A Landing Impact Simulation Test Method for Lunar Lander

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Abstract. The lunar lander shall be suffered transient impact load during the landing process. The structure's ability of withstand the dynamic environment is the key to success of a soft landing. Therefore, it is necessary to conduct the simulation test of landing impact on the ground to examine and verify the structure of the lunar lander on the development stage of the lunar lander. This paper introduces the test system principle, composition and application design, and presents a method to simulate the landing surface material selection, of the design of lifting and releasing separation device, and the composition of measurement system. The test technique is both suitable for the verification test of the structure and the flight phase stage, and shall be carried out in a clean environment. The test method presented in this paper has been successfully applied in the Chang'e lunar landers.

1. Introduction
At the end of the powered decent phase, which is a typical mission of soft landing, the lunar lander will descend freely from an altitude of about 4 meters to the lunar surface. The structural dynamics characteristics in the planetary landing mission of the lander are mainly determined by the following parameters which are the impact velocity of the landing, the dynamic characteristics of the lander, its landing buffer system and the characteristics of the lunar surface at the landing point [1, 2]. The lunar lander will hit the target lunar ground with certain speed and attitude at the moment of soft landing, by which shall produce high magnitude impact force instantly. In general, a majority of the impact energy shall be absorbed by the buffer components of the lander, but the impact load shall exert an impact effect on the lander inevitably. In the development stage of the lunar lander, it is necessary to carry out the landing impact ground simulation test to verify the impact resistance characteristics and the impact resistance performance under typical landing conditions in order to ensure a stable and safe landing on the target landing surface. During the test, the landing velocity, attitude, angular velocity and buffer length parameters should be measured, and the impact response at key positions and key equipment should be measured at the same time so as to verify the reliability of the structural analysis and design.

With the purpose to reproduce the impact dynamics process of soft landing, verify the adaptability of the LM (the Lunar Module) structure and various systems under severe landing conditions, the landing impact test were also be carried out in the NASA/Apollo space program [3]. In the landing impact test of Apollo space program, ITA-3 (the LM Test Article 3) was adopted with the landing buffer component in the flight state. During the test, LTA-3 was released from the setting horizontal position to the landing a platform with certain slope (the landing platform was used to simulate the landing surface environment) to simulate the impact dynamics process during the soft landing. LTA-3 was conducted 16 landing impact tests in total. In order to verify the ability of other LM systems to withstand landing impact load, LM-2 craft system was used to be conducted 5 landing impact tests. All
landing impact tests of the Apollo space program were carried out on the same test platform and all the impact tests passed without any problems [4]. The verification and evaluation tests of the landing buffer component are generally carried out in the out-field without strict requirements [5]. When the technical state of the lander is on the structural model or flight model phases, the test needs to be carried out in a clean environment. After the landing impact test, a number of tests need to be carried out. To ensure that the lunar lander does not suffer non-tested damage during the landing impact test, a set of stable and reliable simulation test methods are needed for structural model or flight model phases, which can be applied in clean environment. The test method presented in this paper has been successfully applied to the simulation tests of landing impact of Chang’e lunar landers.

2. Test principle
In order to simulate the real soft landing impact process of the lander, the constraint conditions and test principles shall be considered in the design of the test system, which show as follows:

- The mass characteristics, load transfer characteristics and force path of the lander during soft landing should be same as those in orbit circumstances: the real main structure of the lander is generally adopted and the mass characteristic is simulated.
- During soft landing, the buffering characteristics of the landing buffer component are same as those in orbit circumstances: generally, the real landing buffer mechanism is adopted;
- The landing surface can be simulated including the topographic, geomorphic, physical and mechanical characteristics of the target landing surface: generally, the simulated landing surface can be simulated through the physical and mechanical characteristics of the target landing surface;
- The speed and attitude of the lander when it hits the target landing surface in ground test are the same as those in orbit circumstances: the initial touchdown energy of the lander is the same as that in orbit. The speed and attitude of the lander when it touching the ground is generally simulated by lifting and releasing separation devices. Initial landing height (the distance between the bottom surface of the foot and the landing surface) is calculated according to the maximum energy during the soft landing in orbit circumstances. Supposing the landing mass of the target landing environment is \( m_{\text{max}} \), the maximum vertical landing speed is \( v_{\text{max}} \). The mass of the ground tester is \( m \), and the average height between the bottom surface of the foot pad and the landing surface is \( H \) at the initial launch. According to the energy equivalence, it can be concluded that the initial setting height required for ground test is:

\[
H = \frac{m_{\text{max}} v_{\text{max}}^2}{2mg}
\]

During the landing process, the lander is in a free state without additional constraints: it is generally simulated by the free-falling process under the gravity of the earth and is generally released from a fixed static point.

3. Composition of test system
The test system is mainly composed of a landing tester, a simulated landing surface, a lifting and releasing separation device and a ground measurement system. The composition of the test system is shown in Figure 1, which is described as follows:

a) Landing tester shall be named tester for short, which can simulate the real mass characteristics, force transmission path and stress state of the lander during landing impact;

b) Simulated landing surface by which the physical and mechanical characteristics and landing surface slope of the target landing surface shall be simulated, and the interaction between the lander and the target landing surface shall also be simulated;

c) Lifting and releasing separation device, which are used for establishing the initial state of the tester. The tester can be lifted to a certain height from the landing bottom surface to the landing surface and the initial attitude of the tester can be established. The releasing separation device releases
the tester, and the tester lands on the simulated landing surface through free fall; during the landing, the hanging beam is restrained by the limit protection belt to avoid interference with the tester.

d) Ground measurement system, which generally composed of high-speed camera system and impact measurement system. It is used to measure the velocity and attitude change process of the tester, the acceleration and strain response at key positions.

![Diagram of test system of landing impact test](image)

**Figure 1** Schematic diagram of the test system of the landing impact test

1 - crane hook, 2 - sling, 3 - electronic hanging hook, 4 - rings, 5 - limit protection belt, 6 - inclined condole belt, 7 - hanging beam, 8 - vertical sling, 9 - electronic hanging hook cable, 10 - electronic hanging hook switch, 11 - high strength bolt, 12 - simulated landing surface, 13 - steel rail, 14 - ground, 15 - acceleration transducer or strain gauge, 16 - signal conditioner or dynamic strain gauge, 17 - response data acquisition system, 18 - high-speed camera, 19 - image targets, 20 - image data analysis system.

3.1 Simulated landing surface

Considering about environmental factors, wood materials are selected to simulate the characteristics of the lunar surface. Partial splice and integral lap are adopted to fix the landing surface on the horizontal steel track with high-strength bolts, as shown in Fig.2A. The surface friction coefficient of the simulated landing surface can be adjusted by processing the plate surface. The main processing method include surface polishing, painting, etc. By sticking nylon fastener tape on the simulated landing surface and landing pad, the spacecraft can be fixed, as shown in Fig.2B. The size design of simulated landing surface should be based on the structural size of the tester. If there is a tester with a buffer component, it should be based on the maximum envelope of the buffer component. If the maximum envelope diameter is \( \Phi \), the surface’s diameter size should be no less than \( 1.2\Phi \) and the thickness is about 100mm. The simulated landing surface can simulate typical topographic, geomorphic, physical and mechanical characteristics of the lunar surface and also the simulated parameters include friction coefficient, bearing strength, landing surface slope, etc. In the Apollo space mission, the friction coefficient between the lunar surface and the landing pad was \( 0.4~\infty \) [6]. Considering about the extremely severe friction between the lunar surface and the pad, the value between the pad and the lunar soil could be calculated from 0.1~1 and \( \infty \) during the test. The landing surface slope can simulate the horizontal slope (0° surface), nominal slope (the slope can be recognized by GNC system) and limit slope (the nominal slope + the equivalent limit slope). The test slope can be realized by raising the simulated landing surface height on one side as shown in Fig.2C.
3.2 Lifting and releasing separation device
Lifting and releasing separation device is mainly composed of electronic hanging hook, hanging beam and limit protection belt, while the release mechanism hanging on the crane hook by sling. The landing release mechanism adopts the vertical lifting way. After the lander is lifted to the certain height, the hanging beam and spacecraft fall at the same time by controlling the electronic hanging hook. In the process of falling, hanging beam component does not separated from the spacecraft to avoid hanging beam hit to the product components. Three limit protection belts are installed between crane hook and hanging beam with one end connected to the crane hook, the other end connected to the hanging beam and ring. By controlling the length of the limit protection belt, the drop height of hanging beam is limited to ensure there has no collision between hanging beam and spacecraft.
The electronic release hook mainly realizes the release function, which is composed of the electronic hanging hook body, the cable and the switch. When the lifting is in use, put the lifting ring on the clamping hook, pull the locking device and tighten the clamping hook; When releasing, the releasing hook is energized, the locking device automatically unlocks, the clamping hook is opened, and the releasing function is realized. The releasing hook is a standard part.

**Figure 3** Schematic diagram of key parameters involved in the calculation of limit belt length

H - falling height of the spacecraft’s center of mass, \( l \) - hanging beam length, \( L_1 \) - length between crane hook and hanging ring, \( L_2 \) - length between hanging ring and hanging beam, \( L_3 \) - the distance between hanging beam and spacecraft.

The limit protection belt is used to control the falling height of the hanging beam. Two protection belts are installed on hanging beam, one protection belt is installed on hanging ring And the other end of the three protection belts are connected with crane hook. The falling height of the hanging beam is controlled by the length of the protection belt so that the hanging beam will not collide with the upper surface of the spacecraft. As shown in Fig.3, it is assuming that spacecraft centroid drop height is \( H \), hanging beam length is \( l \), length between crane hook and hanging ring is \( L_1 \), length between hanging ring and hanging beam is \( L_2 \), the distance between hanging beam and spacecraft is \( L_3 \). In order to avoid the counterforce to spacecraft, the hanging beam should descend a distance as \( \Delta L < L_3 \), so the limit protection belt length connected with the hanging ring is:

\[
L = L_1 + H + \Delta L
\]

(2)

The theoretical design length of the limit protection belt connected with the hanging beam shall be:

\[
L' = \sqrt{(L_1 + L_2 + \Delta L + H)^2 + (l/2)^2}
\]

(3)

### 3.3 Ground measurement system

The ground measurement system is composed of a high-speed camera system and an impact response measurement system. The high-speed camera system measures the position and pose information of the tester at the moment of landing, while the impact response measurement system measures the acceleration and strain at the tester structure or key equipment. Landing impact shock response (including acceleration response or structure strain response) is respectively converted into electrical signals and enlarged.
Figure 4 Schematic diagram of landing impact test posture measurement

Landing impact test position measurement is the test of displacement, velocity, attitude angle and attitude angular velocity by many sets of high-speed cameras synchronization. Its working principle is shown in Fig. 4. Before the test, the lander is in a static state before release, and the three-dimensional coordinates of multiple targets on the lander are measured by total station instrument. In addition, the static state of measurement, a frame of still image is collected by a high-speed cameras the reference. The three-dimensional coordinates of the target and the control points of static state image constitute the spatial positioning of the initial image. When the lander is released, the serial images are extracted. The attitude data, displacement date and velocity date of the landing motion are obtained by combining the smoothing ratio algorithm and the posture parameter solving algorithm based on monocular vision. The data flow chart is shown in Fig. 5.

4. Application of test methods
Chang'e-3 lander is the Chinese first lunar lander, the test method was carried out twice on the structural phase of the lander. Test process photos are shown in Fig. 6 and Fig. 7. In the first test, the landing surface friction coefficient is about 0.3, while in the second test, the surface friction coefficient is ∞ (landing footpad fixed). The two tests successfully obtained the motion characteristics and dynamic response data of the tester during the landing, which provided favorable guarantee for the successful soft landing of the Chang'e-3 lander.
The principle, system requirements and test steps of the landing impact ground simulation test method described in this paper have been well verified in the development process of Chang‘e-3 lander, which can be used as a normative basis for the subsequent landing impact ground simulation test of similar landers. The other Chang‘e lander also adopts the test method presented in this paper to conduct landing impact test in the early stage of development and two working conditions are tested. One is the horizontal landing with four legs and the floor pad is fixed after landing (friction coefficient $\infty$), the other is the $8^\circ$ slope condition, in which the footpad is fixed after landing (friction coefficient $\infty$).

5. References

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