APPROACHES TO ASSESSING SPACECRAFT SURVIVAL IN THE SPACE DEBRIS ENVIRONMENT

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ABSTRACT: An assessment of potential damage to a spacecraft is necessary in order to estimate the risk to mission objectives from meteoroid and orbital debris impacts. A comprehensive assessment may be beyond a flight project's scope for technical, cost, or schedule reasons, thereby encouraging flight-projects' inclinations to completely ignore the risk from particle impact. However, there is a middle ground: approaches that bound the answer, or that concentrate on only the spacecraft subsystems that are most vulnerable, can contribute valuable information to an over-all project risk assessment. Several aspects of a debris damage assessment will be discussed, including the use of bounding estimates to determine areas of the spacecraft that can be ignored, the appropriateness of simplifying assumptions, calculation techniques for obtaining different levels of assessment, and advantages of different procedural options.

1 PRELIMINARY DAMAGE ASSESSMENT

In showing compliance with any environmental design requirement, it is often the case that simplifying assumptions can be used, such that the analysis produces a conservative, bounding result. Simplification is essential for meteoroid and orbital-debris (M/OD) impact assessments, given the large number of variables needed to describe the impactor and target, the complex nature of the impact process, and the difficulty of doing comprehensive ground tests or simulations. A preliminary analysis of a few vulnerable spacecraft components can indicate the ease with which the desired probability level of spacecraft survival will be verified. For this it is useful to first generate plots such as Fig. 1 and 2, using the mission's M/OD fluence. Fig. 1 shows the probability of no incipient spall in a single-wall shield geometry, as a function of wall thickness and exposed area. If, for example, exposed electronics boxes on the spacecraft have a minimum wall thickness of 1mm, and an exposed area of about 1 m^2, then the survival probability will be about 90%. This value is encouraging, but indicates that a more detailed analysis is warranted. However, if only 0.1 m^2 of boxes are exposed, the survival probability is around 99%, and further box analysis is probably not necessary.

Fig. 2 presents information similar to that of Fig. 1, but considers an aluminum double-wall configuration. In both figures, the damage equations are those of (Christiansen, 1993), and the meteoroid environment is that of (Divine, 1993). This type of plot can quickly be generated for three or four shield configurations that represent prominent parts of the spacecraft, to give guidance on the need for further analysis.

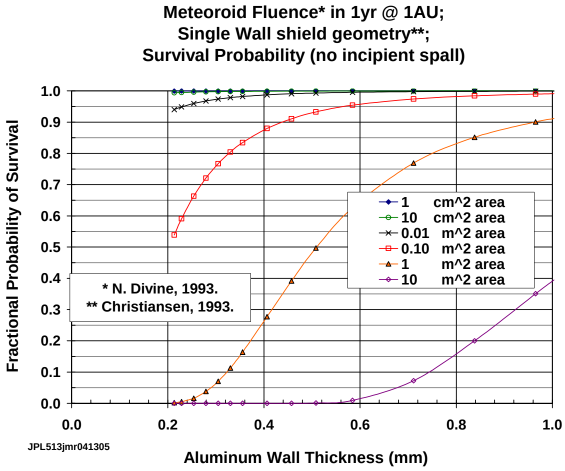

Figure 1. Survival probability of a single-wall M/OD shield in a 1 AU heliocentric orbit for 1 year. Average surface fluence and normal-incidence impact are assumed.

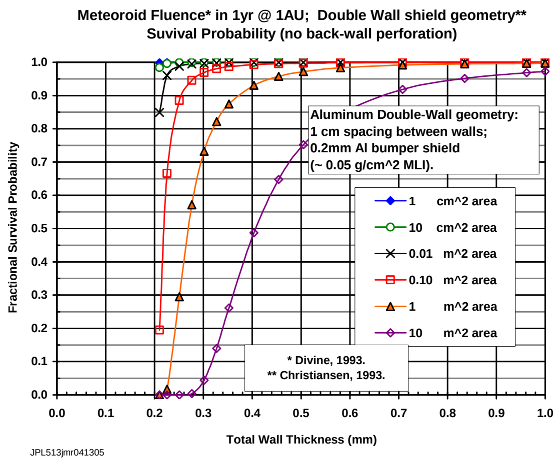

Figure 2. Survival probability of a double-wall M/OD shield in a 1 AU heliocentric orbit for 1 year. Average surface fluence and normal-incidence impact are assumed.

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There will, of course, be more than just three or four different shield geometries that the spacecraft presents to the environment. The problem can be made more tractable by grouping similar geometries into one geometry that is known to be the most vulnerable of the group. As an example, consider a propellant tank that is covered by an MLI (multi-layer insulation) blanket at stand-off distances from 2 to 8 cm. It is generally safe to assume that as the stand-off distance increases, the protection provided by an MLI blanket will remain constant or increase. The entire propellant tank could therefore be treated as a single geometry consisting of MLI and tank wall having a 2 cm separation.

One difficulty in achieving this reduction of geometries is that the geometry most vulnerable to one range of particle mass, velocity, etc., may not be the most vulnerable geometry in a different range of parameters. MLI is a well-known example of this; impact tests show that an MLI bumper shield performs better than its aluminum equivalent at high impact velocity, but worse at low velocity. Another difficulty is that there may not be enough impact data available to identify the most vulnerable geometry. In such cases, one must try to identify and use an overtly conservative representation of the shield geometry.

2 SPREADSHEETS, OR CAD-3D MODELING?

If the initial, simplified analysis shows an unacceptably large failure probability, then further work is needed. However, the level of modeling complexity may not warrant the creation of a full 3D model in computer tools such as Bumper-II or ESABASE/DEBRIS. An advantage of a spreadsheet implementation is that the sensitivity to choice of damage equation and material properties can be quickly assessed. The vulnerability of different shield geometries on the same component can also quickly be noted, and the survival probabilities of each of those geometries can be properly combined to derive the survival probability of the functional component. With some simplifications discussed below, a component's various single- or double-wall shield geometries can all be determined on a single damage-assessment spreadsheet. I have found it useful to have stand-alone spreadsheets for mission-specific M/OD fluence information and for material properties, and to then link the damage-assessment spreadsheets to this information. A change of mission fluence or an adjustment of material properties will then automatically flow down to each component's damage assessment.

3 PARTICLE VELOCITY: SIMPLIFYING METEOROID DAMAGE ASSESSMENTS

3.1 Simplifications

- ignore directionality; use the average surface fluence;
- assume normal impact incidence in damage equations;
- use average speed.

3.2 Advantages?

Average surface fluence, Normal impact - With these simplifications, the angular dependence of the meteoroid fluence does not have to be tracked as a function of spacecraft orientation. The use of the average surface fluence is not conservative, but neither is it unreasonably optimistic; the fluence to a given surface will not be more than a factor of 4 times the average surface fluence, which would generally produce a factor of 4 in the failure probability. The average surface fluence is less of an approximation if the spacecraft orientation changes with time, so that a given surface changes its orientation with respect to the meteoroid environment.

For a conservative bound on the fluence to any surface, the omni-directional form of the fluence can be used. [Recall that the omni-directional fluence is derived by integrating the fluence over the complete solid-angle of a sphere. The integration does not include the cosine(θ) factor that would be used to derive the fluence to a surface, for which cosine(θ) is introduced by the vector dot product $-\boldsymbol{F} \bullet \boldsymbol{n}$, where θ is the angle between the particle fluence $\boldsymbol{F}$ and the surface-normal vector $\boldsymbol{n}$.] The average surface fluence, also known as the fluence to a random tumbling surface (not a recommended operations mode), is then derived simply by applying a factor of 0.25 to the omni-directional fluence. (I am unaware of, and unable to produce, a proof of this for the general case of a fluence having any angular distribution.)

Average speed - It seems to be a good approximation (see Fig. 3) to use the average meteoroid speed to evaluate damage, particularly since the average speed does not fall near a point of dramatic change in the damage equation (e.g. near the 3 km/s or 7 km/s points in Christiansen's double-wall equations).

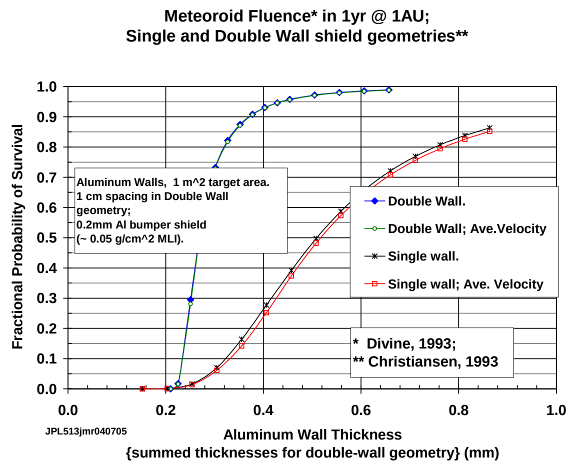

Figure 3. Survival probability of a 1m[2] target in the 1AU meteoroid environment for 1 year. Double- and Single-Wall target geometries are shown. Calculations use either an environment binned in 1 km/s velocity increments, or use the particle-fluence-weighted average velocity of 16 km/s. Average surface fluence and normal-incidence impact are assumed.

4 PARTICLE VELOCITY: SIMPLIFYING ORBITAL DEBRIS DAMAGE ASSESSMENTS

4.1 Simplifications

- ignore directionality; use the average surface fluence;
  - for better results, use fluence to the oriented surface;
- assume normal impact incidence in damage equations.
- use average speed.

4.2 Advantages?

Average surface fluence, Normal impact - With these simplifications, the angular dependence of the OD fluence does not have to be tracked as a function of spacecraft orientation. To derive the average surface fluence from ORDEM (Zhang, 1997), divide the "average flux" in file TABLESC.DAT by 4. Note that the ORDEM "average flux" is the average over an orbit, not the average over all spacecraft surfaces. Using the ORDEM "average flux" in TABLESC.DAT, as is, and using a single impact angle (e.g. normal incidence), is analagous to using the omni-directional fluence and a single impact angle in a meteoroid assessment.

Oriented-surface fluence, Normal impact - The oriented-surface fluence will provide a better vulnerability estimate than the average surface fluence. The angular dependence of the OD fluence will still not have to be tracked as a function of impact angle. The oriented-surface fluence is determined for the given surface by summing ORDEM's angle-binned fluences that are incident on the surface, with each fluence first weighted by a cosine(θ) factor, where θ is the angle between the surface-normal vector and the vector anti-parallel to the particle fluence.

Average speed - The range of OD particle speeds is fairly narrow for particles from a given direction, so the use of the average particle speed in a given angle is a very good approximation when used with the fluence from a given direction (e.g. within a 10 degree angle bin provided by ORDEM). However, the average velocity can vary dramatically with angle, as shown in the example in Fig. 4. The average velocity may still yield reasonably valid results when used with oriented-surface fluence, but less valid results when used with the average surface fluence; caution is urged, particularly in velocity regimes where the damage has a strong velocity dependence.

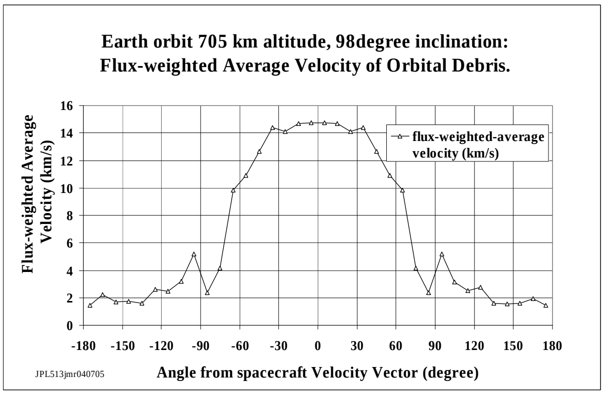

Figure 4. Average velocity of OD impact, as a function of angle measured from the spacecraft velocity vector, for the stated orbit.

5 TAKING ADVANTAGE OF REDUNDANCY

Hardware redundancy is generally not an effective way to increase reliability against the adverse effects of space environments. For example, radiation exposure that damages parts in one electronics unit will probably also damage the identical parts in the redundant unit. It is statistically very probable that a unit will be hit by many radiation particles, and very probable that the redundant unit will be hit by nearly the same number of radiation particles, producing similar degradation in each unit. M/OD susceptibility is different in that you are dealing with the probability of being hit only once by a lethal particle. For physically separated units, the probability of M/OD impact is independent for each unit. In other words, the M/OD environment may or may not damage a unit, and the fact that one unit becomes damaged does not make it imminent that the redundant unit will also be hit and damaged. M/OD damage has a characteristic of a "random failure" in the

sense that the threat from M/OD at a given instant doesn't on depend on past conditions; damage could occur at any point in the mission, or might not occur at all. A precedent for including redundancy in the survival assessment is found in:
Orbital Debris: A Technical Assessment
National Academies Press, Washington, D.C., 1995,
pg 122: "Finally, the vulnerability of the spacecraft to debris can be determined by combining the probability of failure of its various components due to debris impact. This includes accounting for the redundancy of components and their criticality to the spacecraft."

6 PROPERLY ACCOUNTING FOR REDUNDANCY

Before one can use redundancy to assess reliability, it is key that true redundancy against impact damage exists. For example, redundant electronics should be in separate enclosures, not on the same board or even on two boards within the same box. In addition, the survival probability of the cross-strapping connections should be considered, because a very vulnerable cross-strap will negate most of the advantage of having redundant units.

It is, of course, also important that the survival probabilities of the hardware components are combined to accurately represent the survival of the subsystem functionality they provide. For example, consider redundant units B1 and B2, which are both controlled by a third unit A that has no redundant counterpart (Fig. 5). Subsystem functionality is retained if A and B1 both survive, or if A and B2 both survive.

A mission survival probability Ps(unit) can be determined for all three units of Fig. 5. For three units there are $N = 2^3 = 8$ possible combinations of failed/survived states for the units, ranging from a configuration where all survive, to a configuration where all fail. (See Table 1.)

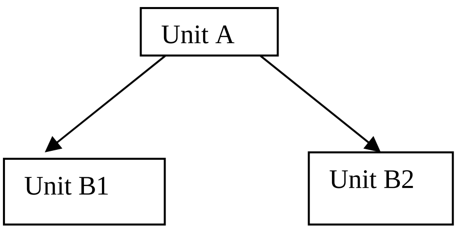

Figure 5. Diagram of redundant units B1 and B2 that are both controlled by a third unit A that has no redundant counterpart.

The occurrence probability of a given configuration is determined by the product of the probabilities that each unit is in its given failed/survived state. For example, the occurrence probability of configuration (2) of Table 1, in which A and B1 survive but B2 fails, is

P = Ps(A)*Ps(B1)*Pf(B2).

Here Pf is the failure probability, Pf = 1 - Ps. The total probability of survival of the subsystem functionality is the sum of the probabilities Pn of all the configurations in which A survives and at least one of the B units survives:

Ps(functionality) = Ps(A)*Ps(B1)*Ps(B2) +
Ps(A)*Ps(B1)*Pf(B2) + Ps(A)*Pf(B1)*Ps(B2).

	Unit A	Unit B1	Unit B2	Function Retained?	Survival Prob.
1)	O	O	O	yes	Ps(A)*Ps(B1)*Ps(B2)
2)	O	O	X	yes	Ps(A)*Ps(B1)*Pf(B2)
3)	O	X	O	yes	Ps(A)*Pf(B1)*Ps(B2)
4)	X	O	O	no	Pf(A)*Ps(B1)*Ps(B2)
5)	O	X	X	no	Ps(A)*Pf(B1)*Pf(B2)
6)	X	O	X	no	Pf(A)*Ps(B1)*Pf(B2)
7)	X	X	O	no	Pf(A)*Pf(B1)*Ps(B2)
8)	X	X	X	no	Pf(A)*Pf(B1)*Pf(B2)

X = fail, O = survive; Pf = 1 - Ps

Table 1. All eight possible configurations of failed/survived unit states.

7 CONCLUSION

It is, in very many respects, a challenge to estimate the likelihood of damage to a spacecraft in the meteoroid and orbital debris environment. Approximations involving impact velocity and direction can be used to obtain conservative bounds on the probability of spacecraft damage. Hardware redundancy is a valid and valuable method of mitigating the M/OD threat.

8 REFERENCES

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