Analysis of Landing Impact Performance for Lunar Lander Based on Flexible Body

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***Abstract*—It is necessary to investigate the lunar lander soft-landing by considering the flexible body and legs because the impact of deformation is significant. There is a new method for research on landing impact performance in this paper. Firstly a dynamical model of 1/4 lunar lander with four suspension legs is build and simplified. After getting oscillation equation of the model, founds two simulation models respectively by multi-rigid-body dynamics method and nonlinear finite element method. The simulation of soft-landing selects MSC.ADMAS and MSC.DYTRAN. Main analysis objects are buffer distance of primary strut in lunar lander and vertical acceleration of box's centroid, then contrasts two simulation results based on the objects. Research results show that the influence of flexible body reduces the maximum of primary strut's buffer distance, but amplifies the vertical acceleration of centroid with periodic oscillation.**

Keywords- flexible body；lunar lander；soft landing；buffer；nonlinear analysis

I. INTRODUCTION

With "Chinese Lunar Exploration Program" in full swing, Chinese lunar lander will achieve the target of soft-landing on the moonscape [1]. In the course of soft-landing, the success depends on the elastic-plastic deformation of lander's buffer material (such as aluminum honeycomb) to absorb the impact energy of landing [2]. In addition, lunar lander's box and legs which use aluminum as the main material can also produce certain deformation during this process. At NASA reports, the serious influence on the landing performance due to the change of connect constraint vice's action position caused by the bending deformation of legs had been proven [3]. At present, research for landing dynamics analysis of lunar lander in China Mainly embodies in: some research on the lander dynamics analysis of soft-landing had been completed by HIT [4]; and some work had been carried out on the amplitude limit of multi-rigid-body dynamics model for lunar lander by using ADMAS [5]; moreover, some scholars build the rigid-flexible model based on the flexible legs, and investigated the pillar deformation's influence on the performance of buffer [6].

In this paper, a new idea for studying on soft-landing impact performance is presented. Make the simulation analysis for soft-landing by multi-rigid-body dynamics method and nonlinear finite element method after establishing dynamic model. Then, research on the landing impact performance for lunar lander based on flexible body by comparing two simulation results.

II. DYNAMICS MODEL OF SOFT-LANDING

This paper uses the model with four symmetric suspension legs for research object by taking "Apollo" lunar lander for reference. Each landing leg has one primary strut having one pad and two secondary struts. Struts connect each other with spherical hinge, and primary strut connects box with hooke hinge [7-8], as shown in Fig. 1.

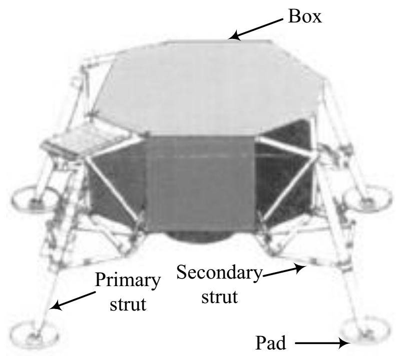

Figure 1. Structure diagram of lunar lander

The literature [5] had deduced the dynamic equation of lunar lander with three mechanical cushioning legs, and gave the conclusion that the vibration form of model in vertical direction was the free vibration with damping. As for the reference, this paper makes a dynamic analysis on the model with four suspension legs. Firstly assumes that:

- The landing surface is horizontal, and no pits or bumps on it;
- The damping and coefficient of elasticity in each primary strut is equal, as well in each secondary strut, so the buffer model is symmetric;
- Four legs touch lunar surface at the same time in soft-landing.

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Based on this assumption, analyzes the process of soft-landing by using the model of 1/4 lunar lander, as shown in Fig. 2.

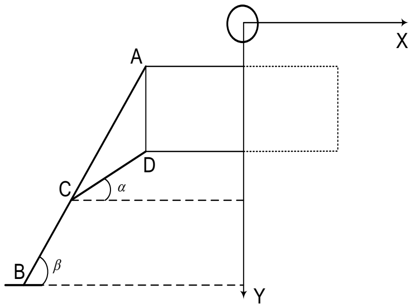


Figure 2. Model of 1/4 lunar lander

Where α is the angle between secondary strut and X axis in coordinate surface, β is the angle between primary strut and X axis. The length of primary strut is l_1, and the other two secondary struts are l_2, l_3. c_1, k_1 mean primary strut's damping and modulus of elasticity, c_2, c_3, k_2, k_3 are secondary struts'.

Fig. 3 shows force analysis on each part of the model.

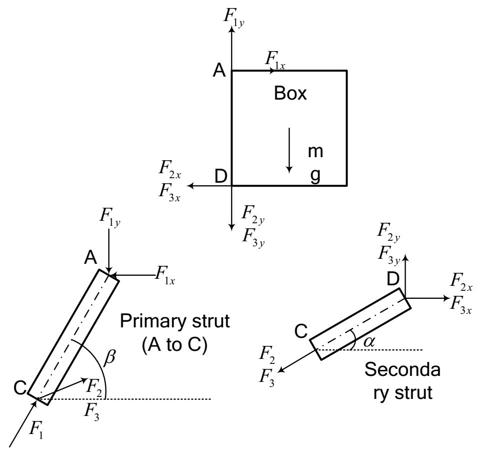


Figure 3. Diagram of force analysis on 1/4 model

Where m is the mass of 1/4 box, F_1, F_2, F_3 are the axial forces of primary strut and secondary struts, F_{1x}, F_{1y} are the primary strut's coordinate component forces, and F_{2x}, F_{2y}, F_{3x}, F_{3y} are secondary struts'. Axial deformation of primary strut is δ_{l1}, and δ_{l2}, δ_{l3} are secondary struts'. δ_1 means the deformation of box along axial of primary strut, δ_2, δ_3 are the ones along axial of secondary struts. There is a motion equation in vertical direction for this model:

$$m\ddot{Y} = mg - F_{1y} + F_{2y} + F_{3y} \tag{1}$$

Taking equilibrium position for origin of coordinates, we can get the equation while static equilibrium:

$$mg = (k_1\delta_1 \sin\beta + k_2\delta_2 \sin\alpha + k_3\delta_3 \sin\alpha) - k_2\delta_2 \sin\alpha + k_3\delta_3 \sin\alpha \tag{2}$$

So equation (1) can be written as:

$$m\ddot{Y} = -[(k_1\delta_{l1} + c_1 dl_1/dt)\sin\beta + 2(k_2\delta_{l2} + c_2 dl_2/dt)\sin\alpha] + 2(k_2\delta_{l2} + c_2 dl_2/dt)\sin\alpha \tag{3}$$

i.e.: $$m\ddot{Y} + (k_1\delta_{l1} + c_1 dl_1/dt)\sin\beta = 0 \tag{4}$$

The geometrical relationship of model is:

$$\delta_{l1}\sin\beta = y, \qquad dl_1 \sin\beta = dy \tag{5}$$

With simultaneous equations we can get:

$$m\ddot{Y} + k_1 y + c_1 dy/dt = 0 \tag{6}$$

Set: $$k = k_1,\ c = c_1 \tag{7}$$

Therefore, the final motion equation of this model is:

$$m\ddot{Y} + c\dot{Y} + kY = 0 \tag{8}$$

This equations gives the conclusion that the vibration form of model in vertical direction is the free vibration with damping, so the model can be simplified like this:

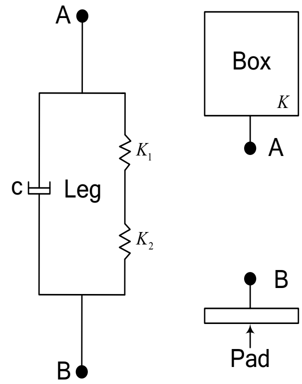


Figure 4. Diagram of simplified model

Where c is the leg's damping, K_1 denotes the leg's modulus of elasticity, K_2 and K are the ones of buffer material and box, pad's one can be ignored.

III. Simulation Methods and Establishing Models

A. *Multi-rigid-body dynamics method*

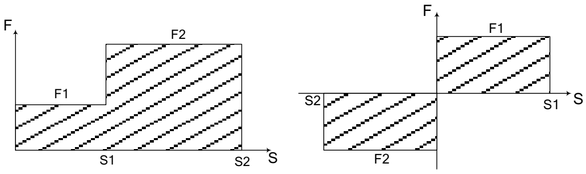
All the parts of lunar lander are treated as rigid body. Systematic dynamics equations of model can be established by using lagrangian multiplier method [9]:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}}\right)^T - \left(\frac{\partial T}{\partial q}\right)^T - \phi_q^T \rho + \theta_{\dot{q}}^T \mu = Q \tag{9}$$

Constraint equation: $$\begin{cases} \Phi(q,t) = 0 \\ \theta(q,\dot{q},t) = 0 \end{cases} \tag{10}$$

Where T denotes the kinetic energy of system, q denotes the generalized array of system, Q denotes the generalized array of force, ρ means the Lagrange multipliers array with holonomic constraints, μ means the Lagrange multipliers array with nonholonomic constraint.

The Multi-rigid-body dynamics software ADAMS/View is used to establish all rigid parts, and to simulate the constraints between components according to the practical situation. Buffer material of legs chooses the aluminum honeycomb which used widely in spacecraft. Characteristics of Al-honeycomb shock absorbers are shown in Fig. 5. The simulation of cushioning force is build using operation functions. Lunar soil is considered as an infinite flexible board while soft-landing, the model are shown in Fig.6.



(a) Crash force in primary strut (b) Crash force in secondary strut

Figure 5. Crush force of Al-honeycomb shock absorbers

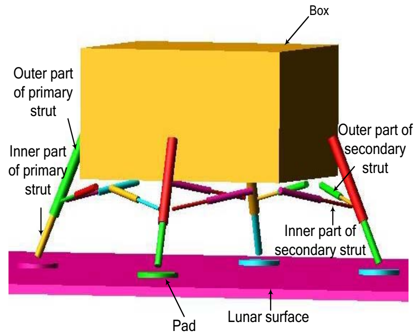


Figure 6. Multi-rigid-body dynamics simulation model

B. *Nonlinear finite element method*

According to finite element method, the structures of soft landing are dispersed in the space domain, and it is different to the tradition analysis method of rigid body dynamics. The soft-landing of lunar lander on lunar surface is a typical structure impact process. Generally, the differential equation of motion of lunar lander is written as [10]:

$$\mathbf{M}\ddot{\mathbf{Y}}+\mathbf{C}\dot{\mathbf{Y}}+\mathbf{K}\mathbf{Y}=\mathbf{F}^{\mathrm{ext}} \tag{11}$$

Where $\mathbf{M}$ denotes the mass matrix of whole structure, $\mathbf{C}$ is the damping matrix, $\mathbf{K}$ is the stiffness matrix, $\mathbf{F}^{\mathrm{ext}}$ means the vector of externally applied loads, $\mathbf{Y}$ is the vector of displacement, $\dot{\mathbf{Y}}$ is the vector of velocity, $\ddot{\mathbf{Y}}$ is the vector of acceleration.

In nonlinear finite element calculations, firstly the differential equation of model must be dispersed not only in space domain, but also in time domain. And explicit integration algorithm is mostly used to calculate these problems. If the current time step is step n in the explicit finite element algorithm, equation 1 is rewritten as equation of motion [11]:

$$\mathbf{M}\ddot{\mathbf{Y}}_{\mathrm{n}}+\mathbf{C}\dot{\mathbf{Y}}_{\mathrm{n}}+\mathbf{K}\mathbf{Y}_{\mathrm{n}}=\mathbf{F}^{\mathrm{ext}} \tag{12}$$

If the vector of internal loads is $\mathbf{F}^{\mathrm{int}}=\mathbf{C}\dot{\mathbf{Y}}_{\mathrm{n}}+\mathbf{K}\mathbf{Y}_{\mathrm{n}}$, the acceleration can be found by inverting the mass matrix and multiplying it by the residual load vector. If $\mathbf{M}$ is diagonal, its inversion is trivial, and the matrix equation is the set of independent equations for each degree of freedom:

$$\mathbf{a}_{\mathrm{ni}}=(\mathbf{F}_{\mathrm{ni}}{}^{\mathrm{ext}}-\mathbf{F}_{\mathrm{ni}}{}^{\mathrm{int}})/\mathbf{M}_{\mathrm{i}} \tag{13}$$

If the acceleration is constant over the time step, the central difference scheme can be used to advance in time.

Based on the above theory, the simulation model of lunar lander is established and meshed in MSC.Dytran. Fig.7 shows the finite element model of al-honeycomb, and Fig.8 shows the finite element model of lunar soil.

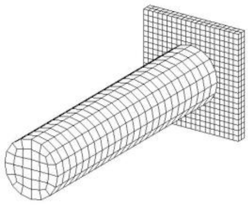


Figure 7. Model of Al-honeycomb

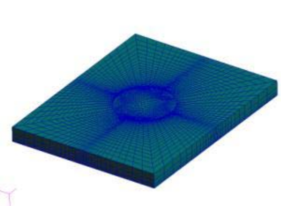


Figure 8. Model of Lunar Soil

When lunar lander is soft landing, components with probable contacting relative movement have friction, and there is friction between foot pads and lunar regolith. This friction belongs to dynamic friction. Application of non-classical friction law is not perfect, so the classical Coulomb friction law is used to calculate the approximate friction. Friction coefficient is set as:

$$\mu=\mu_k+(\mu_s+\mu_k)e^{-\beta v} \tag{11}$$

Where μ is friction coefficient; μ_k and μ_k are sliding friction and static friction coefficient; β means exponential decay coefficient; v means relative sliding velocity between principal and subordinate surfaces.

Finally, the finite element model of lunar lander is established as shown in Fig. 9:

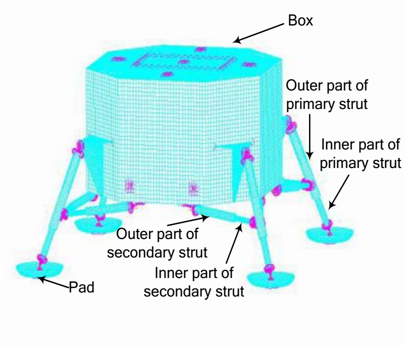


Figure 9. Finite element simulation model

IV. Analysis of Simulation Results

The main factors considering lunar lander's stiffness and allowable strength, characteristics of buffer material and dynamic response, have a great impact on the performance of landing. Main analysis objects are the buffer distance of primary strut in lunar lander and vertical acceleration of box's centroid in above two simulation models.

In order to compare the simulation results easily, the working condition of two simulation models is the same: four legs of lander's model touch lunar surface at the same time with a vertical velocity (set vertical velocity: V_v =4m/s), and no horizontal velocity. The gravity acceleration is lunar gravity. Simulation results are shown in Fig. 10 and Fig. 11.

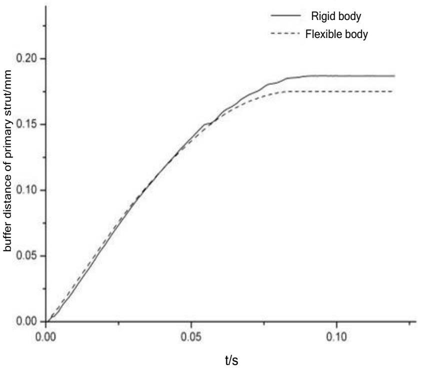


Figure 10. Simulating curve of buffer distance

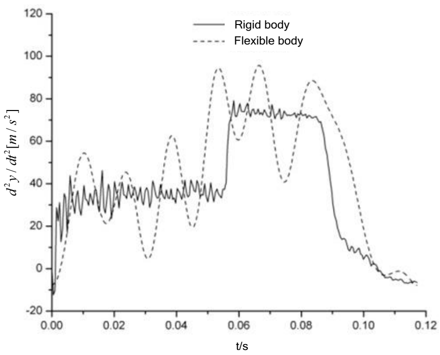


Figure 11. Simulating curve of centroid's acceleration

The flexible body model's maximum of buffer distance is smaller than the one of rigid body according to figure 10, because flexible body can absorb energy in the process of soft landing, share the responsibility of al-honeycomb. And figure 11 shows that the maximum of centroid's acceleration of flexible body is larger than the one of rigid body. The analysis of this phenomenon is that all the flexible parts can be seen as buffer units which conduce to al-honeycomb absorb the energy partly in the former stage of soft landing. Then, the energy absorbed by flexible parts will increase the acceleration of centroid by liberating itself in the later stage with periodic oscillation.

V. CONCLUSION

In this paper, a dynamical model of 1/4 lunar lander with four suspension legs is build and simplified. Found and analyze two simulation models by multi-rigid-body dynamics method and nonlinear finite element method in MSC.ADAMS and MSC.DYTRAN. Main analysis objects are buffer distance of primary strut in lunar lander and vertical acceleration of box's centroid, and contrast two simulation results based on the objects. Research indicates that flexible body reduces the maximum of primary strut's buffer distance, but amplifies the acceleration of centroid with periodic oscillation. So, the impact of flexible body cannot be neglected in designing lunar lander.

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