OPTIMIZATION OF MICROMETEROID AND SPACE DEBRIS PROTECTION SYSTEMS

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ABSTRACT

The paper will present an extension of MDPANTO (Meteroid/Orbital Debris Protection Analysis Tool) to optimize the protection system of a given spacecraft in order to obtain a low number of penetrations and a minimum of additional mass.

The optimization of protection systems is a complex task, due to the strong non-linearity of the problem. The classical, derivative based optimization procedures are unsuited, because of that. Therefore three search algorithms are tested and the results are compared. This process yielded a suitable optimization procedure to design a mass effective protection system against micrometeroids and orbital debris.

The wall configurations investigated include single wall structures and double wall configurations. In the later case the study showed that the governing equations have to reflect the influence of shield thickness properly. Only some of the equations used for calculating the number of penetrations were found to do this.

Key words: Space Debris, Meteroids, Protections Systems, Optimization.

1. INTRODUCTION

The ability to calculate the probability of serious damage to a space structure by micrometeroids or orbital debris is a prerequisite for the design of protective measures. Since additional protective measures represent additional weight to be carried into orbit the designer is required to add only so much mass as to meet the safety requirements.

Among the large variety of optimization strategies, the derivative based algorithms are unsuited in the given case, because of the discontinuous nature of the impact behavior of multiple wall systems and because additional constraints evoke difficulties in the calculation of derivatives. Also, the large number of local optima impose considerable difficulties in identifying the global optimum.

For these reasons, in this study three different search algorithms are tested, namely a genetic algorithm, a simulated annealing program and the Hooke-Jeeves algorithm. They are applied to different spacecraft geometries with different wall configurations. First single wall structures are used to determine a suitable optimization procedure. After that it is tested on double wall structures. The results of these optimizations necessitated an investigation of the applicability of different sets of equations used for calculating the number of penetrations. A summary and outlook concludes the paper.

2. MDPANTO

The code MDPANTO (Meteroid/Orbital Debris Protection Analysis Tool) is used for calculating the number of impacts on a defined spacecraft in meteroid and/or space debris environments. It has been developed during the last ten years. It is a non-commercial code, written in standard FORTRAN 77.

The surface of a spacecraft is described by quadrilateral elements. For model generation, pre- and postprocessing a PATRAN interface is available. The self-shadowing effect is computed using a hidden surface algorithm. The accuracy of the algorithm does not depend on the size of the elements. It calculates the correct size of the surface area which can be hidden from a particle from a certain direction. Therefore the spacecraft geometry can be modelled with relatively few elements, leading to low computational requirements for the calculations. The numerous runs for the optimization process can thus be carried out in an acceptable time.

The program includes the orbital debris model and the meteroid debris model as defined in [1] as well as the orbital debris model given in [2]. The damage equations for single wall structures according to Cour-Palais [3], for double walls according to Christiansen [4] and Reimerdes [5] and for triple walls according to Reimerdes [5] are implemeted. Benchmark comparisons with BUMPER II and ESABASE/DEBRIS have shown good agreement.

3. OPTIMIZATION PROBLEMS

Optimization problems are frequent throughout the engineering sciences (see for example [6]). The theoretic principles fall within the mathematical sciences. For completeness the fundamental relations are stated here, Gill [7] and Baier [8] give a more detailed description of optimization problems.

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The mathematical definition of an optimization problem is given by:

$$\text{Minimize } f(\vec{X}) \tag{1}$$

$$\text{with } g_\alpha(\vec{X}) = 0 \qquad \alpha = 1, 2, \ldots, m' \tag{2}$$

$$\text{and } g_\alpha(\vec{X}) \geq 0 \qquad \alpha = m'+1, \ldots, m \tag{3}$$

$$\text{and } \vec{X}_{\beta_1} \leq \vec{X} \leq \vec{X}_{\beta_2} \qquad \beta = 1, 2, \ldots, n' \tag{4}$$

$$\text{and } \vec{X}_{\beta_1} \in D_{i,\beta} \qquad \beta = n'+1, \ldots, n \tag{5}$$

$$D_{i,\beta} = \left\{ \vec{X}_\beta^{\{1\}}, .., \vec{X}_\beta^{\{d_\beta\}} \right\}$$

The target function 1 describes the feature to be optimized. In this paper it is the average wall thickness, which is proportional to the weight. In the presented study, the wall thickness of single wall configurations or the back wall thickness and shield thickness of double wall structures are the variables, combined in the vector $\vec{X}$. The equalities, inequalities and boundaries in equations 2-5 place restrictions on the variables. In our investigations, the variables have upper and lower boundaries (equation 4) and a chosen number of penetrations must not be exceeded (equation 3)

To illustrate the complexity of the optimization problem described above, table 1 gives two different configurations for a single wall cube as shown in fig. 1, with one meter edge length in a meteroid environment. The maximum allowable number of penetrations was set to $N = 10^{-3}$, the required wall thickness for a constant thickness on all surfaces is $6.226\,mm$.

Table 1. Comparison of two configurations with nearly identical masses

wall thickness $[mm]$	config. 1	config. 2	difference
front	8.485	8.052	5.4 %
back	3.087	2.657	16.2 %
right	6.098	5.555	9.8 %
left	5.123	5.145	-0.4 %
top	5.340	6.359	-16.0 %
bottom	3.040	3.396	-10.5 %
average thickness	5.194	5.195	-0.02 %
numb. of penetrations N	$0.9997 \cdot 10^{-3}$	$0.9965 \cdot 10^{-3}$	-0.3 %

The two configurations have almost identical average wall thicknesses and very similar numbers of penetrations. These properties suggest similar configurations. However, the individual wall thicknesses differ considerably up to 16%. The right and left wall are impacted symmetrically by meteroids. This leads to the expectation of the same wall thickness for those surfaces. Clearly in both configuration this is not the case. All of this shows that the optimization problem has numerous local optima, complicating the identification of the global optimum.

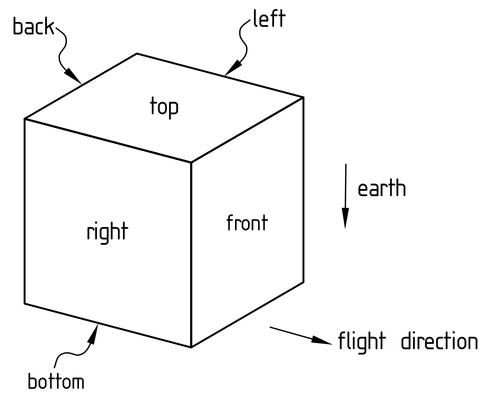

Figure 1. Cubic spacecraft

3.1. Optimization Strategies

In general there is a large variety of optimization strategies. One large group is based on derivative analysis. Many local optima will have zero derivative, necessitating the analysis of numerous potential optima. Also the boundaries and the inequalitiy for the number of penetrations are difficult to incorporate into one target function. One way of doing this is to introduce penalties, whenever one of those conditions is not met. This results in steps in the target function which are not pratical for derivative analysis. For these reasons derivative based algorithms are not used in this study.

Another group of algorithms are the search algorithms. These search according to a specific method for a direction or point, where an improvement of the optimization task is obtained. In the presented case, the search algorithm of Hooke-Jeeves [8] identifies in a first step the direction in which the greatest improvement of the target function is found. This is not done using derivatives but by comparing the target function values of points in a distance defined by a step size. After that it continues moving the investigated point into that direction until no further improvement is found. Then it tries to find a new direction. If no improvement from the current point is possible the step size is reduced. The algorithm stops if a certain minimum step size is met. It is immediately clear that the algorithm will not move away from a local optimum. For that reason, a priori knowledge of the proximity of the global optimum is necessary or it is required to test a wide range of different starting points. In the later case it might become necessary to choose the points at random, if the target functions become so complex that the approximate location of the global optimum is not apparent.

Heuristic algorithm like simulated annealing or genetic algorithms apply principles of sciences that are not related to optimization directly. Genetic algorithms make use of the principles of natural evolution. They maintain a set (the population) of points (individuals) in the search space and evaluate their quality. By a combination of genetic operators like mutation, selection and recombination, they find a new population that constitutes the next generation. The chance of an individual to survive into the next generation or for one of its offsprings to be in that generation depends on the quality of the individual as well as on chance. In this way the overall quality of the population increases over the generations. By introducing the genetic operators with a certain amount of randomness, the algorithms can leave local optima. In this study a genetic algorithm employing simple mutation, recombination and selection is used.

Simulated Annealing algorithms use the principles of the physics of annealing processes. From a starting temperature the specimen is cooled down, to achieve a desired (optimal) crystal structure. This point is characterized by a minimal potential energy. The higher the potential energy, the more instable the system is. However, if the cooling process is too fast, imperfect crystal strctures are formed. These imperfections are local minima of the potential energy, which cannot be left, because the quick cooling process withdraws the thermal energy too quickly. With these information a simulated annealing process for optimization can be derived:

The potential energy of a system in physics is given by the target function in an optimization, while the state of the system is determined by the crystalline structure, respectively the values of the variables. The random change of these corresponds to the change in crystal structure, while in both cases the temperature serves as a control parameter. One important difference to normal search algorithms is the fact that a simulated annealing algorithm accepts an increase (i. e. worsening) of the target function with a temperature depending probability. This allows the algorithm to leave local optima, or in analogy to leave an imperfect crystal structure, if sufficient thermal energy is present [9].

Simulated annealing and genetic algorithms, although stemming from completely different areas, can be transformed into each other. If the genetic algorithm is reduced to population size one using only mutation as genetic operator and the chance of accepting an increase in the target function for the simulated annealing is reduced to zero, the algorithms become identical monte carlo algorithms.

So far heuristic algorithms have not been verified totally by mathematical proof. Michalewicz [10] however gives a clear concept of how the optimization by genetic algorithms works. It is based on the Schema Theorem by Holland [11]. The effects of the three main categories of genetic operators (selection, cross-over and mutation) on schemes lead to the conclusion that genetic algorithms seek near-optimal performance through the juxtaposition of short, low-order above average schemes. For an indepth analysis see [10].

4. INVESTIGATED STRUCTURES

Two spacecraft geometries have been investigated in this study. The first one being a simple cube with one meter edge length (see Fig. 1). The structure has been investigated with independent single walls on all surfaces as well as double walls with indepedent bumper and back wall thicknesses on all surfaces and a fixed spacing of $100\,mm$.

The second structure investigated here, is a cylindrical tube, representative of a pressurized module (see fig. 3). The tube has a diameter of one meter and a length of two meter. The circumferential wall is composed of 24 elements, while each cap is composed of twelve elements having the same wall thickness.

Most investigations have been performed in a meteroid environment, because in the space debris environment modell used, the spacecraft would only be hit from the front and the sides. Therefore the meteroid environment is more demanding for the optimization algorithm.

5. OPTIMIZATION RESULTS

The results of the optimizations performed will be presented in two parts. First the optimization results of single wall configurations of the spacecraft described above will be given. These results are used to evaluate the suitability of the tested algorithm and to subsequently determine a suitable optimization procedure. In a second part double wall configurations were investigated with this optimization procedure.

5.1. Single Wall Strutures

The results from the optimization of the single wall configurations in a meteroid environment were achieved using a maximum allowable number of penetrations of $N = 10^{-3}$. Table 2 shows the results for the different procedures. The first row contains the structures, the second one gives the constant wall thickness for all surfaces, which is required to meet the maximum allowable number of penetrations. The results from the Hooke-Jeeves algorithm are given in the third row, they were calculated from choosing row two as starting values for all walls. For the genetic and the simulated annealing algorithm (rows four and six respectively) a total of five runs were performed for each structure. This is necessary because they are statistical algorithms, which yield different results with the same parameters. The best of these results were then used as starting points for the Hooke-Jeeves algorithm. These results are given in rows five and seven. The best results for each structure are marked by bold letters.

It can be seen that the combinations of the heuristic algorithms with the Hooke-Jeeves as postprocessing algorithm yield the best results. The genetic algorithm has a

Table 2. Average wall thickness [mm] of single wall spacecraft from different optimization procedures

strategy	cube	cylinder
required const. wall thickness	6.226	6.886
Hooke-Jeeves	5.431	6.711
genetic (5 runs)	5.181	5.746
genetic + HJ	5.181	**5.740**
sim. an. (5 runs)	5.183	6.815
sim. an. + HJ	**5.162**	6.123

good performance with all test structures. The simulated annealing algorithm outperforms the genetic one in the case of the cube. For the cylinder though, it yields results that are 6.6% worse than the results from the genetic algorithm. It was also found in other test cases that the performance of the simulated annealing algorithm decreased with increasing number of variables. The last column in table 2 has 26 independent variables as compared to six in the second column. For this reason the combination of genetic algorithm and postprocessing with the Hooke-Jeeves algorithm was determined to be the best optimization procedure. The algorithms need a certain amount of parameters, e. g. mutation rate, cooling speed, initial step size, which can be optimized themselves. These parameters were determined in the first part of the study and remained fixed thereafter. This leads to an optimization procedure which is usefull for a lot of different structures, while at the same time being suboptimal to a certain, acceptable extent.

The wall thickness distributions for the best results of the cube and the cylinder are shown in fig. 2 and 3. The weight savings for the cube, compared to a constant wall thickness for all surfaces, is 17%. For the cylinder it is 16.5%.

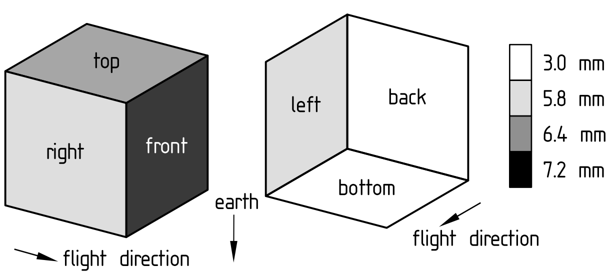

Figure 2. Wall thickness distribution for a single wall cube

To test the procedure in a debris environment the cube with single walls and a maximum allowable number of penetrations of $N = 10^{-3}$ was optimized. The purpose of this was to demonstrate the possibility of using the procedure in this environment and to test the performance of the optimization procedure when the upper and lower bounds of the variables are encoutered. Since the spacecraft is not hit by debris from the top, bottom and back, these wall thicknesses should be at the lower bound of $1\,mm$. The result of this optimization is given in table 3. As expected the three walls that are not hit have a wall thickness of the lower bound.

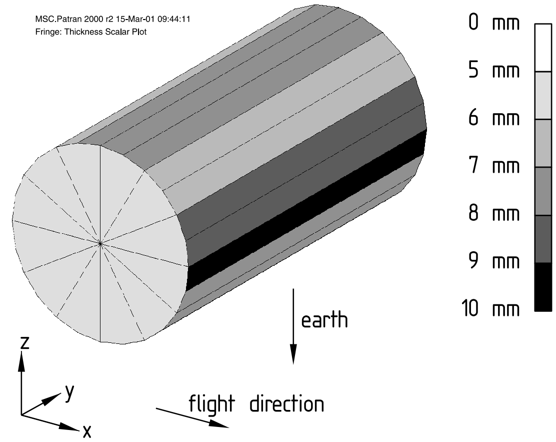

Figure 3. Wall thickness distribution for a single wall cylinder

Table 3. Optimization of a cube with single walls in a debris environment

wall	$t_w\,[mm]$
front	15.0
back	1.0
right	7.4
left	7.8
top	1.0
bottom	1.0
average	5.5

5.2. Double Wall Structures

In the second part of the investigation the optimization procedure was used for double wall structures. Since the bumper significantly increases the protection, the maximum allowable number of penetrations was decreased to $N = 10^{-4}$. This was done purely to obtain thickness values in a reasonable range. The first optimizations showed that the bumper thickness tended to the lower bound set for it. Lowering those bounds did not change this behavior and the resulting configurations were not reasonable as can be seen in columns 2 and 3 of table 4. The bumper thickness was found to be 10 μm, which was the lower bound. A bumper of this thickness can not be expected to shield properly.

The reason for this was found in the equation used for particle speeds greater or equal 7 km/s [3]:

$$d_{crit} = 3.918\, t_w^{\frac{2}{3}}\, \rho_p^{-\frac{1}{3}}\, \rho_b^{-\frac{1}{9}}\, V_N^{-\frac{2}{3}}\, S^{\frac{1}{3}} \left(\frac{\sigma_w}{70}\right)^{\frac{1}{3}} \qquad (6)$$

As the bumper thickness does not enter equation 6, the minimum weight is always found with a minimum bumper thickness. Thus, for optimization purposes a set of equations is needed that properly considers the influence of all variables that are being optimized.

In the next optimization runs the following modified equation for $V_N \geq 7\,km/s$ was used [5]:

$$d_{crit} = 4.096\, F_2^{*\,-\frac{2}{3}}\, t_w^{\frac{2}{3}}\, \rho_p^{-\frac{1}{3}}\, \rho_b^{-\frac{1}{9}}\, V_N^{-\frac{2}{3}}\, S^{\frac{1}{3}} \left(\frac{\sigma_w}{70}\right)^{\frac{1}{3}} \quad (7)$$

with

$$\begin{aligned} F_2^* &= 1\,; & \left(\frac{t_b}{d}\right) &\geq 0.2 \\ F_2^* &= 5 - 40\left(\frac{t_b}{d}\right) + 100\left(\frac{t_b}{d}\right)^2\,; & \left(\frac{t_b}{d}\right) &< 0.2 \end{aligned} \quad (8)$$

It should be noted that equation 6 and 7 differ only by the factor F_2^*, which introduces the dependency on the shield thickness. Fig. 4 illustrates the effect of this parameter. It depicts the required total wall thickness as a function of the ratio between shield thickness and particle diameter. If the ratio is above 0.2 the required back wall thickness t_b is almost constant independent on the shield thickness. Below that ratio however, the required back wall thickness increases by about a factor of five, when the shield thickness approaches zero. This effect is approximated by the parameter F_2^* in equation 7, extending the valid range of the equation down to low shield thicknesses.

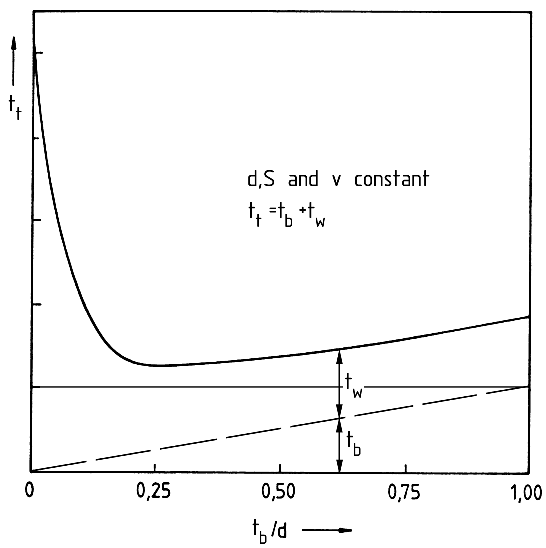

Figure 4. Total wall thickness versus shield thickness/particle diameter

The optimization results of these two equations were compared in two different test cases. First the optimization on the double wall cube described above was performed again using the modified equation 7. In a second test both equations were used on a structure with very thin shields ($10\,\mu m$). The first case tests if the equations enable the optimization algorithms to find reasonable configurations, while the second case checks, whether the equations can handle the continous transition from double wall to single wall configurations.

Table 4. Comparison of optimization results obtained with different equations: cube with double walls (spacing 100 mm) in meteroid environment

wall	original equ.		modified equ.	
	$t_w\,[mm]$	$t_b\,[mm]$	$t_w\,[mm]$	$t_b\,[mm]$
front	2.07	0.01	2.00	0.84
back	1.03	0.01	0.91	0.85
right	2.26	0.01	1.25	0.83
left	1.84	0.01	1.25	0.83
top	1.10	0.01	1.75	0.81
bottom	1.25	0.01	0.98	0.85

The results for the first test are given in table 4. The modified equations yield bumper thicknesses which are clearly more reasonable as for the original ones. For the second test case table 5 shows the results. The last columns displays the results when a single wall configuration was optimized. The average wall thickness obtained with the modified equations agrees very well with those from the single wall configurations. Still there are considerable differences in the individual wall thicknesses. The reason for this can be found in the facts that the double wall equation 7 does not converge into the single wall equation exactly and in the strong non-linearities as shown in table 1.

Table 5. Application of double wall equations to single wall structures: cube with double walls (spacing 100 mm) in meteroid environment

wall	original eq. $t_b = 10\,\mu m$ $t_w\,[mm]$	modified eq. $t_b = 10\,\mu m$ $t_w\,[mm]$	single wall $t_w\,[mm]$
front	2.07	11.55	14.79
back	1.03	6.15	4.96
right	2.26	9.59	10.17
left	1.84	9.53	10.51
top	1.10	10.18	9.13
bottom	1.25	5.48	4.25
average	1.64	8.94	8.97

Table 6 summarizes the results that were obtained for the optimizations of double wall structures. Two reference values are given, first the constant wall thickness on all surfaces for a single wall configuration in order to meet the required maximum number of penetrations $N = 10^{-4}$. The second reference is the average thickness for the same double wall configuration on all surfaces, where the shield is half as thick as the back wall. The weight savings achievable with an optimized double wall configuration are 80% compared to single wall and 9.5% compared to double wall configurations with the same thicknesses on all surfaces.

Table 6. Results of double wall optimizations using different equations: cube with double walls (spacing 100 mm) in meteroid environment

configuration	original eq. avg. $t\,[mm]$	modif. eq. avg. $t\,[mm]$
single wall	11.62	11.21
double wall, const. for all surfaces ($t_w = 2t_b$)	2.52	2.44
double wall, variable t_w and t_b for all surfaces	1.64	2.23
single wall, variable for all surfaces	9.64	8.94
double wall, variable for all surfaces ($t_b = 0.01\,mm$)	1.64	8.97

6. SUMMARY AND OUTLOOK

In this study, an optimization procedure for achieving required protection with minimum weight in the micrometeroid and space debris environment has been determined. The optimization problem encountered in this task is characterized by strong non-linearities even for simple spacecraft geometries such as a single wall cube. During the optimization of the cube it was found that although the left and right side of the spacecraft are symmetrically subjected to impacts the optimal solutions found, did not always show the same wall thicknesses for these walls. For this reason the engineer should consider such symmetries beforehand in order to reduce the complexity of the optimization task. The heuristic genetic algorithm with fixed parameters and the subsequent use of the Hooke-Jeeves search algorithm were found to be the most effective approach. The parameters for the optimization algorithms were fixed once suitable choices were found.

It was also found that for optimization purposes, damage equations are needed that properly describe the influence of the variables that are being optimized. A modification of the Cour-Palais/Christiansen [4] equations proposed by Reimerdes [5] has been found to yield acceptable optimization results, while the original equations produced misleading results.

The future work in this area will focus on improving the optimization procedure to reduce computational time and to include further parameters. Furthermore structures with greater complexity will be investigated. Finally, the study has shown that it is necessary to develop more versatile damage equations.

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