9 Empennage General Design

Empennage design is subdivided into Section 9 (Empennage General Design) and Section 11 (Empennage Sizing). In this first section basic information on empennage design is provided. The size of the empennage is estimated with the aid of the so-called tail volume. This initial estimate of empennage size is important for calculating the aircraft mass and center of gravity. Afterwards detailed calculation methods for determining empennage size will be dealt with in Section 11.

The basic configuration of the empennage has already been established in Section 4 with the configuration of the aircraft. In this section the various types of empennage will be looked at more closely, in order to define the exact configuration.

Empennages are "small wings". Therefore, many of the aspects described in Section 7 (Wing Design) also apply to empennages. The main difference is that empennages – unlike wings – normally only use a small part of the potential lift. If an empennage should come close to its maximum lift coefficient in flight, the empennage design is likely to be faulty.

9.1 Functions of Empennages

Empennages create a force that acts upon a lever arm. Consequently a moment is created through empennages:

- the horizontal tailplane creates a moment around the lateral axis (pitch),
- the vertical tailplane (fin) principally creates a moment around the vertical axis (yaw).

Ailerons and spoilers on the wing (see Section 7) principally create a moment around the longitudinal axis (roll).

Control surfaces on empennages and on the wing are the customary way to create moments. However, there are other possibilities for creating moments:

- moving the center of gravity (tail aft aircraft),
- engine thust (control jets on the VTOL aircraft).

Empennages ensure trim, stability and control. These three aspects are detailed in the next paragraphs.

Trim

The moment created by an empennage balances out moments occurring on the aircraft for another reason. The horizontal tailplane, for example, balances out the wing moment (Fig. 9.1). In the case of propeller aircraft, the rotating slipstream causes a moment at the rear of the fuselage and at the vertical tailplane. The vertical tailplane has to compensate for this moment. If an engine fails on a multi-engine aircraft, the vertical tailplane compensates for an asymmetrical moment distribution around the vertical axis.

CS 25.161 defines the term "trim":

(a)	Each aeroplane must meet the **trim requirements** of this paragraph **after being trimmed**, and **without further pressure upon**, or movement of, either the **primary controls** or their corresponding trim controls by the pilot or the automatic pilot.

In simple terms: an aircraft is trimmed when the primary flight controls (pitch, roll, yaw) are free of forces in controlled flight.

The trim has to be guaranteed for all prescribed center-of-gravity positions, airspeeds, flap and landing gear positions and in the event of engine failure (for details see: CS 25.161).

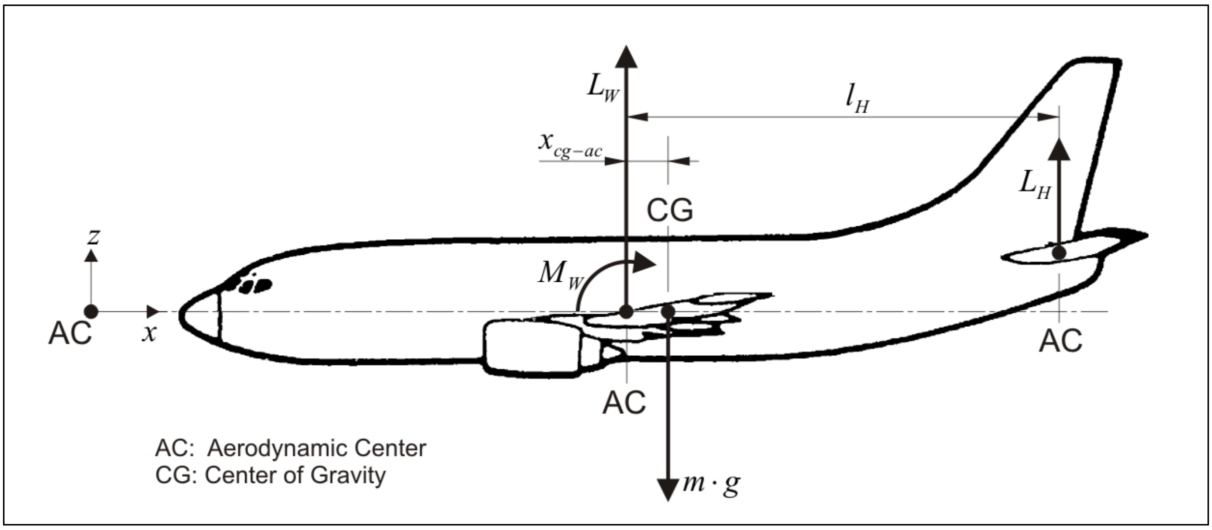

Fig. 9.1 Forces and moments acting on an aircraft during trimmed horizontal flight.

Stability

Stability refers to the capacity of the aircraft to return to the original flying position after a disturbance from outside or after a brief control input. Details are contained in the certification regulations in CS 25.171 to CS 25.181. A distinction is made between static stability and dynamic stability.

- *Static stability*. Longitudinal static stability ensures that the airspeed remains stable. The following is required according to CS 25.173:

(a)	A pull must be required to obtain and maintain speeds below the specified trim speed, and a push must be required to obtain and maintain speeds above the specified trim speed.
(c)	The average gradient of the stable slope of the stick force versus speed curve may not be less than 1 pound for each 6 knots.

The lateral static stability returns the aircraft to a slip-free flight. CS 25.177 requires the following:

(b)	The static lateral stability (as shown by the tendency to raise the low wing in a sideslip with the aileron controls free) for any landing gear and wing-flap position and symmetric power condition, may not be negative at any airspeed

- *Dynamic stability* is contingent upon static stability. But an aircraft is not necessarily dynamically stable when it is statically stable, because if the aircraft returns to its original position after a disturbance, it can, of course, easily overshoot the original position. If this oscillation ceases after a while (or an overshoot does not occur), this oscillation of the aircraft is dynamically stable. But if the amplitude of oscillation becomes greater and greater, this oscillation of the aircraft is dynamically instable. Conventional aircraft exhibit the following "oscillation forms" or, to be more precise, modes (it does not always have to be an oscillation; it might also be a heavily damped movement):

  - in a *longitudinal movement* (i.e. around the lateral axis): short period mode, phugoid.
  - in a *lateral movement* (i.e. around the longitudinal and vertical axis): spiral mode, Dutch roll mode.

  The modes can best be explained with a small model aircraft in the hand or in flight. Therefore, a further description is dispensed with at this point.

  CS 25.181 requires that certification flights must demonstrate the following features:

(a)	Any short period oscillation ... must be heavily damped with the primary controls -
(1)	Free; and
(2)	In a fixed position.
(b)	Any combined lateral-directional oscillations ('Dutch roll') ... must be positively damped with controls free, and must be controllable with normal use of the primary controls without requiring exceptional pilot skill.

Control

An aircraft must be sufficiently controllable in all critical flight states (CS 25.143 to CS 25.149). The control forces should not become too extreme (see CS 25.143(c)). In addition, the increase in control forces is dealt with using the limit load factor (CS 25.143):

(f)	... the stick forces and the gradient of the curve of stick force versus manoeuvring load factor must lie within satisfactory limits. The stick forces must not be so great as to make excessive demands on the pilot's strength ... and must not be so low that the aeroplane can easily be overstressed inadvertently.

Critical flight states for the empennage dimensioning from the point of view of control are:

- *Horizontal tailplane*: critical combination of center-of-gravity position, flap position and airspeed; rotation during take-off; flare when landing: control with trimmed horizontal stabilizer (CS 25.255).
- *Vertical tailplane (fin):* Engine failure in cruise and during take-off and landing. Engine failure during take-off run, landing with crosswind (sideslip to compensate for crosswind component), spinning (CS **23**.221).

An aircraft must possess sufficient **maneuverability** in accordance with its flight mission. It is scarcely possible to derive maneuverability criteria from the civil certification regulations. Instead the findings contained in military regulations – also for transport aircraft – are used in the design (see **MIL-F-8785C** and **MIL-STD-1797**). In the development phase a simulator model is created and the future aircraft is "flown" and assessed by test pilots. The lever arm and aileron must be large enough for sufficient maneuverability. In addition, it must be possible to deflect the control surfaces quickly enough.

9.2 Shapes of the Empennage

Different empennage shapes are shown on selected aircraft in Fig. 9.2.

The **conventional tail** provides appropriate stability and control and also leads to the most lightweight construction in most cases. Approximately 70 % of aircraft are fitted with a conventional tail. Spin characteristics can be bad in the case of a conventional tail due to the blanketing of the vertical tailplane (Fig. 9.3). The downwash of the wing is relatively large in the area of the horizontal tailplane. Rear engines cannot be teamed with conventional tails. Stabilizer trim is possible with comparatively low complexity. A larger vertical tailplane height is more appropriate for a conventional tail than a T-tail.

The **T-tail** is heavier than the conventional tail because the vertical tailplane has to support the horizontal tailplane. However, the T-tail has advantages that partly compensate for the described main disadvantage (weight). Owing to the end plate effect, the vertical tailplane can be smaller. The horizontal tailplane is more effective because it is positioned out of the airflow behind the wing and is subjected to less downwash. It can therefore be smaller. For the same reason the horizontal tailplane is also subject to less tail buffeting. The T-tail creates space for engines that are to be placed at the rear. The T-tail looks good, according to general opinion.

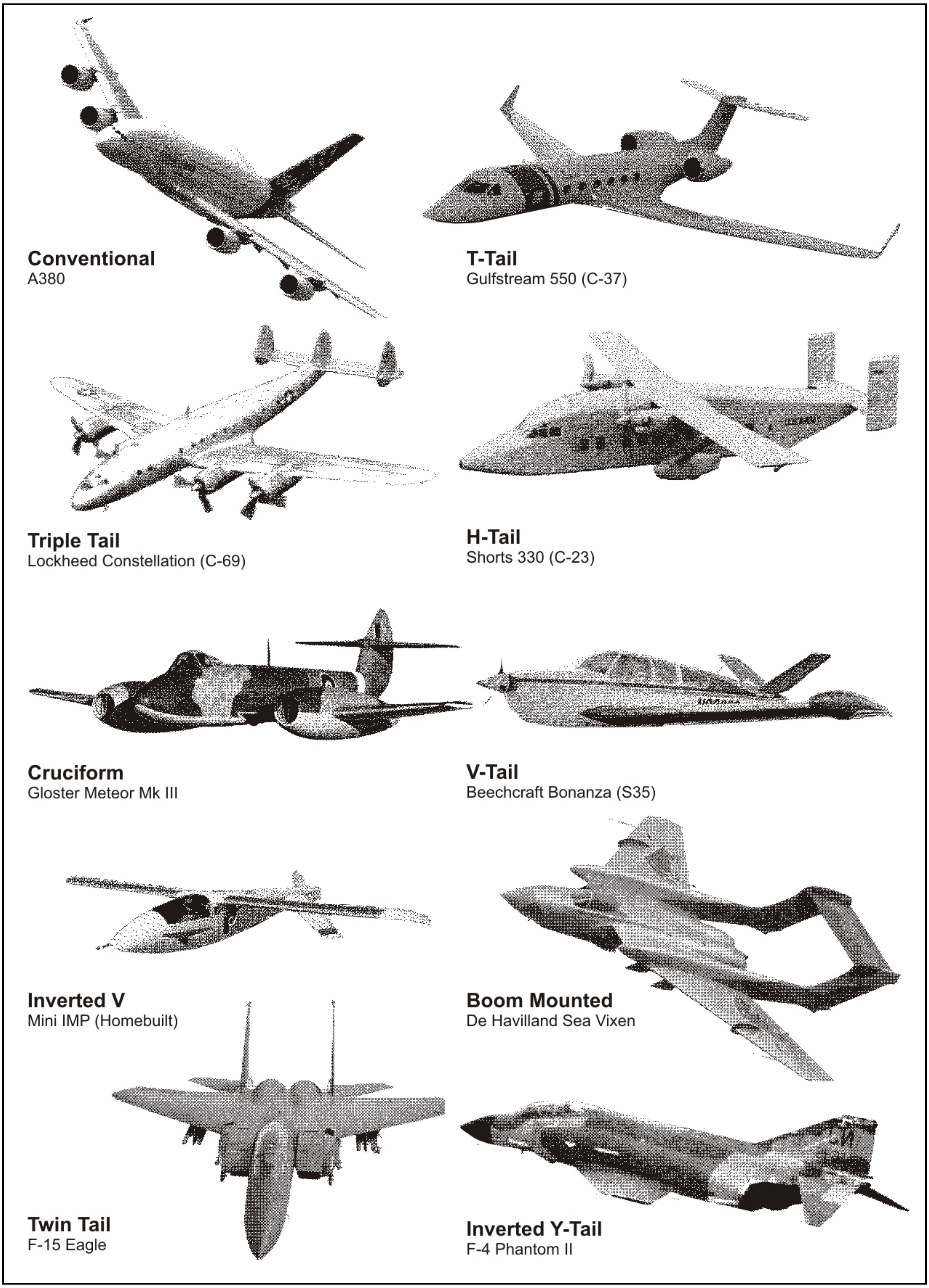

Fig. 9.2 Empennages of conventional aircraft configurations

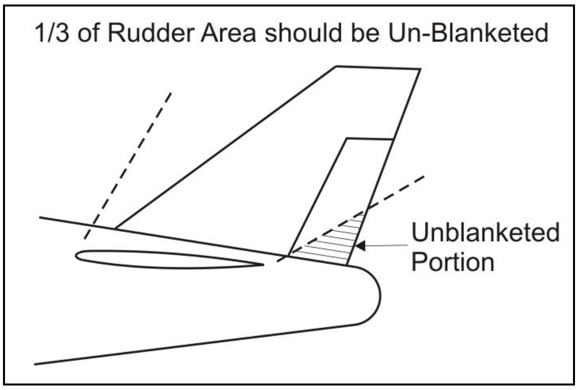

Fig. 9.3 Influence of the empennage design on the spin recovery characteristics

With T-tails the problem of *deep stall* must be taken into account (Fig. 9.4). In the case of high angles of attack the horizontal tailplane can be caught up in the airflow behind the wing and be blanketed. If, in addition, the wing tends to make the aircraft pitch up at high angles of attack (see Section 7), a situation may arise in which the aircraft can no longer be recovered from the stall. Fig. 9.5 shows admissible positions of the horizontal tailplane.

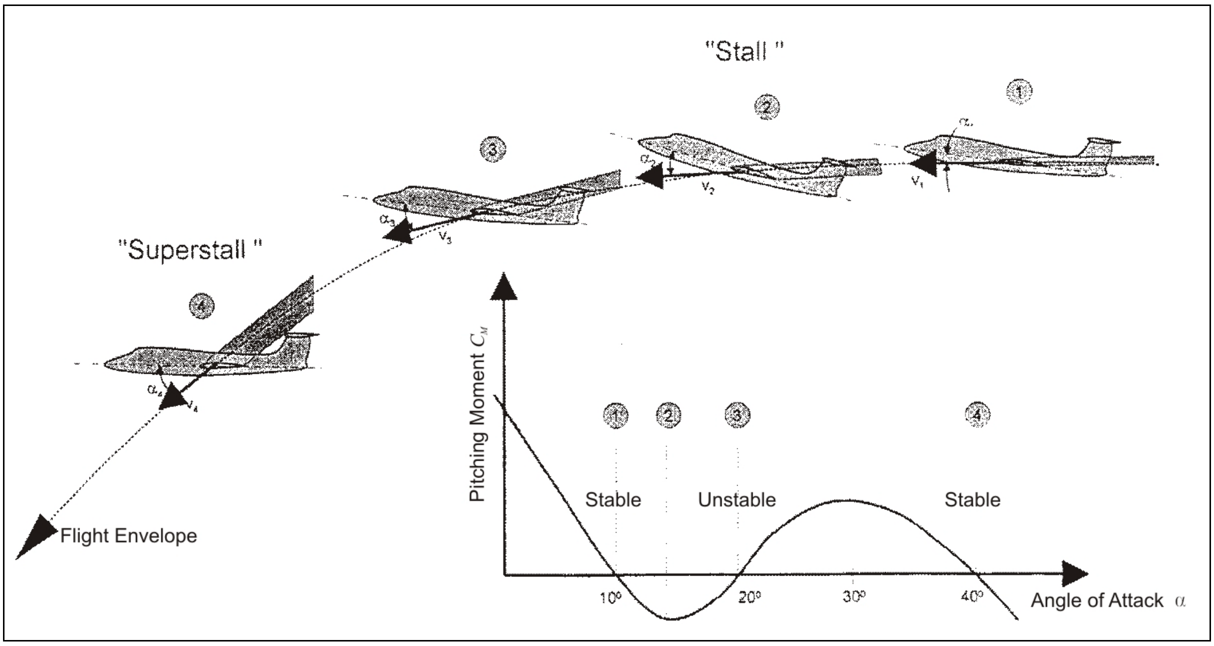

Fig. 9.4 Flight envelope, angle of attack and pitching moment during deep stall and super stall (**Schmitt 1998**)

The **cruciform tail** is a compromise between a conventional tail and a T-tail. The cruciform tail weighs less than the T-tail and allows the engines to be placed at the rear (e.g. Caravelle). However, the cruciform tail does not have a surface area advantage due to the end plate effect like the T-tail.

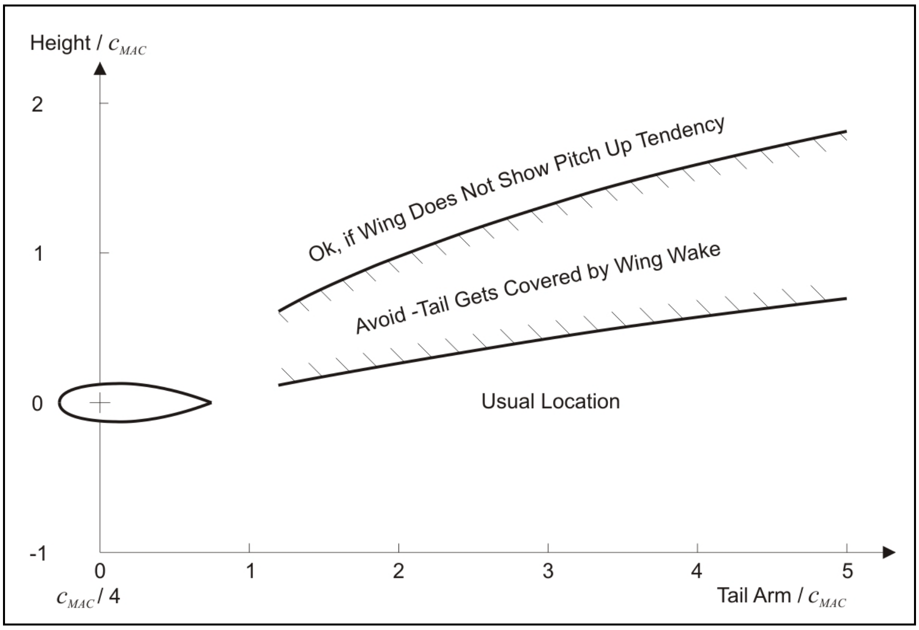

Fig. 9.5 Positioning of horizontal tailplanes

The aim of the **V-tail** is to achieve a smaller tail area than with horizontal and vertical tail-planes, for example in the form of the conventional tail. The V-tail is designed as follows: In the first step the required areas of a conventional horizontal tailplane S_H and vertical tailplane S_V are determined (see below). Theoretically the V-tail provides efficiency as a horizontal and vertical tailplane, corresponding to the projection of the V-tail in the horizontal and vertical. This theoretical approach gives the necessary V angle for the V-tail

$$\nu = \arctan \frac{S_V}{S_H} \qquad \textbf{(9.1)}$$

and the necessary area

$$S_{V-Tail,theory} = \sqrt{{S_H}^2 + {S_V}^2} \quad . \qquad \textbf{(9.2)}$$

On the basis of this theoretical analysis the V-tail only requires a tail area of $S_{V-tail} / \left(S_V + S_H\right) = 70.7\%$ compared to the conventional tail with $S_V / S_H = 1$. With other S_V / S_H ratios the area saving is less. According to the **NACA 823** report, the V-tail must, however, be larger in practice than the theory suggests for the same efficiency, so that the advantage of the smaller area is lost and a tail area

$$S_{V-Tail} = S_H + S_V \quad . \qquad \textbf{(9.3)}$$

is necessary.

With a V-tail the control surfaces deflect in the same direction in the function of the elevator and in opposite directions in the function of the rudder. If the right rudder pedal is pressed, the right control surface of the V-tail moves down and the left control surface up. One of the disadvantages of the V-tail is the complicated mechanics required to combine the elevator and rudder inputs. Inconveniently a "rudder deflection" of the V-tail causes a roll moment against the desired turn. A roll moment in the direction of the desired turn is, on the other hand, achieved with the inverted V-tail. However, many aircraft configurations will not be able to accommodate an inverted V-tail due to the necessary ground clearance.

A **twin tail** can be used if a single vertical tailplane would be too big. Twin tails are covered less by the front fuselage in the case of high angles of attack than a vertical tail in the plane of symmetry. For the latter reason twin tails are seen on fighter aircraft that operate in the high angel of attack range. Fig. 9.2 shows additional tail configurations that might be advantageous under certain circumstances.

Other tail features:

- Through the **dorsal fin** (Fig. 9.6) the efficiency of the vertical tailplane where high angles of yaw exist is improved through vortex formation. The stall is thereby moved to higher angles of yaw.
- The **ventral fin** (Fig. 9.6) is <u>not</u> blanketed even with high angles of attack. The ventral fin also serves to prevent lateral instabilities in high-speed flight.

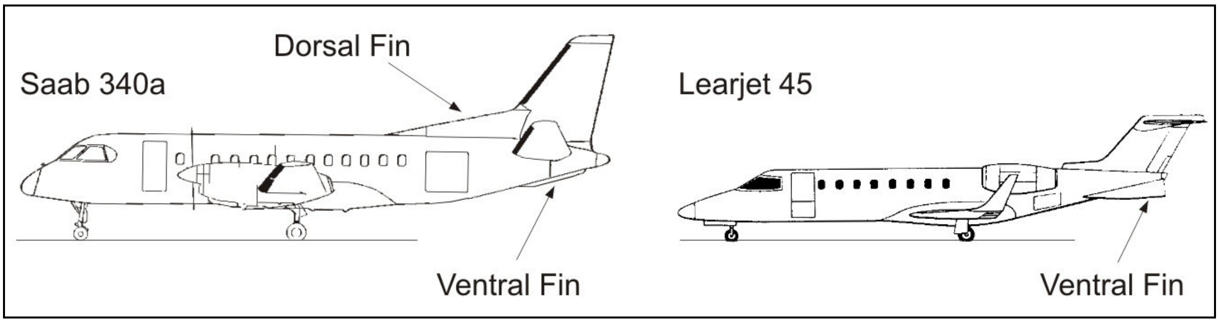

Fig. 9.6 Examples of aircrafts with dorsal fin and ventral fin

The **canard tails** (Fig. 9.7) are subdivided into *control canard* and *lifting canard*.

- In the case of a *control canard* the wing bears the aircraft's weight. Wings and fuselage alone show neutral stability; the canard is only used for control, but makes the system comprising fuselage, wing and tail instable. An electronic flight control system, EFCS, carries out the regulation and stabilization of the instable aircraft. An aircraft with canard must be designed in such a way that the wing can never be stalled. Instead the canard is first stalled. This necessitates that the wing's lift potential cannot be fully utilized.

- The *lifting canard* has less drag theoretically because the canard – in contrast to the horizontal tailplane of the tail aft configuration – creates lift (instead of negative lift) (compare with Fig. 9.1). By using the *lifting canard* the wing must be placed further to the rear. Through this placement the lifting canard is able to facilitate a center-of-gravity range that is normally required. However, the lifting canard displays various disadvantages that restrict its overall utility considerably: the placement of the wing further back on the fuselage increases the nose-heavy moment when using the landing flaps due to the larger lever arm. The wing of the canard must therefore have a greater area with less effective flaps than is customary with the tail aft configuration. Another way of solving this problem is to fit the canard with effective flaps or provide a variable sweep of the canard.

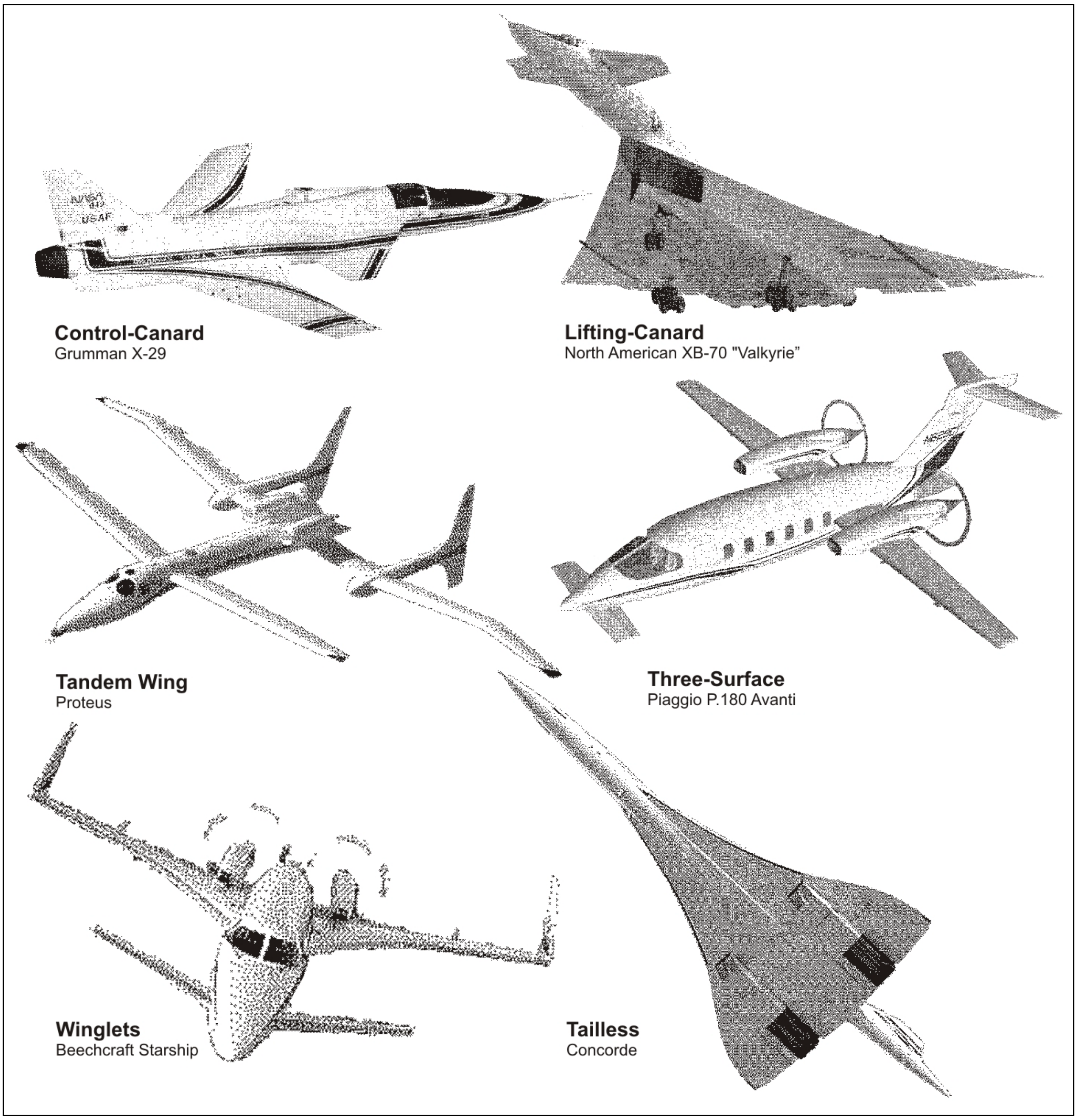

Fig. 9.7 Empennages of unconventional aircraft configurations

The **tandem wing** is a *lifting canard* where the lift forces are approximately evenly distributed between the wing and the canard.

The **three-surface configuration** makes it possible to create a pitching moment without influencing the lift on the wing. Therefore it is possible to better optimize the distribution of lift on the wing and thereby reduce the drag. One of the disadvantages is the additional complexity due to an additional area.

All configurations with canards have the disadvantage that the wing lies in a flow disturbed by the empennage placed at the front.

9.3 Design Rules

- The horizontal tailplane should be installed in a **position** so that it does not lie in the slipstream. If this rule is not observed, it may have the following effects:
  - structure fatigue due to tail buffeting;
  - increased noise in the cabin due to tail buffeting;
  - considerable trim changes with differing choice of engine performance.

  In some small single-engine aircraft the empennage is deliberately placed in the slipstream. Then one benefits from an increased efficiency of the tail assembly during take-off and landing, but may have to accept the disadvantages described above.

- The detailed **placement of the horizontal tailplane** can be determined from Fig. 9.5: low-lying horizontal tailplanes are most suitable for getting an aircraft out of a stall. With subsonic aircraft the empennage can also be installed at the same height as the wing. A T-tail may only be used if the wing is uncritical and is not susceptible to excessive pitch-up (compare Section 9.2: "T-tail").

- The **lever arm** of the empennage should be as large as possible, thereby making it possible to keep the tail areas small, which reduces weight and drag.

- The **aspect ratio** of the horizontal tailplane should be about half the aspect ratio of the wing. T-tails have a smaller aspect ratio of the vertical tailplane than conventional tails (Table 9.1). This allows weight disadvantages to be kept to a minimum.

- Tails with a taper ratio of $\lambda = 1$ are built in some cases as **rectangular tail** especially for general aviation aircraft. Rectangular tails reduce production costs.

- The **critical Mach number** of the empennage $M_{crit,H}$ und $M_{crit,V}$ should be $\Delta M = 0.05$ higher than the critical Mach number of the wing $M_{crit,W}$. Through this measure the efficiency of the tail assembly should also be guaranteed at high speed. Relative thickness, drag divergence Mach number, sweep, and the lift coefficient of the empennage must be chosen so as to ensure that a $\Delta M = 0.05$ can be achieved. With an equation from Section 7 in the form

$$t/c = f(M_{DD}, \varphi_{25}, C_L, airfoil)$$

these parameters can be chosen to approximately suit each other if the drag divergence Mach number M_{DD} of the tail is $\Delta M = 0.05$ higher than for the wing.

- The **sweep of the horizontal tailplane** should be approximately 5° larger than the sweep of the wing. Thus a higher critical Mach number of the horizontal tailplane can be achieved and a loss of efficiency due to shock waves is avoided. In addition, the lift gradient of the horizontal tailplane can be less than the lift gradient of the wing due to the increased sweep, so that the horizontal tailplane only reaches the stall state at larger angles of attack than the wing.

- The **sweep angle of the vertical tailplane** is 35° to 55° for aircraft with "high airspeeds" (flight with compressibility effects). The sweep angle of the vertical tailplane for aircraft with "low airspeeds" (flight without compressibility effects) should be less than 20°. A large sweep angle increases the lever arm and the angle where the vertical tailplane goes into stall, but reduces the maximum lift coefficient.

- The **horizontal tailplane** should have a **relative thickness** that is approximately 10 % less than the relative thickness in the outer wing. Thus, a higher critical Mach number of the horizontal tailplane can be achieved and a loss of efficiency due to shock waves is prevented.

- Symmetrical **airfoils** are chosen exclusively for vertical tailplanes. Symmetrical or virtually symmetrical airfoils with 9% to 12% relative thickness are chosen for horizontal tailplanes. For example, NACA 0009 or NACA 0012 (**Abbott 1959**) can be chosen. Asymmetrical horizontal tailplane airfoils are installed "upside-down" because the horizontal tailplane has to create negative lift.

- If the **left and right elevators** are to be **connected**, the sweep and the taper ratio must be selected so as to ensure that a hinge line is produced perpendicular to the aircraft's plane of symmetry. Reasons for connecting the elevators may be:
  - to reduce the elevators' tendency to flutter;
  - to facilitate joint actuation of the elevators.

- The **dihedral angle** can be chosen so that the empennage is positioned outside the engine slipstream. Dihedral of the horizontal tail is not used to modify roll stability as this is much more influenced by the wing.

- If the horizontal tailplane is fixed, an **incidence angle** of around 2° to 3° downwards should be chosen to create negative lift. A more flexible alternative is a movable, i.e. **trimmable horizontal stabilizer**, THS, which facilitates a larger center-of-gravity range.

- The horizontal tailplane can be designed as an **all moving tail**. An all moving tail only consists of one surface with an adjustable incidence angle. The all moving tail is more effective – especially at high Mach numbers – but also heavier than a fixed empennage with control surface. In the case of large aircraft high output may be required to move the all moving tail in flight with the necessary actuating speed. A compromise is the **trimmable horizontal stabilizer** mentioned above: the horizontal stabilizer is used to trim and is only adjusted gradually (with a low actuating power); the elevator is deflected correspondingly quicker for maneuvering. The trimmable horizontal stabilizer is the standard solution for transport aircraft.

- **Lifting canard** or **tandem wing** are designed like wings (see Section 7).

Tables 9.1, 9.2 and 9.3 contain parameters that can be referred to as guides for empennage design.

Table 9.1 Conventional aspect ratios A and taper ratios λ from empennages on transport category airplanes (**Raymer 1989**)

Type	Horizontal Tailplane		Vertical Tailplane	
	A	λ	A	λ
Conventional Tail	3.00 ... 5.00	0.3 ... 0.6	1.3 ... 2.0	0.3 ... 0.6
T-Tail	as Conventional Tail	as Conventional Tail	0.7 ... 1.2	0.6 ... 1.0

Table 9.2: Conventional design parameters for horizontal tails (**Roskam II**)

Type	Dihedral Angle v [°]	Incidence Angle i_h [°]	Aspect Ratio A_h [-]	Sweep Angle φ [°]	Taper Ratio λ_h [-]
Business Jets	- 4 ... 9	-3.5 fixed	3.2 ... 6.3	0 ... 35	0.32 ... 0.57
Transport Jets	0 ... 11	variable	3.4 ... 6.1	18 ... 37	0.27 ... 0.62
Fighters	-23 ... 5	0 fixed or variable	2.3 ... 5.8	0 ... 55	0.16 ... 1.00
Supersonic Civil Transport	-15 ... 0	0 fixed or variable	1.8 ... 2.6	32 ... 60	0.14 ... 0.39

Table 9.3: Conventional design parameters for vertical tails (**Roskam II**)

Type	**Dihedral Angle** v [°]	**Incidence Angle** i_h [°]	**Aspect Ratio** A_h [-]	**Sweep Angle** φ [°]	**Taper Tratio** λ_h [-]
Business Jets	90	0	0.8 … 1.6	28 … 55	0.30 … 0.74
Transport Jets	90	0	0.7 … 2.0	33 … 53	0.26 … 0.73
Fighters	75 … 90	0	0.4 … 2.0	9 … 60	0.19 … 0.57
Supersonic Cruise Airplanes	75 … 90	0	0.5 … 1.8	37 … 65	0.20 … 0.43

9.4 Design According to Tail Volume

The area of the horizontal tailplane S_H or the vertical tailplane S_V multiplied by the lever arm l_H or l_V is called tail volume. The tail volume coefficient is defined for the horizontal tailplane as

$$C_H = \frac{S_H \cdot l_H}{S_W \cdot c_{MAC}} \qquad (9.4)$$

and for the vertical tailplane as

$$C_V = \frac{S_V \cdot l_V}{S_W \cdot b} \qquad (9.5)$$

l_H the lever arm of the horizontal tailplane is the distance between the aerodynamic centers of wing and horizontal tailplane,

l_V the lever arm of the vertical tailplane is the distance between the aerodynamic centers of wing and vertical tailplane.

As a good approximation the 25 % - point on the mean aerodynamic chord can also be referred to instead of the distances between the aerodynamic centers.

Table 9.4 Conventional tail volume coefficients of horizontal and vertical tails (**Raymer 1989**)

type	**horizontal C_H**	**vertical C_V**
General Aviation - Twin Engine	0.80	0.07
Transport Jets	1.00	0.08
Jet - Trainer	0.70	0.06
Jet - Fighter	0.40	0.07

The tail size can be estimated from the tail volume coefficient if the tail lever arms l_H and l_V are known. The lever arms are not, however, fixed until the position of the wing has been established. However, this only takes place in Step 11 "Mass and Center of Gravity". For this reason the tail lever arms can only be estimated from the length of the fuselage in this case (Table 9.5).

Table 9.5: Conventional tail lever arms of horizontal and vertical tails (**Raymer 1998**)

aircraft configuration	average of l_H and l_V
propeller in front of fuselage	60% of fuselage length
engines on the wing	50 ... 55% of fuselage length
engines on the tail	45 ... 50% of fuselage length
control canard	30 ... 50% of fuselage length
sailplane	65% of fuselage length

- The tail volume coefficients can be reduced by 10% to 15% in the case of **trimmable horizontal stabilizers**.

- In the case of a **T-tail,** the tail volume coefficients can be reduced by 5% for horizontal and vertical tailplane due to the end plate effect and the improved flow.

- In the case of a control **canard** a tail volume coefficient of 0.1 can be set. In the case of a *lifting canard* the tail volume coefficient method cannot be applied. Instead a ratio of the areas of canard and wing is established.

- If the criteria for stability and control determine the dimensioning of an aircraft's tail design, the tail volume coefficients can be reduced by approximately 10% if the aircraft has an electronic flight control system, **EFCS**. However, for transport aircraft other criteria (such as engine failure for the rudder) often determine the dimensioning, so that tail area cannot necessarily be saved through an EFCS.

9.5 Elevator and Rudder

Elevator and rudder start on the fuselage and extend to approximately 90% of the (semi-) span of the tail, or up to the tip of the tail (Fig. 9.8). They have a chord which accounts for approximately **25 % to 40 % of the chord of the tail**. Elevators are deflected downwards by a maximum of 15° to 25° and upwards by a maximum of 25° to 35°. Rudders are **deflected** by a **maximum** of **25° to 35°**. **Torenbeek 1988** and **Roskam II** contain detailed tables with tail and control surface data.

The maximum lift (negative lift or transverse force) that an elevator or rudder on a tail can achieve can be calculated using the method from Section 8 because an elevator or rudder is a plain flap.

Particularly in the case of aircraft with a reversible flight control system (Fig. 9.7) it is important to know the hinge moment required to deflect the rudder in the various flight states. The reason is that the hinge moment determines the hand and foot forces on the flight controls, which may not exceed specific maximum values according to CS 25.143(c). The hinge moment is calculated with

$$M_c = \frac{1}{2}\rho V^2 \cdot C_h \cdot S_F \cdot c_F \quad . \qquad \textbf{(9.6)}$$

V is the airspeed, S_F is the control surface area, c_F is the rudder depth (measured from the hinge line to the trailing edge). The hinge moment coefficient C_h of a control surface is calculated from the hinge moment derivatives C_{h_α} and C_{h_δ} (see **DATCOM 1978** or **Roskam VI**). It is important to bear in mind that asymmetrical airfoils already have a hinge moment coefficient C_{h_0} at $\alpha = \delta = 0$.

$$C_h = C_{h_0} + C_{h_\alpha} \cdot \alpha + C_{h_\delta} \cdot \delta \quad . \qquad \textbf{(9.7)}$$

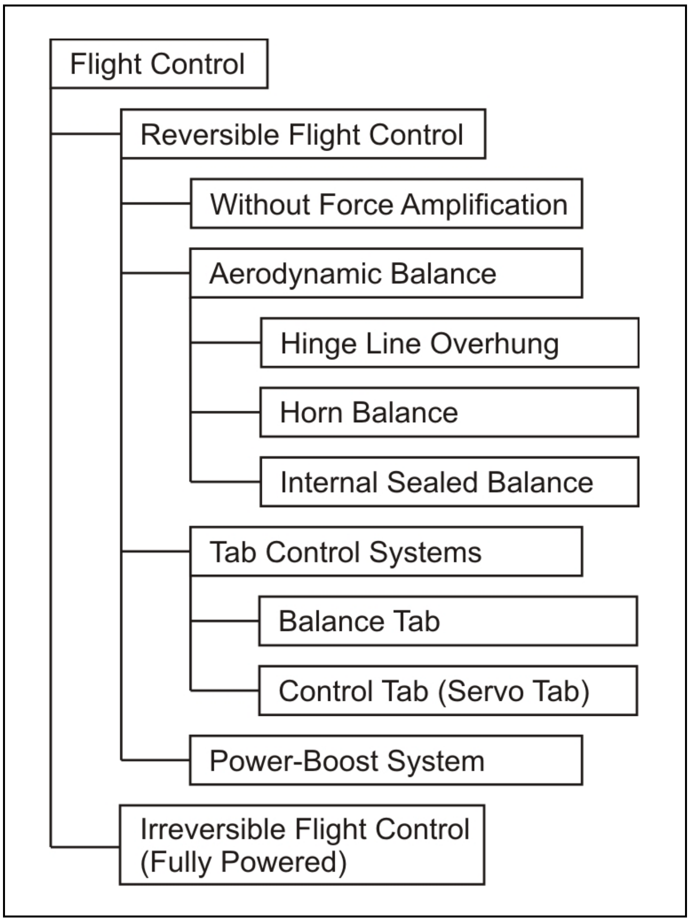

Fig. 9.8 Classification of flight controls and hinge moment reduction possibilities

According to equation (9.6) the aerodynamic hinge moment increases with the size and speed of an aircraft. As the control forces may become too large even in small aircraft, measures must be taken to reduce them. The hinge moment is fully or partially carried by the pilot's muscular force on reversible flight controls. On irreversible flight controls the hinge moment is countered by the aircraft's onboard energy systems. Fig. 9.8 shows the main options for reducing control forces. The options are arranged according to increasing effectiveness but also complexity. Fig. 9.9 shows two of these methods for hinge moment reduction. Horn and overhang balance are often applied on small aircraft owing to their simple design.

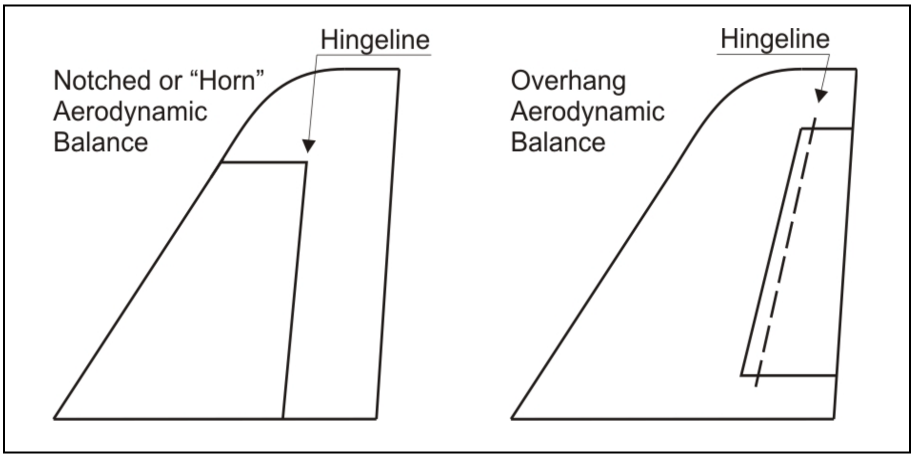

Fig. 9.9 Typical methods of hinge moment reduction