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Investigation on soft-landing dynamics of four-legged lunar lander

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ABSTRACT

In order to improve the efficiency and accuracy of soft-landing dynamic calculation of lunar lander, this paper proposed a new soft-landing dynamic model with seven free degrees and the inertia force was also taken into consideration during the landing process. The force condition of lander during soft-landing was investigated; moreover dynamics and kinematics equations were deduced. Besides, the landing process was studied by mathematical model, which is verified by results of scale lander prototype and landing test platform. The result shows that the calculation could match the test results effectively, which verifies accuracy and availability of seven free degrees soft-landing dynamic model.

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1. Introduction

The complexity and diversity of moon surface environment bring about the difficulties of lunar lander soft-landing, so it involves in extensive contents and problems about soft-landing dynamics and landing stability. In the design of lunar lander, landing dynamic analysis is one of most critical procedures. According to the simulation and analysis of soft-landing dynamic process, dynamic features during the landing would be understood, so that the selection and design of buffer device and material are instructed, which is much helpful to identify and study the influential factors of soft-landing stability forwardly. Finally, objectives of decreasing landing impact loading, keeping landing stability and safety of lunar surface landing can be attained [1,2].

Soft-landing mathematic model of lunar lander is the key part of soft-landing dynamic theory. Early in the late 1950s to middle 1970s, in the period of Apollo missions, Lavender [3,4] puts forward that lunar surface environment, initial condition and structure parameters are summarized as three most important factors during landing by studies of six different kinds of soft-landing models, based on the consideration of elastic, damping and crushing. Hilderman [5] investigates the design advantages of soft-landing device and dynamics of initial landing under the influence of different kinds of lunar surface. Howlett [6] applied a discrete method to separate the landing strut and the whole body as a central mass, and explored the dynamic behaviors of strut and whole body. Zupp [7] regarded the lander as an integration of body and landing legs, in which the body is assumed as a rigid entity. He built mathematic program describing the soft-landing dynamic performance of lander, and meanwhile deduced dynamic equations containing six free degrees. In the year 2000, Doiron [8] summed up the research status of soft-landing dynamic in the period of Apollo missions. In 2012

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year, Anliu [9] studied 1/4 body model with three free degrees. This model reflected the dynamic features between the vertical direction of body and the horizontal and vertical direction of foot pad, but it does not adapt to the situation of requiring body attitude stability in the landing. Above research works regard to static dynamic models, but actually, soft-landing of lunar lander is a dynamic process.

Because of some defects on above models, based on the inertia force during landing, the paper created a soft-landing dynamic model with 2–2 landing mode. This dynamic model has seven free degrees, which has the least free degrees in all current studies of lunar lander dynamics, and it could decrease the difficulties of model analysis and solution. Through the test results of scale prototype obtained by soft-landing testing system, the accuracy and availability of dynamic model are verified.

2. Soft-landing dynamic model with seven degrees of freedom

2.1. Definition of coordinate system

Whole body model of lunar lander contains all degrees of freedom of soft landing. Despite the deformation of landing equipment and buffer internal properties, there could be 18 degrees of freedom which consists of body (6 dof) and four buffer equipments (three dof for each). This will increase the difficulty of the analysis and solution, so the model needs to be simplified. The half type model is simplified from the whole body model in the particular case. There are two types of typical symmetric landing modes: 1–2–1 mode and 2–2 mode. In the first case, the half type model includes the body up and body down movements, pitch motion around the z-axis of the center of mass, up and down movements of the front, middle and back inelastic quality which constitutes 5 dof. When the movement is along lunar surface of body and then inelastic quality is considered, the total degrees of freedom would be 9. 2–2 soft landing includes body up and body down movements, pitch motion around the *z*-axis of the center of mass, up and down movements of the front and back inelastic quality which constitutes 4 dof. Also, when the movement along lunar surface of body and inelastic quality is considered, the total degrees of freedom would be 7. Compare to 1–2–1 half body model, 2–2 soft landing model would greatly reduce difficulty of model analysis and solution when the degree of freedom becomes less during soft landing stability analysis.

Based on 2–2 landing mode of lunar lander, this paper builds a soft-landing dynamic model on 2D space. The diagram of the dynamic coordinate system of the whole lander is shown as Fig. 1.

Body coordinate system $O_BX_BY_B$: The origin point of coordinate O_B is gravity center of body. O_BX_B parallels to the support surface of body and positive direction refers to right; O_BY_B is perpendicular to the support surface of body and positive direction is upward.

Inertia coordinate system $O_IX_IY_I$:The origin point of coordinate O_I is the touch point between foot pad and earth; O_IX_I stands for horizontal direction and positive direction is right; O_IY_I parallels to the gravity direction and positive direction is upward.

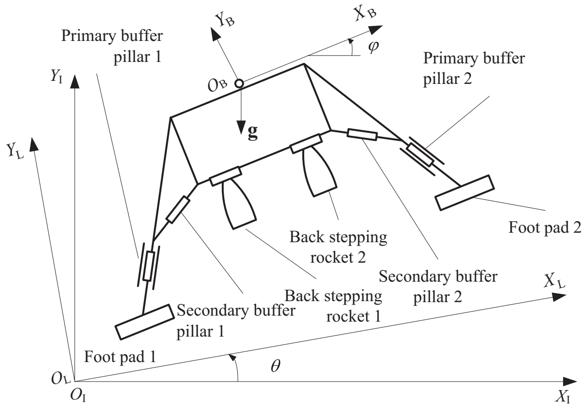

Fig. 1. Coordinate system diagram of lunar lander on 2–2 soft-landing mode.

Lunar surface coordinate system $O_LX_LY_L$:The origin point O_L coincides with O_I point; O_LX_L is the direction along the lunar surface, positive direction is right; O_LY_L is perpendicular to lunar surface and positive direction is upward.

Rotation coordinate system O_IZ_I: is perpendicular to paper flat plane and positive direction is outward.

Body coordinate system can be transformed to the lunar surface coordinate system by transition matrix $\boldsymbol{T}_{IB}$, written as

$$\begin{bmatrix} x_I \\ y_I \end{bmatrix} = T_{IB} \begin{bmatrix} x_B \\ y_B \end{bmatrix} \tag{1}$$

Thus

$$T_{IB} = T_{IB}^{-1} = \begin{bmatrix} \cos\ \varphi & -\ \sin\ \varphi \\ \sin\ \varphi & \cos\ \varphi \end{bmatrix} \tag{2}$$

Lunar surface coordinate system can be transformed to the inertia coordinate system by transition matrix $\boldsymbol{T}_{IL}$, written as

$$\begin{bmatrix} x_I \\ y_I \end{bmatrix} = T_{IL} \begin{bmatrix} x_L \\ y_L \end{bmatrix} \tag{3}$$

where $\boldsymbol{T}_{IL}$ satisfies

$$T_{IL} = T_{IL}^{-1} = \begin{bmatrix} \cos\ \theta & -\ \sin\ \theta \\ \sin\ \theta & \cos\ \theta \end{bmatrix} \tag{4}$$

2.2. Analysis of soft-landing dynamics model of lunar lander

Fig. 2 shows the geometry relationship of model. And Fig. 3 shows the force relationship. Specifically, Fig. 3 is the diagram of stress analysis of the whole lunar lander in 2–2 symmetry landing mode. Table 1 lists the meanings of all symbols. In order to make the simulated results match the real conditions and maintain simplification and convenience simultaneously, the paper does some assumptions as:

(1) In 2–2 landing model, there are two primary pillars taking action. Given the symmetry of their load, two associated secondary buffer pillars are simplified as one primary pillar associated buffer pillar in the 2D space.

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