REQUIREMENTS FOR PARACHUTES OF GLIDER RECOVERY AND PILOT RESCUE SYSTEMS

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Presented at the XXIV OSTIV Congress, Omarama, New Zealand (1995)

Introduction

The German Federal Ministry of Transport (BMV) commissioned the Fachhochschule Aachen (F.H.A.) to investigate the fundamentals of glider parachute recovery systems (GPRS). The final report [1] was completed in April, 1994 but an overview of the whole program had already been presented in Borlänge [2]. The present paper takes a closer look at parachute characteristics and attachment points, as well as bridles and risers, in connection with their influence on the system's dynamic stability. It should be read in conjunction with, and is supplementary to, reference [3].

Systems investigated

The GRS probably is the most widely known system. Ultralight aircraft, supersonic drones and returning spacecraft make use of its principle and have proven concept reliability for decades. Shortly after initiation the system is deployed. The parachute inflates while the whole glider decelerates with the pilot remaining inside the cockpit. Neither unstrapping nor bailing out is necessary. Protecting the occupant in a modern crashworthy cockpit during the ground impact is an important design characteristic of the GRS.

The PRS is a proposal of H. Kiffmeyer and is distinguished from a GRS by the use of a much smaller parachute that is linked to the pilot as well as to the glider. Finally, only the pilot is rescued which results in a small system unit that could be stored behind the headrest. After system initiation the canopy is jettisoned, the parachute deploys, stretches, inflates and decelerates the whole glider. Then the pilots seat belts open automatically, the riser is disconnected from the glider and tightens the remaining part that is linked to the pilot. The glider falls away freely and the surplus parachute drag force pulls the pilot out of the cockpit. A more detailed description can be found in [3].

Parachutes

Parachutes are the most effective aerodynamic drag devices for aviation use. An exhaustive compendium of parachute knowledge is described in [4]. Although many different types exist, only circular and cross main canopies were taken into account. They are a good choice because of their simplicity in design and well known characteristics. The basic elements of all parachute recovery systems are shown in Figure 1.

A bridle (1) is fitted to several attachment points (2) in or outside the glider fuselage. A riser (3), which is connected to the bridle goes up to the confluence point

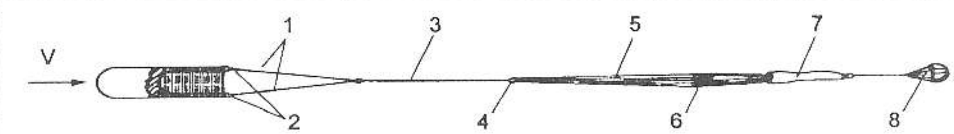


FIGURE 1. Basic elements of a glider parachute recovery system (GPRS).

a large pilot chute will collide with the tail unit even before it is fully inflated (Figure 3a). Only tailless gliders such like the SB13 and FVA27 will successfully make use of a passive system, namely the classical pilot chute (Figure 3b).

(4) of the suspension lines (5). These lines are sewn to the skirt of the main canopy (6). During the first deployment phase the main canopy stays packed in a bag (7) that is normally pulled away by a pilot chute (8).

The increase in diameter and mass if lower descent speeds are requested is clearly described for several parachute systems in [2]. Circular parachutes have high drag coefficients but tend to oscillate with rising C_D. Cross parachutes, have a lower opening shock but start to rotate if not manufactured precisely. Rotation twists the suspension lines and results in a collapse of the cross canopy. This can be prevented by using a swivel.

As most gliders have a T-shaped tail unit the deployment of a GPRS requires an active device such as a rocket (Figure 2a) or a mortar (Figure 2b). Mostly they are propelled by a solid propellant or compressed air.

The rocket, for example, steadily pulls the parachute bag out of the fuselage compartment, lifts it over the stabilizer and orderly stretches the bridle, riser, suspension lines and the canopy itself. Any other order leads to line entanglement and untimely collision with the stabilizer. Lifting parachutes (high L/D) proved to be no alternative for active devices. Wind tunnel experiments disclosed their poor inflation qualities in the turbulent airflow close to the fuselage. During deployment their dynamic stability is unsatisfactory due to the short riser length. Ram-air parachutes do not fill above 50 m/s (165 ft/s) and probably not during spinning. Their L/D changes a lot with angle of attack and air speed. Minimum canopy area will exceed approximately 7 m^2 (75 ft^2). Such

Parachute filling sequence

The parachute filling sequence is best described by its force-time history (Figure 4). This graph is solely valid for the finite mass condition. This assumes a considerable speed reduction of the system during inflation. Pilot chute inflation, for example, is described by the infinite mass condition, as almost no deceleration of the payload occurs.

After the active deployment device has pulled the parachute bag out of its storage compartment (1) or-

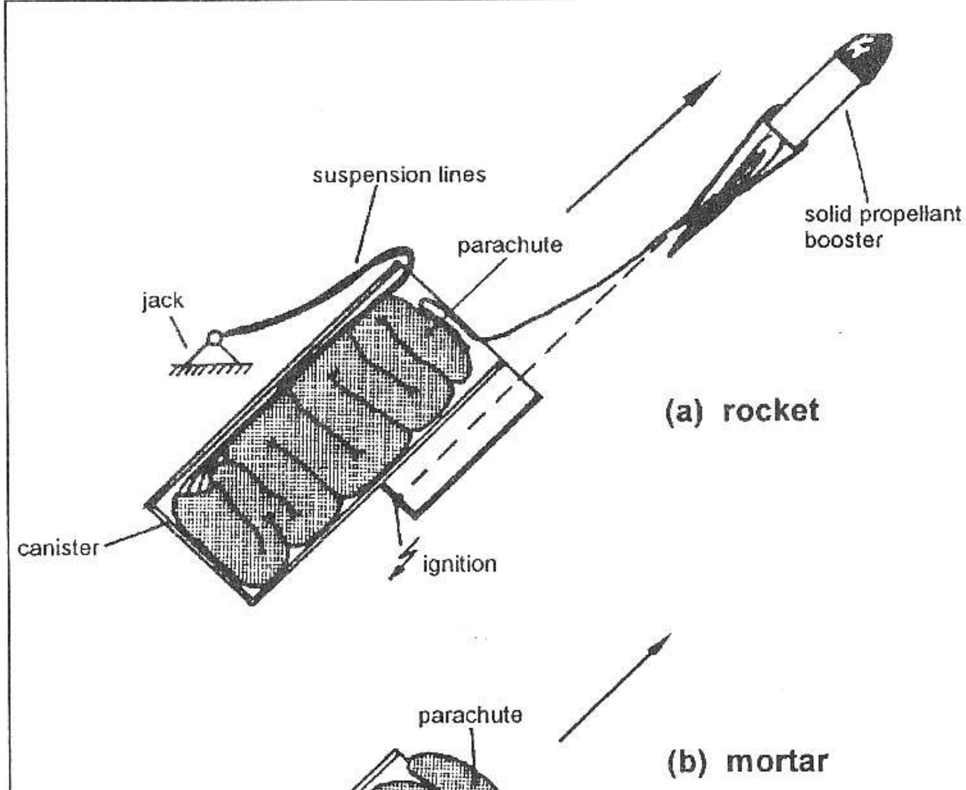


FIGURE 2. Active deployment devices, rocket (a), mortar(b).

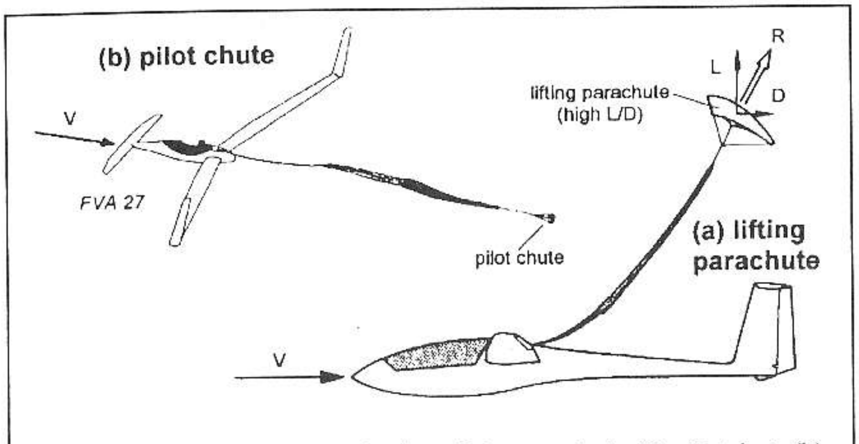


FIGURE 3. Passive deployment devices, lifting parachute (a), pilot chute (b).

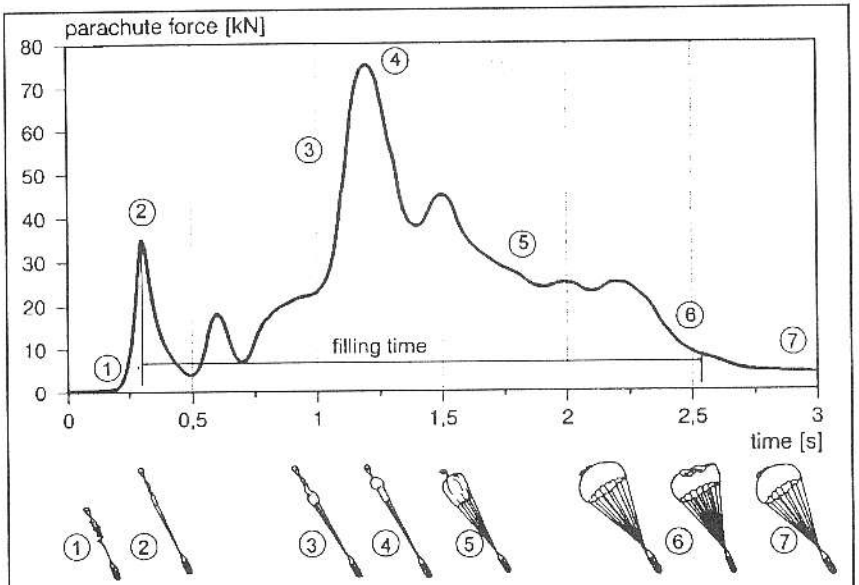


FIGURE 4. Force-time history of a parachute inflation (schematic).

derly line stretching ends with a first peak load called snatch force (2). After the snatch the mouth of the parachute begins to open and a bubble of air streams through the canopy (3). The air mass is abruptly stopped when reaching the crown causing a larger second peak load called the opening shock (4). More air follows inflating the canopy and increasing its drag to full extent (5). Finally accompanying air masses catch up, hit the crown and deform the hemisphere (6). Shortly afterwards the canopy regains its typical shape and the steady state descent phase is reached (7).

After the opening shock no further high peak load occurs. Therefore, the parachute strength is only designed to meet the loads of the first second. Occupant and parachute are able to withstand high decelerations during the filling process, so the weakest chain-link is the glider itself. During this phase the diving glider has a slightly negative angle of attack. As the canopy exclusively inflates with the airstream (Figure 5), an opening shock along the x-axis at V_{ne} or even higher speed generates a tremendous bending moment about the z-axis in the wing root.

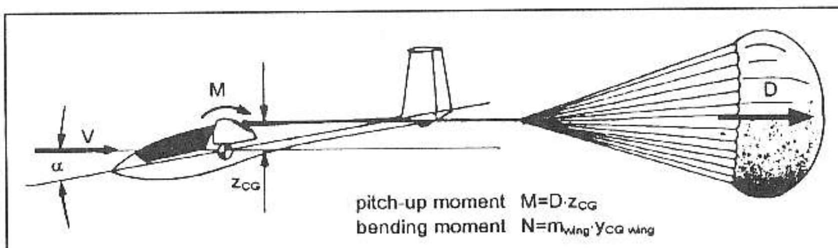


FIGURE 5. Parachute opening force acting on the diving glider.

This might cause a failure of the main spar which is normally not designed to withstand high loads along the x-axis. The wings eventually bend forward, probably crushing the cockpit. High peak loads during inflation also result in heavy pitch-up that could turn the glider over and let it fall into its own bridle. Under these conditions, neither GRS nor PRS can reliably fulfill the task for which they were designed.

These high loads can be reduced by a reefing device. It controls the amount of air flowing through the canopy mouth thus making possible a moderate increase in drag area. Stepwise disreefing by pyrotechnic cutters or continuously by sliders are known and proven technologies. The slider is more advantageous because the filling time is optimized through out the entire speed range. Figure 6 shows both in principle.

Large canopy areas not only increase weight and volume of the system but also require a longer filling distance and filling time. Although the lower opening shock is welcome the filling distance may get too long. In addition, packing, servicing and handling of large single parachutes is impractical. Therefore, the main parachute area is often split up into two or more smaller single parachutes. The canopy area turns out to be a bit larger because of 5% drag loss due to mutual aerodynamic interference. During inflation, clustered parachutes show some sort of Darwinism while struggling against each other for the best airstream. The leading parachute always inflates properly, but has the highest opening force. Lagging parachutes inflate at a lower dynamic pressure, sometimes resulting in a failure of the last canopy which has not got sufficient dynamic

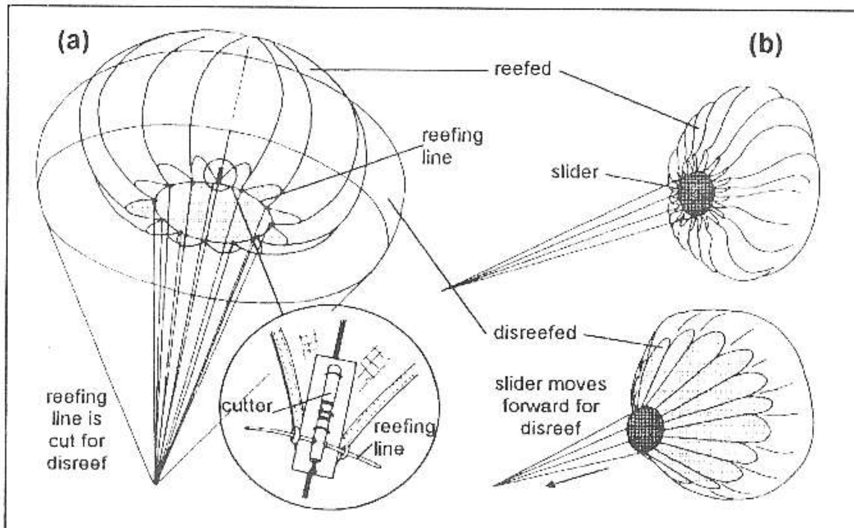


FIGURE 6. Stepwise (a) and continuous (b) disreefing devices (in front of slider not all suspension lines are shown).

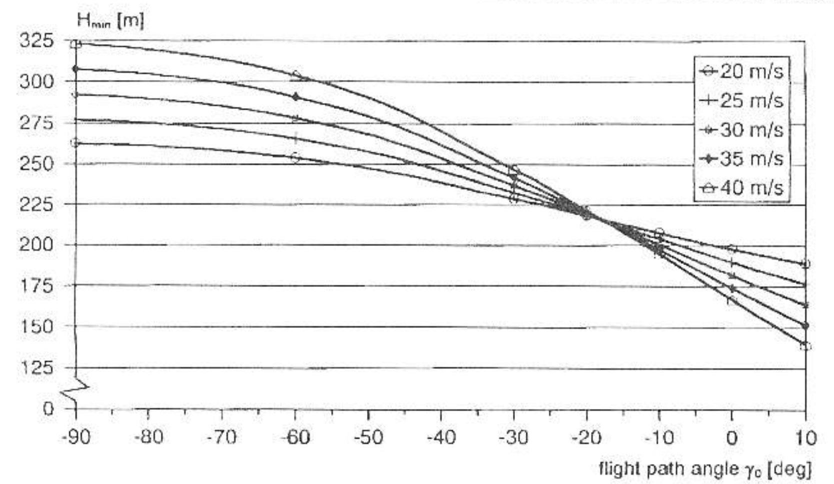


FIGURE 7. Minimum required deployment height H_{min} of a GRS depending on initial flight path angle γ_0 and speed V_0, m = 400 kg, H_0 = 500 m.

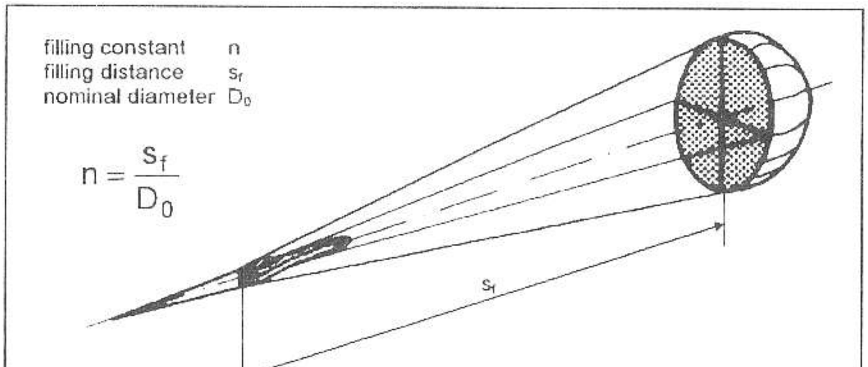


FIGURE 8. Rule of the filling constant.

pressure for inflation. The descent rate with one parachute missing must not exceed a critical value that is limited by the appearance of moderate occupant injuries. All this has to be considered and results in a heavier design. On the other hand, clusters are failure tolerant, smaller parachutes open much faster, and less oscillation occurs.

Minimum required deployment height H_{min}

The lowest height (H_{min}) above which the GPRS operates successfully cannot generally be determined in advance. It depends on the initial values of speed and glide path angle at the time of the mid-air accident. This problem was simulated as the motion of a point mass with two degrees of freedom and a drag area increase according to the Pflanz method [4]. The program was developed by K.-F. Doherr [5] and modified for the purposes of GPRS. The calculation starts with pre-set values for speed V_0 and glide path γ_0 of a glider moving along a ballistic trajectory. 2,5 seconds were assumed for pilot reaction and initiation of the system (phase s_0). Then the parachute system is deployed and a nonlinear increase in drag decelerates the system until steady state descent (phase s_f). Numerous sets of data were processed to cover up the influence of parameters like initial speed V_0, glide path angle γ_0, altitude H_0, mass m, reefing and different parachute systems. Figure 7 shows H_{min} versus γ_0 depending on the speed V_0 at the time of the fatality exemplary for a GRS.

At an assumed level flight with V_0 = 25 m/s (82 ft/s) a H_{min} of about 200 m (656 ft) is needed. At positive path angles kinetic energy is converted into height resulting in a lower H_{min} at high speeds. Values go down to 120 m (394 f) at 40 m/s (130 ft/s). There is no need to say that a vertical dive results in additional height loss especially at higher speeds. A H_{min} of 325 m (1,066 ft) at V_0 = 40 m/s was calculated for this case. This characteristic implies an intersection of the curves at about γ_0^* = -18 degrees. Close to this point H_{min} turns out to be independent of the initial flight speed V_0.

This phenomenon can be explained by the constant filling distance first recognized by W. Müller in 1927. It was noticed that a parachute with a given geometry always covers a typical distance during inflation. At high speeds it will inflate more quickly, and has a longer filling time at low speeds. This is due to the fact that every parachute requires its individual volume of air for inflation. The

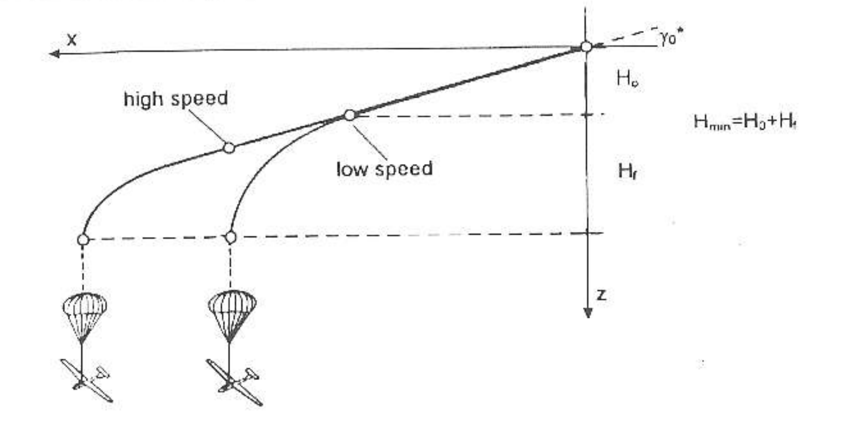


FIGURE 9. Recovery trajectory close to γ_0^* at high and low speed (schematic).

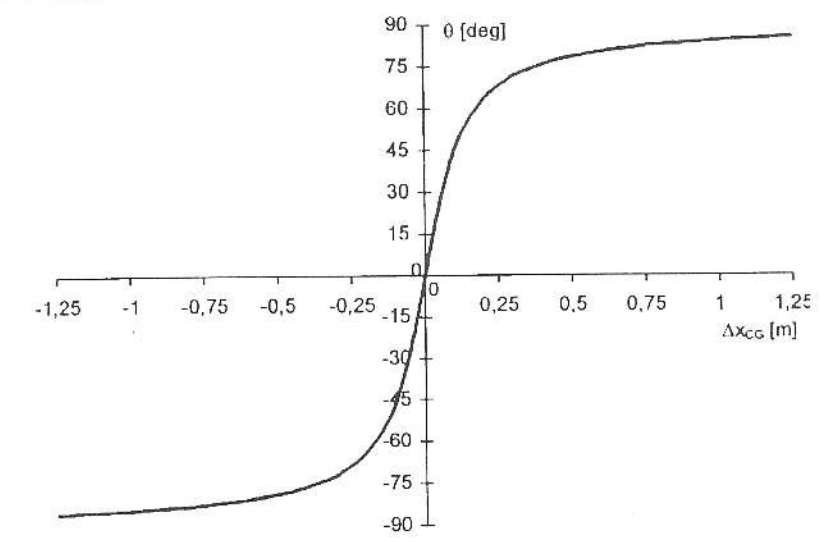


FIGURE 10. Pitch attitude varying with movement of the center of gravity (Δz_{CG} = 0,1 m).

amount of air is gathered along the filling distance that is represented by a cone (Figure 8). This distance is usually divided by the parachute diameter resulting in a dimensionless factor called the filling constant.

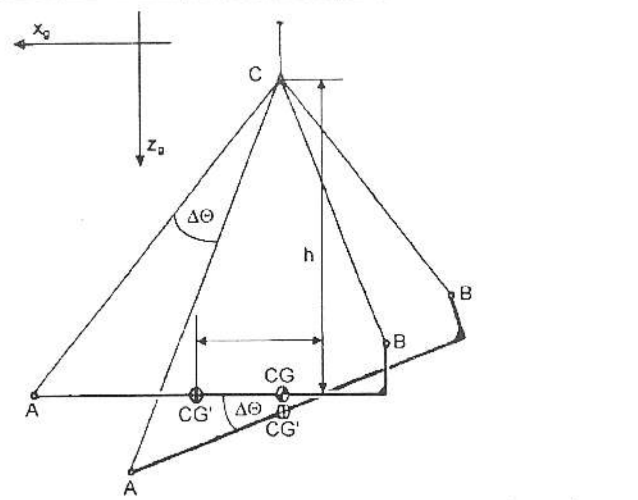
In the small range γ_0* of the intersecting curves the height loss does not increase with higher speeds. Although phase s_0 contributes more to height loss at higher speeds, the ballistic flight path of phase s_f stretches at the same time and increases its radius of curvature (Figure 9).

γ_0* may help to describe the rescue system qualities more precisely. The more γ_0* is shifted to negative values the lesser the system punishes high speed with increasing H_{min}. Large GRS parachutes with high filling constants are found in the -18 degree range while smaller ones for the PRS have a γ_0* of -12 degrees.

The variation of glider mass from 200 to 750 kg (440-1,650 lb), deployment altitudes from 300 to 3,000 m (985-9,850 ft), flat circular and cross parachutes, single or clustered turned out to be less significant. The change of H_{min} is within the ± 25 m range (66 ft) with a little advantage for the PRS.

As already mentioned, properly designed reefing reduces peak loads remarkably but consequently extends filling distance. But calculations on the basis of one reefing stage holding 0,5 seconds at 50% drag area show that in comparison to a halving of the opening force the additional height for a PRS is only about 10 m (33 ft). Even the GRS vertically diving at V_0=40 m/s would only lose less than another 20 m during 0,5 second reefing stage.

Attention must be paid to parachute deployment at high altitudes of about 5,000 m (16,500 ft) and more. As already mentioned above, along with the filling distance, the parachute only needs a constant volume of air for inflation regardless of its density. Thus during high altitude inflation parachutes show a much larger opening force in comparison to an inflation at the same dynamic pressure near sea level. But the increased opening shock can be diminished by reefing devices, especially if dependent



h [m]	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6
ΔΘ [deg]	-26,6	-18,4	-14,0	-11,3	-9,5	-8,1	-7,1	-6,3	-5,7	-5,6	-4,8
h [ft]	3.28	4.92	6.56	8.20	9.84	11.48	13.12	14.76	16.40	18.04	19.69

FIGURE 11. Influence of bridle length on pitch attitude (Δz_{CG} = 0.5 m (1,64 ft)).

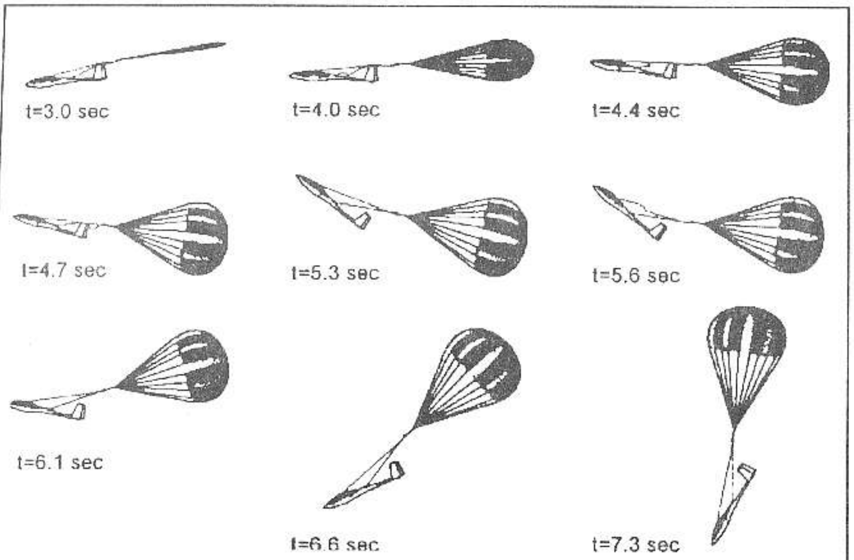


FIGURE 12. Deployment sequence from simulation (two line bridle).

on dynamic pressure.

Bridle and stability

The damaged glider suspended beneath its chute often lacks dynamic stability and contributes to the oscillation of the inherently indifferent behaving parachute. To a certain degree the GRS and PRS are sensitive to heavy oscillations. As static stability is dependent on the pitch attitude, both systems should stay inside a small range of angles in order to achieve a low force ground impact and a proper pilot pull-out. This is described in detail in [3].

A single main riser is unable to compensate any attitude changes resulting from a shifting c. of g. or from aerodynamic forces. Figure 10 gives an impression of the change in pitch attitude if the c. of g. is shifted fore and aft of a single attachment point that is situated 0,1 m (0.3 ft) above the c. of g.

Figure 11 shows the simple geometric relations of a two point attachment that greatly improves the situation. As the points A and B often cannot be chosen freely, a lot can be done by lengthening the bridles L_1 and L_2. Several configurations were investigated during eighty free flight model tests. Scaled gliders (1:4,8), inertially similar and equipped with a flight data recorder were used. Released from a tethered balloon, almost 50 m (164 ft) of steady state descent could be taped on video. Later the acceleration data were examined, together with the slow motion video tapes. Computer simulations with six degrees of freedom showed sufficient comparability between calculations and tests. They pointed out that attachment points and bridle length should be chosen carefully to provide as much damping as possible. A clear result from the simulations is given in Figure 12. Prior to steady state descent the bridle lines stretch alternately and therefore each should be designed to withstand the entire load. The best solution would be a long three line bridle with the forward attachment points moved as far towards the nose as possible. The lines that are attached to the sides of the fuselage are even able to compensate for the banking due to a damaged wing, if the sinking speed is not too high.

Parachute oscillation during descent should be suppressed wherever possible. Vortices detaching from the wings at post stall angles of attack hitting the canopy apply side forces to the parachute. Once pushed out of line, parachutes take time to settle down. Moreover, during wind tunnel tests a considerable loss of drag in relation to total drag was noticed due to vortices. The expression "total drag" stands for the sum of the individual drag of glider and parachute in undisturbed airstream. Figure 13 shows to what extent the forebody wake reduces drag at high angles of attack. How ironical for the gliding movement to complain of the loss of drag!

However, any reduction of drag should be avoided in order to reduce additional canopy area. It was found that the required bridle length should not amount to less than a wingspan, or should be as long as possible. Figure 14 shows recovery of drag of up to 90% of the total drag with increasing riser length. Another important advantage of a long riser is the ability to compensate rotation between parachute and glider. This could replace a heavy swivel when using cross parachutes. Further-

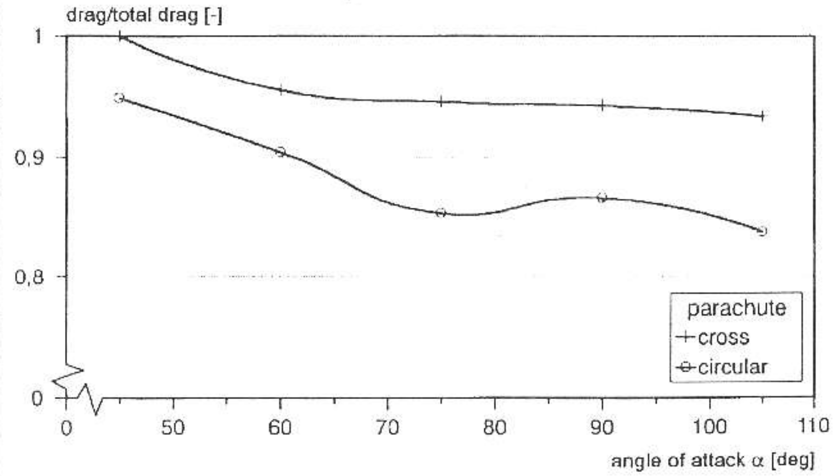


FIGURE 13. Loss of parachute drag caused by forebody wake of the wings at different angles of attack.

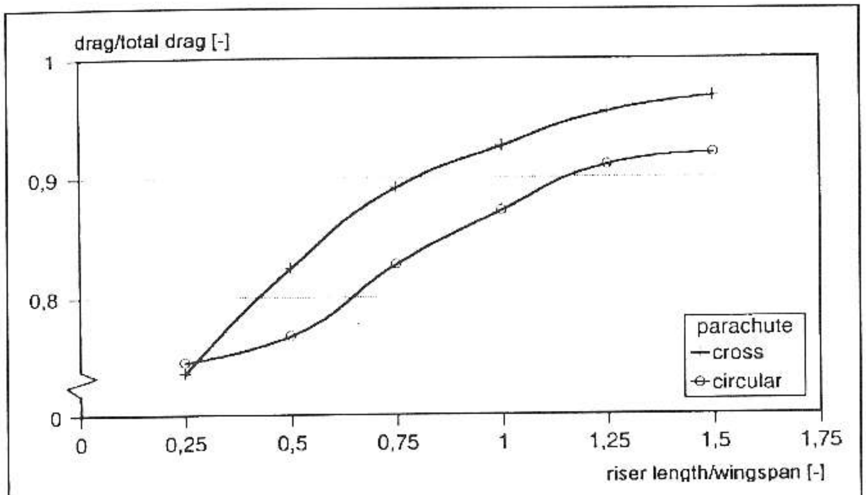


FIGURE 14. Effective parachute drag versus riser length.

more swivels cannot be designed to be failure tolerant. Another source that feeds oscillations is poor static stability of the glider. The basic requirement for static stability is presented in [3].

The bridle should be designed in such a way that the glider stabilizes at about an angle of -30 degrees nosedown respectively, that is about +60 degrees angle of attack. Full scale crash tests [1] showed this attitude proved to be best for low ground impact force.

Conclusions

Glider parachute recovery systems are feasible. The parachute should be deployed actively by a mortar or a rocket to let it go well over the tail unit. The opening peak force must be reduced by reefing to prevent the glider from disintegration and turning over. For a successful rescue the GPRS requires a minimum height of about 180 m (600 ft) at level flight, and even more at higher dive angles. A properly designed reefing phase adds only a minor height loss. A long three line bridle connecting the glider to the parachute at about -30 degrees nosedown angle assures moderate oscillation and satisfactory ground impact behavior. At a bridle length of one wingspan or more, the parachute stays almost clear of the forebody wake. This minimizes the drag loss of the parachute system.

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