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Reliability Determination of a Sounding Rocket Separation System Using its Reliability Block Diagram and FMEA

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Separation system is one of the most important systems in rockets. The influence of this system on mission success cannot be ignored. In this paper, reliability of a sounding rocket separation system is determined using block diagram and FMEA . This system is based on the flexible linear shape charge cross-section and a spring mechanism to accelerate separation. In this investigation, the reliability block diagram of the separation system including mechanical and electrical mechanisms is determined. By considering reliability of each component based on expert opinion and using separation system reliability block diagram, reliability of separation system is determined. Moreover, since spring mechanism is one of the most important parts of separation system, a complete FMEA analysis is conducted for this mechanism. According to this analysis, piston, cylinder, pin, and springs have the highest RPN number. Hence, these parts must have a high reliability. On the other hand, results are shown that bracket and bush have the lowest RPN number; therefore, it is not important for these parts to have a high reliability.

Keywords: Separation system, reliability block diagram, FMEA

Nomenclature

F(t)	Failure Function
N	Number of Components
t	Time
R(t)	Reliability
λ	Failure Rate
I^{FV}	Importance Measure (F-V)
h(t)	Hazard Rate
E(t)	Expected Life

Introduction

Separation system is one of the most important systems in rockets. This system separates active and passive parts of a rocket. In sounding rockets the most important task of the separation system is separation of payload from motor [1]. The dynamic behavior of the separating bodies during the separation process is very critical, since any interference between the separating bodies may jeopardize the mission. Failure of separation mechanisms has adversely affected mission performance in several instances [2]; for example, The launch failures of Atlas Centaur in 1970 and Chinese Long March in 1992, improper placing of satellite orbits of Titan in 1990, Pegasus in 1991, and Delta-II in 1995 are some of the typical examples wherein faulty separation systems were suspected to be the main culprits. Accordingly, reliability determination of a rocket separation system is very important [3]. Several ways are presented to determine the reliability of a system [4]. Reliability block diagram is one of the most effective ways to determine reliability of a system.

An understanding of component reliability and maintenance actions provides the necessary background for determining reliability of a system based on its reliability block diagram [5]. However, component reliability information (equipment data) is not a topic of this paper. This study focuses on, reliability block diagram determination of a sounding rocket separation system. Consequently, by having component reliability information, and using that, the reliability of the separation system can be obtained. One of the separation system mechanisms is spring mechanism which plays an important role in

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performance of these systems. Accordingly, boosting reliability of this mechanism during design will result in a more reliable separation system. One of the most effective ways in integrating reliability into design is failure mode and effect analysis (FMEA) [6]. Therefore, in the course of pursuing this goal, we will demonstrate the use of FMEA as a tool in increasing reliability of spring mechanisms.

In this paper, reliability block diagram of a sounding rocket separation system is determined. By using this diagram and having the reliability of all components, separation system reliability can be obtained. In addition, since spring mechanism is one of the most important parts of separation system, FMEA analysis is used to boost reliability of this mechanism during the design process.

Reliability Block Diagram

A reliability block diagram (RBD) is a diagrammatic method for showing how component reliability contributes to the success or failure of a complex system. RBD is also known as a dependence diagram (DD) [7].

A RBD or DD is drawn as a series of blocks connected in parallel or series configuration. Each block represents a component of the system with a failure rate. Parallel paths are redundant, meaning that all of the parallel paths must fail for the parallel network to fail. By contrast, any failure along a series path causes the entire series path to fail [7].

Accordingly, reliability of a series and parallel network could be calculated as follows:

$$R(t) = \prod_{i=1}^{N} R_i(t) \quad (1)$$

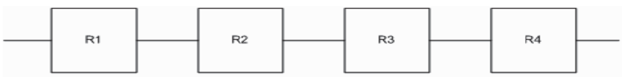

Fig. 1 Reliability calculation of a series network

$$R(t) = 1 - \prod_{i=1}^{N} (1 - R_i(t)) \quad (2)$$

Separation system consists of electrical mechanical components. Figure. 3 shows the reliability block diagram of a sounding rocket separation system.

In this diagram, it is shown how different components are engaged in the separation process and also which components have a more significant role in process performance. It is obvious that those components which are series in the block diagram should have higher reliability, because their failure causes failure of the whole process. This RBD can be used to determine reliability of the separation system.

Exponential Distribution:

Exponential distribution was historically the firstdistribution used as a model of a time-to-failure

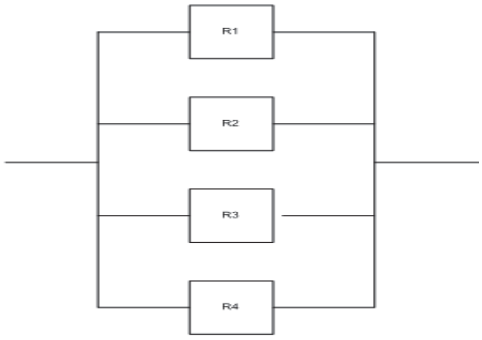

Fig. 2 Reliability calculation of a parallel network

distribution and is still the most widely used in reliability problems. The distribution has one parameter (λ=failure rate) and its reliability function is obtained by:

$$R(t) = 1 - F(t) = e^{-\lambda t} \quad (3)$$

Numerical Analysis

In order to determine the reliability of the sounding rocket separation system, its reliability block diagram is used. To this end, the reliability of all components is determined based on expert opinion. Their exponential distributions are shown in Table 1 and mission duration is approximately 20 minutes.

Table 1. Reliability of separation system components

Component	Failure rate (λ)	R(t=20 min)
Umbilical	0.0151	0.985
Mass spring	0.0090	0.991
Pressure sensor	0.0010	0.999
Micro	0.0304	0.97
Timer	0.0130	0.987
Cable	0.0001	0.9999
Relay	0.0080	0.992
Battery	0.0050	0.995
Connector	0.0202	0.98
Brazing	0.0001	0.9999
Detonator	0.0253	0.975
First cord	0.0512	0.95
Second cord	0.0512	0.95
Plate cutting	0.0408	0.96
Spring	0.0202	0.98
Heating shield	0.0090	0.991

Reliability of the sounding rocket separation system can be calculated as the following:

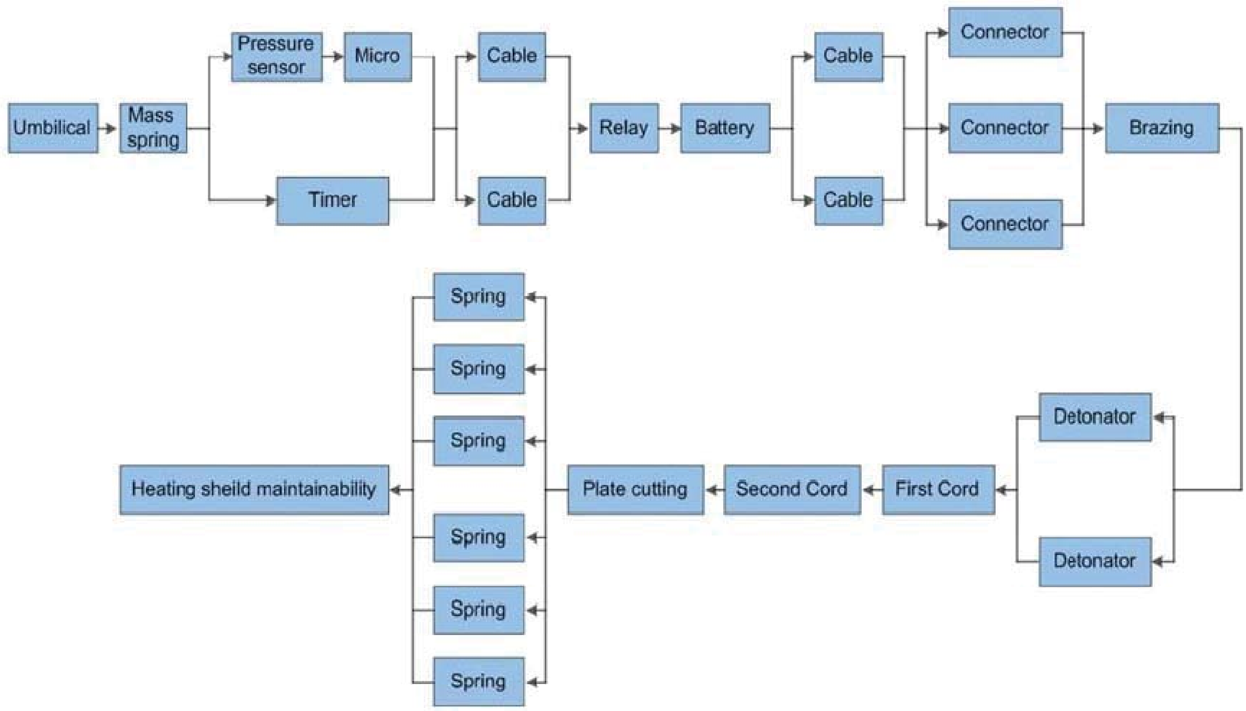

Fig. 3 reliability block diagram of the separation system

(4)

$R_{separationsystem}=R_{umbilical} \times R_{massspring} \times [1-((1-(R_{pressuresensor} \times R_{micro})) \times (1-R_{timer}))] \times [1-(1-R_{cable})^2] \times R_{relay} \times R_{battery}[1-(1-R_{cable})^2] \times [1-(1-R_{connector})^3] \times R_{brazing} \times [1-(1-R_{detonator})^2] \times R_{firstcord} \times R_{secondcord} \times R_{platecutting} \times [1-(1-R_{spring})^6] \times R_{heatingshieldmaintainiiblity}$ =82.629(%)

As it can be seen in Eg.1, the reliability of the sounding rocket separation system is 82.629 %.

Measures of importance:

During the design reliability analysis, or risk assessment of a system, some components and their arrangement may be more critical than others in terms of system reliability. For example, a series of components within a system is much more critical to a system (in terms of failure) than the same set of components in parallel within the system. “The Birnbaum importance measure” gives the contributions to the system reliability due to the reliability of the various system elements. Elements for which a variation in reliability results in the largest variation of the entire system reliability have the highest importance [9]. Fussell and Vesely later proposed a measure based on the cut-sets importance [10]. According to the Fussell–Vesely measure, the importance of an element depends on the number and on the order of the cut-sets in which it appears. Other concepts of importance measures have been proposed and used, based on different views of the influence of the elements on the system performance. The Fussell-Vesely importance is expressed by:

$$I_i^{FV}(t) = \frac{R_i[R(t)]}{R_s[R(t)]} \quad (5)$$

Table 2. Fussell-Vesely importance for separation system

Component	Fussell-Vesely importance
Spring	0.82629
cable	0.82620
connector	0.82596
Detonator	0.80613
pressure sensor	0.01294
micro	0.01294
timer	0.00394
others	1

Probability density function, f(t), is defined as Eq.6

$$f(t) = \frac{dF(t)}{dt} \quad (6)$$

We can define the reliability function R(t) (a.k.a., the survivor or survivorship function) as Eq.7

$$R(t) = 1 - F(t) = \int_t^{\infty} f(\tau)\, d\tau \quad (7)$$

The failure rate, or hazard rate, h (t), is introduced as [5]:

$$h(t) = \lim_{\tau \to 0} \frac{F(t+\tau)-F(t)}{\tau R(t)} = \frac{f(t)}{R(t)} \quad (8)$$

The mean time to failure (MTTF), illustrates the expected time during which the item will perform its function successfully (sometimes called expected life) [5].

$$MTTF = E(t) = \int_0^{\infty} t f(t)\, dt \quad (9)$$

The MTTF for sounding rocket separation system is obtained 100.47 minutes.

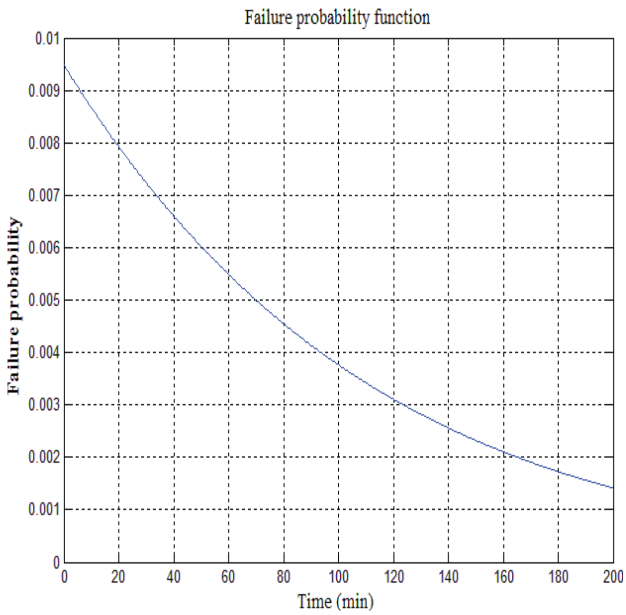

Fig. 4 Separation system failure probability function

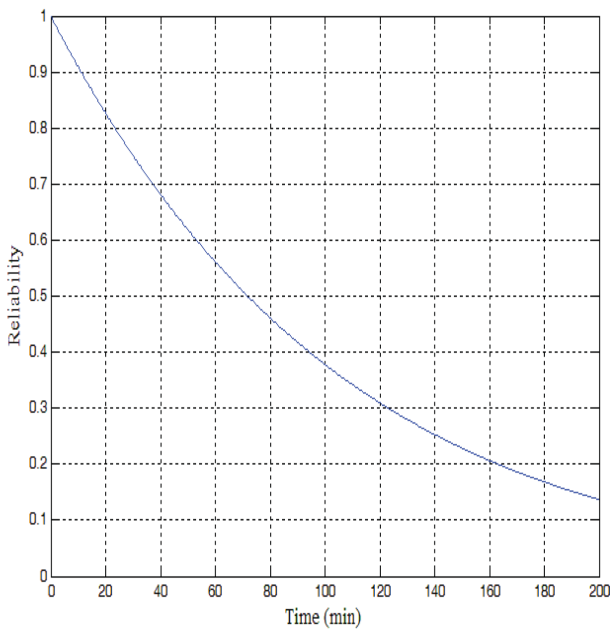

Fig. 5 Separation system reliability function

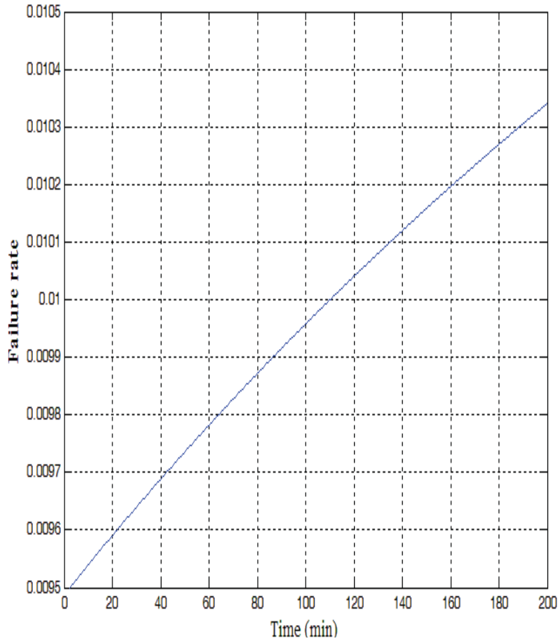

Fig. 6 Separation system failure rate function

FMEA Analysis of Spring Mechanism

A failure modes and effects analysis (FMEA) is a procedure in product development and operations management for the analysis of potential failure modes within a system for classification by the severity and likelihood of the failures [8]. A successful FMEA activity helps a team to identify potential failure modes based on the past experience with similar products or processes, enabling the team to design those failures out of the system with the minimum effort and resource expenditure, thereby reducing the development time and costs. It is widely used in manufacturing industries in various phases of the product life cycle and is now increasingly finding use in the service industry. Failure modes are any errors or defects in a process, design, or item, especially those that affect the customer, and can be potential or actual. Effects analysis refers to studying the consequences of those failures.

The risk priority number (RPN) identifies the greatest areas of concern. It comprises the assessment of the (Table 3 used to assign values for each of FMEA three parameters):

(1) Severity rating,

(2) Occurrence rating, and

(3) Detection rating for a potential failure mode.

RPN = Severity Rating × Occurrence Rating × Detection Rating

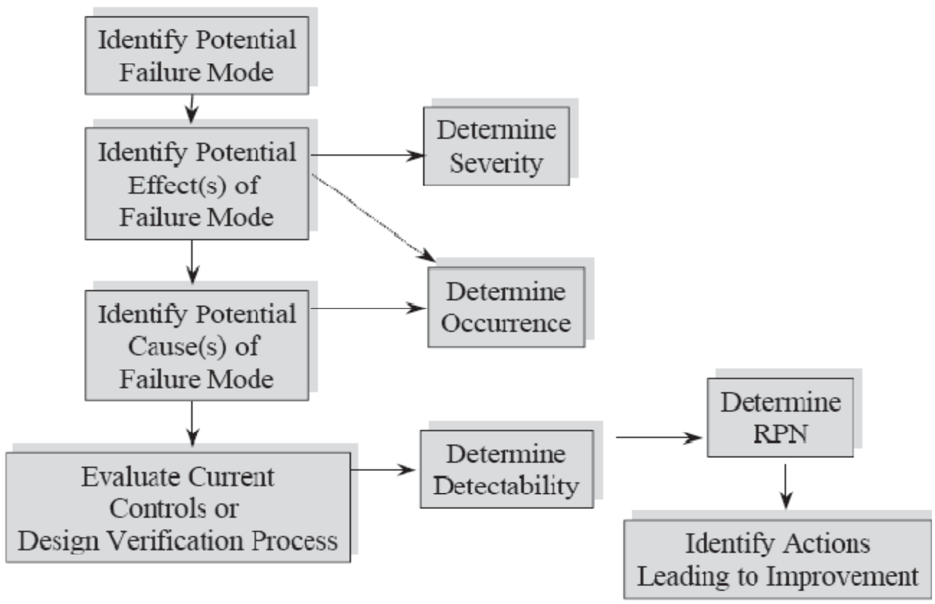

Fig. 7 FMEA analysis roadmap

Table 3. Suggested FMEA parameter evaluation criteria

rating	Severity	Occurrence	Detection
1	The effect is not noticed by customer	Extremely remote	Controls certainly detect (Very High).
2	Very slight effect noticed by customer, does not annoy or inconvenience customer	Remote, very unlikely	Controls almost certainly detect (Very High).
3	Slight effect that causes customer annoyance, but they do not seek service	Very slight chance of occurrence	Controls have a good chance of detecting (High).
4	Slight effect, customer may return the product for service	Slight chance of occurrence	Controls have a good chance ofdetecting (Moderately High**).**
5	Moderate effect, customer requires immediate service	Occasional occurrence	Controls may detect (Moderate**).**
6	Significant effect, causes customer dissatisfaction; may violate regulation or design code	Moderate occurrence	Controls may detect (Low).
7	Major effect, system may not be operable; elicits customer complaint; may cause injury	Frequent occurrence	Controls have poor chance of detection (Very Low).
8	Extreme effect, system is inoperable and a safety problem. May cause severe injury.	High occurrence	Controls have poor chance of detection (Remote).
9	Critical effect, complete system shutdown; safety risk	Very high occurrence	Controls will probably not detect (Very Remote**).**
10	Hazardous; failure occurs without warning; life threatening	Extremely high occurrence	Absolute certainty of Non – Detection (Almost Impossible**).**

Spring mechanism of the considered separation system consists of spring, bush, pin, piston, cylinder, screw and bracket. For all of these components FMEA analysis is performed and is illustrated in Table. 4. According to the RPN of spring system mechanism components, piston, cylinder, pin, and spring have the highest RPN. Consequently, more attention should be paid in their design.

Conclusion

In this paper, the reliability block diagram of a sounding rocket separation system is determined. By considering the reliability of each component based on expert opinion and using separation system reliability block diagram, the reliability of separation system can be obtained. From this RBD, most sensitive components to the performance of the considered separation system can be defined. Inasmuch as spring mechanism is one of the most important parts of separation system, in order to increase the reliability of this mechanism, FMEA analysis of its component is performed. From this analysis and based on RPN of different components, it can be concluded that as piston, cylinder, pin, and spring have the highest RPN, more attention should be paid in their design.

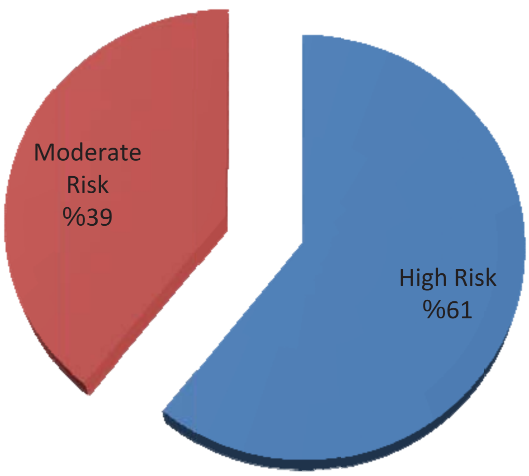

Fig. 8 Risk classification (RPN<80 low risk, RPN<80 Moderate risk, RPN>80 high risk)

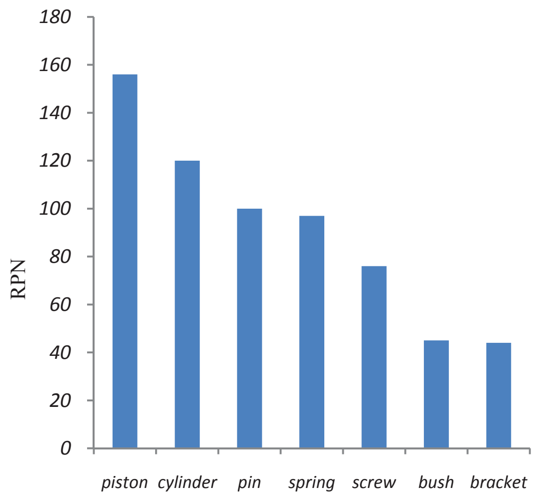

Fig. 9 Bar chart of sorted RPN

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Table 4. FMEA analysis of the sounding rocket separation system

Configuration Item	Explanation & Function	Requirement & Design specification	Potential failure mode	Potential failure effect(s)	Severity	Potential cause/mechanism of failure	Occur	Current design controls	Detect	RPN
Bush	Assembly and consolidation of spring mechanism in its bracket	Bush dimensional accuracy & quality of internal and external threads	Cause problem in assembly of bush to bracket and piston	Unparalleled spring systems	4	Operator errors, machinery and equipments flaws, dimensional non-coincidence and bad quality of bush's Threads	3	Complete set dimensional control & control of production and assembly process & bush threads control using suitable gauge	4	48
Piston	Location consolidation of spring mechanism in bush and related bracket	Dimensional accuracy & acceptable smoothness of external surface & good quality of Threads	Cause problem during assembly of cylinder and consolidation in Bush and Bracket Cause problem in uniform movement of cylinder during separation	Reform and repetition during assembly Non-uniform distribution of springs forces	6	Operator errors, machinery and equipments flaws, not included requirements related to smoothness of surface & non-coincidence of piston's dimensions & bad quality of threads	4	Complete set dimensional control & control of production and assembly process & control of surface smoothness & lubrication before assembly	4	96
Screw	Connection between separation system and motor	Required strength against tensile and shear forces	problem caused in assembling with ring due to non-coincidence in dimensions Failure due to lateral forces during mission or assembly	Repetition & wasting time and cost Cause problem in payload connections	6	Operator errors, machinery and equipments flaws, inadequate strength due to differences in mechanical properties of materials, heat operation, or exceeded forces during assembly	3	Complete set dimensional control & control of entrance materials and production process & fastening allowed torque determination	4	72
Bracket	For connection and maintenance of spring mechanism	Required strength during releasing spring force and dimensional accuracy in assembly location	Springs forces differences due to differences in springs displacement Dimensional non-coincidence related to location of the hole and quality of the thread	Cause different forces in springs during separation Cause problem and repetition during assembly	4	Assembly non-coincidence related to location of connection between bracket and lower ring Operator errors, Machinery and equipments flaws	3	Complete set dimensional control & control of production and assembly process & bush threads control using suitable gauge	4	48
Cylinder	Transmission of forces due to springs release, to the two different halves of separation system	Dimensional accuracy and acceptable smoothness of internal and external surface of cylinder	Cause problem during assembly of cylinder, piston, and springs Cause problem during springs release & impossible smooth and uniform motion	Reform and repetition during assembly Wasting some of springs forces and non-uniform distribution of spring forces	5	Operator errors, machinery and equipments flaws, not included requirements related to smoothness of surface	5	Complete set dimensional control & control of production and assembly process & control of surface smoothness & lubrication before assembly	4	100
Pin	Fixing cylinder and piston of spring mechanism while spring is compressed	Dimensional accuracy and acceptable quality of threads & enough strength against shear forces due to compressed spring	Non-coincidence related to pin dimensions and quality of threads Failure and fracture of pins while spring is compressed	Cause problem during assembly and impossible consolidation of spring mechanism for operation	5	Operator errors, machinery and equipments flaws & non-coincidence of pin materials in comparison with considered materials	5	Complete set dimensional control & control of production and assembly process & control of input raw materials	6	150
Spring	Releasing to produce force and transmitting forces to cylinder during separation	The same stiffness coefficient for all springs & springs dimensional accuracy of diameter, free length and compressed length	Cause problem in assembly springs into cylinder Cause differences in forces of springs mechanism	Reform and repetition during assembly Non-uniform separation and possibility of mission failure	4	Operator errors, machinery and equipments flaws & non-coincidence in springs materials, differences in springs stiffness coefficient or differences in free and compressed length of springs	6	Complete set dimensional control & control of production and assembly process & control of input raw materials, heat treatment and stiffness coefficient measurements	5	120