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Procedia Engineering 103 (2015) 334 – 340

Procedia Engineering

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The 13th Hypervelocity Impact Symposium

Impact Frequency Estimate of Micron-sized Meteoroids and Debris on Tanpopo Capture Panels on the ISS

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Abstract

This study is a part of 'Tanpopo' mission, which is to be mounted on the Exposure Facility of the Japanese "Kibo" Module of the International Space Station. The purpose of this study is to comparing the impact frequency that is predicted from the debris environment model and the impact craters on the exposed instrument. There are two approaches to achieve this plan. The first is to predict the impact frequency of the micron-sized debris onto the Tanpopo capture panels which is exposed to space. The second is to establish methods for calculating key parameters in relation to impacting debris particles from excavated craters on the capture panel material. The debris impact frequency on the capture panels was predicted using the impact-risk analysis tool. It was found that impact of particles of 10μm or less in diameter was expected on the panels. Additionally, the relationship between the debris impact energy and crater was also derived by hypervelocity impact experiments. It was found that regardless of the projectile materials and impact speed, the relationship between the impact energy and the crater volume is nearly proportional.

Keywords: Space debris, Crater equation, Risk assessment code, ISS, Impact frequency

Nomenclature

a,b,c	semi-major axis of spheroid (mm)
d	crater diameter (mm)
E	impact energy (J)
P	crater depth (mm)
V	crater volume (mm^3)
V_{hs}	half of spheroid volume (mm^3)
V_s	spheroid volume (mm^3)

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doi:10.1016/j.proeng.2015.04.055

1. Introduction

There are many objects considered as debris in space. For example, fragments of satellites and rockets are considered as big debris items, and paint flakes and bolts are considered as small debris items. With the development of the space industry in recent years, the number of small debris items generated from low-Earth orbits has been increasing particularly because such orbits are frequently used. Additionally, micron-sized debris items, which are less than 1 mm in diameter, are predicted to affect satellites in operation more than once. Even in the case of small debris impacts, there is a risk that satellites will be deprived of their mission capability. If the distribution of debris is unclear, it is not possible to evaluate the risk of its impact. Since such small debris particulars cannot be detected by ground-based data observations, it is necessary to predict their spatial and temporal distribution with a dynamical flux model. The European Space Agency (ESA) and National Aeronautics and Space Administration (NASA) have independently developed respective engineering models based on their spacecraft measurement data over the past few decades [1]. As the debris environment changes, and as human space activities progress, those flux models must be constantly updated based upon the latest data collected from in-situ space measurements. Such data can be acquired by carrying out the exposure experiment in low-Earth orbits associated with higher debris impact frequencies.

There is an existing plan to compare the impact frequency predicted from the debris environment models and the craters formed on the panels exposed in space, to assess the validity of the distribution model. This is known as the “Tanpopo” mission [2-3], that will involve experiments to capture: a) intact organic-bearing micrometeoroids that reached low-Earth orbit altitudes, i.e., possible aerosol particles containing terrestrial microbe colonies inside them, and b) debris accumulated at the Exposure Facility of the Japanese “Kibo” Module of the International Space Station (ISS). This study is a part of this planned mission. After samples return to the Earth, the capture panels will be investigated in search of these micron-particles mentioned earlier. Because it is considered that small debris impacts capture panels at the same time as they impact microbes, debris flux can also be evaluated. The validity of the model is assessed by comparing the impact frequency that is predicted from the debris environment model, and the impact craters on the capture panels that have been exposed to space while in flight.

There are two approaches to achieve this plan. The first is to predict the impact frequency of the micron-sized debris onto the Tanpopo capture panels for the planned orbit at ISS. The second is to establish methods for calculating key parameters in relation to impacting debris particles from excavated craters or tracks on the target materials, such as from aerogel or aluminum plates. For the former approach, the debris impact frequency on the capture panels was predicted using the impact-risk analysis tool. For the latter approach, the relationship between the debris impact energy and crater was derived.

2. Evaluation of the impact frequency

The ESA’s MASTER-2009 was used as the debris environment model [4]. The debris impact-risk analysis tool, developed by JAXA and MUSCAT Space Engineering Co., named ‘TURANDOT’ [5], was used to predict the debris impact frequency. The tool can construct three-dimensional (3D) models and divide the model faces into face elements. By applying the ballistic limit equations to elements from multiple areas, it can also calculate the impact risk for each face element based on the same debris environment model. Furthermore, it is possible to determine the impact in consideration of the shadowing effect of each part of the model.

With the tool, a simplified 3D model of ISS was generated as shown in Fig. 1. In order to produce the dimension and

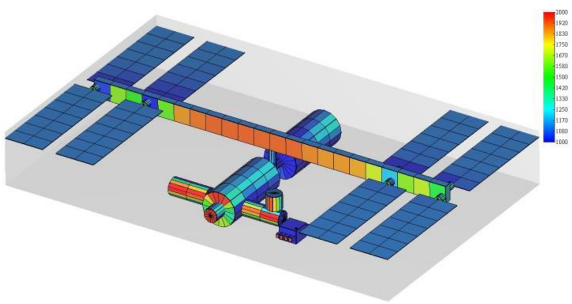


Fig.1. Simplified ISS model in TURANDOT

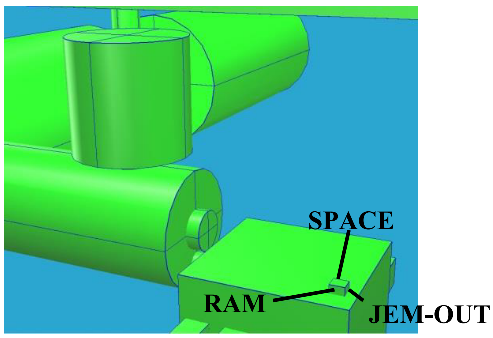


Fig. 2. ExHAM model in TURANDOT

structure of the ISS, main parts were modelled with reference to the dimensions and installation positions of a published diagram [6]. The Tanpopo capture panels are installed on a small pallet called 'Exposed Experiment Handrail Attachment Mechanism (ExHAM) on the Japan Aerospace Exploration Agency (JAXA) Kibo Exposure Facility. Therefore, a box simulating the ExHAM was also generated at a forward exposed position in the TURANDOT, as shown in Fig. 2. The box is 270 mm in height, 460 mm in width and 410 mm in depth. Capture panels are installed on all three sides of the ExHAM. The sides were defined as RAM, JEM-OUT, and SPACE. RAM is the face in direction of the velocity-vector of the ISS that is stabilized by the Earth's gravity, on a three axes controlled spacecraft. SPACE is pointing away from the Earth with its face at 90 degrees with respect to the RAM direction. JEM-OUT is the face on the opposite side of the pressurized module. In this study, impact frequencies on each area for the three sides were calculated. Such results represent the mean impact frequency on the capture panels. The exposed area of a capture panel is approximately 100 cm^2. Since four panels are attached and exposed on each ExHAM side, the particle impact frequency of the capture panels was calculated based on value of 400 cm^2 that represents the total exposure area.

The number of particles that were predicted to impact on the capture panels is shown on Table 1. Such data relate to exposures for the duration of one year, starting from 1 January 2015. It is predicted that particles with size from 10 to 100 μm in diameter impact one or more of the capture panels of each side. On RAM, about 14 particles are predicted to impact. Additionally, significant differences equency by particles that was larger than 1 μm were observed significant difference between RAM and the other two faces. Specifically, the impact number on RAM was over 70, whereas corresponding numbers of approximately 40 particles are recorded on each of the other two faces. It is considered that particles impact more frequently on RAM than the other two faces because this face align with the direction of the velocity vector of the ISS. Furthermore, the ratio of the impact frequencies between meteoroids and debris was calculated. The cumulative number of impacts of particles larger than 1 μm in diameter was investigated as shown in Fig. 3. Its vertical and horizontal axes show the number of impacts on the Tanpopo capture panels and the three pointing faces of the ExHAM. On all of these faces, meteoroids accounted for over 80 % of the impact particles. It is found that meteoroids were almost all of the impact particles on SPACE. On RAM, more impacts were predicted than any of the other faces. Additionally, it can be deduced that the capture panels installed on RAM are most useful in observing the impact frequencies of debris.

3. Evaluation of the impact frequency

The Tanpopo capture panel is shown in Fig. 4. The panel is 100 mm in length on all four sides and about 20 mm in thickness. Silica aerogel with ultra-low density has been developed for these panels. It is held in an A7075-T651 aluminum alloy mesh case, which is aluminum alloy with face treatment. The ratio of the exposed area between the aerogel and the case mesh cover is approximately 6:4. While the panels are exposed to space, debris impacts both the aerogel and the case. Therefore, the first goal is to establish the relationship between the crater to the case and the impact energy.

In a previous study, hypervelocity impact calibration tests were conducted for the Al case [4]. The experiments were performed by changing the materials and diameters of the projectiles. Based on such work, it was found that if the material of the impact particle is unknown, it is possible to calculate the diameter of the particle from the diameter of the crater. It was also found that the crater volume and the impact energy were proportional, regardless of the material of the impacting particle. The tests were conducted at a constant impact speed. Therefore, the same test was repeated at 4 km/s in this study and the effects at this speed were investigated. The tests were conducted using a two-stage light gas gun at JAXA. Spherical

Table 1. Particle impact frequency the capture panels (1/year)

Particle Diameter (μm)	RAM	JEM-OUT	SPACE
>100-	0.18	0.11	0.093
10-100	14.0	6.14	8.42
1-10	70.8	36.6	38.6

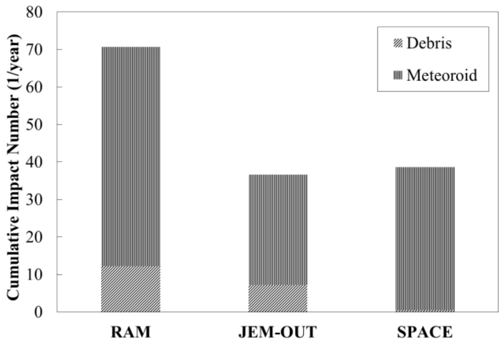


Fig. 3. Comparison of cumulative impact number of meteoroid and debris in each of the three ExHAM faces

projectiles of aluminum, aluminum-oxide and steel particles with diameter ranging from 100 to 500 μm were used. These sizes matched the particle sizes used in the previously conducted study. Multiple projectiles impacted vertically on the target, at a speed of 4 km/s, with a plurality of particles in a single test, using the shotgun method.

After the tests, projectiles and crater sizes were measured with a 3D laser microscope manufactured by KEYENCE. Measurement examples using the microscope are shown in Fig. 5. Also shown are the results of projectile with a diameter of 0.3 mm impacting at approximately 4 km/s. Each of the pictures in Fig. 5 (a)-(c) show the aluminum, the aluminum-oxide, and steel sphere results. Similar to the case of an impact speed of 4 km/s, crater shapes produced by aluminum and aluminum-oxide projectiles do not exhibit visual differences. However, only the crater produced by the steel projectile has an uneven face rougher than the others. Thus, quantitative parameters of the crater's shape were measured, including the crater diameter and its depth, in accordance to the definition introduced in the previous study, as shown in Fig. 6.

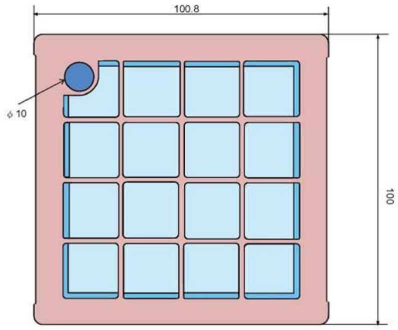
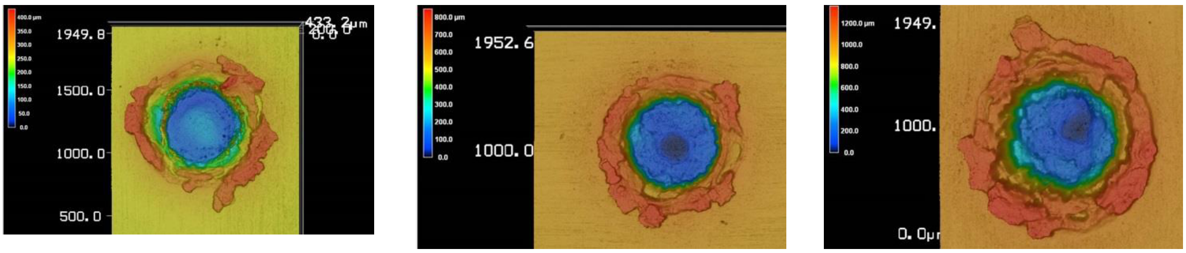


Fig. 4. The Tanpopo capture panel [7]

A comparison of the results from this study at a speed of 4 km/s and the previous study at 6 km/s are shown in Figs. 7



(a) Aluminum (b) Aluminum-oxide (c) Steel

Fig. 5. Three-dimensional images of formed craters

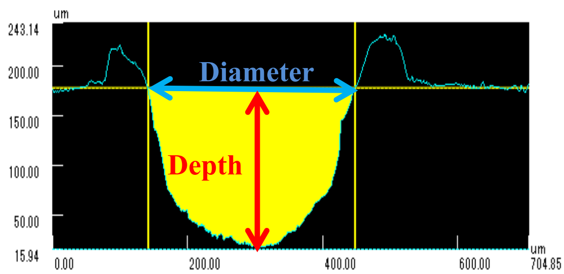


Fig. 6. Schematic explaining the quantification of the crater's depth and diameter [3]

and 8. The red, blue and black symbols represent the results produced by the aluminum, the aluminum-oxide and the steel projectiles, respectively. The closed and open dots respectively represent the results of impact speeds at 4 km/s and 6 km/s. The relationship between the projectile diameters and the crater diameters is shown in Fig. 7. Considering the conditions of this study, it is found that as the crater diameter increased, the projectile diameter also increased, regardless of the projectile material. It was also found that the effect of the impact speed was not significant. In accordance to the fitted line in Fig. 7, the crater diameter increases with 1.13th power of the projectile diameter. Therefore, it is considered that the projectile diameter is proportional to the crater's diameter. The relationship between the projectile's impact energy and the crater's volume is shown in Fig. 8. Following a similar approach to that in the previous study, the crater shape was assumed as a half spheroid as shown in Fig. 9. First, a spheroid's volume was calculated by Eq. (1):

$$V_s = \frac{4}{3}\pi abc \tag{1}$$

Then, a half spheroid's volume was derived by Eq. (2):

$$V_{hs} = \frac{2}{3}\pi abc \tag{2}$$

Finally, the crater's volume was calculated based on the following equation:

$$V = \frac{1}{6}\pi P d^2 \tag{3}$$

Regardless of the projectile materials, it can be observed that the crater volume increases with an increase in the impact energy (E). Furthermore, the empirical formula that relates V and E is given by

$$V = 0.30E \tag{4}$$

Therefore, based on this equation, the relationship between the impact energy and the crater volume is nearly proportional. However, regardless of the impact speed, two of the data points in the case of steel projectiles are far below the value

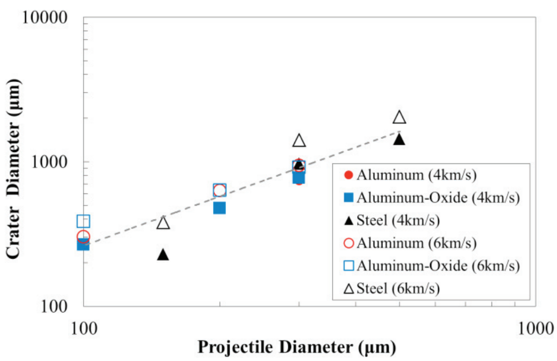


Fig. 7. Correlative comparative plot of the crater diameters against the projectile diameters

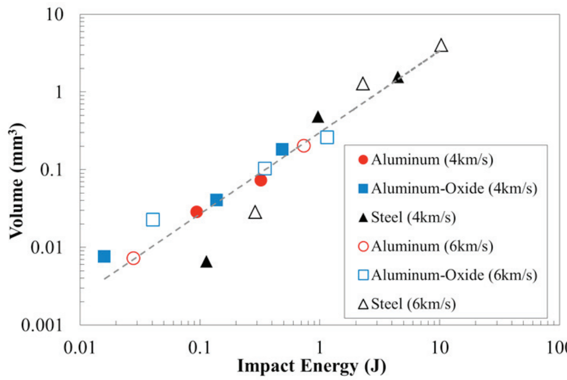


Fig.8. Comparative plot of crater volume against impact energies

predicted by the fitted empirical formula, within an impact energy range of 0.1 to 1 J. As both of these points were

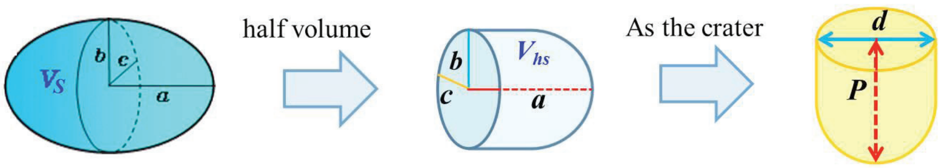


Fig. 9. Assumption of the crater volume [3]

calculated from the nominal diameter of steel spheres (150 µm), individual diameters were considered to have variations from the average value. In this test, many spheres were shot at the same time. Therefore it was not possible to identify impacting projectiles that have exactly the same crater diameter and position. Thus, in the case of the experiments obtained the two points, the sizes of the impacting projectiles has possibility to be smaller than the nominal diameter of 150 µm. The measurement result with optical microscope of the steel projectiles of 150 µm that used in the experiments is shown in Fig. 10. The average of measured value of the diameter was approximately 89.2 µm. The crater's volume was recalculated by using the measured value, as shown by the green symbols in Fig. 11. The recalculated points were closer to the fitted line than the original points. Moreover, steel has larger elongation than aluminium. Therefore, it is also considered that steel's impact energy was used more for elongation than aluminum impact energy.

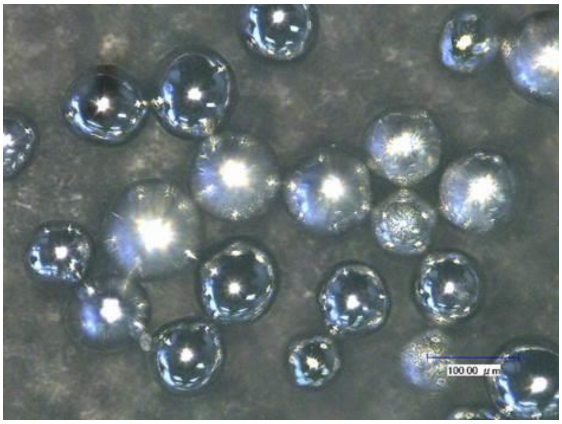


Fig. 10. Image of steel particles observed with a light microscope

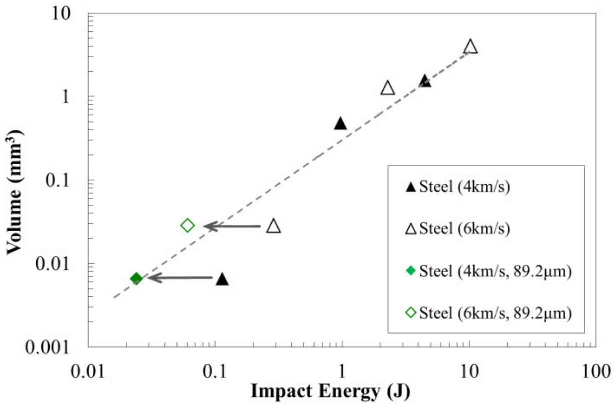


Fig. 11. Plot of crater volume against the impact energy of a steel projectile

Conclusion

From the prediction results of the impact frequency on the capture panels based on the use of the debris impact risk analysis tool, it was found that:

1) Impact of particles of 10µm or less in diameter was expected on the panels. Panels on RAM faces had an impact twice impact frequency as high compared with that of the other faces. In addition, meteoroids formed the majority of the impact particles.
2) There was a considerable amount of debris impact on RAM compared to the other faces. RAM is the best face for calculation of the debris impact frequency.

In this study, a simplified 3D ISS model was employed. Currently, both the degree and the type of the impacting debris is unknown. A revised, detailed model is under construction. Once the detailed model is completed, these factors will be further investigated and analysed.

Additionally, from the hypervelocity impact test it was also found that:

1) Regardless of the projectile materials, and without consideration of the effect of speed, the relationship between the projectile's diameter and the crater's diameter is nearly proportional.
2) Regardless of the projectile materials and impact speed, the relationship between the impact energy and the crater volume is nearly proportional.

Based on the density comparison tests, it is considered that it is useful that the test does not only use steel but also copper. This study will be carried out in the future.

Acknowledgements

The work was supported by the Space Plasma laboratory, ISAS/JAXA, and the facility of the Lunar and Planetary Exploration Program Group, JAXA. In addition, the authors thanks Dr. Shinji Hatta (MUSCAT Space Engineering Co.) for his useful discussion.

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