Selection Criteria for Parachutes of Student-Built Sounding Rockets

Thomas Britting[1], Wesley Leonardus Jacobus Rudolf Toussaint[2], Kristina Vukosavljević[2], Mohamed Sahir Sujahudeen[2], Niklas Emil Knöll[2], Lars Pepermans[3] and Yohan Pascal Hadji[3]

Abstract

Various parachute-type decelerators can be considered in the design of a sounding rocket recovery system. During the development of various flagship missions of Delft Aerospace Rocket Engineering (DARE), the Parachute Research Group of DARE has developed several methods and criteria to select the right parachutes for a given mission. This paper presents and discusses the operational envelopes, advantages, and disadvantages of different parachute types. The parachutes described in the paper are variations of cross parachutes, disk-gap-bands, ringsails, conical ribbon parachutes, and hemisflo ribbon parachutes. Variants of these parachute types have previously been developed in-house and flown, allowing for acquaintance with their design, manufacturing and performance. Apart from the more traditional parachutes used for student-built sounding rockets, this paper will also cover the opportunities and challenges that are associated with the use of less conventional parachutes, such as ringsails, ringslots, and parafoils. Each parachute is described in detail after which all are compared to one another based on several sets of typical requirements. Factors that influence the parachute selection process are, for example, the parachute flight envelope, stability behaviour, and manufacturing complexity.

Keywords

Parachute selection, recovery system design, sounding rocket

[1] Corresponding author: Delft Aerospace Rocket Engineering, the Netherlands, thomasbritting8@gmail.com.

[2] Delft Aerospace Rocket Engineering, the Netherlands.

[3] Chutes.nl, the Netherlands.

Nomenclature

C_d	*Drag coefficient*
A	*Nominal area*
D_0	*Nominal diameter*
C_d*A	*Drag area*

Acronyms/Abbreviations

DARE	*Delft Aerospace Rocket Engineering*
PRG	*Parachute Research Group*
DGB	*Disk-Gap-Band parachute*
AR	*Aspect Ratio*
R&D	*Research and Development*

1. Introduction

Throughout the history of the parachute, many different types have been designed and flown. They all have different strengths and weaknesses, and one must be selected carefully for each specific application. A lot has been written about the characteristics of the many types of parachutes, but little literature exists that focuses on their use in student rocketry. As such, this paper aims to shed light on the selection process for the most suitable types of parachutes for student sounding rockets. As each mission is different, and no single parachute is suitable for every single mission, there is no definitive answer as to what the 'best' parachute is. General guidelines and criteria on performing a tradeoff to select one for a specific mission are instead highlighted.

2. Needs and requirements

In general, the main parachute should safely recover the rocket or payload. This is generally defined as a landing velocity for which the kinetic energy is low enough for landing. This sets the drag area of the parachute. It is up to the team to discover and specify requirements, however, some requirements, such as landing velocity are frequently found. Other common requirements are the maximum loading on the system and the maximum inflation conditions. It is therefore very important for the parachute engineer and systems engineer of the mission to discuss and discover all aspects of the flight.

Other requirements such as the inflation conditions of the parachute influence the possible need for an additional decelerator, for example, a drogue parachute.

Besides these requirements, there are potential requirements imposed by a launch site or mission regarding the flight time and ground range. Small and narrow landing zones might require a later parachute deployment or steerable parachute, resulting in smaller wind drift. Alternatively, when measurements are performed during the parachute phase, it might be that a minimum flight time is needed to ensure there is sufficient time for the experiment. Other requirements that originate from the payload include the maximum allowed oscillations during flight.

Besides requirements from flight, inflation and landing conditions, there might be restrictions when it comes to manufacturing and materials, as some parachutes are easier to manufacture than others.

3. Parachute types

This section provides an overview of what types of parachutes exist and are commonly used. A brief explanation of each type and its characteristics is provided. Moreover, their constructed profiles are illustrated in Figure 1.

3.1. Solid parachutes

Solid parachutes often consist of multiple sheets of fabric sewn together without many gaps or fabric discontinuities. A central vent hole is often the sole source of geometric porosity for these types of parachutes. The low porosity and poor porosity distribution make these parachutes less attractive for supersonic applications, compared to ribbon parachutes.

3.1.1. Cruciform

Cruciform parachutes are, as the name implies, cross-shaped and have been a very popular choice for subsonic recovery systems. Because of their ease of manufacturing, they are often used for amateur or student launched rockets. They have average drag coefficients around 0.7 and also experience average to poor stability during flight. There are many variations to cruciform parachutes possible - such as changing the aspect ratio (AR) of the parachute or making connections between the corners/sides of the cross shape to create a box parachute.

Cruciform parachutes have proven to exhibit unfavourable behaviour at supersonic speeds, and are thus best used as landing parachutes at low speeds [1].

3.1.2. Circular

A circular parachute's gore shape can be chosen such that the shape of the parachute is flat, conical, hemispherical, or a different profile. These parachutes are fairly easy to manufacture and have fairly high drag coefficients often ranging from 0.7 to 0.9. However, they suffer from significant oscillatory instabilities and large opening loads up to 2 times the steady state load. These types of parachutes are also not suited for supersonic flight. They are seldom used for space applications, because of their poor stability and inflation behaviour.

3.1.3. Disk-Gap-Band

Disk-Gap-Band (DGB) parachutes consist of a flat circular disk and a cylindrical band, separated by a gap. The gap and the vent hole in the disk give this parachute a significant geometrical porosity, which contributes to the parachute operating at supersonic conditions.

The DGB has proven to be reliable as a drogue and main parachute in both sub- and supersonic conditions. The ease of manufacturing a DGB parachute has also made it an excellent candidate for amateur and student rocket recovery systems. Although it has a wide operating Mach envelope, it has moderate stability and a low to moderate drag coefficient close to 0.5.

3.1.4. Annular

Annular parachutes have the shape of a half-torus, with their suspension lines attached to both the outer perimeter and the vent hole. These parachutes have higher than average drag coefficients, ranging from 0.9 to 1.0, exhibit moderate stability and show opening loads close to 1.4. Their flight envelope is, however, limited to subsonic regimes.

Annular parachutes have become very popular for military, recreational and other non-space related applications, however, have only been used very rarely for space missions.

3.1.5. Guide-surface

Guide-surfaces are parachutes that are constructed with a rounded crown and an inverted conical surface - running from the apex to the skirt. Ribs are additionally used to maintain their characteristic shape. These parachutes are known for their excellent stability behaviour, however, typically have very low drag coefficients in the order of 0.3 to 0.4. Hence these tend to be relatively heavy compared to the other solid parachutes, to achieve the same drag. The inflation behaviour of guide surfaces, especially ribbed guide-surfaces, is generally favourable with opening load factors as low as 1.1.

In past missions, these have primarily been relatively small, in the order of 1 metre diameter, and were used as stabilisers, pilot chutes, or main parachutes for small spacecraft. The fact that guide-surface parachutes are difficult to produce and used in subsonic conditions, makes them less advantageous compared to other parachutes, except when stability is of utmost importance to the mission.

3.1.6. Asymmetric drag parachutes

Asymmetric drag parachutes are a subset of the solid parachute on which asymmetric vent holes are placed. This allows for air to escape the canopy, creating a thrust-like force. The gliding can be controlled, allowing for control over the landing location. In general, the glide ratio of these parachutes is 0.5 to 0.7 and the aerodynamic coefficient is 0.85 to 0.9, which describes the resulting aerodynamic force on the canopy.

3.2. Slotted parachutes

As discussed in the previous section, solid parachutes are usually designed without many gaps. Slotted parachutes, conversely, consist of multiple individual or ring segments with gaps so that the geometric porosities lie in the 10 to 35% range. The first slotted parachute design was the flat ribbon parachute, after which the conical ribbon parachute was designed [2]. Furthermore, in order to reduce the cost of the parachute, the ringslot parachute design was introduced. Further improvement of the design resulted in the ringsail parachute.

3.2.1. Ribbon

There are a few different types of ribbon parachutes, including the flat ribbon parachute, the conical ribbon parachute, the hemisflo ribbon parachute and the variable porosity ribbon parachute.

Flat ribbons are circular and consist of concentric ribbons supported by smaller horizontally spaced tapes and radial ribbons at gore edges. The ribbons and tapes are accurately spaced to provide the desired ratio of open space to the solid fabric over the entire canopy. Gores are triangular and dimensions are determined in the same manner as for the solid flat circular parachute. The flat circular ribbon parachute has a lower drag per unit surface area than its solid-cloth analogue, but its stability is excellent and maximum opening force is low in comparison. The canopy is relatively slow in opening and its performance reliability depends on specific design parameters. Compared to solid cloth hemisflo parachutes, the flat circular ribbon canopy is more difficult to manufacture.

The constructed shape of the conical ribbon canopy is similar to solid cloth conical parachutes. These show higher drag than the flat circular ribbon just as the solid cloth conical parachute does over the solid flat parachute of the equal construction area.

The canopy of a hemisflo ribbon is a spherical surface that continues a preset angle past the hemisphere at the skirt. The canopy design retains effective drag and stability performance over the range from Mach 1.5 to 2.5, although conical ribbon parachutes are as good or better at speeds below Mach 1.5. Hemisflo parachutes are used almost exclusively for drogue applications, which require stabilisation and deceleration at supersonic speeds. The hemispherical profile makes for reduced breathing and reduced high-frequency flutter - both proponents of fatigue and drag reduction - but are more susceptible to canopy rotation.

The last type of ribbon parachute considered is the variable porosity ribbon parachute. This modification to ribbon parachute profiles involves a variation in geometric porosity from the vent to the skirt. The steady-state drag coefficient can be increased without a large loss of stability using this change, but the opening load factor also tends to see an increase.

3.2.2. Ringslot

In an attempt to reduce the cost of the ribbon parachute, the ringslot parachute was developed. It has similar aerodynamic characteristics, however, it has an increase in drag, most often 10 to 14%. Using multiple individual segments in the design of the ringslot parachute, the horizontal ribbons of the ribbon parachute are replaced. They are then sewn together to create concentric rings which are afterwards joined using radial tapes. Similarly to ribbon parachutes, the aerodynamic performance is controlled by the total porosity and the allowable increase in effective porosity.

3.2.3. Ringsail

Developed as an improvement over the ringslot, the ringsail consists of many small sails arranged in concentric rings, often with a slotted section near the crown for increased geometric porosity. It is an attractive choice due to its high drag coefficient at around 0.8 to 0.9, moderate to good stability and suitability for reefing [3]. It is also a relatively lightweight parachute for the amount of drag it produces, has gentle inflation characteristics and is commonly used on manned space flights. Major disadvantages of the ringsail are the fact that it is a very complex and time-consuming parachute to manufacture.

There is also little literature available for ringsails in the size range that would be appropriate for most amateur and student rocket projects. For these reasons, it is rarely used for such applications.

3.3. Parafoils

Commonly used in skydiving, a parafoil is mainly characterised by its airfoil shape, giving it its lift generating capability. A parafoil is often composed of only three different parts: the intrados, the extrados, and a series of ribs. The intrados and extrados are two rectangular pieces of fabric making up the bottom and the top of the wing. In simple designs, the ribs can all be identical. Two main parameters affect the flight: the rib's profile, linked with both lift and drag, and the AR of the parafoil. The AR is defined by the ratio between the span of the parafoil and its chord, and this is the determining factor in parafoil design. A larger AR lowers the strength of the wing vortices and improves the lift to drag ratio of the parafoil, but deployment becomes more difficult. In most cases, parafoil deployment requires the use of a deployment bag and an extraction parachute. These are used to tension all the lines in the air shortly before the parafoil is deployed, reducing the risk of line entanglement.

Another important parameter in the choice of a parafoil design for a given flight mission is the nominal airspeed. The airspeed of a parafoil can only be adjusted in a very narrow range, in comparison to a fixed-wing aircraft with the ability to pitch down to trade potential energy for kinetic energy. A higher nominal airspeed allows the parafoil to keep a forward ground speed, even when flying against a strong headwind. Higher performance parafoil wings looking closer to paraglider wings can also be used in cases where flight performance (glide ratio) and controllability is needed. However, the deployment of such wings is currently considered harder. It's also important to keep in mind that choosing a steerable parachute will require a significant effort of R&D for the control mechanism and algorithm.

3.4. Rotating parachutes

Some parachute types generate more drag than others due to their shape and behaviours. One example is the rotafoil. This parachute consists of asymmetric vent holes placed in the canopy which means the parachute will start to rotate. Alternatively a vortex ring parachute can be used. This rotation creates a centrifugal force on the canopy and lines, increasing the projected diameter. These parachutes are often small, no more than about 3 metres D_0.

4. Comparison of parachutes

In this section, the different types of parachutes will be compared.

First, one should determine whether a parachute should be steerable or not. Ballistic parachutes are not steerable and thus have larger landing areas. Guided parachutes can be steered to a final landing location. Guided parachutes can be divided into lift generating parachutes and asymmetric drag parachutes, with the difference being that a lift generating parachute can fly further and has more control over the landing location.

Within the category of ballistic parachutes, rotating parachutes can be distinguished. The other two categories are high and low dynamic pressure at deployment. The high dynamic pressure systems are usually slotted parachutes which modify the geometric porosity to ensure the parachute can survive inflation. Low dynamic pressure systems are usually solid cloth parachutes and can range from crosses to circulars to ellipsoidal parachutes.

A table with the typical values of parachute performance parameters is provided in Table 1. Gliding parachutes are instead presented in Table 2. These tables serve as the first reference during a preliminary design study to gauge which parachute types are feasible and how they compare to each other. One of these, the angle of oscillation, is a parameter often used in literature to gauge the stability of a parachute. However, the stability of small-scale parachutes can be affected greatly by the manufacturing errors that for example give rise to asymmetry. Additionally, the wake-effects of a body in front of the parachute will also affect its stability behaviour in flight. Furthermore, parachute stability can be improved by increasing the effective porosity of the canopy, with the penalty of a lower drag coefficient.

5. Conclusion

When selecting the main parachute for a particular mission, the first thing to consider is the required landing velocity, as this immediately fixes the drag area C_d*A regardless of the type of parachute that is chosen. The maximum allowable force that the structure can take is next, as this may exclude certain types of parachutes that generate high shock loads, such as the circular parachute, or require the use of an additional decelerator such as a drogue parachute prior to the deployment of the main parachute. Another factor that may introduce such a requirement is the Mach number at deployment. This Mach number depends on when the parachute is deployed, which in turn may depend on several factors such as the size of the landing area and the consequent limit on acceptable wind drift distance. In case a precise landing location is required, choosing a steerable parachute will likely be necessary. A last important point to consider is whether the complexity of the parachute is feasible within the available manufacturing capabilities. A final comparison of the various types of parachutes may be found in Tables 1 and 2.

References

[1] H. N. Murrow, J. C. McFall Jr., Some Test Results from the NASA Planetary Entry Parachute Program, Journal of Spacecraft and Rockets, Vol. 6, No 5, pp. 621-623, 1969.

[2] T. W. Knacke, Parachute Recovery Systems Design Manual, Para Publishing, 1991.

[3] P. Delurgio, Evolution of the Ringsail Parachute, 15th Aerodynamic Decelerator Systems Technology Conference, AIAA 1999-1700, 1999.

[4] E. G. Ewing, H. W. Bixby, T. W. Knacke, Recovery Systems Design Guide, Irvin Industries Inc, 1978.

[5] J. S. Lingard, The Aerodynamics of Gliding Parachutes, *9th Aerodynamic Decelerator and Balloon Technology Conference*, AIAA 1986-2427, 1986.

[6] J. C. Underwood et al., Subsonic Wind Tunnel Testing of Various Parachute Types, *23rd AIAA Aerodynamic Decelerator Systems Technology Conference*, Florida, USA, 2015.

[7] R. J. Niccum, E. L. Haak, R. Gutenkauf, Drag and Stability of Cross Type Parachutes, University of Minnesota, 1965.

[8] H. G. Heinrich, E. L. Haak, Stability and Drag of Parachutes with Varying Effective Porosity, University of Minnesota, 1971.

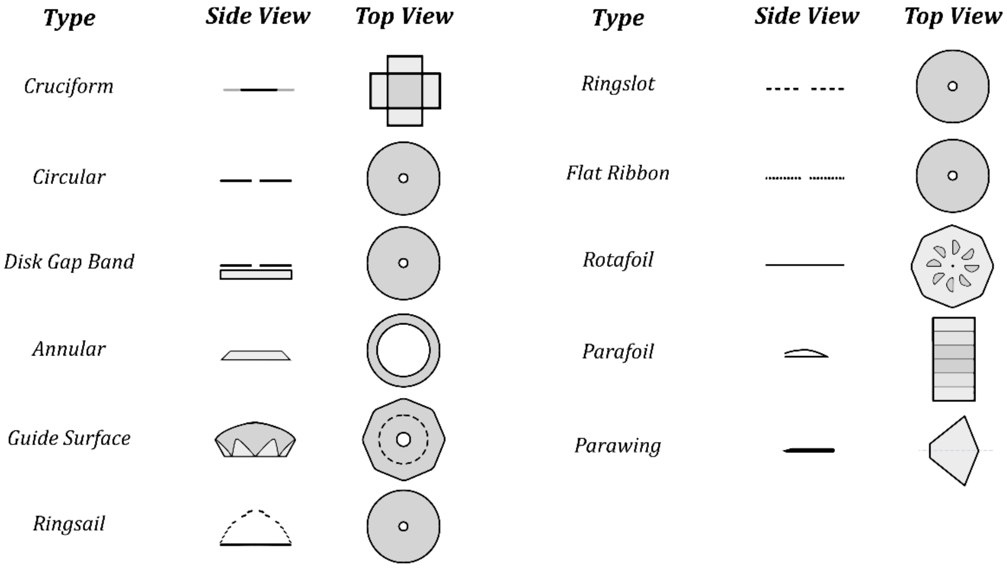

Figure 1: Constructed profiles of the different types of parachute geometries

Table 1: Typical values of performance parameters for different types of main parachutes [2,4,6,7,8]

Parachute type	C_d [-] subsonic	C_d [-] supersonic	Angle of oscillation [deg]	Shock load factor [-]	Manufacturing complexity	Supersonic capable
Cruciform	0.6 – 0.8	N/A	0 – 40	1.2	Very low	No
Circular	0.6 – 0.95	N/A	10 – 40	1.4 – 1.8	Very low	No
DGB	0.4 – 0.6	0.45 – 0.7	5 – 15	1.3	Low	Up to Mach 2.7
Annular	0.9 – 1.0	N/A	0 – 5	1.4	Low	No
Guide-surface	0.3 – 0.4	N/A	0 – 5	1.4	Low	Yes
Ringsail	0.75 – 1.0	N/A	5 – 20	1.1	High	Yes
Ringslot	0.55 – 0.65	N/A	0 – 5	1.05	High	Yes
Ribbon	0.45 – 0.65	0.25 – 0.6	0 – 3	1.0 – 1.3	Medium	Up to Mach 3
Rotafoil	0.8 – 1.0	N/A	0 – 5	1.05 – 1.1	Medium	No

Table 2: Typical values of performance parameters for different types of gliding main parachutes [4,5]

Parachute type	Glide ratio [-]
Asymmetric drag parachute	0.5 – 0.7
Low AR ram-air parafoil	2.5 – 3.5
High AR paraglider	5.0 – 13.0