Vibration Characteristic Analysis and Simulation of High Speed Impact Penetrator

Haitao Luo[1, *], Guangming Liu[1], Shipeng Chen[2], Wei Wang[2], Peng Wang[2]

[1]State Key Laboratory of Robotics, Shenyang Institute of Automation, CAS, Shenyang 110016, China
[2]Northeastern University, Shenyang 110019, China

*Corresponding author e-mail: luohaitao@sia.cn

Abstract. In this paper, the gauge of a small penetrator prototype structure is designed to provide a kind of used for detection of high speed impact through soil structure. The penetrator structure of lightweight, high stiffness, good vibration damping performance, can effectively impact penetration, the small and internal composition and structure of the body to carry out scientific exploration. Results show that the design of the penetrator can effectively guarantee the existence of the internal components, its internal instrument installation module is less than the input value of the acceleration response, achieved the effect of slow shock, protect the internal instrument to make it working normally after the impact.

1. Introduction

High speed impact penetration detection as a means of celestial detection is different from surrounding detection and lander detection. Low energy demand, low cost and more effective through the interior of the celestial body is its major advantages. It is also suitable for studying small objects with ice covered surfaces. Because of the way single emission and multi-point impact, penetrator can form a detection network. A scientific study of internal material and structure of the celestial body carry out by impacting it. In this way, the subsurface layer below the surface of the target can be detected. And it can also provide a lot of useful information to uncover the evolution of the solar system and explore the origins of life [1]. At the same time, the research of impact penetrator can also lay the foundation for deep space exploration and space-based weapon system research.

The special means of impact penetration detection has attracted widespread attention of scholars both at home and abroad. The NASA of DS-2 successfully crashed into a comet [2], and the Mars-96 of Russian has carried out a Mars penetration test [3], and British [4], Japan [5], and other countries have carried out the study of the moon penetrating device, and carried out ground tests. In the deep space exploration and high-speed impact penetrator, our country start relatively late, and the scientific research doesn't carried out deep enough. China Institute of Space Technology [6] and Shanghai Academy of Spaceflight Technology [7] respectively conceptual design the Mars penetrator and lunar penetrator. But the modeling and simulation technology of high-speed penetrator for deep space exploration, and collision "survival" have seldom been studied.

In conclusion, this paper will study the principle and technology of penetrator protection to solve the problem of modeling and protection of penetrator. Through modeling and simulation technology,

the experimental cost is reduced, and the theoretical and technical basis for penetrating dynamics technology, impact protection analysis and design are established, which is an important theoretical and practical significance work. It will provide the basis for space exploration and impact penetrator development in the future.

2. Mode establishment of impact penetrator

The impact penetrator mainly includes the shell, the instrument mounting module, the separation end cover, the cushion damping structure and the diving head structure, as shown in Fig.1.
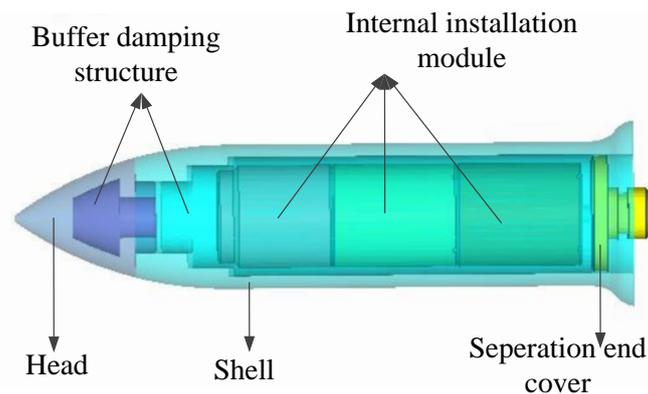

Figure 1. Geometric model of the penetrator

The above geometric model is imported into hyper mesh software for pre-processing and meshing. The pre-processing of geometric model is to remove some small chamfer, inverted arc and short edge in the model to reduce the number of mesh to get the final finite element model. After mesh generation, the entire finite element model consists of about 76 thousand nodes and 271 thousand units. In all parts of the penetrator the tetrahedral element (CTETRA) is used, the rigid element (RBE2) is used to simulate bolt connections between components; adhesive connection (HEMMING) is used between the damping layer and the component, Adopt the ton-mm unit system.

The material property parameters of each part of the penetrator are given here. Wherein, the penetrating shell, the diving head and the separating end cover are alloy steel, the internal mounting module is made of aluminum alloy, and the material of damping layer is rubber, as show in Table 1.

Table 1. Material Properties.

Part Name	E(MPa)	μ	ρ(Ton/ mm^3)	G(MPa)	GE
Shell/head/the separation cap	2.1e5	0.28	7.7e-9	/	/
Internal module	7.2e4	0.33	2.8e-9	230	/
Damping structure	/	0.45	1e-8	1.5	1.05
Fixture	2.1e5	0.28	7.7e-9	/	/

3. Analysis of impact respond test

3.1. Model Setting

In order to examine the damping performance of the internal damping structure, we conducted an impact test. The geometric model of the impact test is shown in Fig.2. It consists of two parts penetrator body and impact test fixture. The simulation model of impact response is completed on the basis of modal analysis model. Fixture is applied to the finite element model and they are connected with rigid elements (RBE2) to simulate the bolt connection. A fixed constraint point (SPC) is

established at the bolt hole connected to the fixture and impact station and acts as an input point for the impact response load.
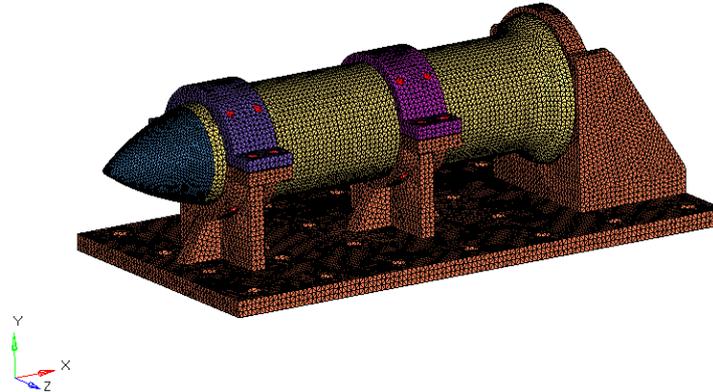

Figure 2. Finite element model of impact response

For further mechanical analysis, the material properties of the parts are given here. The material of the penetrator shell, the head, the separation cap and fixture is alloy steel. The impact simulation adopts the condition of the impact test at the identification level, the test conditions are shown in Table 2.

Table 2. Impact test condition.

Frequence (Hz)	100~400	400~1000
Impact spectrum	+12dB/oct	400g

3.2. Test Aanalysis Results

When we apply an X-direction impact to the fixture floor, the acceleration response contours of the penetrator shell, the head, the internal assembly module and the damping layer are shown in Fig.3.
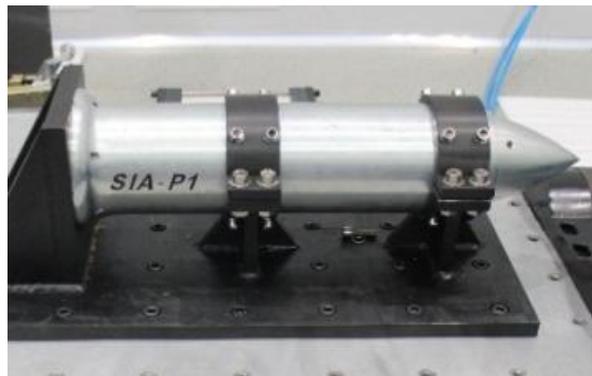

Figure 3. The acceleration response contours of module

From the graphs above, the following conclusions can be drawn:

1) The maximum acceleration of the penetrator occurs in the front of the damping structure. The maximum is 13230g and the magnification is about 22.

2) The maximum acceleration response of the penetrator shell and the head occurs at the side of the head with a maximum of 460.7 g and a magnification of about 0.77.

3) The maximum acceleration response of the internal assembly module occurs at the side of the module with a maximum of 252.1 g and a magnification of approximately 0.42.

4. Penetration analysis

4.1. Model parameter setting

In the case of penetration analysis, the penetrator body used the model for modal simulation with total length of 600 mm and diameter of 140 mm. The target model is set to a cylinder with a radius of 5m. The contact between the penetrator and the target is eroding contact. We assume that the top meshes of the target are free and the other meshes are infinite areas. At the same time, no reflecting boundary constraint is applied to eliminate the influence of the expansion wave and shear wave [8]. Due to the unknown environmental factors in flight, the ideal vertical penetration state may not be achieved, that is, there is a certain angle of incidence. In fact, the incidence angle will have a dramatic impact on the depth of penetration, so the simulation was carried out at different incidence angles of 45º, 60º, and 90º. The finite element model is shown in Fig.4.
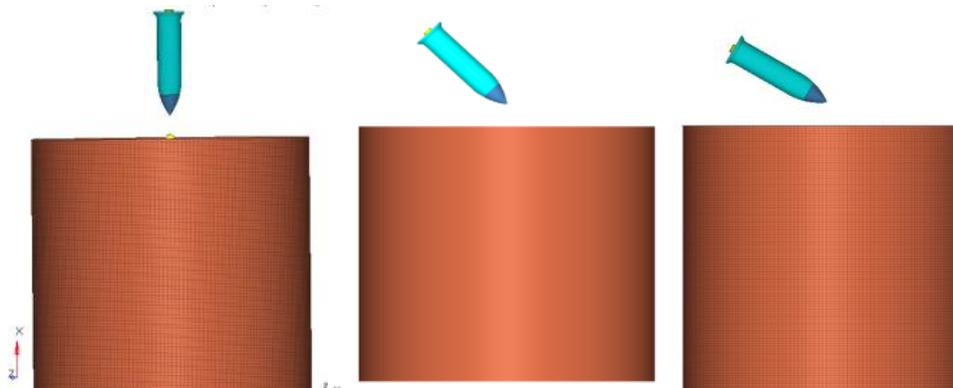

Figure 4. The finite element model of penetration simulation

The material parameters used in the simulation are shown in Table 3. Here, RO is the density; G is the shear modulus; BULK is the volume unloading modulus [9], and the unit is g-cm-µs.

Table 3. The material parameters of the target.

Parameter	Value	Parameter	Value
$RO(\mathrm{g/cm^3})$	1.8	A2	0.123
G(MPa)	1.6e-4	PV	0
$BULK$(MPa)	1.33e2	VCR	0
A0	3.3e-3	REF	0
A1	1.31e-7	/	/

4.2. Analysis of numerical simulation results

Oblique penetration is an inevitable state of motion when the penetrator strikes the target, and the penetrator may have a certain skew angle due to environmental factors during the flight. The skew angle reduces the depth of penetration. In order to analyze the effect of the incident angle on penetration of the penetrator, it is necessary to analyze the motion of the oblique penetration (Figure 5).
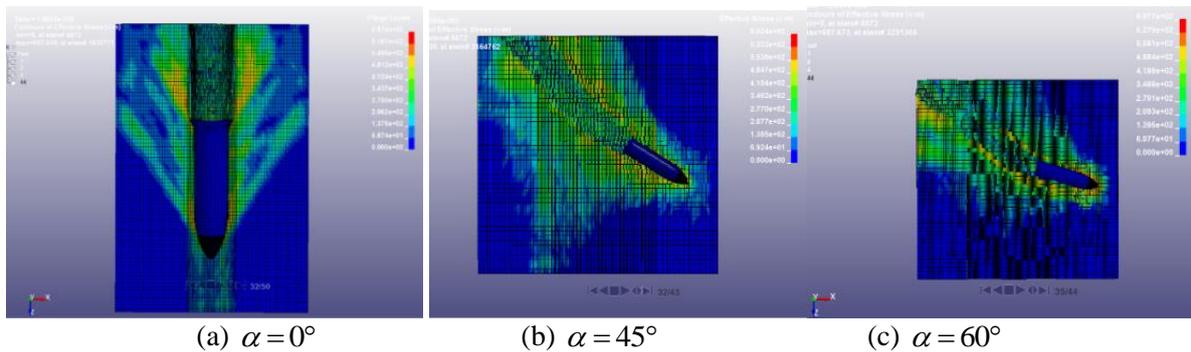
(a) $\alpha = 0°$ (b) $\alpha = 45°$ (c) $\alpha = 60°$

Figure 5. Oblique penetration with different initial obliquity angle

From the graphs above, we can see some elements of the target are removed when the penetrator enters the target, indicating that the elements of the soil target is squeezed and failed. The removed elements are mainly subjected to forces from the head, and in turn, the internal resistance of the target also acts primarily on the penetrator's head. At the same time, we can see that the trajectory of the vertical penetration is nearly a straight line. The yaw angle of the penetrator trajectory continues to increase with the increase of the incident angle, and the maximum yaw angle happened on the Oblique penetration with the initial obliquity angle $\alpha = 60°$. At the beginning, the trajectory of the penetrator in the target is approximately a straight line, and then the trajectory of the penetrator is deflected. The resistance mainly from the head can be broken down into two components: one is the resistance along the Z direction, which reduces the velocity of penetrator; the other is the normal resistance along the Y direction. The two forces form a deflection moment, which causes the penetrator to deviate from the route. The results of the penetration are shown in Fig.6
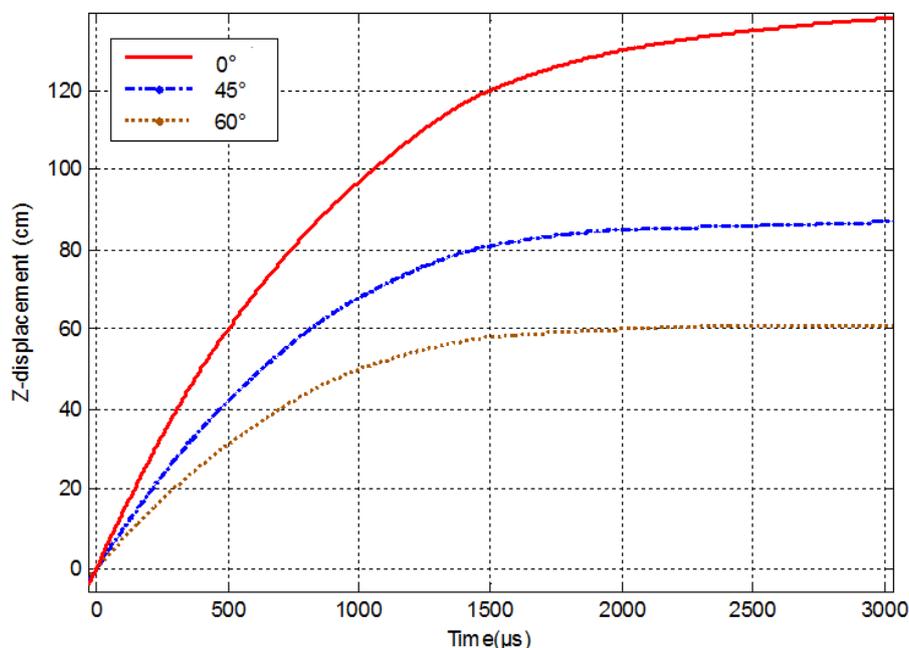

Figure 6. Penetration depth of the penetrator

As can be seen from the graph above, the depth of the oblique penetration is significantly smaller than the depth of the vertical penetration, which indicates that the acceleration of the oblique penetration is significantly greater than the vertical penetration. The maximum acceleration occurs at

the target stage of penetration. As the penetrator is deflected and the contact area between the penetrator and the target increases, the resistance and the load increase.

5. Conclusion

This paper deals with modal analysis of penetrator used for deep space exploration, numerical simulation is carried out for impact overload test. Simulation analysis has drawn the following conclusions:

1) The maximum acceleration response of the internal assembly module occurs at the side wall of the intermediate module with a maximum value of 252.1g and a magnification of 0.42. The large acceleration response occurs on the vibration-damping structure, indicating that the vibration-damping structure achieves the expected effect.

2) The acceleration response of internal assembly module is less than the input value, which achieves the effect of vibration-damping and protects the internal instruments so that they can still work after the impact.

3) When the velocity of impact is the same, the depth of the vertical penetration is greater than the depth of the oblique penetration. When the penetrator is obliquely penetrated into the soil, the trajectories of the penetrator have a yaw angle, and the larger the incident angle is, the greater the yaw angle is. Therefore, the incident angle of the penetrator should be minimized by controlling the trajectory in flight.

Acknowledgments

References

[1]   Ying Chen, Lu Zhou, Li Wang, A conception of Mars multi-mode combination exploration mission, Journal of Deep Space Exploration, J. 1 (2014) 156 - 160.
[2]   WH Blume, Deep impact mission design, Space Science Reviews. J. 117 (2005) 23 - 42.
[3]   Linkin V, Harri A M, Lipatov A etc, A sophisticated lander for scientific exploration of Mars: scientific objectives and implementation of the Mars-96 Small Station, Planetary and space science. J. 46 (1998) 71 7- 737.
[4]   RA Gowen, A Smith, AD Fortes etc, Penetrators for in situ subsurface investigations of Europa, Advances in Space Research. J. 48 (2011)725 - 742.
[5]   R Yamada, I Yamada, H Shiraishi etc, Capability of the penetrator seismometer system for lunar seismic event observation, Planetary and Space Science. J. 57 (2009) 751 - 763.
[6]   Xinghua Zhang, Lu Zhou, Zhengai Cheng etc, Structure design of Mars penetrator and research on numerical simulation of penetration, Committee of Deep Space Exploration Technology, Chinese Society of Astronautics, 2013.
[7]   Ying Chen, Lu Zhou, Deep space multi-mode detection task report, 2012.
[8]   Yong Li, The simulation of projectile penetration process and analysis of influencing factors, Nanjing University of Science and Technology, 2014.
[9]   Dongmei Zhang, Ya Zhang, The Analysis of Effects of the Nose Shape for the Process of the Earth Penetrating Shell into Soil by ANSYS/LS-DYNA, Modern Machinery. J. 5 (2010) 21 - 23.