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微小重力下での着陸パッド動的貫入における柔軟地盤の機械的特性

Mechanical Properties of Soft Ground during Dynamic Penetration of a Landing Pad in a Microgravity Environment

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1. Introduction

Since the world's first soft landing on the moon with the former Soviet Union's Luna-9[1)], 120 spacecraft have attempted celestial landings to date[2)], starting with the U. S. Ranger-3 attempt[3)]. A total of 44 lunar landers were launched until the former Soviet Union successfully returned the sample from the lunar surface with Luna-24 in 1976. However, there was a gap of nearly 40 years until China successfully landed on the moon with Change'3[4)] in 2014. Although spacecraft by several private companies have attempted to land on the moon in recent years, with no success, India successfully accomplished this feat[5)] as the fourth nation in August 2023. In the meantime, the United States has shifted its focus towards exploring Mars and is methodically deploying its lander and rover to the surface of the Red Planet[6-10)]. In Japan, the OMOTENASHI (Outstanding Moon exploration Technologies demonstrated by Nano Semi-Hard Impactor) spacecraft[11, 12)] was launched aboard SLS (Space Launch System) in November 2022 and operated in orbit as a full-scale landing on a high-gravity object, following the touch-and-go exploration of small bodies by the Hayabusa series[13)]. Also, in 2023, the Smart Lander for Investigating Moon (SLIM) spacecraft[14)] is set to launch for lunar landing while a spacecraft, Martian Moons eXploration (MMX)[15)], is scheduled to be launched to a Martian moon in 2024. Thus, landing explorations on the surface layer of celestial bodies are gaining momentum not only in Japan but also in other countries worldwide.

MMX plans to collect more than 10 grams of surface samples from the Martian moon and bring them back to Earth, with the goal of landing safely and staying for several hours on the microgravity surface multiple times. From these results, it is expected that a clearer understanding of the origin of the Martian moon will be obtained through close observation and sample analysis. Two prevailing theories will be investigated to determine their accuracy. The two theories exist for the origin of Mars' moons: the capture of an asteroid after the Mars formation and the accumulation of debris scattered by a giant impact of Mars. For this MMX mission, it is imperative to design a landing gear that will enable safe landing, extended stay and smooth take-off. The landing gear is currently being developed for planetary probes, including small celestial bodies. The intention is to prevent destruction during landing due to impact and kinetic energy of the spacecraft, as well as to gradually reduce surface missions due to regolith. Currently, many landers employ a combination of reverse-thrust rockets with solid or liquid fuel and shock-absorbing materials such as aluminum honeycombs that rely on plastic deformation to protect the spacecraft from impact and tripping over upon landing. Most of planetary landers have a free-fall period at the end of the landing sequence to avoid regolith fly-up contamination caused by the reverse injection manoeuvre. Upon touchdown, it is standard practice to cushion the impact with legs equipped with the shock-absorbing materials utilizing aluminum honeycombs. Especially in aluminum honeycomb, the acceleration can be controlled, and the total energy absorption can be passively adjusted by designing its crash cross section and volume. On the other hand, Luna-9 achieved the world's first soft landing of an observation instrument on the lunar surface by releasing the lander, covered in an airbag, just prior to landing on lunar surface after taking the reverse injection for deceleration. Recently, the Skycrane method9) has been developed for lowering a large rover, such as Curiosity and Perseverance, by actively controlling it in a suspended form. Such advanced methods are being developed on the moon and Mars, but when exploring small bodies with extremely low gravity, measures such as avoiding ascent immediately after taking samples within reach are taken due to uncertainties in surface properties. This is the case with both the Hayabusa series spacecraft and OSIRIS-REx, neither of which involve active landing and staying. On the contrary, Philae16), which endeavoured to delicately land on the comet, transported multiple landing equipment such as a reverse injector, a harpoon, drills, and a shock-absorbing damper. However, except for the damper, the equipment did not work, and Philae severally rebounds, resulting in landing in the shade of rocks at where the sunlight does not reach. It significantly decreases the worth of the mission, and it is undisputed that the equipment should function normally even for landing on a small body. Therefore, it is essential for the MMX spacecraft to quantitatively assess the interaction with the soft ground composed of regolith covering the surface of celestial body in advance and to design the landing gear appropriately.

To test equipment in a microgravity environment on Earth, free fall in a drop tower and parabolic flights are required. However, due to cost limitations, both the time and frequency of execution are restricted. Therefore, it is essential to develop a methodology for predicting the mechanical properties of the soft ground on the surface layer of small celestial body at an early design stage and use it for proactive verification in the landing gear design. In this context, the Hourglass mission17) was undertaken on the International Space Station with the aim of acquiring a comprehensive understanding of the behaviour of the regolith particles that comprise the ground in low gravity. However, analysis to improve accuracy is limited to predicting the scattering of regolith and attachment of floating regolith. Evaluating the behaviour of these particles is intricate. Thus, it is considered that the deeper testing is necessary to predict the reaction force when a large spacecraft touches a small body. In other words, it is crucial to obtain the necessary information for design from microgravity tests conducted on the ground.

In this paper, we present the results of the dynamic penetration test of the landing pad under microgravity using the drop tower and the obtained findings. Firstly, we report that dynamic penetration tests have been carried out on two types of granular media in the drop tower, and that the sinking tendency of the specific granular media does not differ from the result of the 1G test. In addition, the relationship between the drop tower test with a scale model and the 1G test with a full-scale model is also mentioned, as the drop tower test has significant dimensional limitations.

2. Basic principle

In the Martian moon landing sequence of the MMX spacecraft, the state in which the spacecraft first touches the surface of Phobos is defined as ‘grounding’, the state in which the spacecraft is expected to remain stationary is defined as ‘landing’, and the state in which the spacecraft leaves the surface is defined as 'take-off'. Here we show what the issues are and how to deal with them when interacting with the celestial surface layer in a low-gravity environment, i.e., the landing dynamics that occur during the transition from ‘grounding’ to ‘landing’.

First, the MMX spacecraft is larger than the conventional landers for small celestial bodies, and it remains on the surface of the Martian moon for several hours after landing. The landing gear plays a crucial role in exploration missions as it safeguards the spacecraft against damage, ensures a secure landing, and eliminates hindrances to mission success. Specifically, a landing gear is required that yields a low impact to the spacecraft, avoids tripping it over upon landing, and prevents scattering of regolith covering the celestial body’s surface. Moreover, it must retain a stable posture for an extended period. The MMX spacecraft intends to perform a controlled free fall from a 10 meters altitude to avoid the scattering of regolith resulting from reverse injection.

However, the velocity upon ‘grounding’ is expected to reach 0.5 m/s, with a corresponding kinetic energy of approximately 200 J. This would be equivalent to landing on a high-gravity celestial body like the moon or Mars. Therefore, it is essential to examine the incidence of falls and rebounds in the surface layer of the Martian moon where the restoring force by gravity is inadequate. On the contrary, as the Martian moon possesses a greater gravity than other small celestial bodies, the influence on the surface layer upon ‘grounding’ is greater than that of its counterparts. Accordingly, the landing deceleration encountered by the spacecraft in the deployed state should be adequately mitigated.

Figure 1 (left) shows the configuration of the MMX spacecraft’s leg. The MMX spacecraft is equipped with the four landing legs, which are designed to be able to control acceleration and dissipate energy with shock-absorbing materials, to suppress sinking and reduce the amount of regolith scattering with tapered landing pads, to stabilize the attitude during stay with the leg extension function and to absorb shock with the same shock characteristics multiple times. Other features include dynamic load measurement on the chassis (shown on the right in Figure 1) and contact detection at the bottom of the landing pad.

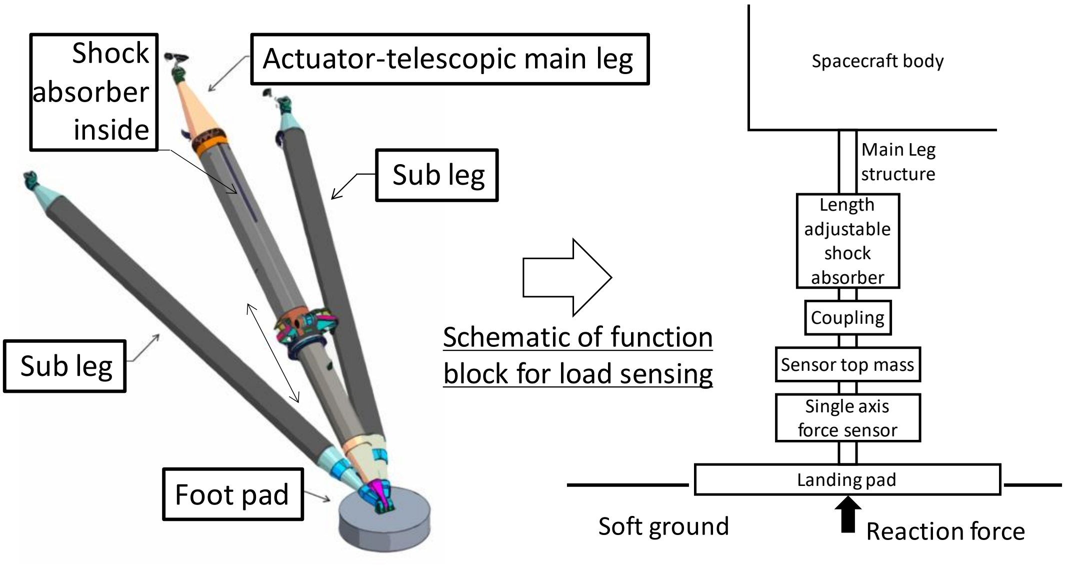

Figure 1. Configuration of the landing leg of the MMX spacecraft and composition for load measurement[18)] by the main landing leg.

Figure 2 presents an example of the time history of the reaction force applied to the landing pad during ‘grounding’ with celestial surface. When the time history of force during ‘grounding’ of the pad with the soft ground is divided into three phases, firstly, in Phase-1, the pad begins to settle into the soft ground. Then, in Phase-2, the shock-absorbing material receives the reaction force at a constant load within the Plateau region, achieving limited acceleration and the dissipation of the kinetic energy. Due to the considerable dissipation of the kinetic energy in MMX, most of the time taken for landing dynamics is occupied by this phase, in which the act of settling onto the ground does not make progress. Then, in Phase-3, rebound occurs or stays with the remaining energy after dissipating as much energy as possible. Therefore, it is necessary to predict the mechanical properties of the soft ground during Phase-1 until the shock-absorbing material begins to collapse, due to the dynamics interacting with the celestial surface. Excessive sinkage in Phase-1 increases the constraints of planetary protection and increases the risk of pad failure. In essence, determining Phase-1 holds significant importance in deciding the size of the landing pad and subsequent response, especially in the amount by which terminal sinkage must decrease before the shock-absorbing material begins to collapse.

The verification for the MMX spacecraft is advancing two strategies for predicting mechanical properties at the surface of celestial bodies. One is to create a simulated regolith of the surface layer of small celestial bodies, obtain the response of the scale model in a microgravity environment such as a drop tower test, collect data to match the responses as closely as possible, and directly verify the design. 6 types of simulated regolith assuming a Phobos surface layer were produced[19)], and the validity of the settling condition is evaluated by microgravity testing using the simulated regolith with the smallest reaction force among them (Phobos simulant, Model 3-1), which will be mentioned in this paper. However, since it is difficult to reproduce both gravity and instrument dimensions in experiments, interpolation by analysis is also essential.

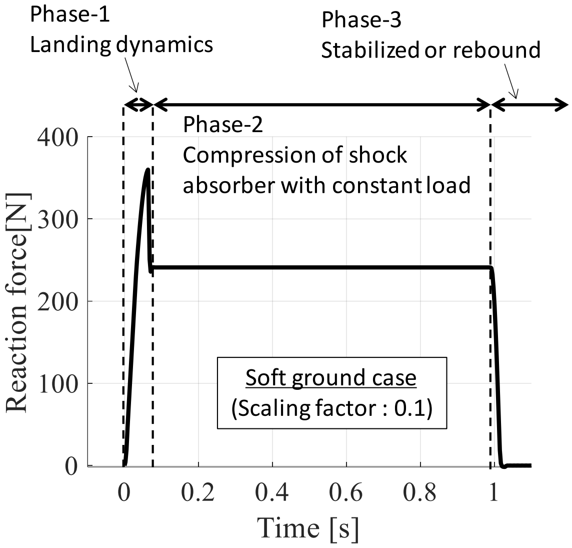

Figure 2. Typical load history on the force sensor located at the top of the landing pad.

Another strategy is to select and use macro models of interactions, and to analyse them to see if they hold intentionally over a wide parameter range. Settlement is predicted using methods based on the Hyperbolic Load-Settlement model20) and the model based on the Resistive Force Theory (hereinafter called RFT) 21). The latter can be easily introduced into simulators as it can also be used as an explicit method to calculate when the pad angle or penetration direction changes. The scaling factor (hereafter referred to as SF), which is a parameter of the RFT, is measured by aircraft experiments using the other simulant (Phobos simulant, Model 2-2) and the difference in bulk density and reaction force due to different dimensions is measured to limit the range used in the design. As a result, by limiting the scope of the verification in the simulator and clarifying the calculation method, including the expression expansion, we have been able to construct a system in which the verification can be widely carried out, including the development manufacturers.

However, in the microgravity tests with the simulant as described above have confirmed some phenomena with different governing physical laws, which limit the perfect reproduction in RFT. Since the compressive state of the shock-absorbing material accounts for most of the spacecraft behaviour in the MMX spacecraft at the time of ‘grounding’, it is assumed that the effect of different amplitudes, e.g., a peak position, other than the amplitude, is poor for the behaviour in a very short time until the settling stops, considering the response speed of the spacecraft. Therefore, it is assumed that the spacecraft behaviour to be verified can be reproduced by swinging the parameter range of the RFT, and the complete reproduction of the time history is a future issue, and the reproduction of the landing dynamics using the RFT model has already been performed22).

In this presentation, to investigate the first strategy, the reaction force response in Phase-1 until the shock absorber begins to collapse is captured in the microgravity environment, and the results provide guidance on how to conduct a full-scale leg performance evaluation test at 1G. However, the correction of the reaction force prediction equation of the second strategy with pads of different sizes is beyond the scope of this paper, and only the experimental results with the pad of one size are mentioned.

3. Experiments and results

3.1. Experimental setup and conditions

Figure 3 shows the experimental setup used for the dynamic penetration test of the landing pad in a microgravity environment. Table 1 shows the specifications of the experimental setup and the experimental conditions. Using Tohoku Silica Sand No.8 (hereinafter called TK8) and Phobos Simulant Model 3-1 (hereinafter called PS) as granular media samples, experiments are conducted in which an aluminum disc simulating a landing pad is dropped into the soft ground at a constant speed. A weight with measurement instruments is connected to the top of the pad and the sample is placed under reduced pressure in an acrylic vacuum chamber. The behaviour of the pad is monitored by a high-speed visible light camera from outside the chamber, and the flight position of the pad and the position of the ground surface are always measured by two laser displacement sensors. In addition, a triaxial accelerometer is mounted inside the weight, and a high-sensitivity force sensor (Kistler 9217A) and a 6-axis force-torque sensor (ATI Mini 40) are mounted on the leg, uniaxially restrained by guide rails. Furthermore, a separation mechanism using an extrusion spring and a shape memory alloy device (E500 from the former TiNi company) enables timely and constant speed injection. The bulk density is then deliberately controlled by hammering a sand bucket filled with the sample, and the test measurement is the bulk density calculated from the position of the ground surface when the pad finally strikes. Lastly, the vacuum chamber is retracted into the drop capsule, and the capsule is allowed to free fall for approximately 2.5 seconds without any resistance from the outside air, and then collides with the inside of the capsule, which is slowed down by an air damper, with an impact of approximately 40 G on landing.

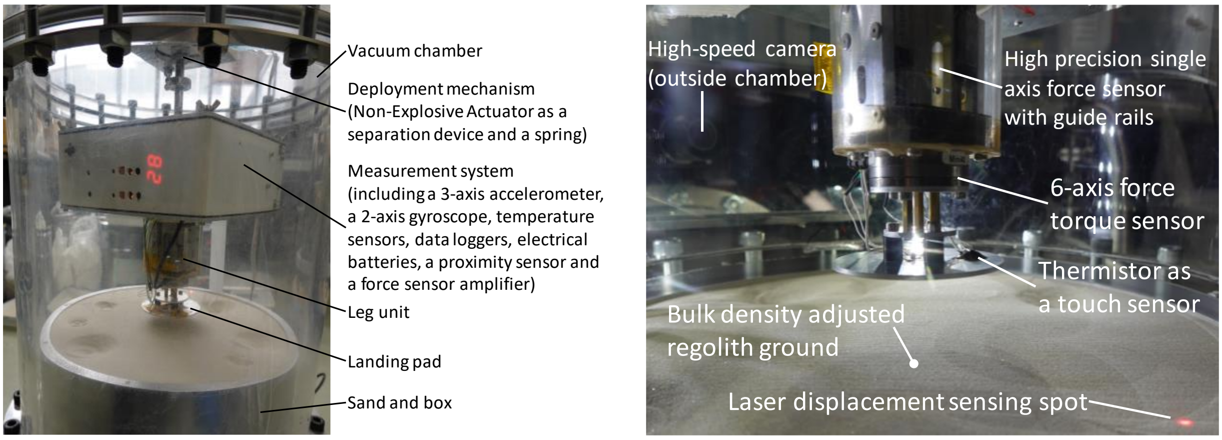

Figure 3. (left) Overall configuration of the experimental setup for the landing pad; (right) enlarged view of the leg unit and its measurement configuration.

Table 1. Summary of the experimental setup parameters and the experimental conditions.

Terms	Value	Unit
Pad diameter	70	mm
Flying mass	2.5	kg
Impact speed	> 0.50	m/s
Degree of vacuum	> 100	Pa
Granular media	Tohoku silica sand #8 (TK8) Phobos simulant (PS)	
Bulk density (TK8)	1211~1474	kg/m^3
Bulk density (PS)	1034~1299	kg/m^3
Scaling factor (SF)	0.1~9	-

3.2. Results and considerations

Figure 4 shows a graph plotting the amount of terminal sinkage that occurred when a landing pad collided with the granular media sample in the microgravity environment and the bulk density at that time in each sample. There are two types of results for each sample in vacuum at 1G and vacuum at μG, and totally four types of results appear. However, self-weight compensation, which is not applied to the μG results, is subtracted from the 1G results. As a result, in TK8, the difference in the amount of sinkage is large due to the difference in gravity, while in PS, the result is almost the same. Figure 5 also shows the behaviour of sand (regolith) during pad collisions in the microgravity environment. The results show that TK8 has scattering fine particles, whereas PS has no scattering particles and appears to have collapsed in situ with no effect on the surrounding granular media. A similar trend was observed for the conditions with different bulk densities.

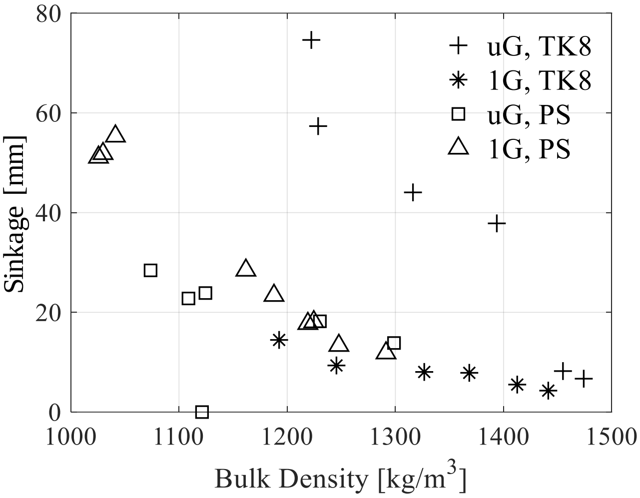

Figure 4. Terminal sinkage (settlement) when the pad penetrates the ground at the given bulk densities (1G/μG & TK8/PS).

Figure 5. The impact of the pad on each test ground in microgravity (left: TK8, right: PS).

These results are attributed to the interaction with the surrounding granular media. At 1G, the granular media pushed by the flat plate will try to move in a direction away from the compression point and gradually flow upwards to distribute the force, but the weight of the surrounding granular media will become a large resisting force and the amount of settling will be suppressed. On the other hand, at low gravity, the weight of the surrounding granular media becomes almost zero, so the force to hold the granular media in place by the flat plate compression is no more than a small inertial or adhesive force, and as the result it sinks greatly. This was observed in the case of highly compressible granular media such as regolith in static penetration tests (measurement of ultimate bearing capacity) in the reference[23)], and the same result was obtained there. As a result, the same phenomenon was thought to occur even at the time of dynamic penetration, and the behaviour of the granular media in Fig. 5 seemed to reinforce the correctness of the phenomenon.

In summary, gravity independent results can be obtained by evaluating the amount of dynamic compression penetration using granular media such as regolith forming the test bed. Conducting a full-scale compression penetration test at 1G would be equivalent to performing the same test at μG. The same amount of subsidence means that the changes in the amplitude and time direction of the force history are very similar. Consequently, don't different sizes have different phenomena? Since the current behaviour is a granular particle phenomenon and the particle size does not change when the pad size is changed, it can be judged that the same result can be obtained when viewed locally.

4. Conclusions

In this paper, we presented the results of dynamic penetration tests to investigate the gravity dependence of the landing pad behaviour under microgravity and the findings obtained. As the result, it was found that for highly compressible granular media such as regolith, the settling tendency is no longer different from the result of the 1G test. This result suggests that the 1G test can predict the response results without performing a size-constrained microgravity test, which would extremely reduce the resources for the verification of the spacecraft design. In the future, we will try to compare the dynamic penetration results at μG with different size pads.

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