CHAPTER 1

INTRODUCTION

Abbreviations

AFB	Air Force Base
AIAA	American Institute of Aeronautics and Astronautics
ASTM	American Society for Testing and Materials
CARE	Crew Module Atmospheric Re-entry Experiment
CVCM	Collected Volatile Condensable Material
FMEA	Failure Mode and Effects analysis
FTA	Fault Tree Analysis
HAHO	High Altitude High Opening
HALO	High Altitude Low Opening
INCOSPAR	Indian National Committee for Space Research
ISRO	Indian Space Research Organization
MiL-STD	Military Standard
NASA	National Astronautics and Space Administration
NTRS	NASA Technical Report Server
PDS	Parachute Deceleration System
RBD	Reliability Block Diagram
TML	Total Mass Loss

1.1 Introduction to Parachute Deceleration System

A retardation system consists of components that function together to control deceleration and to stabilize the payload in flight. The basic component of a retardation system is the deployable flexible structure called aerodynamic decelerator, which transfers the momentum of the moving payload to the atmosphere by acceleration of the ambient air. The decelerator's aerodynamic lift, drag and stability determine its operational characteristics. A modern decelerator is desired to be flexible and efficient in terms of weight and packed volume.

One of the most important features of the recovery process of any space payload is the deceleration and landing. Flexible parachute is one of the decelerators used for airdrop of personnel, military equipment, and recovery of missiles, adventures, rockets and spacecraft. In these application areas, the velocity of the objects at the time of the use of the parachute is found to be different and with wide variation. This variation in the term of parachute performance-envelope and is as shown in Figure 1.1. The US Air Force at Wright-Patterson AFB initiated a program in 1950 with Cook research Laboratories (CRL) to develop parachutes to operate at supersonic speed for the recovery of missiles and drones (Downing, 1954). Gupta (2010) describes such flexible structured parachutes used for the recovery of various types of payloads. These parachutes are also used in landing of rovers on other planets, supplies to victims of natural disaster, recovery of space shuttle, and precise deliver of military troops to the battlefield. Payloads used in space programs, etc., are very expensive and therefore recoveries are essential for reusability of such payloads.

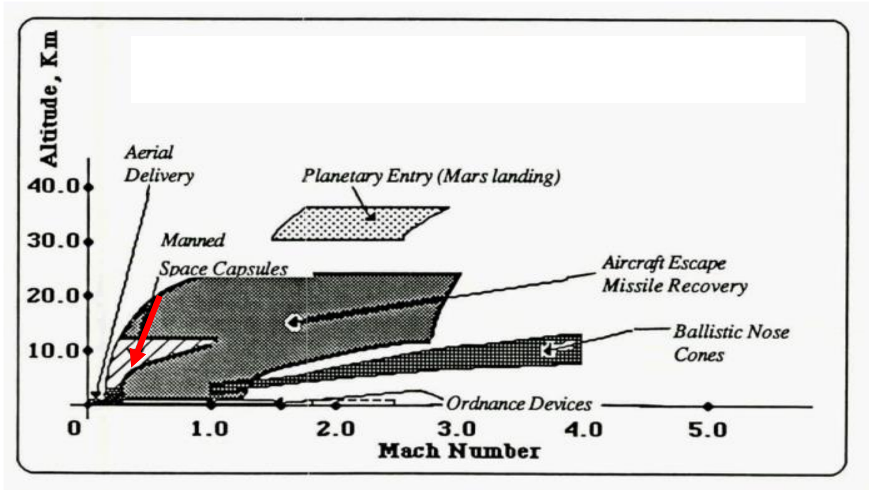

Figure1.1: Parachute performance-envelope

In view of the above, a reliability-based methodology needs to be adopted for the design of inflatable parachute structures. The research has to be carried out for the design of parachutes from this perspective, while mitigating the risk challenges by studying the various failure modes. Even though a lot of work is going on across the world in this regard, but it is hard to find the used design criteria, testing methodology, failure and reliability data, and analyses details in complete.

1.1.1 Challenges in Design for Operational Reliability

As mentioned earlier, Parachute Deceleration System for space mission requires very high reliability and confidence level for the success of a mission. The designing of the system has to take care of such concerns. The design would involve various numerical analyses and the product development testing on model as well as prototypes. The following are the few challenges that need to be addressed in the design.

(i) PDS must be human rated.

(ii) Reliability should be very high (> 0.999), practically no chance of failure during the operation as the failure of PDS will cause loss of the mission and loss to the life.

(iii) The weight, cost, development time and packing volume should be the minimum.

(iv) Operation, even in varying and random operational conditions (wind, storm, gust), should be robust.

(v) There should be ease in packing and the packing density should be low.

(vi) Smart and right mechanism for parachute deployment is required.

(vii) Material selection is required as per space standard.

(viii) Proper staging of parachutes has to be ensured

1.1.2 Problem Related to Design and Development of a PDS

Any decelerator system for recovery of the payloads must be validated before actual use. NASA had designed a two-stage decelerator system for their 5-ton payload consisting of drogue and main parachutes (West, 1973). So was the case with the Apollo-Soyuz (the first international space mission carried out jointly by the US and Soviet Union in July 1975 (Apollo-Soyuz, Wikipedia)), Gemini 8 (the sixth crewed space flight in NASA's Gemini program) launched in March 1966 (John, 1966; MacDonnell, 1965), or Shenzhou (Guo *et al.*, 2011). But the designing based on the reliability had been a big challenge due to non-availability of sufficient data. Lutomski and Garza (2012) could estimate somewhat measure of reliability of Soyuz crewed spacecraft only after a loss of 44 supply flights to the International Space Station, two losses of crew incidents and two losses of mission incidents. From this perspective, it becomes important to design and develop prototype

PDS for reliable and successful performance of the mission. Various problems encountered in the designing of PDS are described below.

Problem 1: Designing of architecture of the parachute deceleration system

The architecture of parachute system for recovery of any space payload is the most important part of the design. Since the parachutes are made for retardation of an object falling with very high-speed in lower part of atmosphere, it is necessary to estimate and evaluate expected forces on the parachute system. Ray (2017) has studied the performance the capsule parachute assembly systems only with variation in their architecture. Staging of parachute is the most important dimension of the architectural design. Besides, the cost of testing, packing volume and reliability of the designed parachute are the major issues to be addressed. In addition to all these factors, major challenges are encountered in terms of the space available for parachute packing and also the velocity at which the parachutes are to be initiated.

Problem 2: Design and selection of materials for space application

Fixing the stages, the size, shape and number of parachutes at each stage need to be decided. Special provision to the shape, etc also, needs to be worked out. Once the design is finalized based on numerical computation and simulation, the materials for the various components of the parachutes are to be suitably decided. The parachute may be with reefed canopy. Most of these required materials are not available within the country. This also poses a lot of challenges. The use of available materials necessitates the use of two or three stage of parachute (or parachutes in cluster) in place of a single parachute. In any flexible structural system, material margin has an important role to play. For its one-shot use, the margin of safety is generally kept in the range of 20-30% or more. In its multiple or repeated usage, fatigue factor is also taken into account and thus margin of safety is kept very high. Quality is the other main issue in material selection. It is to be addressed through quality checks at all levels of processes including third party inspection in order to ensure conformity to the required space standards.

Problem 3: Testing for space endurance

The environment of the space has a lot of impact on the material degradation etc. To account for the effect of space environment on the parachute deceleration system, Total Mass Loss (TML), Collected Volatile Condensable Material (CVCM) and thermo-vacuum tests are to be carried out in lines with ASTM-E-595 specifications. The strength of parachute materials before and after subjecting to thermo-vacuum environment is to be evaluated. Further, one complete parachute assembly, including pilot, drogue and main parachute packed and stored in parachute container for six months followed by thermo vacuum exposure is to be tested in dummy drop trial in order to account for the effect of packing. Environment tests hot soak cold soak, fungus, thermal shock and salt mist as per MIL Std. 810 F procedure I and II) are also to be carried out on stitching joints of parachutes. The strength evaluation of these stitching joints, before and after subjecting to environment test, is also to be carried out.

Prototype parachute has to be tested for static and dynamic conditions at the simulated speed and at a dynamic pressure equivalent to re-entry atmospheric conditions.

Problem 4: Identification of underlying risk and hazard

The parachute application in space recovery module is prone to failure. Some failures could be fatal and lead to the total failure of the mission. This demands a serious effort on the risk analysis. Bedford and Cooke (2011) also highlight the importance of the same. The factors responsible for failure may be technical or unforeseen environmental conditions or even may be due to human. Human errors have been found during packing of parachutes or while integration with module.

Problem 5: Integrated FTA-FMEA for investigation of the parachute failures

Traditionally, only Failure Mode and Effects Analysis had been carried out in aerospace industry to take care of the safety issues, and the analysis was not so deep as it is desired. The analysis has to focus each and every stage of the parachute right from its design, manufacturing, testing and deployment to operation. Fault Tree Analysis was generally conducted independent of FMEA. The two analyses approaches (Philipson and Wilde, 2000) can complement to each other to provide powerful insight, particularly in enhancing the reliability of the parachute operation.

Problem 6: Design for reliability

Integrated FTA-FMEA would provide a complete picture on the reliability of each and every component including their impact on the fatal failures (Dhillon, 1999). This data would then have to be used in coming up with a design with high reliability (~ 0.999) or ultra-high reliability (> 0.999) for space payload recovery decelerators (Knacke, 1992).

1.2 Introduction to Tether

Tether is a flexible structure used in many applications, such as station-keeping of the aerostat, space cable, underwater towing, holding the highly dynamic floating bodies and blimps (Gupta, 2007). The tether consists of the composite multi-core electro-mechanical cables having high strength to weight ratio. Tether's design depends upon several factors.

Light weight, high strength, and high reliability are the most important factors for deciding the material to be used for the tether. As shown in Figure 1.2. The tether used in this study has multifunctional elements within one cable: Vectran layers for strength, lightening wires, conducting wires, optical fibers for data transfer and outer PU jacket (Gautam *et al*., 2017). Tether is used to transmit various electronic data, electrical signals, and provides mechanical strength against the buoyancy of helium filled balloon.

Figure 1.2: Construction details of hybrid tether

1.3 Relevance of the Present Work

1.3.1 Related to Designing of Parachute Deceleration System

Indian space program began in 1962 under Indian National Committee for Space Research (INCOSPAR) and then it was vested in ISRO with 1969. Indian space program is going very fast. India has completed 109 spacecraft missions, 77 launch missions, 10 student satellites, two re-entry missions, 319 launches of foreign satellites, one Mars mission and two moon missions. First re-entry experimental mission was launched on 10 Jan 2007(SRE-I) and the second one on 18 December 2014 (CARE mission). India has a futuristic plan to send its astronauts to the International Space Station and then to moon. In this process, India is ready to send its astronauts in lower earth orbit. It is natural to safely recover the crew module. For the recovery, still PDS is considered to be the best option towards recovery due to the following reasons.

(i) PDS is most tried and tested method and is still employed for deceleration of space vehicles.

(ii) Availability of wide range of parachutes.

(iii) Parachute can work in differing conditions, High Altitude Low Opening (HALO) velocity or High-Altitude High Opening (HAHO) velocity.

(iv) Light weight and minimum space required for packing.

(v) Ease in maintaining a right descent velocity

(vi) Low carrying cost compared to any other deceleration devices.

(vii) High performance reliability

1.3.2 Related to Designing of Hybrid Tether

Since hybrid tether is a crucial component of an aerostat used in surveillance. Its designing should be optimal with respect to pre-specified reliability. The complete designing has to ensure that the tether is of the least possible weight and possesses required strength and high reliability. So far, this kind of work is neither available in the literature nor is ever done.

1.4 Research Objectives and Goals

The present research work is devoted (i) to design and develop a PDS for manned-mission, a system for safe recovery of the crew module, and (ii) to design and develop tether for an aerostat for their reliable performance.

1.4.1 Related to PDS

The PDS has to reduce the velocity of the-entry space payload of 3.5 ton for safe landing. To this end, the present research work is devoted to

(a) Designing of the complete PDS by

  (i) identifying a suitable parachute architecture,

  (ii) deciding proper size, shape, number and improvisations in the parachutes to be used at each stage,

  (iii) deciding right material for the parachute components from the available choices,

  (iv) validation by conducting tests on parachute joints and materials to ensure safety against environment factors, and further validation through static and dynamic qualification tests, and also by flight tests, and

(b) Modification in the designed PDS based on the test study for ensuring performance to the specified reliability level by

  (i) carrying out integrated FMEA and FTA,

  (ii) performing risk and hazard analyses,

  (iii) improving the low reliability parts,

  (iv) testing the prototype PDS with the modified design for reliable performance, and

  (v) testing the prototype PDS with the modified design under further severe conditions to ensure failsafe operations of PDS.

As mentioned earlier, there is no work available in public domain that provides a complete framework related to the design of PDS for re-entry module. The work carried out in the present research work will provide a complete framework, particularly to Indian scientists, to design a reliable PDS even for future manned mission.

1.4.2 Related to Tether

The following research objectives have been taken up regarding design and development of a flexible hybrid tether used in aerostat:

(i) determining the tether diameter based on classical design approach considering specified loads and factor of safety,

(ii) determining the reliability of the tether for the worked-out diameter of the tether considering random environmental and usage factors, and

(iii) determining the right diameter [different from worked-out diameter in (ii)] for the tether to provide high reliability at the least extra cost for repeated use under uncertain working condition.

1.5 Organization of Thesis

The focus of the research is to design and develop a descent system for the safe atmospheric re-entry flight. The descent system is subdivided into stages of deceleration required to slowdown the payload velocity. Then analysis carried on risk involved, failure modes and estimation of reliability based on trials data captured during prototype testing during development stage.

The current research work has been structured and partitioned into ten chapters as depicted in Figure 1.3. A brief of the contents provided in the various chapters is presented below.

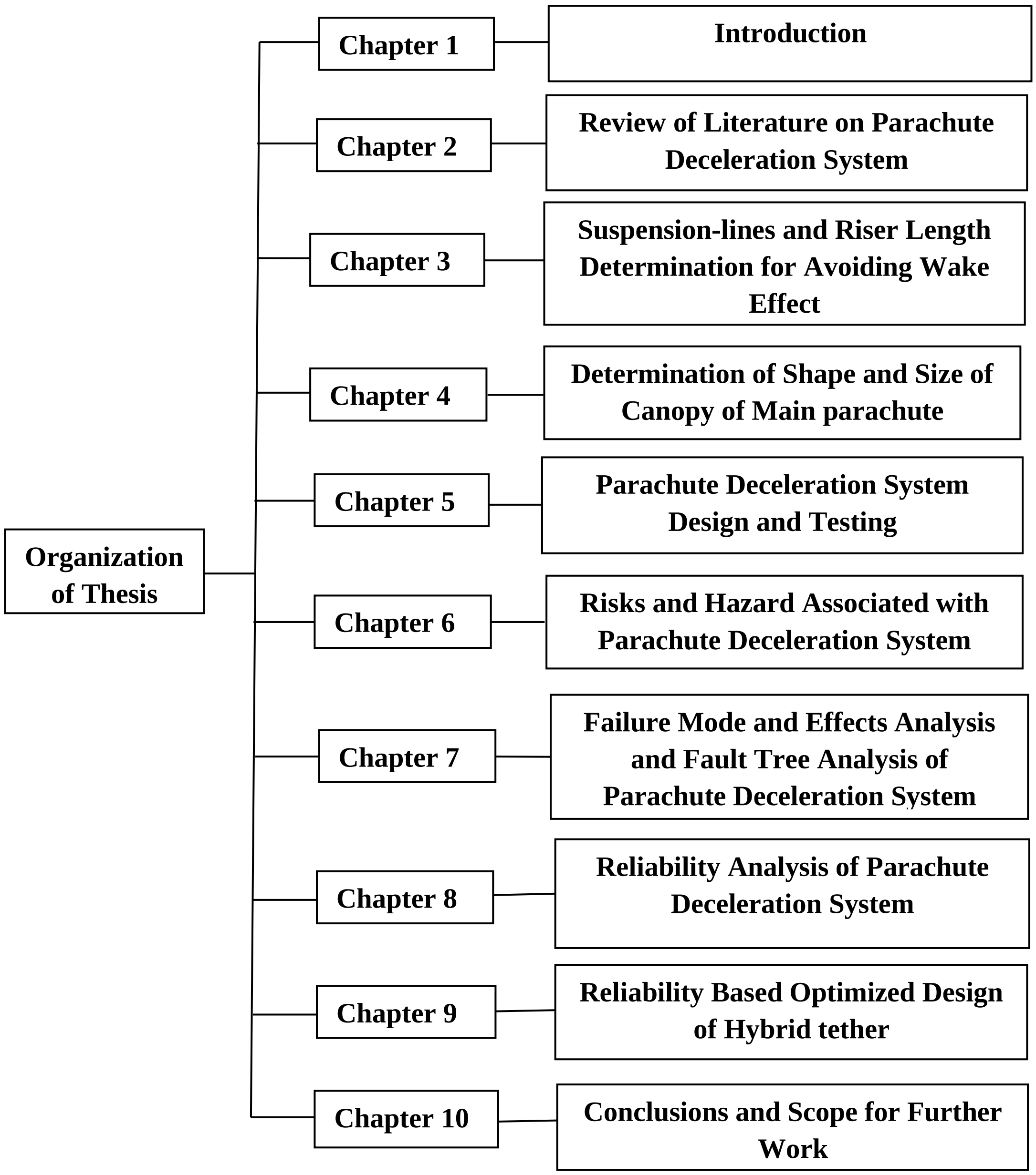

Figure 1.3: Flowchart representing the thesis structure

Chapter 1: Introduction

Chapter 1 explains the concepts, origin of parachute and cost effectiveness of using parachute deceleration system for the recovery of a re-entry module. Background of parachute, design reliability and its relevance in contemporary space missions being in practice in the world are discussed. Challenges faced during design, testing and realization of PDS is also presented. Besides, the hybrid tether is also explained that is used to support aerostat balloon with the ground station.

This chapter also draws importance of carrying out reliability-based design of flexible aerodynamics structure as parachute deceleration system for manned mission and hybrid tether for aerostat application. Besides, the relevance of the present work, research objectives is covered in detail.

Chapter 2: Review of Literature on Parachute Deceleration System

In carrying out the present work, the research papers were collected from the database of reputed publishers like Elsevier, Defence Science Journal, Journal of Mechanical Engineering, Conference papers, Wikipedia on Apollo (USA), Soyuz (Russia), Shenzhou (China) and other NASA mission programs while using the keywords such as re-entry capsule recovery, drogue parachute, main parachute and other AIAA/NTRS reports and Scopus indexed papers. Also, journal papers, design manuals, earlier space mission conducted so far and reputed reports were also referred. In addition to journal papers, research and scientific articles, internet, blogs, conference papers and books were also studied in order to get better insight into the subject. Chapter 2 provides literature review related to PDS including summary of current design practices and their shortcomings. Literature of earlier successful space missions are classified and explained.

Chapter 3: Suspension-lines and Riser Length Determination for Avoiding Wake Effect

The size and shape of the crew module causes wake behind itself during its descending. In case the parachute canopy does not go beyond the wake zone, it will not inflate causing loss of mission. Determination of right length of suspension-line and riser, combined together, becomes very important from this perspective. This chapter details the related experiments that were carried out to determine the least and the safe length of the two put together.

Chapter 4: Determination of Shape and Size of Canopy of Main Parachute

It is the main parachute that finally brings the crew module to the ground at a low terminal velocity. Its size is huge. Since space-mission is desired to carry less amount of load as far as it may be possible, a drastic cut in the weight can be achieved by properly choosing the size and shape of the canopy of the main parachute. This chapter details the slotted-solid circular canopy worked out in this research work. This kind of canopy has not been tried in any of the space missions so far. The proposed canopy has more coefficient of drag. Naturally, the use of a canopy with high coefficient of drag is going to reduce its size and, therefore, its weight.

Chapter 5: Parachute Deceleration System Design and Testing

Chapter 5 discusses the approach used to implement the design methodology as mentioned in the research objectives. The design takes input from the work presented in Chapters 3 and 4. This chapter covers the design philosophy used in identifying a right architecture for the parachutes, and selection of materials and margin of safety. In the present research, two stage deceleration systems with redundancy at each stage is proposed and system reliability validation is carried out through quality controls and various testing / trials.

Once the design methodology set, the results were compared with the similar work published worldwide on such recovery missions to discover any discrepancies or weakness in the design method.

Chapter 6: Risks and Hazard Associated with Parachute Deceleration System

Chapter 6 outlines the probable risks involved in the design of parachute system keeping in view the space application. Since human life is involved, therefore, proper functioning of parachutes is required to be ascertained in terms of probable risks involved in packing, integration, operation and safety. It is necessary to highlight severity of the risks and to eliminate the causes of failure. In this regard, hazard model scenario, hazard-risk matrix, accident scenario and their probable causes have been worked out presented. Many factors were identified that deserved the designers' attention during fabrication, testing, packing and installation on the module.

Chapter 7: Failure Mode and Effects Analysis and Fault Tree Analysis of Parachute Deceleration System

Chapter 7 describes the various modes of failures of flexible parachute system and the recommended corrective actions during design, post-design and before installation on the crew module. FMEA and FTA tools were used to identify the weakness in design, process, product development and interference of other components. Initially, FMEA was used to focus upon safety issues related to manned mission wherein no failure could be tolerated. For the judgment of the failures, a brainstorming with all stakeholders was conducted, and the data was compiled for analysis and also to identify remedial actions. These tools help in decision making through failure analysis for minimizing defects and failures. Integrated FTA-FMEA framework helps in determining component failure effects on the system, components that might be overlooked based on the traditional FMEA technique. Integrated FTA-FMEA prioritizes the risks based on their ranking and sets proper direction in identifying a right design and relevant testing policies.

Chapter 8: Reliability Analysis of Parachute Deceleration System

Safety and reliability are generally considered to be the most important design parameters in space missions. This chapter presents reliability block diagram and reliability analysis of various components of a parachute system. This chapter uses the stress-strength method to assess the system reliability. Certain reliability values of bought-out items were taken from the available standards. If the components are not directly contributing in the parachute function, its reliability has been ignored for the analysis of system reliability. Only critical parts of the aerodynamic deceleration have been considered.

Chapter 9: Reliability Based Optimized Design of Hybrid Tether

A reliability-based design optimization of a flexible hybrid tether has been discussed. After performing certain tests, the diameter and material of the hybrid tether were determined. The analysis also indicated as how to choose a right diameter for the tether to provide a reasonable reliability without increasing much of weight.

Chapter 10: Conclusions and Scope for Further Work

Chapter 10 covers the research conclusions from the work carried out related to parachute deceleration system and a hybrid aerostat tether. This chapter complies and summarizes the present research work and its limitations. This chapter also provides the recommendations for future research work in this field.

1.6 Summary

This chapter details the problems and research issues related to flexible aerodynamics structures as parachute deceleration system for manned mission and a flexible hybrid tether for aerostat application. This chapter also discusses the important characteristics, concepts, application of parachute decelerator system for various payloads and also of the hybrid tether. In addition to these, this chapter provides details on the relevance of the thesis, objectives and challenges in parachute design and reliability considering the contemporary space missions being in practice in the world.