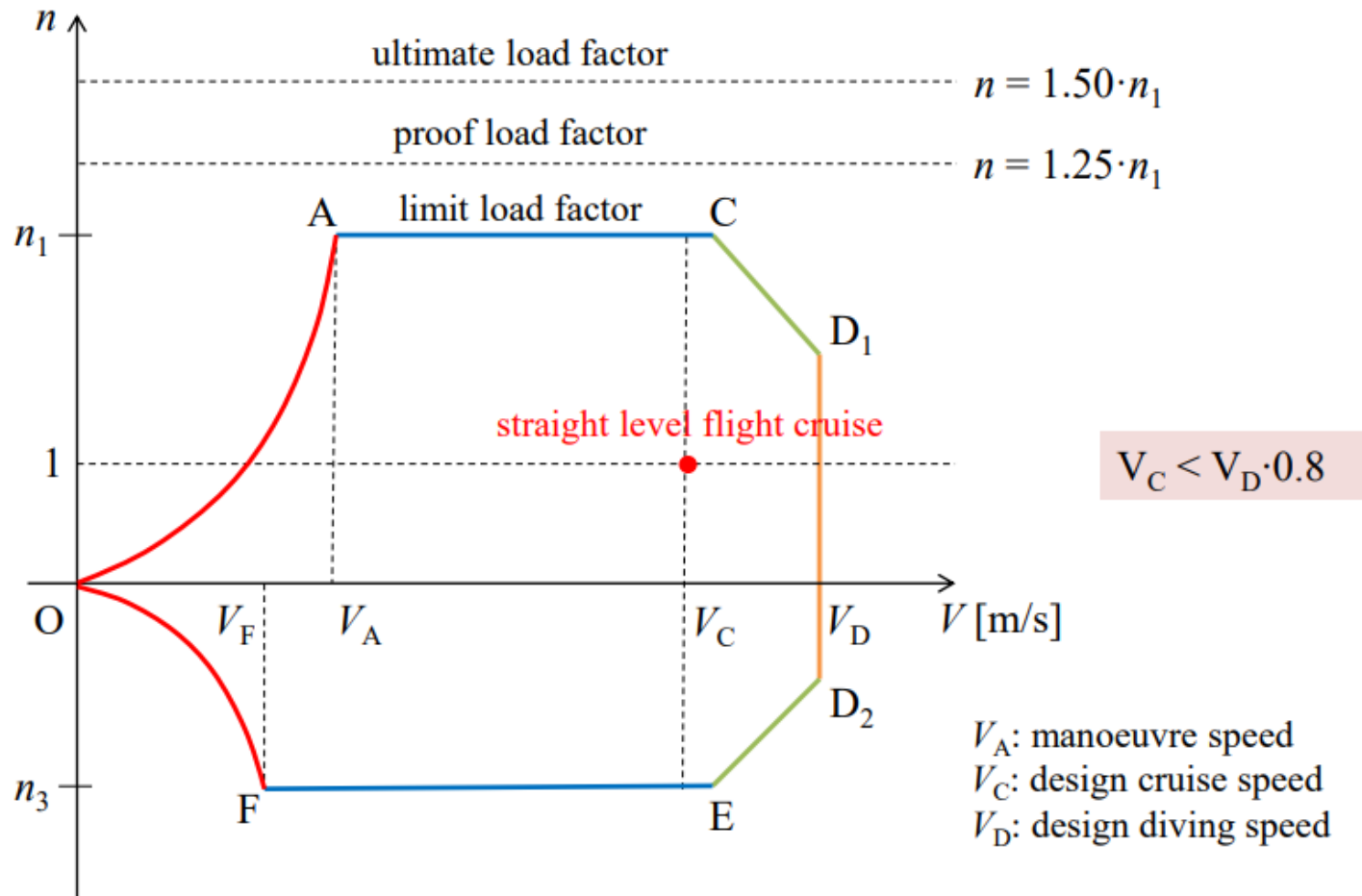
$$n_{MAX} = f(V^2)$$

How do flaps change the red lines?



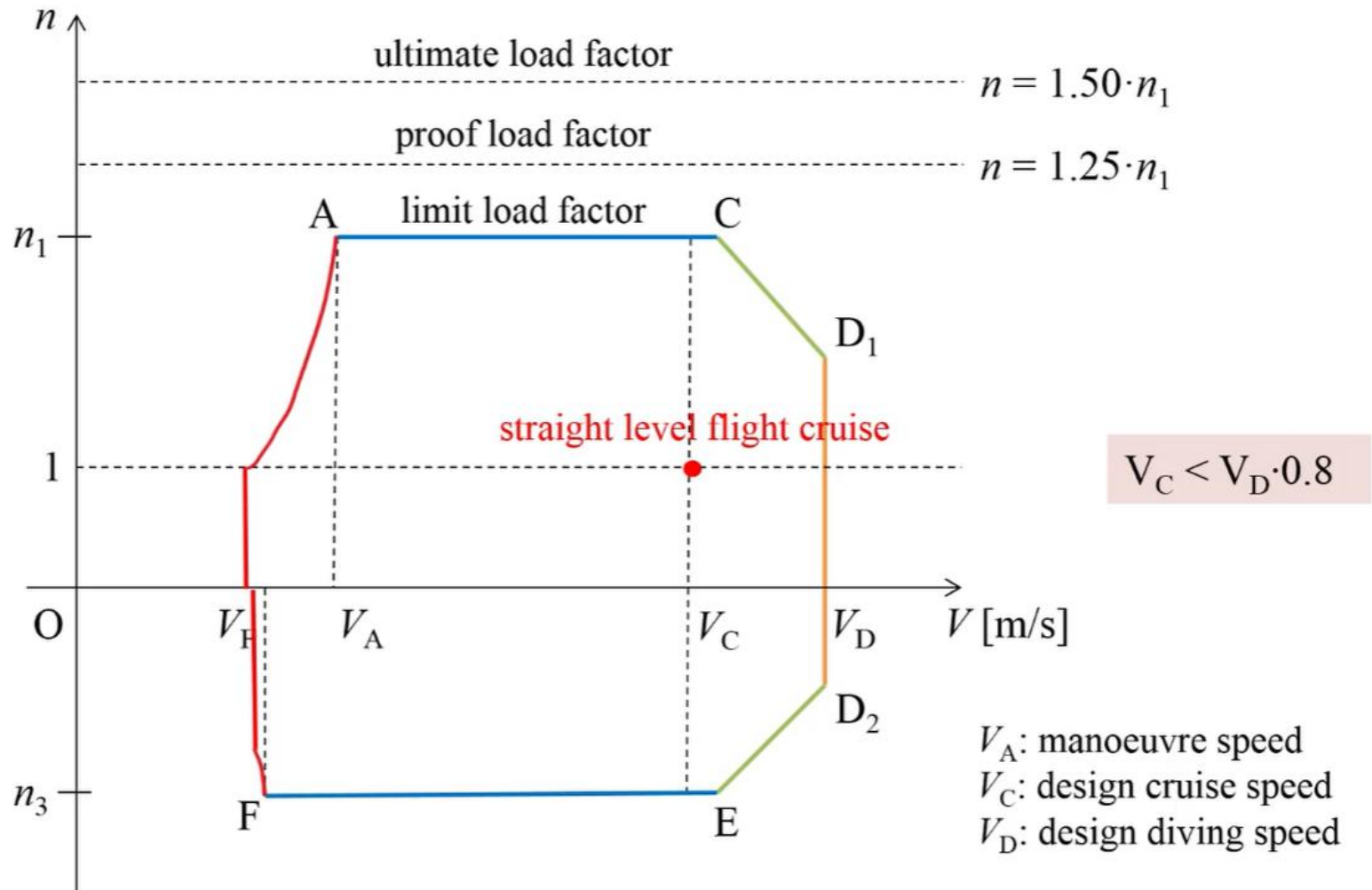
The Flight Envelope

V-n Diagram



The Flight Envelope

V-n Diagram



Symmetric Manoeuvre Loads

V-n Diagram: Limits on Load Factors

Structure must be designed to withstand flight conditions at **any point** in the flight envelope. Load limits are pilot and role dependent, set by Airworthiness Authorities (BCAR, JAR)



Category: normal ↑

$$n_1 \leq 2.1 + \frac{24,000}{W + 10,000}$$
$$n_3 \geq -1.0$$



Category: semi aerobatic ↑

$$n_1 \leq 4.5$$
$$n_3 \geq -1.8$$

$$n_1 \leq 6.0$$
$$n_3 \geq -3.0$$

Category: aerobatic ↓



A Light Sport Airplane Flight Envelope

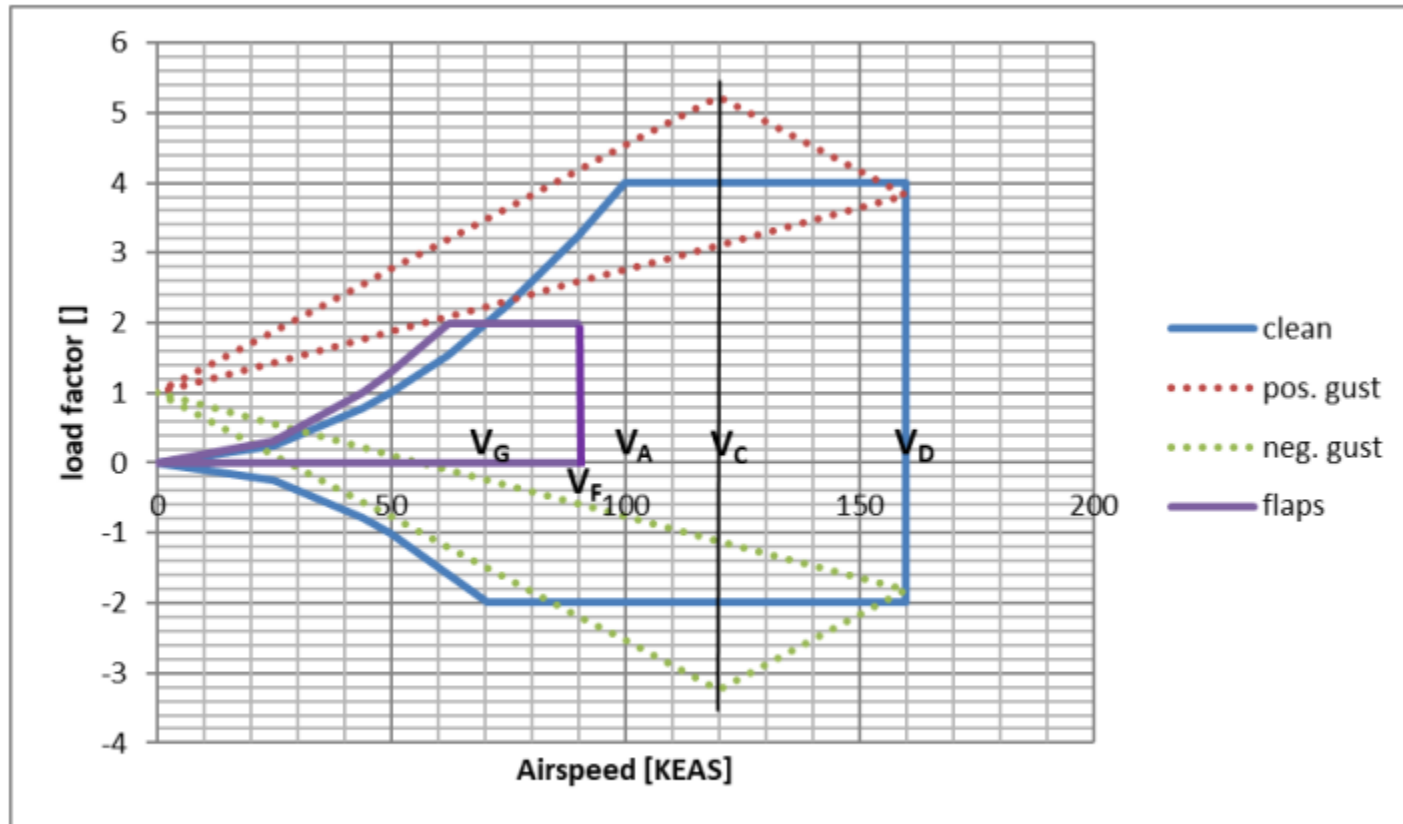


Figure 1 – Reference flight envelope (W_{MTOw} , FL 100)

Taken from EASA document “ABCD-FL-57-00 - Wing Load Calculation - v1 08.03.16.docx” in the Articles Folder, copied from here:
<https://www.easa.europa.eu/download/general-aviation/documents-guidance-andexamples/ABCD-FE-01-00%20Flight%20Envelope%20-%20v1%2008.03.16.docx>

A Light Sport Airplane (LSA) is a simple two-seater with a maximum take-off weight of 600kg. See
<https://www.easa.europa.eu/faq/19386>

Symmetric Manoeuvre Loads

Section 25.337 FAR

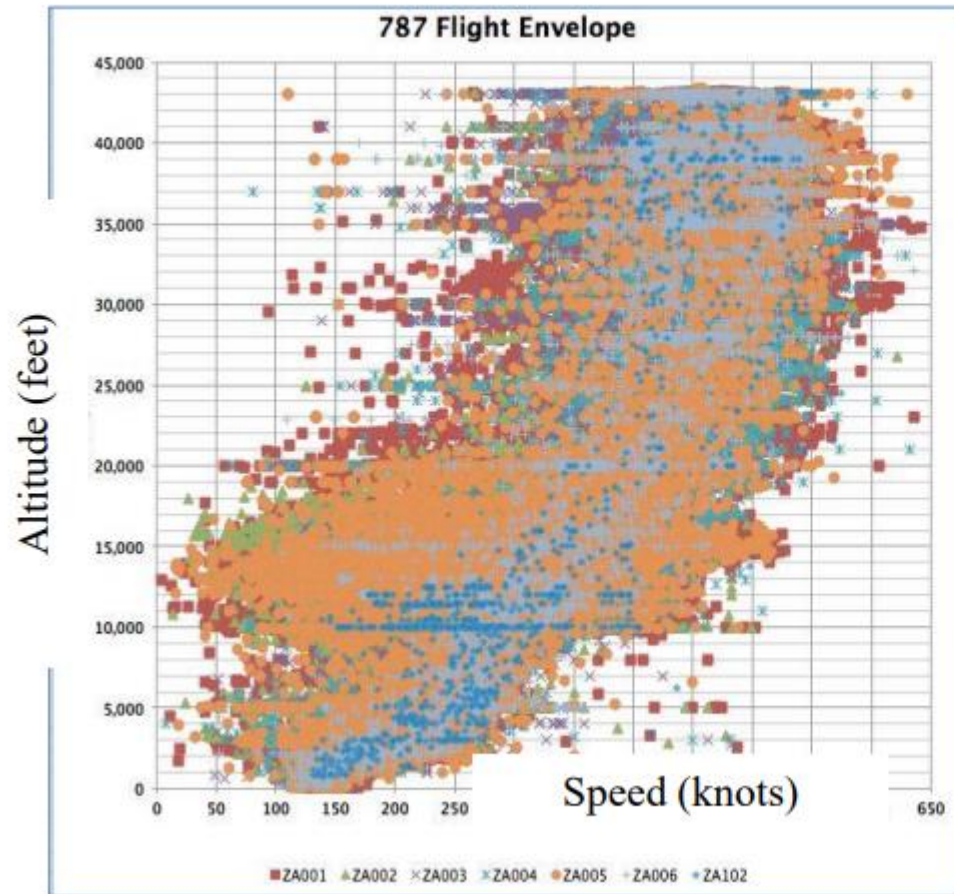
§25.337 Limit maneuvering load factors.

- (a) Except where limited by maximum (static) lift coefficients, the airplane is assumed to be subjected to symmetrical maneuvers resulting in the limit maneuvering load factors prescribed in this section. Pitching velocities appropriate to the corresponding pull-up and steady turn maneuvers must be taken into account.
- (b) The positive limit maneuvering load factor n for any speed up to V_n may not be less than $2.1 + 24,000 / (W + 10,000)$ except that n may not be less than 2.5 and need not be greater than 3.8—where W is the design maximum takeoff weight.
- (c) The negative limit maneuvering load factor—
 - (1) May not be less than -1.0 at speeds up to V_C ; and
 - (2) Must vary linearly with speed from the value at V_C to zero at V_D .
- (d) Maneuvering load factors lower than those specified in this section may be used if the airplane has design features that make it impossible to exceed these values in flight.

787 Dreamliner Flight Envelope

Real performance data

<https://aviation.stackexchange.com/questions/7956/what-is-the-maximum-pitch-for-the-boeing-787-dreamliner>

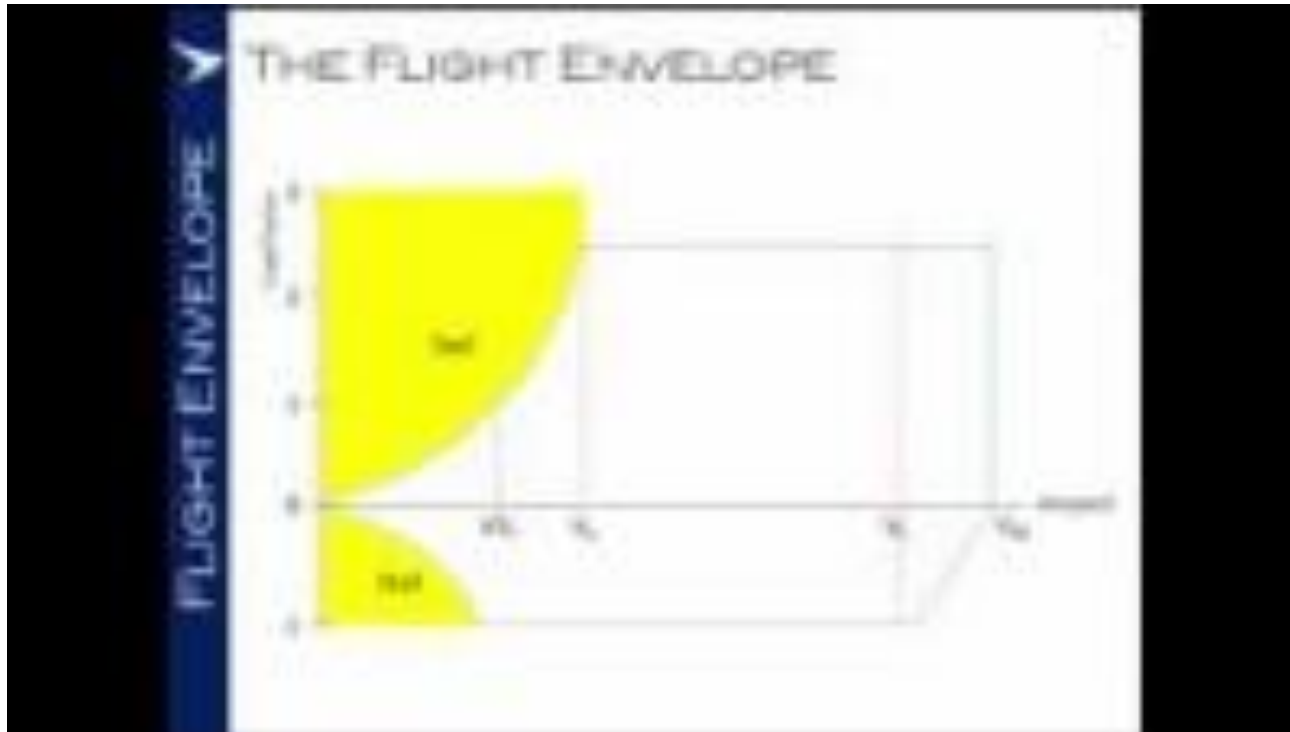


Note the flight envelope is **altitude dependent**. The full range of possible altitudes should be investigated in determining the worst case loads.

The Flight Envelope

V-n Diagram: Summary

- The maximum limits in which to operate the aircraft safely and predictably
- Normally larger than the actual flight envelope
- Flight envelopes are multi-layered to account for different altitudes and different lifting configurations
- Different aircraft types have different limits set on the Load Factor, $n = L / W$
- For commercial airliners, normal certification has $n = 2.5$
- Outside of the envelope, stall occurs at relatively low speeds and structural damage is likely above the maximum Load Factor



https://www.youtube.com/watch?v=YqTQCixybSo&feature=emb_logo&ab_channel=WingPro