Hypervelocity Impact Protection by a Nominal Two-Plate Aluminum Spacecraft Shield against Milli- and Centimeter-Sized Space Debris

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Abstract

Hypervelocity collisions with space debris (SD, natural meteoroids and man-made artifacts) can significantly affect the performance of spacecraft. Here, I use an adaptive-mesh Eulerian hydrodynamic code, Mie-Grüneisen solid-mechanics, and a simple material-failure model, running on a modern PC, to analyze the protection afforded by a nominal two-plate aluminum shield to hypervelocity collisions with millimeter- and centimeter-sized aluminum and iron-nickel spheres, considered as SD proxies. The results indicate that such a shield would stop a 1-mm iron-nickel impactor at 9 km/s (the nominal mean speed of SD), and would stop a 1-mm aluminum impactor at 20 km/s. The shield would fail to stop a 1-cm aluminum impactor at 9 km/s, and 1-mm, and 1-cm, iron-nickel impactors at 20 km/s. These results variously validate, and characterize some limits of applicability, of the ballistic limit equations (BLEs) that are commonly used in spacecraft shield design and spacecraft mission planning.

Keywords: hypervelocity, micrometeoroids, space debris, orbital debris

1.0 Introduction

The region extending from the Earth's surface to ~2000 km altitude contains natural meteoroids and man-made artifacts, collectively known as space debris (SD, [13]). The nominal size of individual pieces of SD ranges from less than a micron, to largely intact satellites and rocket bodies ([13]). Individual SD particles exhibit speeds in any Earth-orbiting-spacecraft-inertial frame ([6]) of from a few meters per second to ~20 km/s ([13]). The flux of SD particles >0.1 cm in diameter is estimated to be $10^{-2}/m^2$/year; the flux of SD particles >1 cm in diameter is estimated to be approximately $10^{-6}/m^2$/year ([13]). The mean speed of these particles in an Earth-orbiting-spacecraft inertial frame is ~9 km/s ([13]).

Hypervelocity collisions with SD can significantly affect the performance of spacecraft. Sub-micron and micron-sized impactors can degrade some sensors and control surfaces and thermal protection. Millimeter-sized impactors can penetrate the walls of exposed lines and tanks. Larger bolides can directly compromise the integrity of the entire spacecraft.

Almost all spacecraft shielding in use today is some variant of one or more parallel aluminum plates separated by a gap; the gap can be empty or filled with energy absorbing materials such Kevlar. These shields are generically known as “Whipple shields” ([16]). Mass, volume, cost to orbit, cost of materials, and protection trade harshly in the shield design space.

Spacecraft shielding design frequently uses ballistic limit equations (BLEs; [4]), assuming that the ballistic limit strongly dominates all else in the regime of interest. Even though they are semi-analytical, BLEs must be validated using actual hypervelocity experiments or first-principles hydrodynamic codes ([5]). It has not been possible for a variety of technical and funding reasons to perform well controlled hypervelocity experiments for 0.1-1.0-cm sized impactors above ~10 km/s.

All hypervelocity experiments, and most hydrocode simulations, of SD to date have assumed aluminum (density ~2.7 g/cm^3) impactors, because the properties of aluminum are regarded as sufficiently close to those of most SD. This assumption is somewhat problematic. Although aluminum may be a reasonable proxy for SD of human origin, the majority of natural micrometeoroids are brittle silicates (density ~3.4 g/cm^3; [14], p. 71), and a small fraction are iron-nickel (Fe-Ni, density ~7.8 g/cm^3, [14]).

Here, I use a highly portable, adaptive-mesh Eulerian ([3]) hydrodynamic code, SAIC’s Adaptive Grid Eulerian (SAGE; [1], [7]), to generate two-dimensional (2D) simulations of collisions of millimeter- and centimeter-sized aluminum and Fe-Ni spheres with a nominal two-plate aluminum shield.

2.0 Method

The SAGE (SAGE; [1]) software was used to generate a two-dimensional (2D) simulation of the impact of (a) aluminum and iron-nickel spheres, each with 1-mm and 1-cm diameters, respectively, with (b) a pair of parallel aluminum plates, each 0.1 cm thick and separated by 2.0 cm ([4]; see Figure 1 for a representative configuration). In each case, the plate length is at least 5 impactor diameters. The inter-plate gap was filled with air at an initial pressure of ~10^6 dyne cm^{-2}, or 1.0 dyne cm^{-2}. Each of the spheres is initially normally incident to the upper plate at 9 km/s, or 20 km/s.

As configured for this study, SAGE utilizes a Navier-Stokes hydrodynamic model ([9]), a strength-of-materials package which includes an isotropic stress (Grüneisen; [11], IX.4; [8]; [15]) model, and a simple material-failure model that tests whether the minimum hydrostatic pressure, P_{min}, required to maintain material integrity, has been met. Table 1 shows some of the materials properties used in the simulations.

	Aluminum alloy (plates)	**Inter-plate gap, air**	**Aluminum (sphere)**	**Fe-Ni (sphere)**
Initial density (g/cm^3)	2.8 ([10])	Corresponding to initial pressure	2.8 ([10])	7.9 ([10])
Shear modulus ($dynes/cm^2$)	2.7e11 ([10])	N.A.	2.7e11 ([10])	5.0e11 ([10])
Yield strength ($dynes/cm^2$)	1.0e12 ([10])	N. A.	1.0e11 ([10])	2.0e12 ([10])
Modulus of elasticity ($dynes/cm^2$)	7.0e11 ([10])	N.A.	7.0e11 ([10])	2.0e12 ([10])
Initial pressure ($dynes/cm^2$)	1.0, or 1e6	1.0, or 1e6	1.0, or 1e6	1.0, or 1e6
Initial velocity in rest frame of plates (cm/s)	0	0	9000e2, or 20000e2, normally incident to plates	9000e2, or 20000e2, normally incident to plates
P_{min} ($dynes/cm^2$)	-1.0e9 (nominal)	N.A.	-1.0e9 (nominal)	-1.0e10 (nominal)
c_0, speed of sound (cm/s)	5.3e5 ([11])	Corresponding to density	5.3e5 ([11])	5.6e5 ([12], E-47)
c_v, specific heat (erg/g-eV)	10.7e10 ([11])		10.7e10 ([11])	5.8e10 ([12], D181)
Γ_0, Grüneisen constant	2.0 ([11])	N.A.	2.0 ([11])	1.9 ([11])
s_1, Grüneisen parameter ([15])	1.3	N.A.	1.3	1.5
s_2, s_3, Grüneisen parameters ([15])	0.0	N.A.	0.0	0.0

Table 1. Material properties, initial conditions, and parameters used in this study. Property values are nominal.

The simulations were run on a 3.1 GHz Pentium-4 Windows/Intel platform. Density-plots from these simulations were visualized using the SHOW ([2]) software. An example of the results is presented in Section 3.0.

3.0 Results

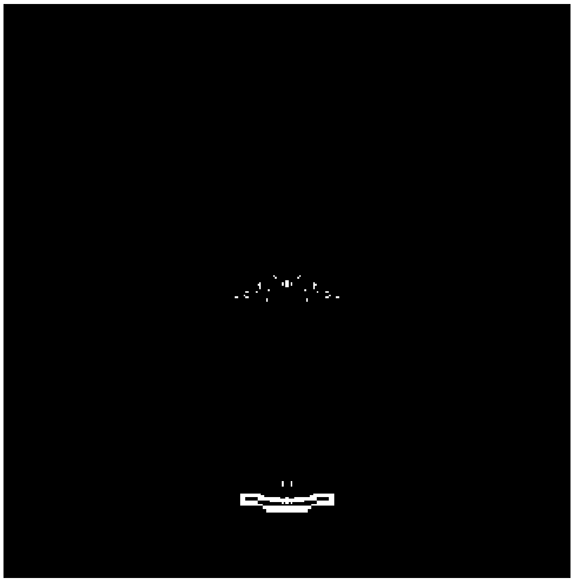

Figure 1. Density plot of 1-mm-Fe-Ni sphere/aluminum plate system at 10 microseconds. The initial velocity of the sphere was 9 km/s normally incident toward the plates. The upper plate is completely destroyed. The lower plate, though significantly distorted, remains intact.

The 9 km/s, 1-mm sphere, 10^6 dynes cm^{-2} setups described in Section 2.0 each required ~0.75 cpu-hours, and their meshes had a maximum resolution of ~11,000 cells. The 20 km/s, 1-mm sphere setups each required ~4.5 cpu-hours, and their meshes had a maximum resolution of ~25,000 cells. The 1-cm sphere setups described in Section 2.0 each required ~1.5 cpu-hours, and their meshes had a maximum resolution of ~50,000 cells. ~70% of the cpu time in each configuration was spent in SAGE's solver and hydro routines.

Table 2 summarizes the shield response to the regimes analyzed in this study.

Impactor size/material	**At 9 km/s**	**At 20 km/s**
1-mm aluminum	survives	survives
1-mm iron-nickel	survives	fails
1-cm aluminum	fails	fails
1-cm iron-nickel	fails	fails

Table 2. Summary of shield response to collisions simulated in this study.

4.0 Discussion

Fine details of the hydrodynamics at initial pressures 1 dyne cm^{-2}, and 10^6 dyne cm^{-2}, respectively, were sensitive to the choice of those pressures. However, whether the second plate was breached was in all cases independent of the choice of initial pressure in the inter-plate gap.

The specific two-plate shield configuration analyzed in these studies stops 1-mm Fe-Ni, and Al, impactors moving at 9 km/s. These results are consistent with those obtained in several BLE models ([4]).

The shield stops a 1-mm diameter aluminum sphere at 20 km/s, but will not stop a 1-cm aluminum impactor at 9 km/s.

The shield does not survive a collision with a 1-mm iron-nickel impactor at 20 km/s normal to the plates. Several BLE models ([4]) predict that the shield *would* survive under these conditions; this result indicates that a single BLE is not likely to apply uniformly throughout the SD velocity/density phase space.

Only spherical impactors were analyzed in the study, following common convention. Shape is likely to matter, however, in some regimes. Some preliminary calculations (unpublished) by the author suggest that cylinders with a length/diameter ratio of 5 and with the same mass as the impactors used in the current study penetrate faster and deeper than the spheres. Furthermore, calculations (unpublished) by the author indicate that as non-brittle ([15]) spherical bolides enter the atmosphere, they are transformed to cylinders.

Although the specific regimes analyzed in this study bracket a range of SD material properties and speeds, the extension of these results to other regimes requires care. The spall caused by a 1-mm aluminum impactor moving at ~4 km/s, for example, creates more damage than that same impactor moving at 9, or 20, km/s ([5]).

These results demonstrate, in any case, that a 2D adaptive Eulerian hydrocode with a Grüneisen solid mechanics model and a simple material-failure model, running on a modern PC, can validate the BLEs typically used in modern spacecraft shielding design. In addition, the studies motivate further validation work at different speeds, plate thicknesses, inter-plate distances, and gap materials. SAGE has been ported to several parallel platforms and with trivial changes to its input parameters, will automatically configure the calculations reported here for those environments.

5.0 Acknowledgements

This work benefited from discussions with Bill Spangenberg, Mike Gittings, Dale Ranta, and Mike Clover. For any errors that remain, I am solely responsible.

6.0 Disclaimer

This work is not claimed to represent the views of SAIC or its customers.

7.0 References

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