



# Aerodynamics of parachutes

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## AERODYNAMICS OF PARACHUTES

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## AERODYNAMICS OF PARACHUTES

### 1. NOTATION AND UNITS

|          |                                                                             | <i>SI</i>        | <i>British</i>    |
|----------|-----------------------------------------------------------------------------|------------------|-------------------|
| $b$      | span of high-glide parachute canopy, see Table 4.3                          | m                | ft                |
| $C_{Do}$ | drag coefficient based on $S_o$ and $q$                                     |                  |                   |
| $C_{Dp}$ | drag coefficient based on $S_p$ and $q$                                     |                  |                   |
| $C_k$    | opening shock factor, $C_x X_1$ , see Section 6.1                           |                  |                   |
| $C_L$    | lift coefficient based on $S_o$ and $q$                                     |                  |                   |
| $C_m$    | pitching moment coefficient based on $S_p$ , $d_p$ and $q$ , See Sketch 7.1 |                  |                   |
| $C_R$    | resultant force coefficient based on $S_o$ and $q$                          |                  |                   |
| $C_T$    | tangential force coefficient based on $S_o$ and $q$                         |                  |                   |
| $C_x$    | opening force coefficient, see Equation (6.2)                               |                  |                   |
| $c$      | chord of high-glide parachute canopy, see Table 4.3                         | m                | ft                |
| $c_e$    | effective porosity, see Equation (5.7) and Sketch 5.3                       |                  |                   |
| $D$      | aerodynamic drag force, see Sketch 5.1                                      | N                | lbf               |
| $d_B$    | equivalent forebody diameter, see Equation (5.15)                           | m                | ft                |
| $d_c$    | constructed canopy diameter, see Sketch 4.3                                 | m                | ft                |
| $d_o$    | nominal canopy diameter, $2\sqrt{S_o/\pi}$                                  | m                | ft                |
| $d_p$    | projected inflated canopy diameter, $2\sqrt{S_p/\pi}$                       | m                | ft                |
| $d_R$    | reefed canopy diameter, see Section 6.2                                     | m                | ft                |
| $d_V$    | canopy vent diameter, see Sketch 4.3                                        | m                | ft                |
| $F_c$    | steady state drag force, see Sketch 6.2                                     | N                | lbf               |
| $F_s$    | snatch force, see Sketch 6.2                                                | N                | lbf               |
| $F_x$    | peak opening force, see Sketch 6.2 and Equation (6.3)                       | N                | lbf               |
| $g$      | gravitational acceleration                                                  | m/s <sup>2</sup> | ft/s <sup>2</sup> |
| $h_e$    | length of canopy extension of flat parachute, see Sketch 4.4                | m                | ft                |
| $h_p$    | height of inflated canopy, see Sketch 4.3                                   | m                | ft                |

|             |                                                                                                              |          |            |
|-------------|--------------------------------------------------------------------------------------------------------------|----------|------------|
| $K_1$       | constant in Equation (5.9)                                                                                   |          |            |
| $K_2$       | constant in Equation (5.9)                                                                                   | $m^{-1}$ | $ft^{-1}$  |
| $k$         | discharge coefficient, see Section 5.2.3                                                                     |          |            |
| $L$         | aerodynamic lift force, see Sketch 5.1                                                                       | N        | lbf        |
| $l_e$       | suspension line length, see Sketch 4.3                                                                       | m        | ft         |
| $l_p$       | distance between moment reference point and point of action of aerodynamic normal force, see Sketch 5.1      | m        | ft         |
| $l_R$       | reefing line length, see Section 6.2                                                                         | m        | ft         |
| $l_T$       | trailing distance from payload base to canopy leading edge, see Sketch 5.9                                   | m        | ft         |
| $M$         | aerodynamic pitching moment, see Sketch 5.1                                                                  | N m      | lbf ft     |
| $M_\infty$  | freestream Mach number                                                                                       |          |            |
| $m$         | mass                                                                                                         | kg       | slug       |
| $m_a$       | added mass, see Equation (7.3)                                                                               | kg       | slug       |
| $m_b$       | body or payload mass                                                                                         | kg       | slug       |
| $m_p$       | parachute mass                                                                                               | kg       | slug       |
| $N$         | aerodynamic normal force, see Sketch 5.1                                                                     | N        | lbf        |
| $n$         | canopy filling constant, see Table 6.1                                                                       |          |            |
| $p$         | pressure                                                                                                     | $N/m^2$  | $lbf/ft^2$ |
| $\Delta p$  | pressure drop across canopy fabric, see Section 5.2.1                                                        | $N/m^2$  | $lbf/ft^2$ |
| $q$         | kinetic pressure, $\frac{1}{2}\rho V^2$ or $\frac{1}{2}\gamma p M_\infty^2$                                  | $N/m^2$  | $lbf/ft^2$ |
| $R$         | aerodynamic resultant force, see Sketch 5.1                                                                  | N        | lbf        |
| $Re$        | unit Reynolds number, $\rho U/\mu$                                                                           | $m^{-1}$ | $ft^{-1}$  |
| $R_m$       | mass ratio, see Equation (5.6)                                                                               |          |            |
| $S_B$       | forebody cross-sectional area, see Section 5.4                                                               | $m^2$    | $ft^2$     |
| $S_o$       | nominal area; total surface area of canopy including any vents or slots and surfaces such as ribs and panels | $m^2$    | $ft^2$     |
| $S_p$       | projected inflated canopy area                                                                               | $m^2$    | $ft^2$     |
| $S_w$       | 'wing' area of high-glide canopies, see Table 4.3                                                            | $m^2$    | $ft^2$     |
| $T$         | aerodynamic tangential force, see Sketch 5.1                                                                 | N        | lbf        |
| $T_{fluid}$ | kinetic energy of fluid, see Equation (7.3)                                                                  | J        | ft lbf     |

|                       |                                                                              |                   |                      |
|-----------------------|------------------------------------------------------------------------------|-------------------|----------------------|
| $t$                   | time                                                                         | s                 | s                    |
| $t_f$                 | canopy filling time, see Equation (6.1)                                      | s                 | s                    |
| $U$                   | notional approach velocity used in porosity calculations, see Equation (5.8) | m/s               | ft/s                 |
| $\bar{U}_{(x,y,z,t)}$ | fluid velocity vector, see Section 7.2                                       | m/s               | ft/s                 |
| $u_o$                 | fluid velocity through canopy material, see Equation (5.10)                  | m/s               | ft/s                 |
| $V$                   | velocity                                                                     | m/s               | ft/s                 |
| $V_e$                 | equilibrium descent velocity, see Section 5.1                                | m/s               | ft/s                 |
| $V_s$                 | velocity at line stretch                                                     | m/s               | ft/s                 |
| $\forall$             | representative displaced volume, see Section 7.2                             | m <sup>3</sup>    | ft <sup>3</sup>      |
| $X_1$                 | opening-shock reduction factor                                               |                   |                      |
| $x, y, z$             | generalised Cartesian co-ordinates, see Section 7.2                          | m                 | ft                   |
| $\alpha$              | angle of attack, see Sketch 5.1                                              | deg (rad)         | deg (rad)            |
| $\beta$               | trim angle, see Section 5.1 and Sketch 5.2b                                  | deg (rad)         | deg (rad)            |
| $X_1$                 | opening-force reduction factor, see Equation (6.3)                           |                   |                      |
| $\epsilon$            | reefing ratio, $(C_D S)_{Reef} / (C_D S)_{fo}$ , see Section 6.2             |                   |                      |
| $\gamma$              | ratio of specific heat capacities                                            |                   |                      |
| $\delta$              | cone angle for conical parachutes, see Sketch 4.5                            | deg               | deg                  |
| $\rho$                | density of air                                                               | kg/m <sup>2</sup> | slug/ft <sup>3</sup> |
| $\theta$              | trajectory angle, measured positive down from horizontal, see Section 7.2    | deg (rad)         | deg (rad)            |
| $\lambda_g$           | geometric porosity, see Section 5.2.2                                        |                   |                      |
| $\lambda_T$           | total porosity (fabric and geometric), see Section 5.2.3                     |                   |                      |
| $\mu$                 | dynamic viscosity of air                                                     | kg/ms             | slug/fts             |
| $\tau$                | reefing line ratio, $d_R/d_o$ , see Section 6.2                              |                   |                      |

## Subscripts

|              |                                                    |
|--------------|----------------------------------------------------|
| $( )_{Reef}$ | <i>relates to canopy in a reefed condition</i>     |
| $( )_{fo}$   | <i>relates to canopy in fully opened condition</i> |

## 2. INTRODUCTION

Parachutes are usually soft fabric devices whose shapes have been designed to produce, upon deployment, a retarding force for the purpose of slowing and/or stabilising a given payload during its movement through the air. The word *parachute* itself comes from the combination of the French words *parare*, to protect or shield, and *chute*, the fall; the combination of words in '*parachute*' actually means "fall protection". The main design criteria are that when stowed it should have minimal mass and occupy minimal space, and upon deployment it should reliably open within an acceptable time frame with acceptable transitional loads, and provide the desired rate of descent with an acceptable level of stability.

In the development of this Item it has been borne in mind that the end user would most likely be an aeronautical engineer or student with little or no previous knowledge of parachute aerodynamics or design. The aim is to provide such a reader with a basic grounding of the aerodynamic principles of parachutes and some familiarisation with the design solutions that have been executed to date. The Item does not aim to be a design guide; the design process is one which involves much multi-disciplinary knowledge, of which aerodynamics is just one component; structural considerations, weight, packaging, operational requirements and cost may all have a strong, if not decisive, bearing on the final outcome. Furthermore, it is clear that parachute systems tend to be rather individualistic in nature and evolve largely from extensive experimental programmes, both captive and free flight, together with large computer models and, in some instances, CFD simulation.

The design and development of most parachute systems is in fact undertaken by a small number of specialist organisations and practitioners, whose publications, both corporate and personal, are the sources of information contained herein. The aim of this Item is to provide a basic introduction into this highly specialised field, with emphasis on applications relating to the airframe industry, not only as an introductory overview but in two particular areas that have been identified as most likely to be of interest; the choice and sizing of aircraft braking and spin recovery parachutes. Although far from exhaustive, these subjects are covered in sufficient detail to offer some basic canopy size and selection guidance.

Section 3 provides a brief historical résumé of parachute design and usage to the present day. Section 4 outlines the main parachute designs and provides basic aerodynamic, geometric and performance data for each type; it also provides definitions of the main geometric and aerodynamic parameters. Section 5 covers the effects of the main flow and geometric parameters and Section 6 describes the inflation process and drag area control methods, cluster parachute systems and pilot parachutes. Section 7 provides an introduction to stability, the added mass approximation and trajectory analysis, and Section 8 covers the specific applications of parachutes to vehicle braking, spin and deep stall recovery, ordnance stabilisation, emergency escape systems, supersonic deceleration and load extraction.

## 3. HISTORICAL BACKGROUND

The first known design for a parachute is found in the notes of Leonardo da Vinci, dating from the beginning of the sixteenth century. His outline drawing shows a simple pyramidal frame over which is stretched a cloth fabric, apparently for the purpose of escaping from a burning building. The device was never made, but the illustration is convincing enough for him to be credited as the conceptual inventor. Almost a hundred years later a similar device, assumed to be based on the da Vinci design, was constructed by Fauste Veranzio, who demonstrated its capabilities by leaping off a four storey building in Venice in 1617, and surviving. Few other documented events occurred until the Montgolfier brothers, of ballooning fame, used rigid-framed devices to drop animals from balloons and buildings in 1783. A rigid frame design was also employed in the first known use of a parachute as an escape device, when in 1795 Jean Pierre Blanchard jumped from his hot air balloon, after it suddenly and unexpectedly exploded.

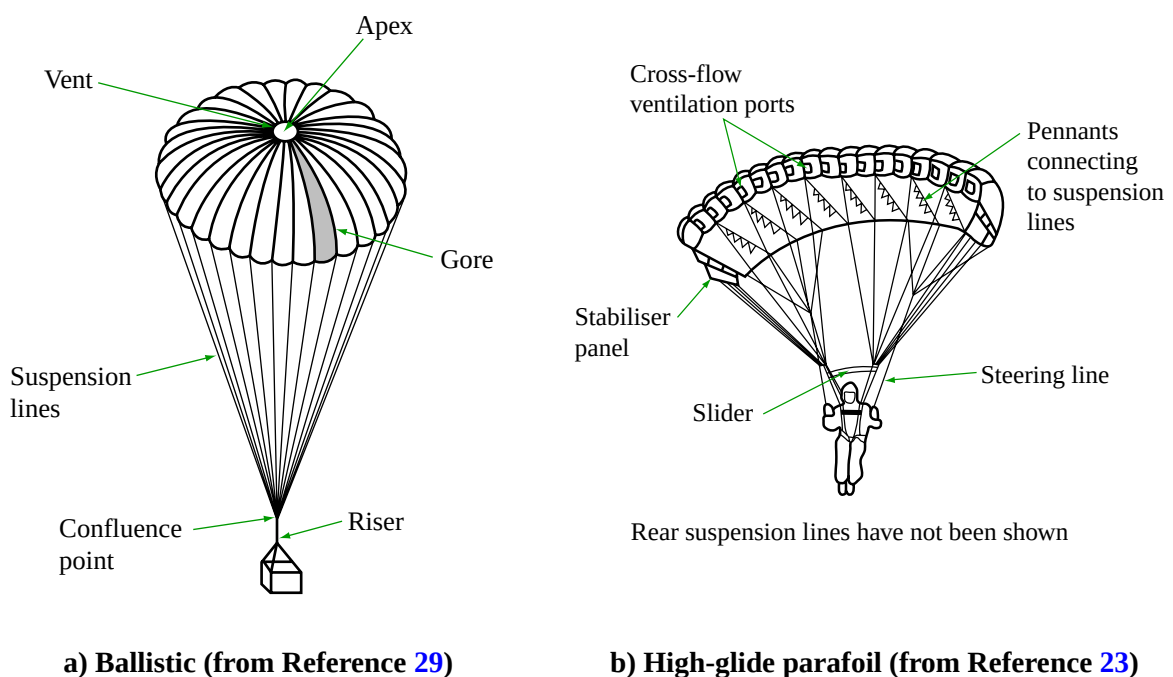
The first parachute without a rigid frame was demonstrated in 1797 by Andre-Jacque Garnerin. One of his high altitude balloon jumps (8000 ft) was witnessed by the French astronomer Lalandes, who noted the oscillations of the canopy and suggested the introduction of a central vent to alleviate the problem. This artifice proved to be very successful and became a standard feature of round parachute design. Little notable development occurred over the next century, until the harness was invented by Captain Thomas Baldwin in 1887, and then the concept of folding and stowing the parachute in a knapsack was developed by Paul Letteman and Kaethe Paulus (both exhibition jumpers) in 1890; Paulus went on to demonstrate the use of a smaller parachute to pull out a second, main parachute. Although parachutes were introduced for balloonists as a means of escape early in the First World War, such innovations only became standard military practice for aircraft in the latter part of the war, and deployment continued to be by static line (*i.e.* a line permanently connected to the aircraft). Between the wars the design of conventional round silk parachutes remained essentially unchanged, most of the development going into the area of carriage and deployment. Parachutes continued to be used primarily as escape devices by fledgling air forces, but some specialist air corps were formed in the US and Europe, which reached their zenith in the 1930s with the Luftwaffe when Kurt Student proposed and established a rapid deployment strike force of parachuting troops, supported by equipment and weapons supplied by a combination of both parachutes and gliders. Also during the 1930s in Germany the ribbon parachute was developed by Knacke and Madelung, a design which proved to be exemplary in terms of stability and strength, and for the first time allowed the air-drop of heavy loads at high speeds. Two important derivatives of the ribbon parachute were later developed: the ringslot parachute by Knacke, which was considerably simpler and cheaper than the ribbon design, and the more complex ringsail parachute by Ewing which, on account of its slow inflation rate, low transient loads and stability, was selected for use in the final descent of the Mercury, Gemini, and Apollo space capsules.

Considerable advances in parachute technology occurred in parallel with the development of ejector seats and space vehicles, especially for very high speed use. In particular, Heinrich invented the guide surface parachute for use as a pilot parachute or for vehicle stabilisation in the supersonic deployment regime at Mach numbers up to 3, and Sims invented the hyperflo parachute, which is a hypersonic pilot parachute for Mach numbers up to 5. The 1960s saw much development of parachutes for sporting use. Traditional solid cloth parachutes were modified by the introduction of turning and drive slots to provide greater stability, manoeuvrability and horizontal speed. During the early space projects there were developments of the parawing for space vehicle recovery, building on the single-skin flexible wing design of Rogallo. These suffered from low opening reliability at high speeds, but smaller, low-speed versions were adapted for sporting applications and spawned further derivatives, including the sailwing and the ram-air parafoil, which offer excellent manoeuvrability and high forward speed. A comprehensive history of parachuting for personnel usage is given in Reference 32.

In recent decades parachutes have also found applications in extra-terrestrial roles, and have now become almost a standard mechanism for surface delivery of unmanned spacecraft. This has involved the design and development of lightweight multiple parachute systems, suitable for deployment at high supersonic speeds, after a long period of stowage, in extreme and hostile environments.

## 4. BASIC TYPES OF PARACHUTE

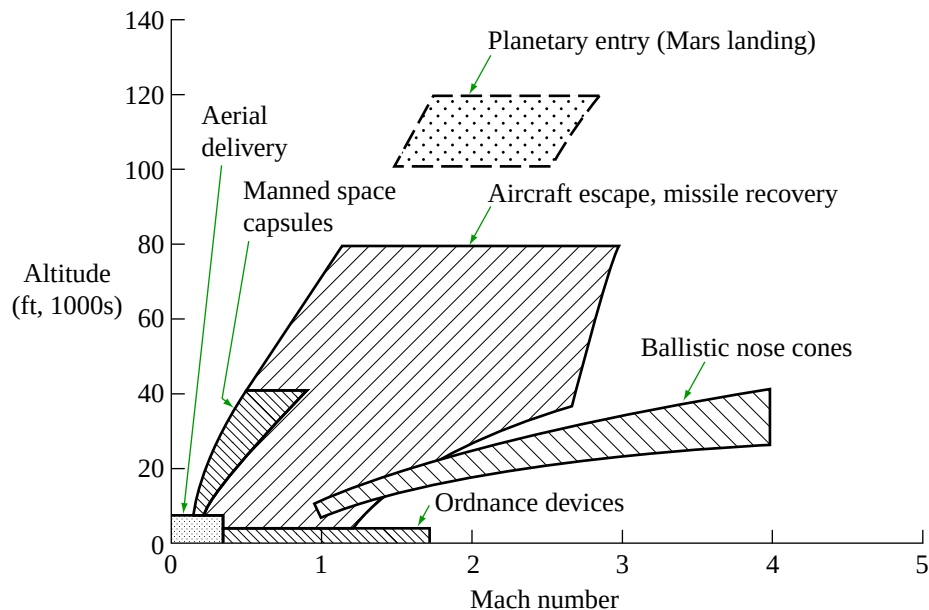
Parachutes fall into two main categories, *ballistic* and *steerable*. Ballistic parachutes are essentially axisymmetric (with the exception of the cross parachute, see Section 4.8) and designed solely to produce a retarding force. These have many applications including personnel safety, air-drop of personnel, stores and supplies, dispensing, retarding and dispersion of munitions, aircraft and ground vehicle braking, recovery of rockets and solid propellant boosters and landing of unmanned spacecraft. The basic components of a ballistic parachute are shown in Sketch 4.1a. Sketch 4.2 shows the wide range of Mach number and altitude for which ballistic parachutes have been designed, and indicates the relevant application.



**Sketch 4.1 Typical ballistic and high-glide parachutes and their components**

Steerable or gliding parachutes fall into two sub-categories; the simplest are those that are essentially adaptations of circular or ribbon-type parachutes that have slots or vents cut into the canopy symmetrically about the fore-aft axis. These act to stabilise the otherwise highly unstable parachute and produce a degree of glide (which in turn generates lift as a result of the airflow over the curved canopy). Many variations and combinations of slots and vents have been employed with differing levels of sophistication and they are generally named after either their inventor or a simplistic description of their shape (*e.g.* Tojo, Derry, U and T *etc.*). Steering of round gliding parachutes is implemented by distortion of the slots or by the closing of secondary vents on the side of the canopy, called Le Moigne slots, using steering lines.

The second category comprises the most effective gliding parachutes, where the canopy acts as a low aspect ratio wing designed for high lift rather than high drag. Gliding parachutes that have lift-to-drag ratios ( $L/D$ ) up to unity are usually termed 'low-glide' parachutes, those with ( $L/D$ ) ratios between 1 and 2 are known as 'medium-glide' and above 2 'high-glide' parachutes. The high-glide class includes the parawing originated by Rogallo, the ram-air parachute (or parafoil) by Jalbert, the sailwing by Barish and the Volplane by the Pioneer Parachute Company. In all cases control is obtained via lines to the parachute trailing or side edges to produce spoiler or aileron-type effects. A typical parafoil-type parachute is shown in Sketch 4.1b.



**Sketch 4.2 Ballistic parachute performance envelope (Reference 30)**

In addition to main parachutes there are also pilot and drogue parachutes. Pilot parachutes (see Section 6.4) are used in the deployment process by being ejected into the airflow (sometimes aided by a mortar, if necessary) and are used to provide the extracting force for a second, larger canopy, either through a direct connection to the larger parachute vent or a deployment bag. (A comprehensive description of deployment methods is given in Reference 30.) The size of the pilot canopy must be carefully selected to provide sufficient force to achieve extraction, but without unduly delaying or preventing (in the case of permanent attachment) the inflation of the secondary canopy. A drogue parachute is one that is used to stabilise and/or provide a first stage of deceleration for a payload and usually will act, subsequently, as a pilot parachute for a larger canopy.

The main designs of parachute are summarised in Sections 4.1 to 4.11, and the main geometric and aerodynamic parameters associated with each type, together with a more extensive list of other designs, are listed in Section 4.12 in Tables 4.1, 4.2, 4.3 and 4.4 for solid fabric, slotted fabric, gliding and balloon-type designs, respectively.

The definitions of some commonly used parameters given in the tables and throughout this Item are useful:

**Nominal area,  $S_o$** , is the total surface area of canopy, including any vents or slots and surfaces such as ribs and panels. Nominal area is often used in defining aerodynamic coefficients as it is invariant with rigging geometry and flow conditions.

**Nominal diameter,  $d_o$** , is the diameter of circle of area  $S_o$ ,  $d_o = 2\sqrt{S_o/\pi}$ .

**Constructed diameter,  $d_c$** , is defined in Reference 21 as ‘the distance measured along the radial seam between the points where the maximum width of the opposing gores intersects that radial seam’. This is sometimes used because  $S_o$ , and hence  $d_o$ , is not always clearly defined. (See Sketches 4.3 to 4.11.)

**Projected area,  $S_p$** , is the projected area of the canopy when inflated and under aerodynamic loading. (Note that this will have a dependency on suspension line length.)

**Projected diameter**,  $d_p$ , is the diameter of circle of area  $S_p$ ,  $d_p = 2\sqrt{S_p/\pi}$ .

**Drag coefficient**,  $C_{D_o}$ , is the drag coefficient based on  $S_o$  and  $q$ . This indicates the effectiveness of the parachute at producing drag based on total surface area. This can be misleading in terms of mass efficiency since the area includes slots and vents for round parachutes but only the cloth area for cross parachutes.

**Opening force coefficient**,  $C_x$ , is the ratio of the maximum instantaneous opening force to the steady drag force at constant velocity (often referred to as the *infinite mass* case, see Section 6.1). This is usually derived from wind-tunnel tests or in applications with very high canopy loading such as aircraft landing and first stage drogue parachutes.

**Porosity** is the parameter with the most influence on drag and stability performance. Porosity in a parachute canopy is provided in two ways: geometric porosity,  $\lambda_g$  comes from open areas in the parachute and fabric porosity (or permeability) comes from the flow passing through the canopy fabric driven by the pressure difference across the canopy, see Section 5.2.

**Oscillation angle** is the range of angle of attack over which the parachute is observed to oscillate during descent. This term should not be confused with trim angle, see Section 5.1.

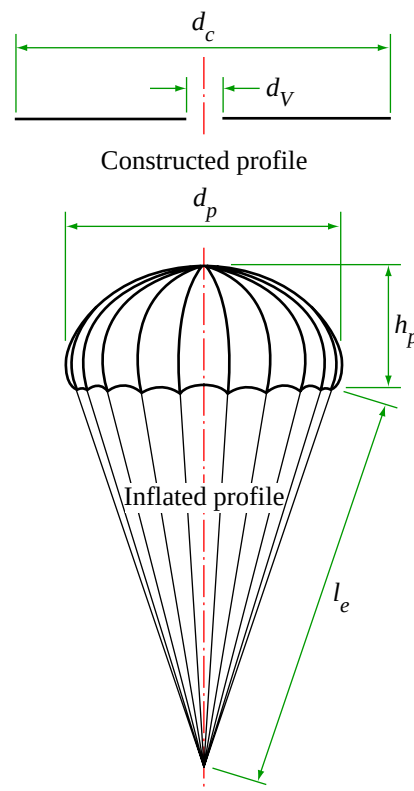
**Canopy trim angle**,  $\beta$ , is the angle of attack at which the parachute is statically stable and should not be confused with oscillation angle or descent stability. A parachute with a trim angle of zero will always descend vertically. A parachute with a trim angle other than zero will descend in one of three modes: oscillating, coning or gliding, see Section 5.1. The mode adopted depends on a parameter called *mass ratio*, see below. The trim angle may be obtained from wind-tunnel tests.

**Mass ratio**,  $R_m$ , is the ratio of the mass of fluid associated with the canopy to the payload mass and defined in Equation (5.6). With a high mass ratio the payload mass is small compared to the mass of fluid associated with the canopy, and the centre of mass of the system is near the canopy. In these circumstances the system glides at the trim angle, see Sketch 5.2b. When the mass ratio is low, the system centre of mass is close to the payload and the system oscillates or cones.

**Drag area** is the product  $C_{D_o}S_o$  and is a main parachute design parameter.

## 4.1 Flat Circular or Round Parachutes

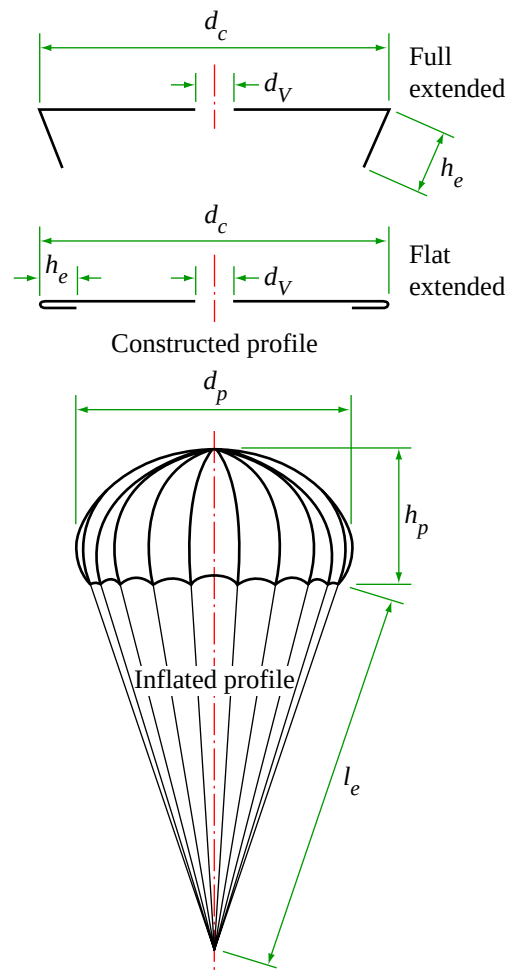
The simplest form of parachute is the flat circular or round parachute design (see Sketch 4.3). These devices are fabricated from triangular shaped segments (or 'gores') of material stitched together around a central vent and are inexpensive to manufacture. Such parachutes are flat when laid out (the sum of the individual gore angles equalling 360 degrees), but form a dome when inflated under load carrying conditions. This design has found applications in emergency and cargo dropping roles, and is suitable for low dynamic pressures. However, they lack stability when used in isolation and exhibit substantial oscillations during descent (up to  $\pm 40$  degrees). The instability may be reduced through the use of increased porosity of the fabric or the introduction of further geometric porosity. The stability issue may also be overcome by the use of clusters of similar devices (usually three or more), see Section 6.3. The drag coefficients of such parachutes are high and offer a low-cost, low-weight solution. In the design of large solid fabric parachutes, weight and volume savings may be achieved by using two or more graded fabric weights, the heaviest being used at the top where stresses during inflation are greatest.



Sketch 4.3 Flat circular parachutes (References 21 and 30)

## 4.2 Extended Skirt Parachutes

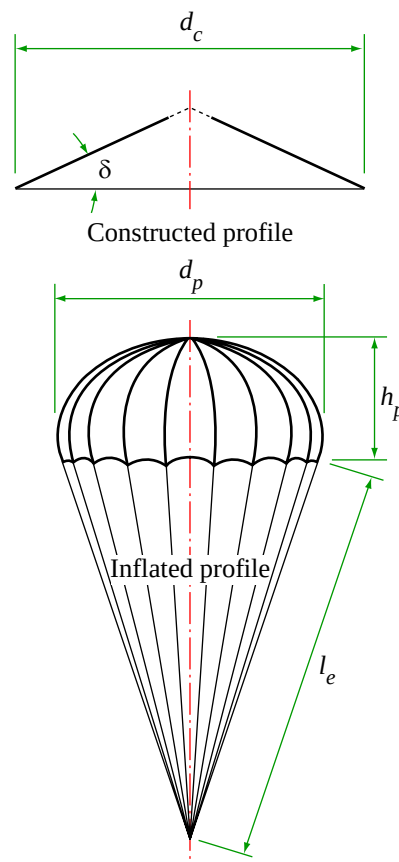
The extended skirt parachute (see Sketch 4.4) is a development of the flat parachute, and is used for similar tasks. It has a lower drag coefficient and a longer opening time than the equivalent flat parachute, which reduces the transitional loads. The extension itself aids stability as it acts as an inverted frustum whose angle matches that of the suspension lines; the extensions themselves vary in length from design to design and may be manufactured as a flat annulus or 'full' to match the taper of the converging suspension lines, as shown in Sketch 4.4.



Sketch 4.4 Flat circular parachutes with extended skirt (References 21 and 30)

## 4.3 Shaped Parachutes

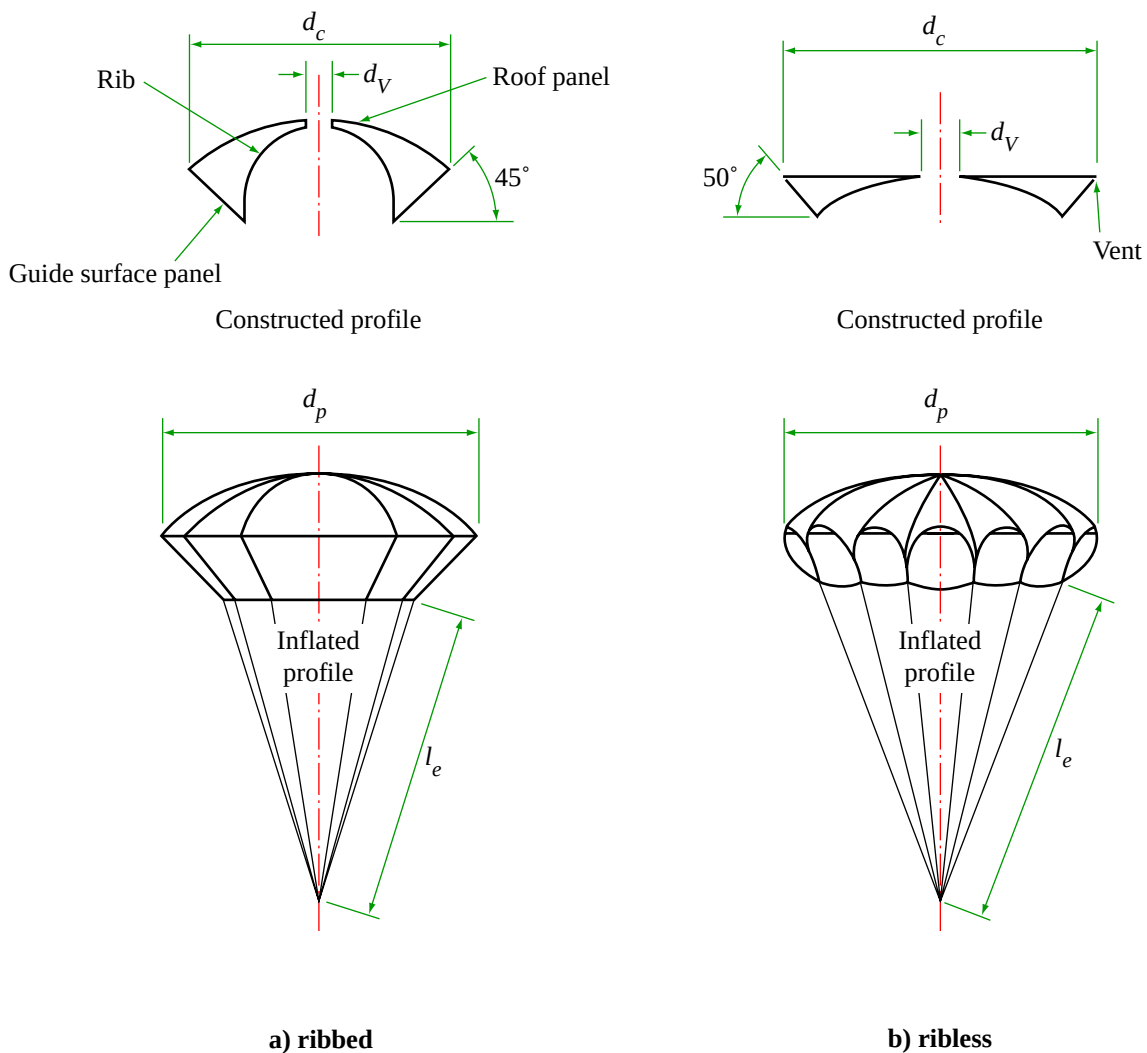
The basic design of the flat parachute may be modified by tailoring the canopy so that it forms a shallow cone (Sketch 4.5). This is achieved by making the sum of the gore apex angles less than  $360^\circ$ . Such parachutes exhibit a higher drag coefficient than a flat parachute but experience higher fabric stresses during inflation. The highest drag coefficient occurs for a constructed cone angle,  $\delta$ , in the range  $25^\circ$  to  $35^\circ$ . The design can be further modified by the introduction of one or more cranks along the sides of the gore panels to produce bi-conical or even tri-conical forms, generally resulting in an even higher drag coefficient. The roles for which these parachutes are used are the same as for the flat circular type.



Sketch 4.5 Shaped parachutes – conical (References 21 and 30)

## 4.4 Guide-surface Parachutes

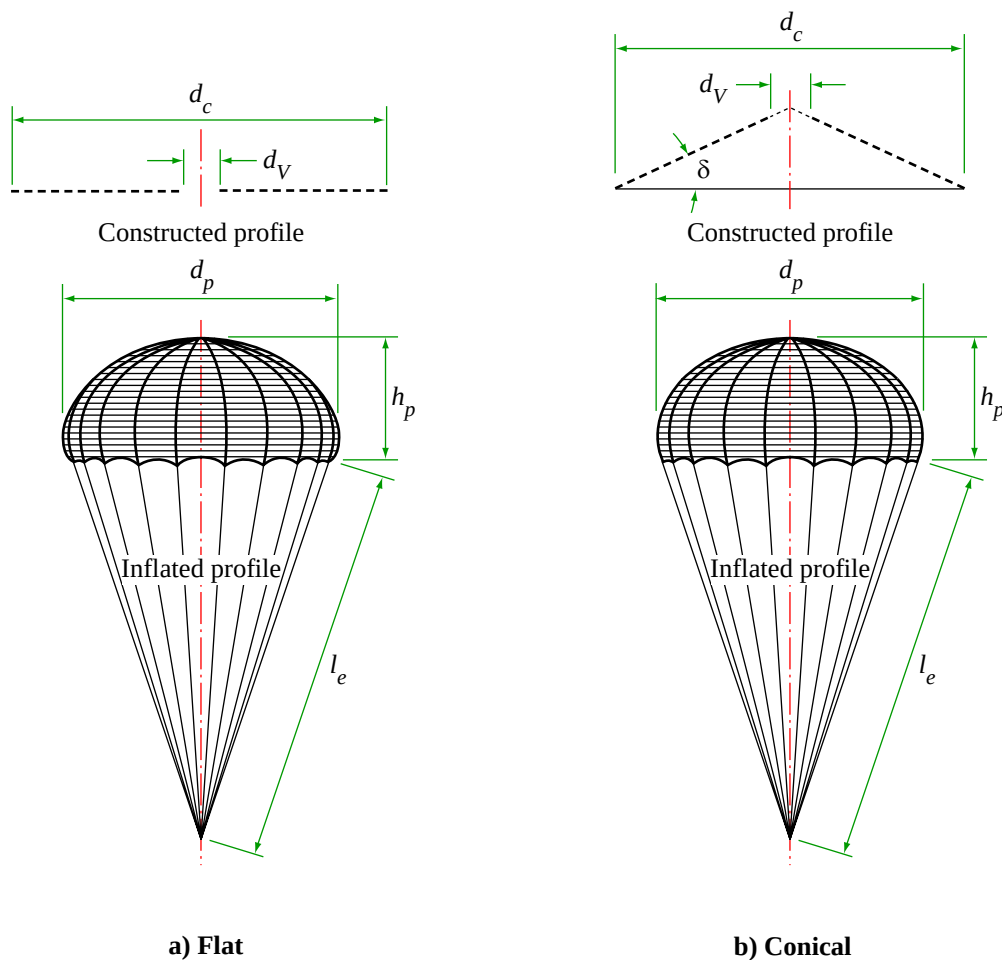
The guide-surface parachute (see Sketch 4.6) was invented by Heinrich, primarily for deployment at high speeds for the stabilisation of munitions; some versions operate at supersonic speeds. They are also often used as pilot or extraction parachutes for ejection seats and may be used successfully at both low and very high dynamic pressures. The low porosity fabric used leads to rapid inflation and excellent reliability, but it has a relatively low drag coefficient. The combination of its flare-type stability and the sharp separation achieved at the canopy edge results in the greatest stability and damping characteristics of all parachutes. It is expensive and complex to manufacture; the ribless version is more compact when stowed and less expensive, but is somewhat less stable.



Sketch 4.6 Guide-surface parachutes (References 21, 29 and 30)

## 4.5 Ribbon Parachutes

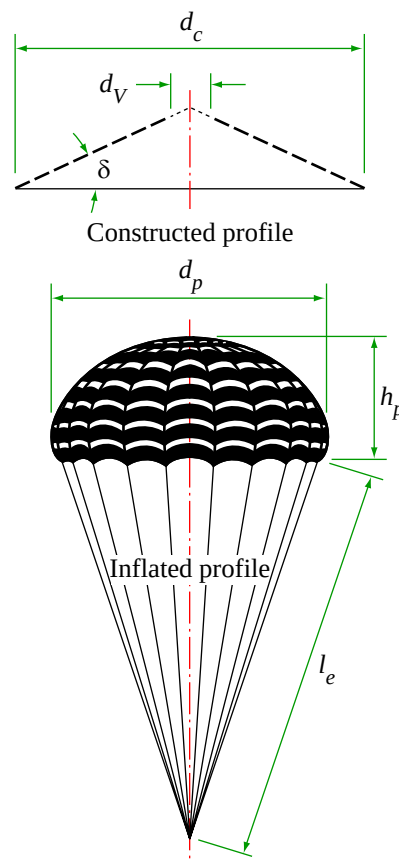
Knacke and Madelung developed the ribbon parachute for decelerating heavy stores and aircraft at high speeds. A ribbon parachute is normally formed from a sequence of spaced, concentric material bands connected by lines and ribbons which, when fully inflated, assume the form of a dome. The horizontal ribbons are generally around 0.05 m wide, with the gaps in the range 0.01 to 0.03 m. It may be constructed to a flat or conical design (see Sketch 4.7), the latter (defined by the cone angle  $\delta$ ) giving a higher drag coefficient and is thus the most commonly adopted. This design offers potential for a strong canopy, particularly when fabricated from a material like Kevlar, and provides lower opening loads. Thus it is suitable for deployment at high dynamic pressures, including supersonic operation. It has a lower drag coefficient than the equivalent solid canopy, but exhibits excellent stability in pitch and is extremely robust. The optimum porosity is defined by a trade-off of higher stability versus lower drag coefficient. Porosity may also be varied from vent to skirt to increase drag without compromising stability. Filling time and shock loading are also affected by porosity. The aerodynamic load is taken mainly by the horizontal ribbons and transferred to the radial lines. The vertical ribbons control the shape of the horizontal ones and therefore also affect porosity. Horizontal ribbon strength is graded over the canopy to minimise both mass and volume, the stronger ribbons being located near the vent to accommodate the initial inflation loads.



Sketch 4.7 Ribbon parachutes (References 21, 29 and 30)

## 4.6 Ringslot Parachutes

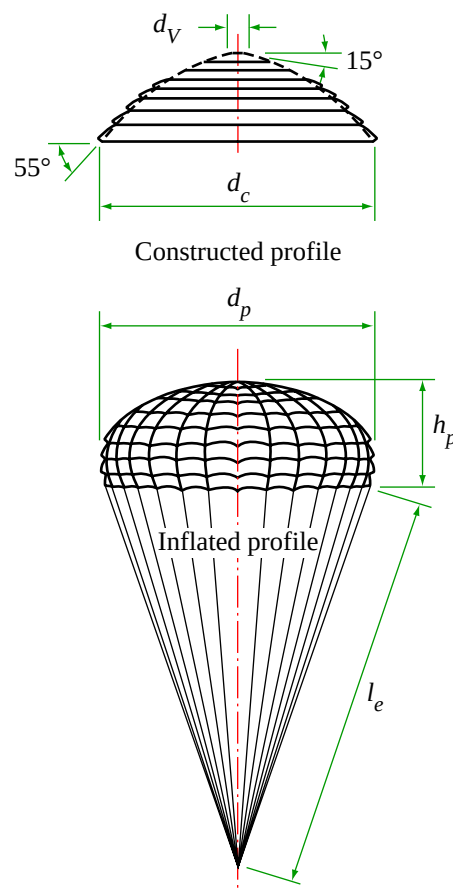
Knacke invented the ringslot parachute for use at moderate subsonic speeds, see Sketch 4.8. It is used primarily for cargo delivery and aircraft deceleration. It is significantly cheaper to manufacture than the ribbon parachute. It may be constructed as a flat or, more usually, conical design. The cost saving is achieved by the use of much wider bands than the ribbon parachute (around 0.3 m). In all other respects its performance is similar to that of the ribbon parachute, although it is less durable in that it is more susceptible to local damage.



Sketch 4.8 Ringslot parachute (References 21, 29 and 30)

## 4.7 Ringsail Parachutes

The ringsail parachute is a derivative and more expensive version of the ringslot parachute and was invented by Ewing (Reference 10). Its construction follows that of the ringslot parachute, with broad bands of fabric separated by gaps around the crown area. Below the crown the bands of fabric are adjacent with no gap, as such, between the ribbons. Geometric porosity is provided by *fullness* in the leading edge of each band *i.e.* the leading edge of each band is longer than the trailing edge of the band below it and a crescent shaped gap opens when the canopy inflates. The result is a canopy with higher drag than a ringslot parachute and faster opening time, but at the expense of a higher opening force coefficient. Ringsail canopies were used in the recovery of Mercury, Gemini and Apollo capsules, because they offered the advantages of lower weight, greater stability and lower opening loads compared with a solid canopy. The outline design is shown in Sketch 4.9 and further design details may be found in Reference 10.



Sketch 4.9 Ringsail parachute (References 10, 20, 29 and 30)