NON-GUIDED PARACHUTE SYSTEM
FOR RECOVERY OF SMALL ORBITAL PAYLOADS

Victor Koldaev
Paulo Moraes Jr.
Instituto de Aeronáutica e Espaço/Centro Técnico Aeroespacial
12228-904 São José dos Campos, SP, Brasil, E-mail: koldaev@iae.cta.br.

Abstract

A non-guided high performance parachute system has been developed and tested for the ground recovery of orbital payloads or platform. The system is safe, efficient and affordable for use on small size vehicles. It is based on a pilot, a drag and a cluster of main parachutes and an air bag aimed to reduce the ground impact to 8 g. The system has been designed to maintain a stable descent and prevent failures. To assure the achievement of all these characteristics, the determination of the parachute canopy areas, land impact, inflation and flight dynamics have been considered. Due to the mainly empirical nature of parachute design and development, wind tunnel and flight tests were conducted in order to achieve high reliability imposed by user requirements. The present article describes the system and discusses in detail the design features and testing of the parachutes.

Keywords: Space platform, Recovery system, Non-guided parachutes, Air bag, Wind tunnel

1. INTRODUCTION

Parachutes are used as aerodynamic decelerator systems for a wide spectrum of applications, as for instance: load recovery after drop test, rocket payload recovery, aircraft landing deceleration, vehicle stabilization etc., (Pepper & Maydew, 1971 and Peterson, 1990). They differ in type and size according to their application, so, practically the mission specifies the most adequate parachute system.

Small returnable orbital payloads or platforms need safe, efficient and affordable recovery systems. The systems, based on parachutes, are the most adequate choice, due to their proven reliability and low cost. The present work deals with the design features of a high-performance parachute recovery system for small orbital payloads.

The development of such a system includes the consideration of:
- determination of parachute area and mass,
- drag, stability and stress analysis of the parachute,
- filling time and flight dynamics calculation,
- wind tunnel testing,
- flight and land (impact) testing, and
- materials selection and manufacturing processes.

Therefore, a lot of initial work has to be done concerning the design concept of the recovery system. Good concept and design lead to maximization of performance and, consequently, to the weight minimization of the complete system, which is of great importance for any space system (Deweese, Schultz & Nutt, 1978).

However, parachute design and development are still largely empirical, so, great effort is necessary in the elaboration and execution of several testing methods and programs.

The present paper shows and discusses the mean aspects of the design of the proposed system and the specification of its testing procedures.

2. RECOVERY SYSTEM

A small space platform, known as SARA, is under development at IAE-*Instituto de Aeronáutica e Espaço,* The platform will be used to perform microgravity experiments in orbit, (Moraes, 1998), and its recovery should be safe and soft in order to protect the payload from high ground impact, (Koldaev & Moraes, 1998). Figure 1 shows schematically the procedure of re-entry and landing of the space platform.
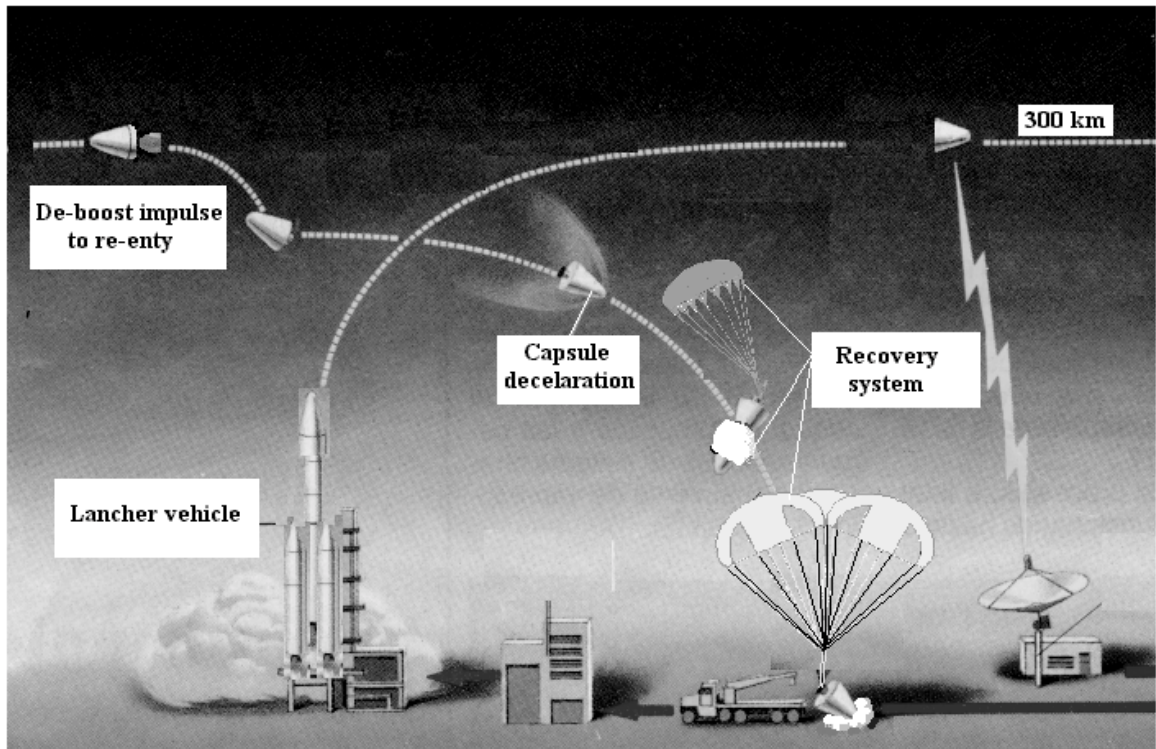

Figure 1. Scheme of platform re-entry

After re-entry the shaped platform will decelerate to subsonic velocities. At 6 km altitude, the velocity of the platform is approximately 135 m/s, so, here the recovery system, based on parachutes, can be put in action, thus carrying the platform to the ground. The specification of the altitude of the parachute system opening depends on the wind conditions during the descent, thus, dispersions due to wind influence must be kept very small. Reason for this lies in the intention to carry out recovery on the ground and the maximum permissible landing area has a diameter of 25 km.

3. DESIGN REQUIREMENTS AND FEATURES

The system under study is specified to carry orbital payloads to 300 kg mass, which will be recovered on the ground with the land dispersion of approximately 20 km.

Basic design requirements for the recovery system are:

- high reliability (better than 0.999), small weight of the system (less than 10% platform weight),
- low platform deceleration during parachute opening and ground impact (up to 8 g),
- stable descent (system oscillations with amplitude less than 10 degrees),
- minimal wind carrying of platform,
- use for a wide range of platform weight (up to 300 kg).

High reliability of the recovery system requires simplicity of construction that means a small number of system functional stages and high safety of systems components.

Small system weight is achieved by selection of a high performance parachute design and optimization of the system parameters, as for instance, altitude and velocity for parachutes opening, areas and types of parachute, materials, etc., (Koldaev & Moraes, 2000).

In order to reduce the landing load, an impact attenuator should be used as decelerator. So, air bag or similar devices must be considered in the specification and design of the recovery system. According to general requirements in order to prevent major damage to the platform and to minimize system mass a rate of descent of 10 m/s is established, Figure 2, (Koldaev & Moraes, 2000).
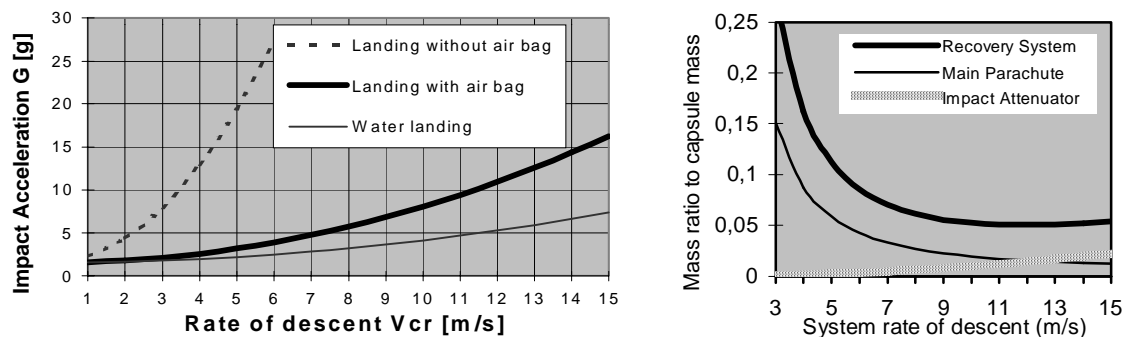
Figure 2. Platform impact load factor and relative system mass vs rate of descent

In order to reduce wind influence on the land dispersion of the platform, the parachute system should be opened at altitudes closer to the ground. The pilot parachute is specified to open at an altitude of 6 km. The main-parachute-opening altitude of 4.5 km can be considered. Simulations have shown that the complete deployment takes up to 35 s.

4. DESIGN CONCEPT

The preliminary concept of the proposed recovery system, Figure 3, is composed of:
- pilot parachute,
- drag parachute,
- cluster of main parachutes,
- air bag as impact attenuator,
- deployment bags, risers, container and separation equipment.

4.1 Pilot parachute

Pilot parachute is intended to provide system reliable putting of the system into action by means of the parachutes stretching out from the container with a definite effort and taking the drag parachute cover off. For more effective filling and stable motion in the turbulent zone

behind the platform, a fabric skirt (band) with a slot will be used. Figure 3 shows the band type of the pilot parachute.
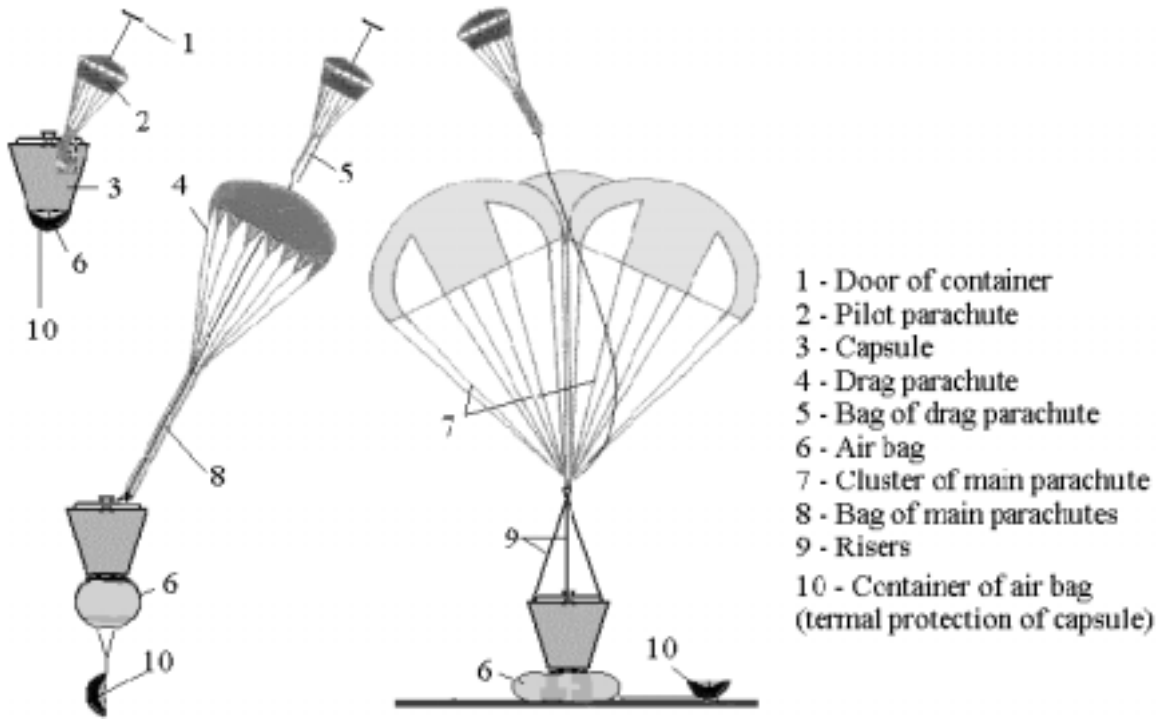

1 - Door of container
2 - Pilot parachute
3 - Capsule
4 - Drag parachute
5 - Bag of drag parachute
6 - Air bag
7 - Cluster of main parachute
8 - Bag of main parachutes
9 - Risers
10 - Container of air bag (termal protection of capsule)

Figure 3. Recovery system component and sequence

4.2 Drag parachute

Drag parachute has function of decelerating the platform down to permitable for the safe speeds, admitted to deployment of the main parachute. The main requirements for drag parachute are:
- to support high dynamic pressure and
- to produce low parachute opening force.

Taking in account these requirements, the ribbon canopy types are the most reliable. Comparatively high opening force coefficient $C_x \sim 1.3$, (Knacke, 1992), and complicated canopy construction because of the necessity to connect a great number of ribbons of different sizes are the main demerits of this parachute. So, for that reason a blade ribbon type is suggested, Figure 4, (Koldaev, 1986).
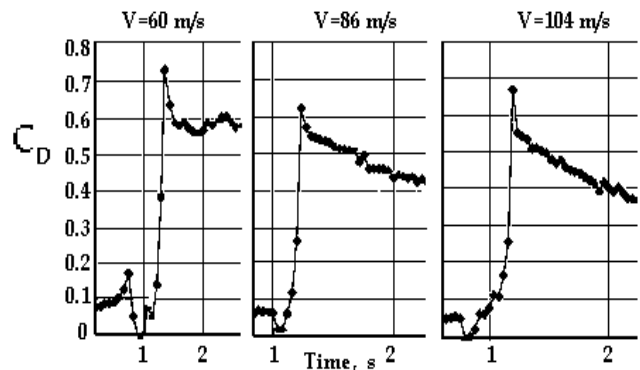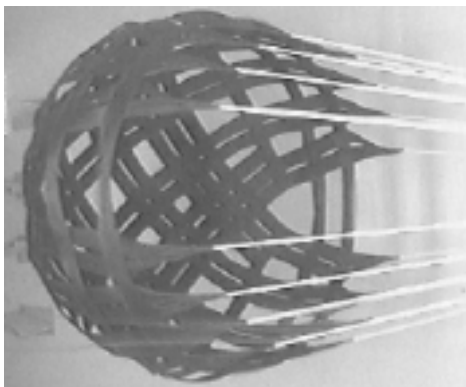

Figure 4. Blade ribbon drag parachute in TA-2 wind tunnel

The blade ribbon canopy is made of groups of parallel longitudinal ribbons, so it excludes the necessity of ribbon junctions, simplifies and lightens drag parachute construction.

4.3 Main parachutes

The main parachute is intended for guaranteeing the necessary rate of descent of the capsule during its approach to the landing surface. There is a recovery system that uses the main parachutes cluster, Figure 5.Use of parachute clusters provides the following advantages:

- A cluster has less probability of a catastrophic failure than a single parachute.
- A parachute cluster provides a stable descent.
- Clustering permits use of one and the same number of the parachutes for a large range of capsule weight (from 50 up to 300 kg).
- It is easier to fabricate, to test and to maintain several small parachutes.

Use of cross parachutes in cluster systems allows alleviating the problem of the dynamics of the deployment of each separate parachute. Cross parachutes are widely used for different purposes and are known as safe, simple and cheap to make.
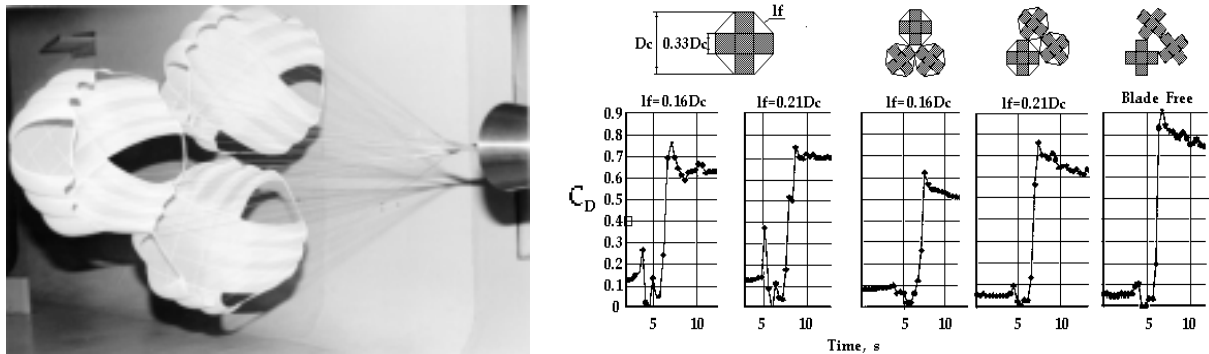

Figure 5. Main parachutes model in TA-2 wind tunnel

4.4 Impact attenuator

Use of attenuators is proposed to reduce the main parachute area that leads to the reduction of the recovery system total mass, as it was shown in Figure 2.

The most suitable attenuator for small payloads is an air bag, (Figure 3). The air bag is inflated just after the deployment of the drag parachute, and, so it can maintain the impact deceleration up to 8 g, which is permissible for sensible payloads. Yet, the attenuation capability of the air bag is limited by its height, i.e., it is determined by the condition of the payload motion stable during the descent and the impact with land surface. So, the maximum air bag height should be less than 1.2 of the payload diameter, (Koldaev & Moraes, 1998). When the air bag capability is insufficient, then, a retrorocket, an elastic riser, a crushable platform or another impact attenuator can be additionally used.

5   SYSTEM CALCULATIONS

5.1 Air bag sizing

To save the electronic equipment of the capsule, the impact acceleration should be less than 5-8 g, (Knacke, 1992). For water landing the load factor can be several times, and

sometime dozens of times, less than at hard landing due to the possibility of suppressing the energy of the capsule impact in the process of its immersion into the water. For preliminary estimation of the load factor value of the capsule landing, it is possible to use its semi-empirical dependence versus sea-level rate of descent, shown in Figure 2, (Koldaev & Moraes, 1998). During the landing of the capsule of a streamlined form with the 1.2 m high air bag or at water landing without an impact attenuator, rather stringent load factor requirements ($< 8g$) to the capsule sensors equipment may be also satisfied with rather high $V_{cr} = 10$ m/s, (Figure 2).

5.2 Parachutes areas

The area of the pilot parachute is determined after the known area ratio $S_p/S_d = 0.01\text{-}0.03$ (Knacke, 1992). For small capsule of 100-300 kg the pilot parachute area is ~ 0.1 m^2. Its mass makes up not more than 2% of the recovery system total mass and may not be taken into account for preliminary calculations.

Maximum area of drag parachute S_d has been calculated after its opening force F_x (coefficient C_x), the permitted capsule load factor G and the initial dynamic pressure q_o, which depends on capsule ballistic parameter $C_c\, S_c\, /m_c$ in descent equilibrium condition without parachute

$$F_x = m_c\, g\, G = q_o\, C_x\, C_{Dd}\, S_d \tag{1}$$

$$m_c\, g = q_o\, C_c\, S_c \tag{2}$$

$$S_d = G\, m_c\, g\, /(q_o\, C_x\, C_{Dd}\,) = G\, C_c\, S_c\, /(C_x\, C_{Dd}) \tag{3}$$

For a drag area of SARA capsule $C_c\, S_c = 0.4$ m^2, $G = 6.5$ and for a drag coefficient of blade ribbon parachute $C_{Dd} = 0.55$, $C_x = 1.2$ the maximum area of parachute from (3) is $S_d = 4$ m^2.

The number n and the area S_m of the main parachute can be determined as:

$$C_{Dm}\, S_m\, n = 2\, m_c\, g\, /(\rho_o\, V_{cr}^2) - C_c\, S_c \tag{4}$$

The required number of the unified main cross parachutes, calculated after formula (4) with the drag coefficient $C_{Dm} = 0.8$, is shown in Figure 6 for small capsules with drag area of $C_c\, S_c < 0.5$ m^2 in sea-level conditions, (Koldaev & Moraes, 1998).
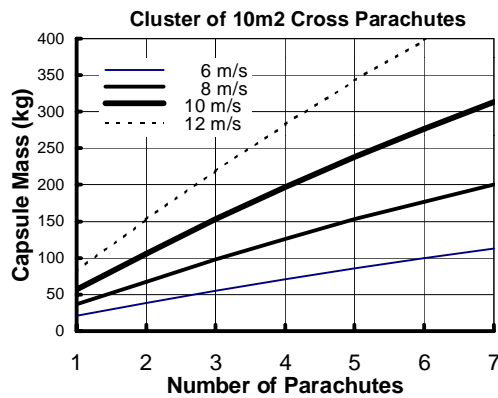

Figure 7. Required number of the unified main cross parachutes

5.3 System dynamics

The result of the dynamic calculation for SARA capsule, which is 215 kg of weight, with the help of the program, (Koldaev, Guimarães & Moraes, 1999), is shown in Figure 7.
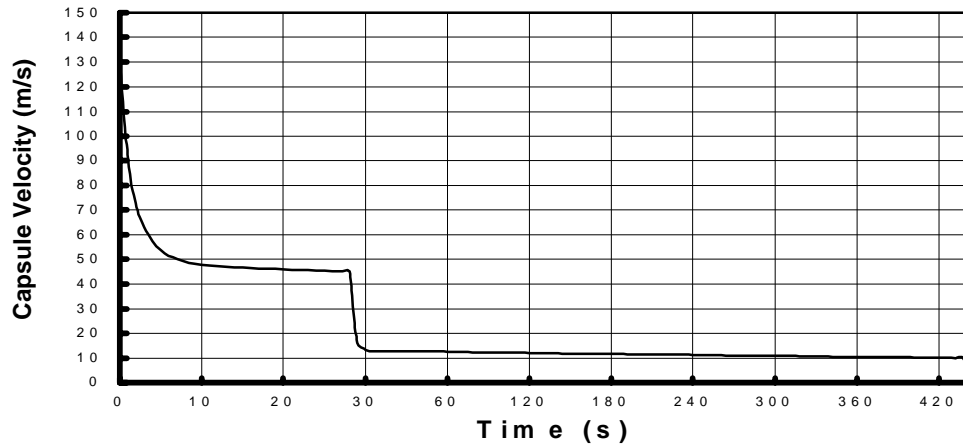

Figure 7. SARA system deceleration with drag and main parachutes

At an altitude of 6100 m with the initial velocity of 135 m/s, the command is given with the help of the parachute release system (baro-switch). The pyrotechnic separation equipment releases the container door and puts the pilot parachute into the wake behind the capsule. After that the pilot parachute stretches the system to its full length and breaks the cord of the drag parachute fixation in the bag and pulls the casing from the drag parachute canopy, which is filled under the influence of the airstream flow. In the process of the drag parachute canopy functioning the capsule decelerates down to the speed of 45 m/s. At 4500 m altitude the device releases the deployment bags and opens the main parachutes. Then, the drag parachute canopy ejects deployment bags off from the main parachutes and due to the connection of the drag parachute canopy with the main parachutes points of junction, keeps them from filling too quickly, decreasing the main parachutes opening force. In the process of the capsule descending by the main parachutes the rate of descent of the system decreases to 10 m/s.

6   TESTING OF PARACHUTE SYSTEM

Preliminary estimation testing of parachute models is performed at initial stages with the aim of choosing the best solution and obtaining approximate estimation of the system parameters. At the last stage of the parachute system development, testing of the complete system is required. And it is of great importance that testing conditions should be close to real ones in order to reveal and to exclude all possible reasons of occasional failures and to prove necessary level of safety and reliability. So, a complex of experimental work secures the design of such a parachute system, which satisfies all the requirements. Reference (Koldaev & Figueredo, 1996) shows several testing devices, which can be used for ground testing of parachute systems.

6.1 Wind tunnel testing

With the aim of selecting the recovery system configuration for SARA space capsule (150-250 kg of weight) and to determine the parachute aerodynamic characteristics, the TA-2 wind tunnel testing was conducted in the *Centro Técnico Aeroespacial,*(Koldaev, 1996). The

capsule model, two variants of the main parachute in 1:5 scale, the blade ribbon drag parachute in 1:2 scale and the band type pilot chute in real scale, all made of Nylon, were used. To register the parachute force, a special three-direction pies-dynamometer was placed in the capsule model. The cutting knife was used to separate the parachute model from the capsule model to put it into action during the test. The results of the parachute force registrations are shown in Figure 3 and Figure 4. In the result of testing the parachute inflation time, the opening force and the drag coefficient were determined for all parachute models.

The blade ribbon drag parachute and the band-type pilot chute were tested with velocities from 40 up to 110 m/s. The test observations showed, that the drag parachute, Figure 4, and the pilot chute had high stability, presenting no canopy oscillation and rotation. As for real condition the main parachutes were tested with the air velocity from 30 up to 40 m/s. The test observation showed, that the cross parachute suffered intensive rotation, which caused the lines to twist and shorten.

Use of a canopy cluster reduces parachute rotation. The drag coefficient of a three cross parachute cluster depends on the type of fixation between the canopies. The cluster with free blade canopies has the highest drag coefficient, Figure 5.

6.1 Flight testing

The aircraft flight-testing was conducted using a drop method, (Koldaev, 1997). For testing, a three cross parachute cluster and one annular parachute in real scale were manufactured, a cylindrical cloth casing of 60 kg of weight was used as a capsule model. The parachutes were put into action at an altitude of 500÷700 m with the help of a break cord, connected with a light aircraft. The initial flight altitude, H_o and the time of the system descending with the filled parachutes, t_d, were registered during each experiment. The main parachute drag coefficient, C_{Dm}, was calculated for sea-level air density ρ_o after the formulas

$$V_{cr} = H_o / t_d \tag{5}$$

$$C_{Dm} = 2 \, m_c \, g \, /(\rho_o \, V_{cr}^2 \, S_m) \tag{6}$$

Two variants of test parachute systems deployed and filled without delay, had stable canopy forms and descended without rotation and oscillation. They could be recommended as the recovery systems prototypes for conducting future experiments.

Another more complex test device is described in reference, (Moraes, 1997). In this case stratospheric balloon is used to elevate the capsule up to 32 km of height. After reaching this height, the capsule will take approximately 4.5 min to drop to the ground. During this time a lot of experiments can be performed, as for instance, aerodynamic measurements, retro motor test, telemetry, etc., and the recovery system can also be verified at higher velocities, which are closer to the velocities, encountered by the re-entry flight.

7 CONCLUSIONS

A recovery system for small returnable orbital payloads, based on parachutes, has been proposed and discussed. High reliability and low cost of parachute systems lead to their choice as the most adequate for the present case.

The high performance recovery system under study is based on a three-stage parachute system to recover orbital payloads up to 300 kg at ground. The designed system also considers the use of impact attenuators, with the aim of reducing the loads down to 8 g.

To design the recovery system of the orbital platform SARA, the canopy areas of parachutes have been determined, which guarantee minimum system mass and volume.

Compared with the basic system, the system so optimized has simple design and high functional reliability due to the exclusion of the parachute-reefing load during parachute opening and landing impact.

Acknowledgements

8   REFERENCES

- Ewing, E. G., 1968, "Design Development of U. A. Recovery System", SAMSO 68-244 (AD 8359172).
- Deweese, J.H., Shultz, E.R., Nutt, A.B., 1978, "Recovery System Design Guide", Technical Report AFFDL-TR-78-151, California.
- Knacke, T.W., 1992, "Parachute Recovery Systems Design Manual", 1sted., Para Publishing, Santa Barbara, California.
- Koldaev, V., 1986, Ribbon Parachute. The Invention n^{0} 281556 with priority from 30.06.86, Inventions and Discoveries Affairs State Committee of USSR.
- Koldaev V., 1996, Sistema de Recuperação SARA. *Ensaios de Pára-quedas em Túnel de Vento*. Technical Note NT-142/ASE - N/96, CTA/IAE, *São José dos Campos*.
- Koldaev, V., 1997, Sistema de Recuperação SARA. *Ensaios de Sistema de Pára-quedas em Vôo*. Technical Note NT-/ASE-N/96 (internal report), CTA, *São José dos Campos*.
- Koldaev, V., Guimarães, M., Moraes, P.Jr., 1999, "Simmulation of Parachute Dynamics", *XV Congresso Brazileiro de Engenharia Mecânica*, COBEM'99, Águas Lindoia.
- Koldaev, V., Moraes, P.Jr., 1998, "Design of Impact Attenuators for Ground Recovery of Small Space Capsules*", V Congresso Brasileiro de Engenharia Mecânica Norte-Nordeste*, Fortaleza-CE.
- Koldaev, V., Moraes, P. Jr., 2000, "Method for Optimization of Recovery System Parameters and its Application", Article accepted for CONEM'2000, Natal.
- Koldaev, V. & Figueredo, E. Q., 1996, *"Estudo Preliminar para Implantação de Infraestrutura Básica para Desenvolvimento de Sistemas de Recuperação de Cargas Úteis Espaciais"*, CTA/IAE, NT-121-ASE-N (internal report), CTA, *São José dos Campos*.
- Moraes, P. Jr., 1997, *Uso de Balão Estratosférico para Ensaios em Vôo do SARA*, CTA/IAE, NT-133/ASE-N (internal report).
- Moraes, P.Jr., 1998, "Design Aspects of the Recoverable Orbital Platform SARA", 8° *Congreso Chileno de Ingenieria Mecánica, Concepción*, Chile.
- Peterson, C. W., 1990, "High Performance Parachutes", American Scientific Aircraft Journal, pp. 108-116.
- Pepper, W. B., Maydew, R. C. Aerodynamic Decelerators - An Engineering Review, J. of Aircraft, vol. 8, no. 1, pp. 3-19, 1971.