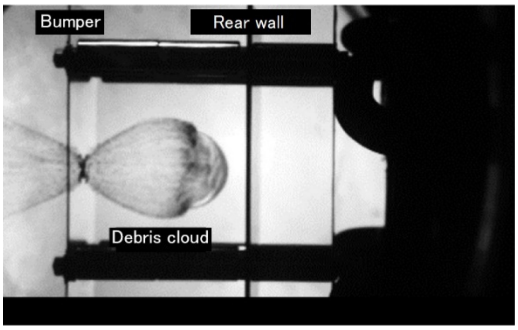
Hypervelocity Impact Evaluation Technology of MMOD Protection Structure Mounted on Spacecraft in Lunar Environment



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Manned spacecraft require a high-performance structure to protect against incoming micro-meteoroids and orbital debris (MMOD) to secure the safety of the crew onboard. It is expected that manned activities in the lunar vicinity will become more active in the future, and thus, initiatives toward the safety improvement and structural weight reduction of spacecraft are required. As methods to simulate a micro-meteoroid impact and to evaluate the performance of protection structures used for spacecraft, this report introduces case studies of hypervelocity impact tests using a two-stage light gas gun and hypervelocity impact analyses using hydrocode.

1. Introduction

For lunar surface development, the development of lunar orbital stations (Gateway), lunar landers, and lunar exploration vehicles are underway both in Japan and abroad. In addition, research on construction and power generation technologies aimed at living on the lunar surface are also being conducted. In particular, systems designed for manned operations need to be equipped with a protection structure against possible incoming MicroMeteoroids and Orbital Debris (MMOD) in order to prevent loss of human life(1). A typical MMOD protection structure for manned spacecraft is a Whipple shield consisting of a plate called "bumper" and the rear wall, bumper is attached to the outer surface of the rear wall with standoff(2) as shown in **Figure 1**(a). The Japanese Experimental Module (JEM) of the International Space Station (ISS) and the H-II Transfer Vehicle (HTV), which are currently in operation, use a MMOD protection structure developed by Mitsubishi Heavy Industries, Ltd., and have experienced no functional damage due to micro-meteoroids or space debris impacts (Figure 1(b)).

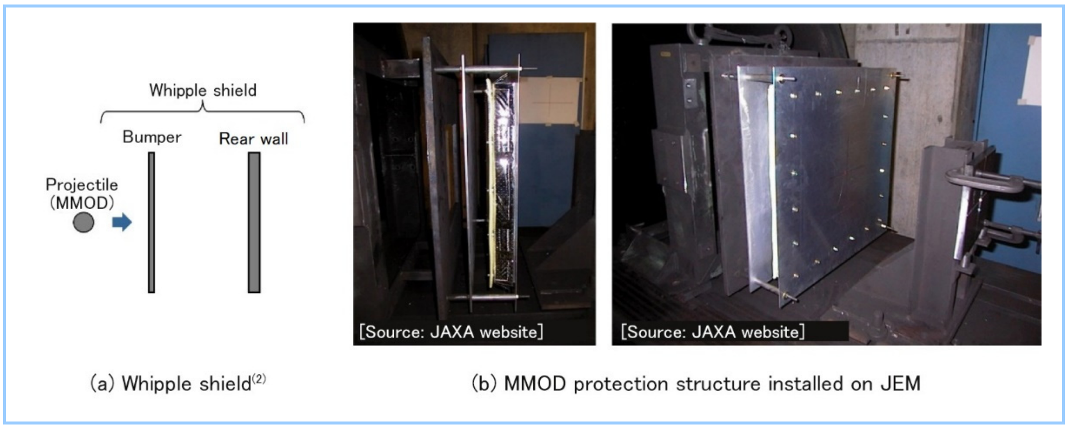

Figure 1 MMOD protection structure example

We are currently working to improve our evaluation technologies for impacts between MMOD and a protection structure in preparation for future development in the lunar near-surface region. This report presents case studies of impact tests and analyses that we conducted. Particularly, incoming

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micro-meteoroids are anticipated in the lunar peripheral environment, and therefore we simulated micro-meteoroids with a density of 3.5 to 4.0 g/cm^3, which have a high probability of impacting and causing significant damage, using projectiles made of alumina for evaluation.

2. MMOD protection structure installed on manned spacecraft

As Figure 1(a) shows the Whipple shield, installing a bumper with a gap between it and the rear wall can disperse the damage to the rear wall [(1)] because, when incoming projectiles penetrate the bumper, they are fragmented, melted, and vaporized and then break up in the form of a debris cloud[(1)] (**Figure 2**). This effect makes the rear wall more high performance to protect than single plate of the plate thickness, thus this structure can reduce the overall weight of the spacecraft when having the same protection performance. In addition, as shown in Figure 1(b), it is considered that a structure with higher protection performance can be achieved by installing additional plate between the bumper and the rear wall, and protection structures similar to this are installed in Destiny and Columbus, the ISS experimental modules[(3)(4)].

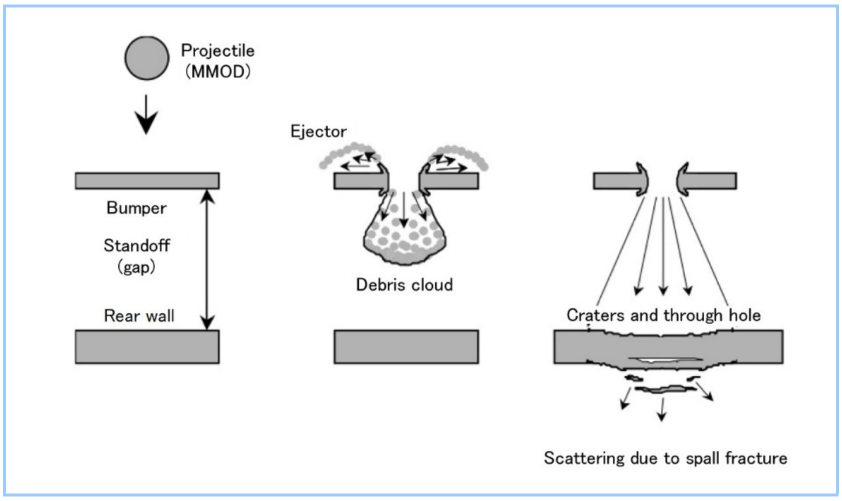

Figure 2 Mechanism of Whipple shield to protect against projectiles[(1)]

3. Hypervelocity impact test using two-stage light gas gun[(5),(6)]

It is generally considered that the average impact velocity of MMOD is 9 km/s in the case of space debris, and 19 km/s for micro-meteoroids. The size of projectiles that manned spacecraft need to be protected against is considered to be no larger than 1 mm to 10 mm in diameter when they have a spherical shape[(1)]. To impact such velocity and diameters projectiles to a MMOD protection structure, an accelerator called a two-stage light gas gun (**Figure 3**) is used.

As shown in Figure 3(b), this device ignites the gunpowder to accelerate the piston and compress light gas (hydrogen, helium, or the like) filled inside the tube. When the pressure of the light gas exceeds a certain value, the diaphragm breaks, and the compressed gas that breaks through the diaphragm accelerates the projectile set inside the launch tube and its sabot (a plastic container that holds the projectile). The accelerated projectile is separated from the sabot while flying and impacts the target. Since many testing technologies are required, such as adjustment of the amount of gunpowder, design of the diaphragm and the sabot, etc., test evaluations are conducted with the cooperation of domestic and overseas research institutes that have such test facility and testing technologies.

Figure 4(a) shows images of the impact of a projectile simulating a micro-meteoroid on a typical debris protection structure (Whipple shield) at about 3 km/s and about 6 km/s, which were taken by a high-speed camera. The images show the velocity (in the flying direction and the orthogonal direction) and the scattered state of the debris cloud after the impact with the bumper. For example, Figure 4(a)-(i) shows that fragments were concentrated at the leading edge of the debris cloud. These test results allow the evaluation of the relationship between the state of debris cloud and the projectile material or impact velocity, it makes possible to organize the complex impact phenomena in a time history.

Figure 4(b) shows the state of the rear wall after impacted by the debris cloud. The diameter and depth of the craters formed on the surface of the rear wall and the size of the through-holes were measured using a microscope. From the measurement results, the size of the fragments in the debris cloud is estimated, and the obtained data can help to build a model for the hypervelocity impact analysis described in Section 4.

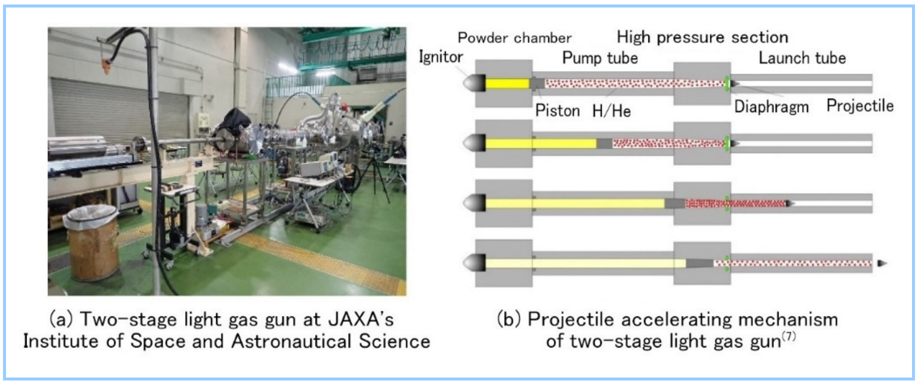

Figure 3　Test facility for hypervelocity impact tests (two-stage light gas gun)

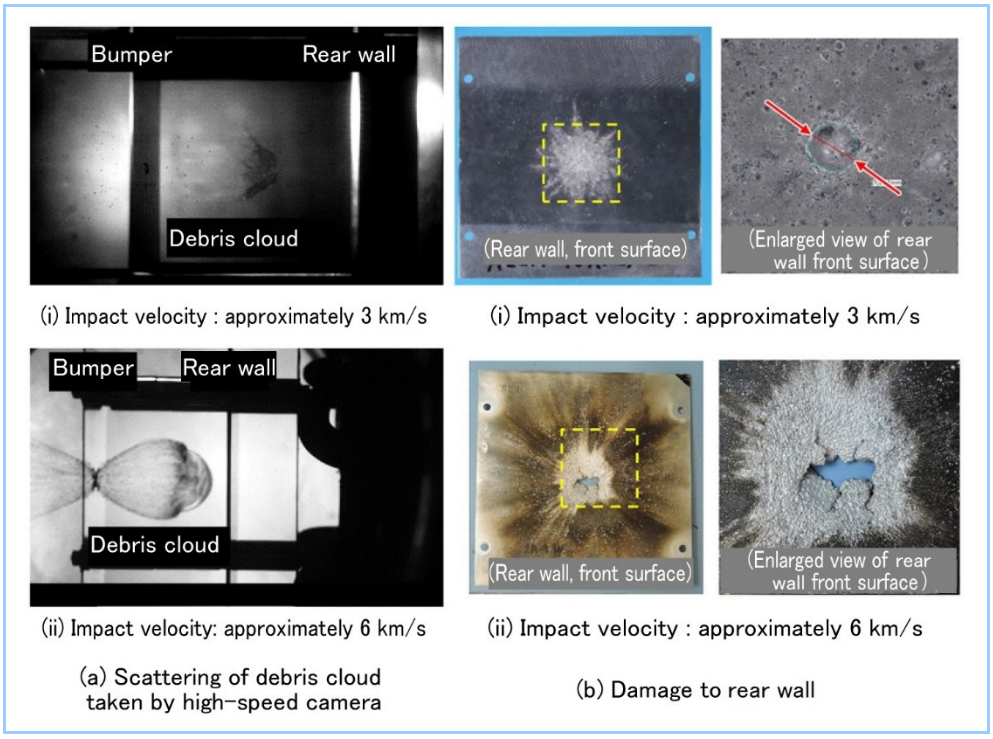

Figure 4　Results of impact tests on Whipple shield using two-stage light gas gun

4. Hypervelocity impact analysis using SPH method[5],[6]

It is difficult to conduct hypervelocity impact tests using a two-stage light gas gun for all combinations of parameters due to the setting time per one case. Therefore, it is necessary to construct a hypervelocity impact analysis model based on the test results, and to reduce the number of test cases using this model.

Since penetration and phase change occur on the impact phenomenon between a projectile and a MMOD protection structure within several tens of microseconds, impact simulations were conducted using the Smoothed Particle Hydrodynamics (SPH) method, which evaluates by the interaction between particles assuming the object as an aggregate of particles. Since a hypervelocity impact induces a high-pressure compressive phenomenon at tens to hundreds gigapascals, the equation of state, strength and failure model are needed for the material model, thus several dozen parameters are required. Furthermore, the strain rate dependency of materials also has an influence, but there are not much reference concerning material properties in the strain rate range in the order of 10^5 to 10^7 1/s.

Material models were constructed based on the test results which obtained from the tests described in Section 3. Using hydrocode (Ansys AUTODYN©) for the calculations, the parameters that have high sensitivity for the calculation results were analyzed based on the material models in the software's material library to simulate the fragmentation of the projectiles, and the parameters of mechanical properties were correlated within a realistic value.

Figure 5 shows the calculated results using a two-dimensional axisymmetric model to evaluate the depth and diameter of craters formed on the rear wall and the velocity of debris clouds. In this test case, the difference between the calculated results and the test results (the ratio of the difference to the latter) was +3.4% for the crater depth, -28.6% for the diameter, and +5.6% for the velocity of debris cloud. The calculated results for the crater depth and the velocity could approximately simulate the impact phenomena in the test, but further consideration of the analytical model is needed in terms of the crater diameter. In the future, we will continue to refine the analytical model and study the applicability of the model for other impact conditions.

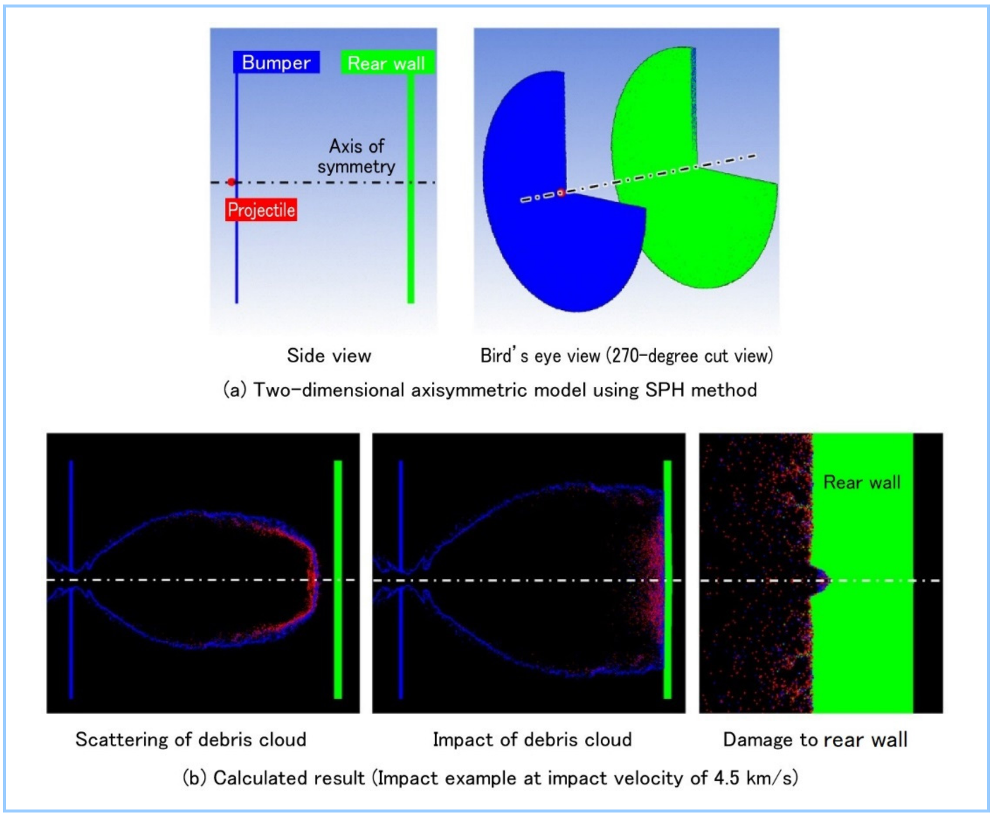

Figure 5 Hypervelocity impact analysis using AUTODYN©

5. Conclusion

This report introduced case studies of the technology to evaluate the protection performance of a MMOD protection structure used for manned spacecraft: hypervelocity impact tests using a two-stage light gas gun and hypervelocity impact analyses using hydrocode. The hypervelocity impact tests were conducted in cooperation with domestic and overseas organizations that own a two-stage light gas gun, and can evaluate the protection performance against MMOD at impact velocities of 7 km/s or less. The hypervelocity impact analysis is considered to be made possible to simulate the actual impact phenomena by correlating the influential parameters within a realistic value as described in this report.

One of the issues is the development of a method for evaluating protection performance in the impact velocity range beyond 7 km/s. The impact velocity that can be achieved with a two-stage light gas gun is approximately up to 7 km/s, and there is an issue with impact tests at velocities exceeding 7 km/s that it is difficult to conduct tests under the actual impact conditions in space due to limitations such as the diameter of the projectile. The use of shaped charge enables impact tests at velocities exceeding 10 km/s, but it is thought that the control of the shape and mass of the projectile is difficult[8]. In addition, it is also necessary to refine the analytical model and verify the applicable range. We will continue to work on these issues using another test data.

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