COST OF PARTICLE IMPACTS ON A SATELLITE

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ABSTRACT

Impacts of space debris objects can damage satellites. These damages can cause failures or even the loss of a spacecraft. The loss of a satellite reduces its expected useful lifetime. As a result, financial investments cannot be amortized completely. This loss of amortization causes cost. To prevent damages, it may be useful to protect the satellite against debris impacts. To achieve this, it is necessary to modify the satellite. This causes increased development and production effort. Consequently damages as well as protection measures can produce additional cost. In this paper a procedure for a rough estimation of the order of magnitude of debris related risk and cost is presented. A risk analysis is made by combining the probability of a penetration with the failure probability of the satellite. The cost estimation comprises the loss of amortization and the additional effort for satellite protection. The most critical part of the analysis is the estimation of the failure probability. A more precise estimation would require a more sophisticated vulnerability model.

1. INTRODUCTION

The goal of this work is to combine debris and meteoroid hypervelocity impact risk analysis with cost estimations. For the determination of the orbital debris flux, the MASTER 2001 model is used. The probability of a satellite failure is estimated by combining the probability of a penetration with a very simple vulnerability model based on the kinetic energy of the impacting particles. The failure probability is weighted with the satellite mission cost, resulting in a probability of loss of amortization. This amortization loss is used as a rough estimation for the cost of damage due to hypervelocity impacts. In this way it is possible to attribute cost to damaging impacts. The risk analysis is made for two examples. One satellite is modeled with a standard satellite hull and a second satellite with an additional debris shield. The cost of satellite damage is compared with the cost of adding a debris shield. The reference satellite used here is a scientific satellite with a Beginning Of Life (BOL) mass of 3 t. The satellite is placed on two orbits. A polar orbit with an orbital altitude of 830 km and an inclination of 98° has been chosen. In this orbital altitude the number of space debris objects has a maximum. For comparison the satellite is also placed in GEO. The lifetime of the satellite is set to 7 years in both cases. The satellite hull is modeled by assuming a simple honeycomb (sandwich) structure. A cost analysis is made by using the estimated subsystem masses as input parameters. The cost of the satellite is determined. The loss of amortization is estimated by weighting cost of replacing the satellite with the failure probability. Furthermore the additional development and production cost due to shielding are considered by applying a complexity factor to the structures and mechanisms subsystem. To determine the flux on the surface, a model for the average cross-sectional area of the satellite is needed. In a first step the design is simplified. The area of solar arrays and antennas is neglected, because impacts in these elements do not cause a loss of the mission. Only impacts on the satellite body are considered. Furthermore the satellite body is simplified to a sphere. These simplifications are shown in Fig. 1.

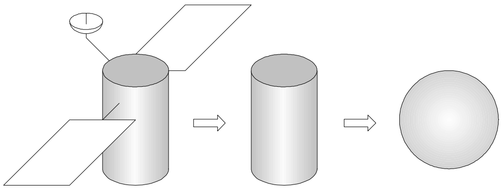

Figure 1. Simplification of the satellite shape. Solar arrays and antennas are not considered. The satellite body is assumed to be spherical in shape. The average cross-section of the satellite is represented by the cross section of the sphere.

From the geometric dimensions of several cylindrical satellites, a model for the average cross-sectional area *A* of a randomly oriented satellite has been developed. Taking the BOL mass m_{BOL} as input parameter, the average cross-section can be estimated using Eq. (1).

$$\begin{aligned} A &= c_1 m_{BOL} \\ c_1 &= 7.56814\text{E-}3 \end{aligned} \tag{1}$$

The calculated area for a satellite with a BOL mass of 3 t is 22.7 m².

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2. SHIELDING

The shield design shall be cost effective. An optimization of the shield is not required here. A useful decision seems to modify the satellite hull dimensions in the order of magnitude of its thickness. The purpose of this slight modification is to prevent a significant change of the satellite dimensions which are very often the critical parameters for the launcher selection. The satellite hull shall be a simple aluminum honeycomb structure without multi-layer insulation (MLI). To design a cost effective shield, a double honeycomb structure with a 50 % increased hull thickness is proposed here. This concept is shown in Fig. 2. Using ballistic limit equations for single (SHC) and double honeycomb (DHC), the minimum penetrating projectile diameter can be calculated (Turner et al., 2001). For both honeycomb assemblies an identical sheet thickness of 0. 4 mm is assumed. The spacing between the sheets is set to $S = 3$ cm (SHC) and $S = 2.25$ cm (DHC), resulting in a DHC hull thickness of 4.5 cm.

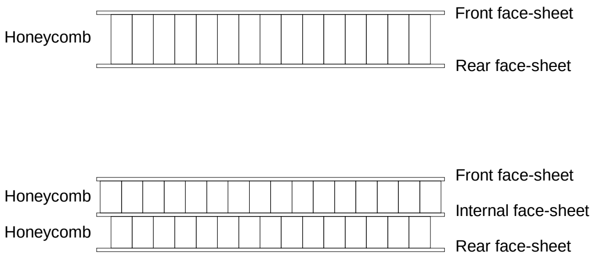

Figure 2. Design of the satellite hull. The satellite hull is designed as simple aluminum honeycomb structure (top). In the case of shielding, an additional internal face-sheet is added (down).

Fig. 3 shows the ballistic limit for both assemblies. All impacts are assumed to be in normal direction. The whole satellite body will be covered with a shield.

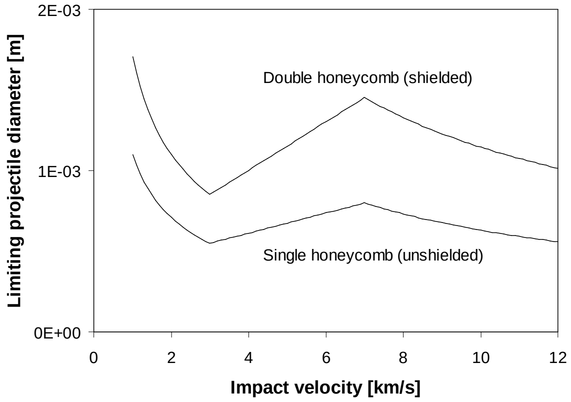

Figure 3. Ballistic limit for SHC and DHC. The DHC wall has an improved shielding effect. (The material of projectile and walls is aluminum.)

3. RISK ANALYSIS

The damage probability should be estimated using a satellite vulnerability model. Simple models do not exist, because the vulnerability depends strongly on the individual satellite design. Thus only a rough estimate can be given here. This estimate is based on the concept of a linear interpolation between defined minimum and maximum values for the damage probability. This interpolation is based on the kinetic energy of the projectiles. A minimum value can be defined by taking the kinetic energy of the limiting diameter as lower boundary where no damage occurs. The limiting diameter has just the energy to penetrate the wall. In this case the damage probability is "zero". A maximum value can be defined, if a kinetic energy of 2 MJ is reached. (This corresponds to a spherical aluminum projectile of 3 cm diameter with an impact velocity of 10 km/s.) In this case the damage probability of an impact is "one". For a kinetic energy larger than this maximum value, one single impacts results in a loss of the satellite. In this way it is possible to allocate a damage probability between 0 and 1 to each penetrating particle, depending on its kinetic energy. Knowing the flux and the satellite lifetime, the number of impacts and penetrations can be determined. The results are shown in Tab. 1 and 2.

Source	Impacts > 100 µm	Penetrations (unshielded)	Penetrations (shielded)
Fragments	2774	370	61
SRM-Slag	157	3	-
Paint Flakes	2368	-	-
Ejecta	129	-	-
Meteoroids	2344	19	16
Total	**7772**	**392**	**77**

Table 1. Number of impacts and penetrations in LEO at 830 km altitude (inclination: 98°, cross-sectional area of satellite body: 22.7 m², mission duration: 7 years).

Source	Impacts > 100 µm	Penetrations (unshielded)	Penetrations (shielded)
Fragments	11	-	
SRM-Slag	-	-	-
Paint Flakes	6	-	-
Ejecta	-	-	-
Meteoroids	1648	13	9
Total	**1665**	**13**	**9**

Table 2. Number of impacts and penetrations in GEO. (cross-sectional area of satellite body: 22.7 m², mission duration: 7 years).

In LEO most penetrating particles are fragments. If the satellite hull is protected by an additional shield, the number of penetrations is significantly reduced. In GEO the number of impacts and penetrations is much lower. Thus for the following risk and cost analysis only the

LEO case will be considered. Figure 4 shows the failure probability for each single source. The risk of fragments and meteoroids is dominating. Both are reduced due to shielding. The influence of MROs (Launch/Mis) is low and cannot be reduced by shielding. MROs are large enough to destroy every satellite, if a collision occurs. Also the risk of NaK droplets does not change due to the fact that only larger droplets exist today. Slag particles are reduced by shielding.

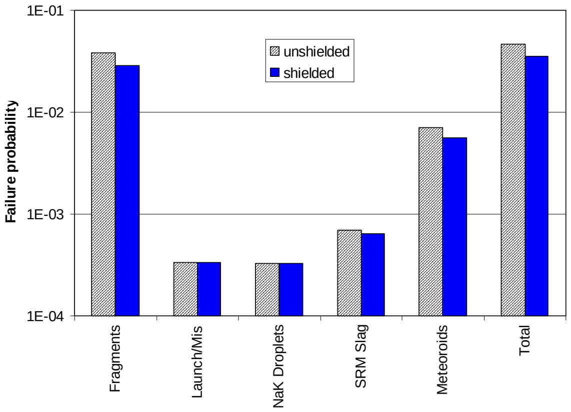

Figure 4. Risk analysis for LEO. Probability of mission loss for two satellite hull designs: The unshielded and the shielded satellite surface.

The results depend strongly on the parameters of the vulnerability model. Therefore this risk analysis should be treated as rough order of magnitude estimation. The result of this estimation is that for the unshielded satellite the risk of loosing the mission is 4.65 %. Adding a shield reduces the risk to 3.56 %. Thus shielding reduces (under the simplified assumptions considered here) the risk by 1.09 %.

4. COST ESTIMATION

The cost related to the risk of loosing the satellite due to hypervelocity impacts will be referred to as "damage cost" in the following. This cost is estimated by comparing the cost of satellite damage to cost of shielding. The cost estimation procedure is a revised version of that presented by Wiedemann et al. (2003, 2004a, 2004b). The shielding of the satellite body requires modifications of the structures and mechanisms subsystem (mass of this subsystem: m_{str}). These modifications cause an increasing complexity of the subsystem. As a result the subsystem hardware cost is increasing. The satellite cost estimation is made for a protoflight unit. The average launch cost is estimated by using data of several rockets from Isakowitz et al. (1999). The specific launch cost is based on the price of a launcher related to its payload capability. The specific launch price is about 15,000 $/kg for LEO. For a satellite with a mass of 3 t, considering 83 % utilization of the payload capability, the launch cost is about 50 $M. The shielding cost model is based on the concept of considering the complexity increase due to a subsystem modification. At first the cost of a complete satellite is estimated. In a next step the complexity of the modified subsystem is increased. The subsystem cost is multiplied by the complexity factor. Both cost calculations are compared. The difference between the modified satellite and the original design gives the additional cost due to shielding. A complexity factor can be defined as combination of a measurable technical criterion with a weighting factor. As cost driver only one technical criterion is selected here due to simplicity. This is the additional mass due to shielding Δm_{shield}. The additional mass is estimated by using a model for the satellite dimensions for calculating the overall surface of the satellite body assuming a cylindrical shape. From the geometric dimensions of several cylindrical satellites, models for the body length and diameter have been developed. Taking the BOL mass as input parameter, the length l and diameter d can be estimated using Eq. (2).

$$\begin{aligned} &l = c_1 m_{BOL}^{\ c_2} && d = c_1 m_{BOL}^{\ c_2} \\ &c_1 = 6.44980\text{E-2} \quad , && c_1 = 1.06984\text{E-1} \\ &c_2 = 6.17487\text{E-1} && c_2 = 4.45257\text{E-1} \end{aligned} \qquad (2)$$

The shield is part of the structures and mechanisms subsystem. The mass of the shield is calculated assuming an additional aluminum wall with 0.4 mm thickness which covers the whole satellite body. The cost driver is combined with a weighting factor which is defined in Tab. 3. This factor includes three main criteria. Each of them consists of a quantity and quality criterion.

Weighting criterion	Quantity	Quality
Elements	Number of elements	Diversity of elements
States	Number of states	Multidisciplinary capabilities
Interactions	Number of connections	Strength of interactions

Table 3. Definition of the complexity weighting factor. The weighting factor is defined as combination of three main criteria, each including a quantity and quality criterion.

It is assumed that two weighting criterions should be considered. These are an increasing "number of elements" and "multidisciplinary capabilities" due to the additional function of debris protection of the satellite hull. The resulting complexity factor $k_{complex}$ (the product of subsystems mass increase and weighting factor w) is estimated to be 1.09, according to Eq. 3. This factor is multiplied with the cost of the structures and mechanisms subsystem.

$$k_{complex} = 1 + \frac{\Delta m_{shield}}{m_{str}} w = 1.09$$
$$\Delta m_{shield} / m_{str} = 0.282 \qquad (3)$$
$$w = 0.333$$

The cost increase causes also an increase of Integration, Assembly, and Test (IA&T) as well as Program Level efforts. The resulting additional hardware cost for adding a shield is estimated to be 1.6 $M according to Tab 4. This corresponds to a satellite hardware cost increase of 0.57 %.

Cost unit: FY05$M	Unshielded design	Shielded design	Cost increase
Scientific Payload	107.13	107.13	0
Propulsion	13.90	13.90	0
ADCS	18.64	18.64	0
TT&C/DH	13.36	13.36	0
Power	19.79	19.79	0
Thermal	2.46	2.46	0
Structure	11.70	12.80	1.10
IA&T	41.30	41.53	0.23
Program Level	54.17	54.44	0.27
Total	**282.44**	**284.04**	**1.60**

Table 3. Satellite hardware cost. Comparison of cost estimations for an unshielded an shielded design of a scientific satellite with a BOL mass of 3 t.

Cost in FY05$M	Replace-ment cost	Failure proba-bility	Damage cost	Add. HW cost	Cost compa-rison
Unshielded	332.44	4.65 %	7.73		7.73
Shielded	334.04	3.56 %	5.95	1.60	7.55
Cost saving					**0.18**

Table 4. Cost estimation for LEO. Cost comparison of shielded and unshielded satellite design, considering different damage costs and additional hardware (HW) cost due to shielding.

To compare the cost of shielded and unshielded designs, it is necessary to estimate the damage cost due to hypervelocity impacts. The damage cost are calculated by multiplying the risk of loosing the satellite with satellite replacement cost. The sum of launch cost (50 $M) and satellite hardware cost (282.44 $M) is the satellite replacement cost. Thus the damage cost is expressed as lost amortization of launch and satellite cost. The satellite replacement cost are estimated to be 332.44 $M. Considering that a collision induced satellite failure can occur at a point of time somewhere between mission start and mission completion, the sum is weighted with a factor of 50 %. By multiplying this value with 4.65 % failure probability for the unshielded case, the satellite damage cost due to damage risk is estimated to be 7.73 $M. For the shielded case (3.56 % failure probability multiplied with 334.04 $M) the damage cost is reduced to 5.95 $M. Consequently the cost saving due to damage risk reduction is 1.78 $M. The additional hardware cost of the shielding is 1.60 $M. Thus the overall cost saving due to shielding is 0.18 $M (s. Tab. 4).

5. SUMMARY

A risk analysis for debris and meteoroid hypervelocity impacts on a typical satellite is made. The MASTER 2001 tool is used for predicting the particle flux on the satellite body. The influence of penetration and shielding on the failure probability of the satellite is investigated. The risk analysis is combined with a cost estimation. The example satellite is intentionally placed on an orbit with the highest spatial density of debris. This results in a high collision risk, causing relatively high damage cost. Comparing this cost with the reduced damage probability plus the additional hardware cost due to shielding, it is found that the estimated cost saving is in the order of magnitude of the damage cost. The work is based on simplified assumptions. Thus the results should be treated as rough order of magnitude estimation. The most critical part of the analysis is the estimation of the failure probability. A more precise estimation would require a more sophisticated vulnerability model.

6. ACKNOWLEDGMENTS

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