Overloading of Landing Based on the Deformation of the Lunar Lander

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Abstract

Along with the progress of sciences and technologies, a lot of explorations are taken in many countries or organizations in succession. Lunar, the natural satellite of the earth, become a focus of the space discovery again recently because of its abundant resource and high value in use. Lunar exploration is also one of the most important projects in China. A primary objective of the probe in lunar is to soft-land a manned spacecraft on the lunar surface. The soft-landing system is the key composition of the lunar lander. In the overall design of lunar lander, the analysis of touchdown dynamics during landing stage is an important work. The rigid-flexible coupling dynamics of a system with flexible cantilevers attached to the main lander is analyzed. The equations are derived from the subsystem method. Results show that the deformations of cantilevers have considerable effect on the overloading of the lunar lander system.

Keywords: lunar lander; rigid-flexible coupling; deformation; overloading

1 Introduction

For soft-landing a manned spacecraft on the lunar surface, during the first critical seconds of touchdown, the lander system must absorb the kinetic and potential energies of the vehicle without causing the lander to be toppled and must attenuate the landing loads to prevent the spacecraft being damaged during the landing impact and to bring it to rest in an upright attitude so that no any part of its tasks such as the deployment of instruments or re-launch will be obstructed.

To ensure arresting the spacecraft safely, the analysis of touchdown dynamics during landing stage is important. Such analysis will influence the landing stage planning as well as put limits on the permissible vertical and horizontal velocities, vehicle attitude, and pitch rate during touchdown.

This paper first reviews the previous simulation efforts on the landing dynamics of lunar lander and notes that they did not take account of the elastic deformation of cantilevers[1-13]. In reality, lander strut loads are transmitted through the primary and secondary strut attachment points on the vehicle structure, deform the cantilever structures and subsequently change the positions of the attachment points in the body coordinates. Many experiments show that the deformation effectively softens the elastic character of the honeycomb shock absorber and has the capability to store energy. Using lumping masses to represent the system, the dynamic motion is analyzed. Finally, based on ADAMS mechanical simulation software, the rigid-flexible coupling dynamics of a system with flexible cantilevers attached to the main lander is analyzed.

2 Mathematical Model

Equations used for the analysis are developed
and corresponding to the two-dimensional touchdown dynamics model as shown in Fig.1. This model is applicable to the analysis of either three or four legged vehicle. Motion takes place in a plane such that two legs contact the surface simultaneously for four-legged vehicle. It is assumed that the vehicle has feet with sufficient area to prevent penetrating the lunar surface[14-15].

![Figure 1: Touchdown dynamic model.](image1)

From Newton’s second law, the equations of motion are

\[ m \ddot{Y} = F_{n1} + F_{n2} - W \cos \theta - (T_1 + T_2 - T) \cos(\varphi - \theta) \quad (1) \]

\[ m \ddot{X} = F_{t1} + F_{t2} - W \sin \theta - (T_1 + T_2 - T) \cos(\varphi - \theta) \quad (2) \]

\[ m r^2 \dot{\varphi} = (F_{t1} + F_{t2})Y + F_{n2}X_3 - F_{n1}X_1 + T_1 L'_1 - T_2 L'_3 \quad (3) \]

where \( m \) is the mass of the lander, \( W \) is the weight of the lander on lunar surface, \( F_{n1}, F_{n2} \) are forces normal to the surface, positive direction is along the positive direction of \( Y \)-axis, \( F_{t1}, F_{t2} \) are forces tangential to the surface, positive direction is along the positive direction of \( X \)-axis, \( T_1, T_2 \) are stabilization rocket thrusts, \( T \) is total engine thrust, the product of the amplification factor and the normal thrust, \( \varphi \) is the vehicle’s altitude angle, \( \theta \) is the angle between the lunar surface and the horizontal, \( r \) is vehicle’s radius of gyration with respect to the center of gravity, \( X_1, X_3 \) are distances from the first pad and the third one to the center of gravity.

### 3 Finite Element Analysis of Primary Strut

Fig.2 shows a typical configuration of a primary and secondary strut assembly for lunar lander. A series of buffering materials are housed inside the struts.

![Figure 2: The honeycomb buffer of lunar lander.](image2)

#### 3.1 Coordinate systems

Based on the model shown in Fig.2, the simplified model used in this analysis is shown in Fig.3[16].

![Figure 3: The simplified model and the coordinate systems.](image3)

The coordinate systems are explained as follows:

1. Inertial coordinate system \( XOY \): the negative direction of \( Y \)-axis coincides with the gravity vector;
2. The local coordinate system \( \xi_{i-1} \): the origin of the coordinate system is located at node \( i - 1 \), the \( \xi_{i,i-1} \)-axis is tangent to the strut at the mass point and is directed to the node of \( i \).
3. The local coordinate system \( \eta_{i+1} \): the origin of the coordinate system is located at node \( i + 1 \), the \( \eta_{i,i+1} \)-axis is tangent to the strut at the mass point and is directed to the node of \( i - 1 \).

#### 3.2 Equations of motion

It is assumed that the strut is represented by a number of mass points connected by massless beam elements. These elements are different from each other, i.e. the length and stiffness parameters may
differ from one element to the others.

Newton’s equation of motion for the system takes the following forms for \( i = 1, 2, \ldots, n \):

\[
m_i \ddot{x}_i = F_{X,i} + F_{X,i+1} + F_{e,X_i} \quad (4)
\]

\[
m_i \ddot{y}_i = F_{Y,i} + F_{Y,i+1} + F_{e,Y_i} \quad (5)
\]

\[
I_i \dddot{\alpha}_i = M_{\alpha,i} + M_{\alpha,i+1} \quad (6)
\]

where \( F_{X,i} + F_{Y,i} \) are forces and moments acting on mass point \( i \); \( F_{X,i+1} + F_{Y,i+1} \) are forces and moments acting on mass point \( i+1 \); \( F_{e,X_i}, F_{e,Y_i} \) are external forces.

4 The Simplification of the Strut Taking Deformation into Account

The influence of the strut deformation on the lander touchdown dynamics can be analyzed with an idealized strut-structure system as shown in Fig.4 [17-18].

\[
K = \frac{K_m \times K_s}{K_m + K_s} \quad (7)
\]

The slope of the deflection of the strut \( (K_s) \) can be computed with the simply supported beam theory. As shown in Fig.5, the governing differential equation that defines the shape of the beam is

\[
EI \frac{d^2 \delta}{dx^2} = M \quad (8)
\]

The deformation of the primary strut had been derived in Ref.[17].

\[
\delta = \frac{F_e \sin^2 \left( \frac{L_n}{2} \right)}{F_n \sqrt{E/I}} \quad (9)
\]

So the equivalent \( K_s \) can be derived as follows

\[
K_s = \frac{F_e}{\delta} \quad (10)
\]

Honeycomb has the unique property of crushing in a uniform status. It is very reliable and lightweight, thus it is well adaptable for energy absorption applications. A typical honeycomb crush strength curve is shown in Fig.6.

5 Example

As shown in Fig.7, a Russian lunar lander model is analyzed as an example. The model is built in Pro/E and the primary cantilever is generated by the ANSYS finite element software. The flexible cantilever is defined according to the precision of the segment mirror. It is required that the flexible cantilever has enough flexibility along the deforming direction. Then the rigid-flexible coupling dynamics of a system with a flexible cantilever attached to the main lander is analyzed with the ADAMS[19].

The weight of the model during touchdowns is taken as 1 200 kg, and the corresponding vertical and horizontal velocities at landing position are 4
m/s and 1 m/s respectively. Through analyzing the rigid model and rigid-flexible model, the comparison of the main landing parameters as a function of time are made as shown in Figs.8-11.

Fig.7 Configuration of the rigid-flexible coupling of lunar lander.

Fig.8 Comparison of the vertical acceleration as a function of time.

Fig.9 Comparison of the primary strut compression load as a function of time.

Fig.10 Comparison of the secondary strut load as a function of time.

Figs.8-11 show the comparisons of the main parameters of the lunar lander during the first 0.25 s. Through the comparison analysis, it is found that the deformation of the primary strut have significant influence on the performance of the lunar lander. Though the deforming of the primary strut can absorb the energy during landing, the deformation can cause changes in the position of the attachment points and soften the elastic character of the honeycomb shock absorbers. So considering the deformation of the primary strut, the axis force and overloading are larger than that of taking no account of the cantilever elastic deformation.

6 Conclusions

The fundamental method of modeling the deformation during the landing of lander is introduced and the mathematical model of the lunar lander is derived. Based on ADAMS and ANSYS simulation software, the rigid-flexible coupling dynamics of a system with a flexible cantilever attached to the main lander is analyzed. For both taking account of deformation and taking no account of deformation, the simulation results indicate that the deformation of the primary strut has a considerable effect on the stability of the lunar lander system.

References


Biography:
Chen Jinbao  Born in 1980, Ph.D candidate in Nanjing University of Aeronautics and Astronautics. He has published several scientific papers in various periodicals. His main research interest is the soft landing of lunar and other planet.

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