LOW-VELOCITY CATASTROPHIC IMPACT ON MICRO SATELLITE

K. Nakashima[1], T. Hanada[1], Y. Akahoshi[2], T. Harano[2], Y. Machida[2] and S. Fukushige[2]

[1] *Kyushu University, 10-1 Hakozaki 6-chome, Higashi-ku, Fukuoka, Fukuoka, 812-8581, JAPAN*
kyo_hei@aero.kyushu-u.ac.jp, toshi@aero.kyushu-u.ac.jp
[2] *Kyushu Institute of Technology, 1-1 Sensui-cho, Tobata-ku, Kitakyushu, Fukuoka, 804-8550, JAPAN*
akaho@mech.kyutech.ac.jp, d348929t@tobata.isc.kyutech.ac.jp,
a104109y@tobata.isc.kyutech.ac.jp, shinyafk@yahoo.co.jp

ABSTRACT

This paper characterizes the physical properties of fragments from a low-velocity catastrophic impact on a micro satellite. A catastrophic impact means that target and projectile are totally fragmented, whereas a non-catastrophic impact is characterized primarily by fragmentation of projectile and by crater or hole on target. The difference between a catastrophic and a non-catastrophic impact would be determined by the ratio of kinetic energy at impact to target mass. The NASA standard breakup model has defined if the ratio is equal to or greater than 40 J/g, then the impact is catastrophic. Therefore, we hit a micro satellite of a mass of approximately 680 g by an aluminum alloy solid sphere of a mass of 36 g at a speed of 1.35 km/s.

1. INTRODUCTION

Artificial objects in geosynchronous Earth orbit (GEO) are distributed uniquely. Most of them are originally placed on the equatorial plane, and then they change orbital plane due to the lunar and solar gravitational perturbations combined with the Earth's oblateness. The change in inclination starts at a rate of about 0.8 degrees per year, but shifts the direction of the change after the inclination reaches the maximum of 15 degrees by 27 years (Friesen et al., 1995). If a satellite under north-south station keeping is to be hit by another artificial object, the angle of collision must be less than 15 degrees. Semi-major axis and eccentricity are also subject to various perturbations, but variation of these elements is not significant. All orbits are essentially circular at nominal geostationary altitude. Objects in inclined orbits make a daily excursion in north-south direction relative to stationary satellites. Since the orbital velocity is about 3 km/s, the collision velocity is less than 800 m/s. Therefore, most collisions in GEO would be low velocity collisions. Noted that considering a collision between a GEO satellite and an object in geostationary transfer orbit (GTO) raises the collision velocity up to 1.5 km/s, corresponding with required delta velocity to insert a satellite into GEO from GTO.

Harada (1996) and Goto (1997) investigated low-velocity impact phenomena possible in GEO though laboratory impact tests and developed a low-velocity collision model in a similar manner to what had been done in the area of hypervelocity impacts. Many international space communities working on GEO space debris environment modeling have adopted their low-velocity collision model (Bade, 1998; Martin, 2002; Rossi, 2002; Lewis, 2001). They also have adopted the NASA standard breakup model 2000 revision (Johnson et al., 2000) because it is reported that the present environment estimated using their own model combined with the NASA standard breakup model matches well with the observation result (Bendisch et al., 2002). Of course, the NASA standard breakup model was developed based on a hypervelocity impact differs from the phenomenon that artificial objects GEO may experience. Besides, the NASA standard breakup up model has been formulated in a completely different manner from Harada (1996) and Goto (1997). Therefore, they treat separately low- and hyper- velocity collisions. They apply Harada (1996) and Goto (1997) to low-velocity collisions, whereas they apply the NASA standard breakup model to hypervelocity collisions.

Hanada (2000) analyzed the low-velocity impact data obtained by Harada (1996) and Goto (1997) based on the method used in the NASA standard breakup model, and then compared with the NASA standard breakup model. As a result, Hanada (2000) has concluded that the NASA standard breakup model could be applied to low-velocity collisions with some simple modifications. Since the low-velocity impacts that Harada (1996) and Goto (1997) conducted were considered as a non-catastrophic collision, characterized primarily by fragmentation of the projectile and by crater or hole on the target, we are not sure if it can also be applied to low-velocity catastrophic collisions, wherein both projectile and target are totally fragmented. The difference between a catastrophic and a non-catastrophic collision would be determined by the ratio of kinetic energy at impact to target mass. The NASA standard breakup model has defined if the ratio is equal to or greater than 40 J/g, then the collision is catastrophic. Therefore, we hit a micro satellite of a mass of approximately 680 g by an aluminum alloy solid sphere of a mass of 36 g at a speed of 1.35 km/s. This paper characterizes and reports the physical properties of the fragments from the low-velocity catastrophic impact performed.

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2. LOW-VELOCITY IMPACT

The following subsections address the detailed description of low-velocity impact on a micro satellite performed.

2.1. Two-Stage Light Gas Gun

A two-stage light gas gun as shown in Fig.1, of which bores of a pump tube and launch tube are 60 mm and 14/30 mm, in Kyushu Institute of Technology was used to launch a projectile. This gun was originally installed in Tohoku University, Japan, and was moved to Kyushu Institute of Technology January 2002. From March 2003 this gun was settled at Hypervelocity Impact Test Laboratory in Kyushu Institute of Technology. This gun is often used to develop a new bumper shield with the bore of 14mm. In this test a launch tube was exchange from 14 mm to 30 mm.

2.2. Target

Fig. 2 shows the target impacted, a cylindrical-shaped micro satellite, whose diameter and height were 140 mm and 160 mm, respectively. The mass of the micro satellite was approximately 680 grams. This micro satellite had four layers and one ceiling made by CFRP plates but no side panel. This micro satellite was fully functional with a Global Positioning System (GPS), a magnetic sensor, two sun sensors, a thermal sensor, two gyro sensors, a memory card unit, two lithium-ion batteries, four micro computers, two DC-DC converters and communications devices. The target satellite was hungered from the vacuum chamber ceiling with wires. The inner walls of the vacuum chamber were covered with polystyrene foams to collect fragments scattered after impact without any further damages.

2.3. Projectile

The projectile launched to hit the target satellite was a solid sphere made of an aluminum alloy, A 2017. The diameter and mass of the projectile were 30 mm and 40 grams, respectively.

3. RESULTS AND DISCUSSIONS

The impact velocity measured before the projectile hit the target satellite was 1.35 km/s. Therefore, the resulting ratio of kinetic energy at impact to the target mass was 48 J/g so that this low-velocity impact satisfied the NASA definition on a catastrophic collision.

As Fig. 4 shows, the target satellite was totally fragmented after the impact. The mass of the projectile recovered after the impact was 35.7 grams, slightly lighter than its initial mass. From Fig. 4 and the recovered projectile, this low-velocity impact could be designated as a catastrophic collision. Noted that white-colored materials in Fig. 4 were polystyrene foams used to collect fragments.

From the reassembled micro satellite structure shown in Fig. 5, we understood the fragmentation process at the impact. The projectile was traveling from right hand side to left hand side. The first plate from right was the ceiling plate, on which a GPS antenna was put as shown in Fig.2 and we can observe the simple hole. The last plate from right was the bottom plate and was damaged more than the ceiling plate. As Fig. 5 shows, the damaged areas on the layer plates get bigger and bigger as the projectile traveled.

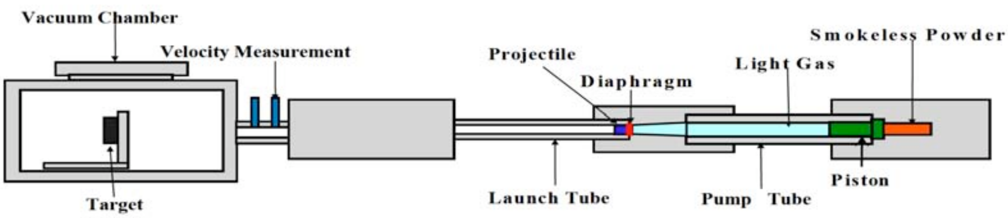

Figure 1. Two-stage light gas gun.

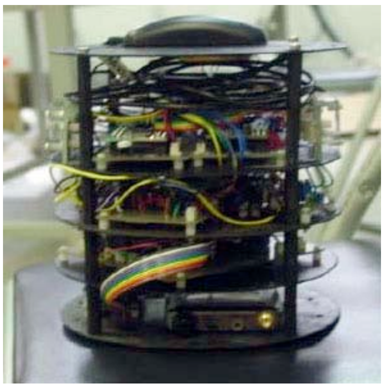

Figure 2. Micro satellite impacted as target.

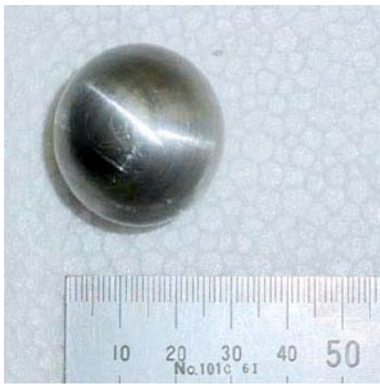

Figure 3. Projectile launched to hit the target satellite.

To date, we have individually collected and analyzed 1,568 fragments, which amount for 79 weight percentages of the target and projectile masses. Figs. 6, 7, 8, 9 and 10 show some fragments generated by the impact. The fragment shown in Fig.6 had a memory unit to store housekeeping and mission data but lost it. Fig. 7 shows an IC tip on a fragmented circuit board, whereas Fig. 8 shows an IC tip released from a circuit board. We can observe a crack on both tips. The lead line shown in Fig. 9 was not cut but its coating was broken into several pieces. Fig. 10 shows several fragments from CFRP plates.

Finally, Fig. 11 compares the fragment size distribution obtained from this study with that produced based on the NASA standard breakup model 2000 revision (Johnson et al., 2000). Fig. 11 shows a good agreement between them but we can observe a leveling off of the data at the smaller size range. This leveling off would be caused by the physical inability to collect and analyze smaller fragments because the size range where we can observe this leveling off deceases as fragment collection and analysis proceeds.

Figure 4. Micro satellite fragmented after low-velocity impact.

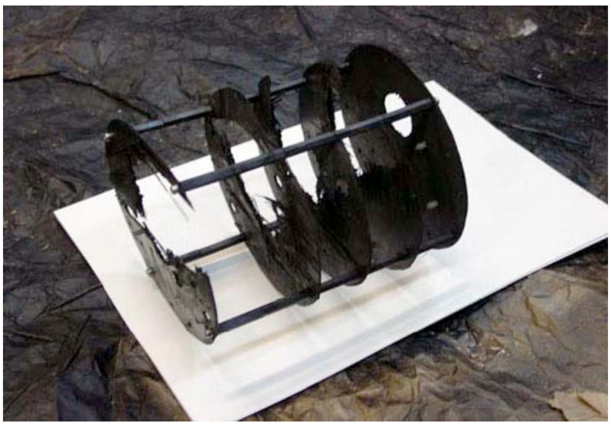

Figure 5. Reassembled micro satellite structure.

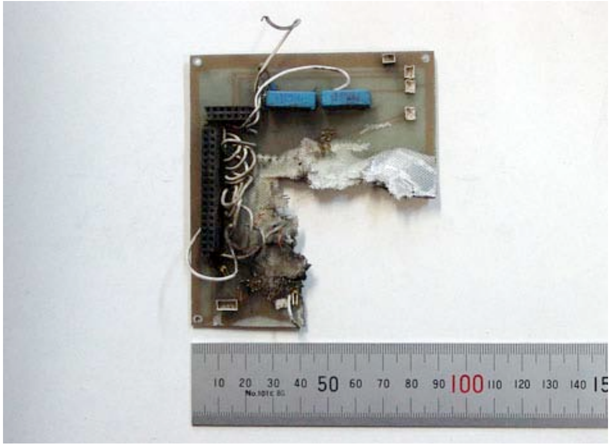

Figure 6. A fragmented memory board.

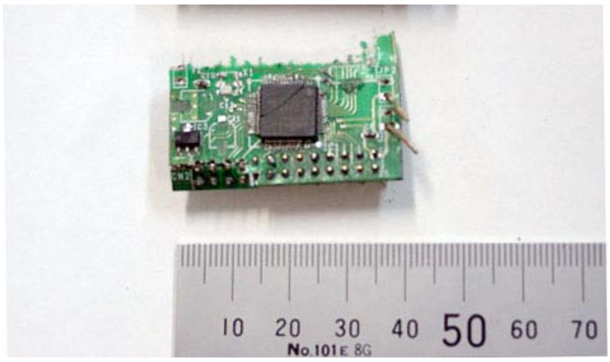

Figure 7. A fragmented circuit board.

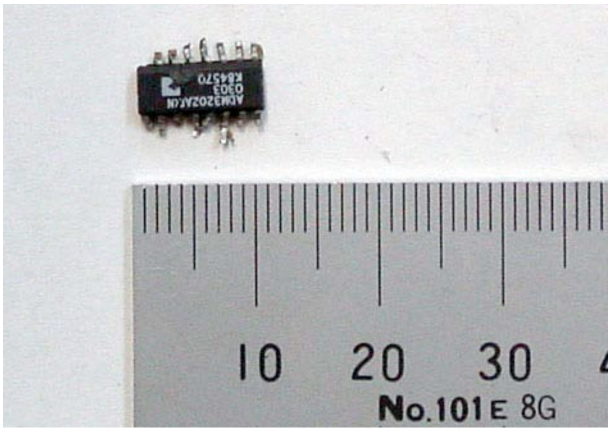

Figure 8. An IC tip broken from a circuit board.

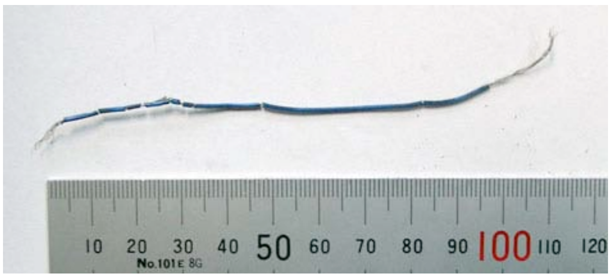

Figure 9. A fragmented lead line.

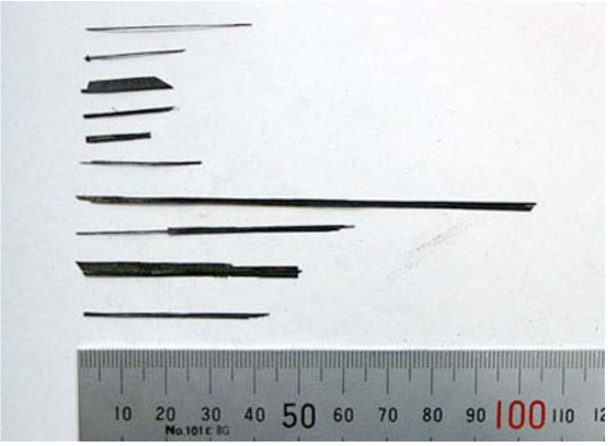

Figure 10. Fragments from CFRP plates.

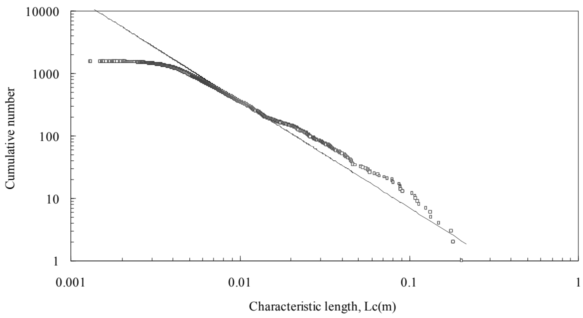

Figure 11. Fragment size distribution. Circles represent fragment size distribution obtained by this study, whereas solid line represents that produced based on the NASA standard breakup model.

4. CONCLUSIONS

We hit a micro satellite of a mass of approximately 680 grams with a projectile of a mass of 36 grams at a speed of 1.35 km/s. The projectile and target micro satellite were totally fragmented to be designated as a catastrophic impact. After this impact test, 1,568 fragments, which account for 79 weight percentages of the target and projectile masses, have been collected and analyzed individually to characterize the fragment properties. The following concluding remarks can be drawn:

1. When the projectile hit the ceiling plate, it released fine particles like powder. When the projectile hit the layer plates, on the other hand, they released plate-shaped fragments.
2. Circuit boards outside the damage area on the layer and ceiling plates have no damages but do not work because of broken lead lines.
3. The coating of not-broken lead line was broken into several pieces.
4. The shape of some fragments seems to depend on where the fragment was.
5. Even though a circuit board has no cracks or was not broken into pieces, IC tips on it have some cracks.
6. The size distribution obtained from this study agrees well with that produced based on the NASA standard breakup model.

Now we are investigating fragments area-to-mass distribution and size-to-area conversion equation. The results will be presented in International Astronautical Congress 2005 held in Fukuoka, Japan.

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