Dynamics of cable in constant tension in lunar gravity simulation system

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Abstract: Lunar rover plays an important role in the lunar exploration. Lunar gravity is an important environmental factor concerning the locomotion performance of the rover, which has to be simulated in the ground test. In this paper, a lunar gravity simulation system (LGSS) is proposed based on the cable suspension method, and the modeling and the dynamic analysis of the control servomechanism of the cable in constant tension in the LGSS, as the key issue of the system, are specially addressed. By discretizing the cable into a series of mass-spring-damping systems, a multiple body system is obtained in place of a continuous elastic system, and then the numerical method is applied to study the dynamics of the cable system. The parameters, such as the point mass, the stiffness and the damping of the cable, are analyzed to improve the design of the lunar gravity simulator.

Key words: lunar gravity simulation system; cable in constant tension; mass-spring-damping systems; multi-rigid body; numerical simulation

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0 Introduction

Lunar rover plays an important role in the lunar exploration. The adaptability of the rover to the lunar environment must be considered for it to work properly on the moon surface. Among the diversified environmental factors, the lunar gravity is one of the main factors, which will affect the locomotion performance of the rover. Various experiments or tests should be performed in the development of the rover to verify its design, especially, the locomotion test. One of the essential conditions for the locomotion test is the simulation of the lunar gravity, which is 1/6 of that of the earth.

Early successful rovers include: lunar rovers, such as, Lunokhod 1/2/3 launched by the Soviet Union, and Moon Buggy of the USA; and also Martian rovers, such as, Sojourner and Spirit. Different rovers require different gravity simulation methods in their ground tests. After the successful mission of CE-1, a lunar rover is being developed for the second stage of China’s Lunar Exploration Project. In this paper, a new lunar gravity simulation system (LGSS) for the Chinese rover will first be briefly described, including its standard position tracking and the cable constant tension control system. Then, the dynamic modeling of the system is derived and simplified by discretizing the cable into a series of mass-spring-damping systems. Finally, a numerical method will be applied to study the effects of some parameters, to verify the feasibility of the LGSS.

1 Description of the system

There are many methods to simulate the low gravity on the ground. In this paper, a lunar gravity simulation system (LGSS) is proposed based on the cable suspension method, as is shown in Fig. 1. The rover moves on the soft lunar soil simulant, stacked as the lunar surface terrain, and the rover is suspended by a cable from the platform, mounted on a crane to cover a large area by the trolley. The cable length between the platform and the rover is 10 m. From limitation to present conditions, we consider only the movement of the rover in the horizontal plane. The objective of the LGSS is to offset 5/6 of the rover gravity by the cable force to simulate the lunar gravity.

The equipment on the platform consists of two main subsystems: a position control servomechanism (PCS) with sufficient precision, and a constant cable tension control servomechanism (CICS), which is suspended under the first one.

The PCS is used to keep the tension force of the suspending cable passing through the mass center of the rover. It includes two parts: the position measurement part and the...
position tracking part. The first part is to monitor the 3D coordinates of the mass center of the rover, and the results are transferred to the second part. The second part includes the multi-level driver elements, such as two dimensional drivers of the crane and the two dimensional driver element of the platform itself.

The CICS is to make the internal force of the cable acting on the rover constant, when the mass center of the rover moves dynamically in the vertical direction. It includes the cable tension measurement part and the driver elements to keep the cable force constant by rolling up or down the cable.

Fig. 1 Main configuration of the lunar gravity simulation system (LGSS)

2 Modeling of lunar gravity simulation system

In this section, the dynamics model of the LGSS is built in terms of the Newton equations. According to the configuration of the LGSS, there are three parts: the rover, the upper platform, and the cable between the rover and the upper platform.

2.1 Modeling guidelines

The first part is the rover, which could be modeled as a point mass or a rigid body, even a multi-body system. If it is assumed that the cable force passes through the mass center of the rover and the variable soil-wheel forces are ignored, we could simplify the rover as a point mass, and the interaction between the rover and soil is modeled as an unilateral contact. The effect of the LGSS can be evaluated by the normal contact force under the lunar conditions. The interaction between the rover and the soil under the LGSS requires further study.

The second part, the upper platform, includes the PCS, the CICS and other auxiliary structures and mechanical devices. If the tracking precision of the PCS and the control accuracy of the cable tension by the CICS meet the requirements of the LGSS, we can also model the upper platform as a point mass by neglecting the internal interaction of the upper platform. The interaction between the rover and the soul under the LGSS requires further study.

The last part is an elastic cable, which is almost vertically suspended from the upper platform to the moving rover. There are many different methods to model the cable. In this paper, by discretizing the cable into a series of mass-spring-damping elements, we will get a multi-rigid body system instead of a continuous elastic system, and the numerical method can be easily applied to study the dynamics of the cables subsystem.

2.2 The governing equations of the LGSS

Under the guidelines and assumptions mentioned above, the LGSS is modeled as a system of two mass points and a cable, as shown in Fig. 2.

In the following equations, the subscript “p” denotes the point mass of the upper platform, “r” denotes the point mass of the rover, and “ci” denotes the ith point mass of the discretized cable. Let \( r_0 \) denotes the position vector of the kth rigid body in the global reference frame \( O-xyz \). Let \( c \) and \( k \) denotes the equivalent stiffness and damping of the cable elements.

To further simplify the notation, define

\[
\begin{align*}
\mathbf{r} &= \begin{bmatrix} r_1^T, & r_2^T, & \cdots, & r_p^T, & r_{p+1}^T, & \cdots, & r_{p+c}^T \end{bmatrix}^T, \\
\mathbf{M} &= \text{diag}(m_{p+1}, m_{p+2}, \cdots, m_{p+c}), \\
\mathbf{F} &= \begin{bmatrix} F_{r1}^T, & F_{r2}^T, & \cdots, & F_{r1}^T, & F_{r2}^T, & \cdots \end{bmatrix}^T
\end{align*}
\]

where: \( m_k \) is the mass of the kth point mass, \( k = r, p, p+1, \ldots, p+c \); \( F_k^T \) is the force acting on the kth point mass, including the applied force and the constraint force; \( I_j \) is the 3x3 identity matrix.

Applying the Newton’s second law and Lagrange multipliers, we obtain the governing equations of the system as follows

\[
\begin{bmatrix}
\mathbf{M} & \Phi_r^T \\
\Phi_r & 0
\end{bmatrix}
\begin{bmatrix}
\ddot{\mathbf{r}} \\
\lambda
\end{bmatrix} =
\begin{bmatrix}
\mathbf{F}^T \\
\gamma
\end{bmatrix},
\]

where \( \lambda \) is the vector of Lagrange multipliers; \( \Phi_r, \gamma \) are the assembled constraint Jacobian and the acceleration of the joints. In this paper, only two planar joints are studied. The detailed derivation of the constraint equations for these joints is given in Ref.[1].
2.3 Mass-spring-damping elements of the cable

In the modeling of the system, the cable subsystem is represented as a series of mass points, with spring-damper elements between them. The acting forces on the spring-damper elements are shown in Fig. 3.

Let $P_{ci}$ and $P_{cj}$ be the positions of two mass points. The vector from $P_{ci}$ to $P_{cj}$ is
\[ d_{ij} = r_j - r_i. \]  
(3)

Thus, the square of the length of that vector is given by
\[ l_{ij}^2 = d_{ij}^T d_{ij}, \]  
(4)

and the time rate of the change of the length is
\[ \dot{l}_{ij} = \left( \frac{d_{ij}}{l_{ij}} \right)^T (\dot{r}_j - \dot{r}_i). \]  
(5)

The magnitude of the force between the two mass points, with the tension being taken as positive, is
\[ f_{ij} = k \left( l_{ij} - l_{ij0} \right) + c \dot{l}_{ij}, \]  
(6)

where $k$ is the spring coefficient; $c$ is the damping coefficient; and the $l_{ij0}$ is the initial length of the $j$th cable element. Thus, the constrained force between the cable elements is
\[ F_{aj} = \frac{f_{ij}}{l_{ij}} d_{ij}. \]  
(7)

3 Simulation results

In this section, the simulation results for the cable subsystem are computed by using the model and the assumptions described in the previous sections. The system is modeled by the software: MD Adams R3\footnote{2}. The simulation system includes: a point mass for the rover, a point mass for the upper platform, and twenty mass points for the cable elements. The point mass of the platform is constrained by a planar joint in the crane plane, which is fixed 8 m high above the ground. The point mass of the rover is constrained by a planar joint with the ground plane instead of a unilateral contact, if the vertical component of the counter-acting force of the planar joint is greater than zero. These two mass points and other twenty mass points of the cable elements are connected by the bushing connection of the software to simulate the spring-dampers, as shown in Fig. 2\footnote{3}.

3.1 Case 1: Simulation of the upper platform without tracking error

As the first case, it is assumed that the upper platform has an idealized PCS and CICS, which means that the tracking precision of the upper platform and the control precision of the cable tension are both very high. And it is implemented in the software by assuming a same displacement of planar joints on the upper platform and the rover in $x$ direction, and the preload of the spring is set as $5/6$ of the rover gravity, while the length of the cable is not varied.

Under the above idealized condition, the response of the displacement of the rover and the upper platform is consistent, as shown in Fig. 4.

The spring forces of three different cable elements are shown in Fig. 5, which includes top, middle and bottom cable elements. From the spring force of the top element of the cable, it follows that the cable tension is almost constant and equal to $5/6$ of the rover weight.

The normal force between the soil and the rover is shown in Fig. 6, which varies in a small range around the mean value of 196 N, which is almost equal to $1/6$ of the rover weight.

Fig. 4 Responses of displacement of the rover and the upper platform

Fig. 5 Variation of the spring forces of different cable elements

Fig. 6 Normal force between the soil and the rover
3.2 Case 2: Simulation of the upper platform with tracking error

So far, the cable model in this paper can not simulate the up and down movement of the cable due to its rolling on the crane, which means that effect of the CICS can not be simulated. Therefore, the two ends of the cable are fixed on the upper platform and the rover. As for the simulation of the tracking ability of the PCS, the displacements of the planar joints are the same as in section 3.1, while the displacement of the upper platform has a small range error with respect to the rover’s, as shown in Fig. 7, which means that the tracking error is dynamically oscillating about the target values with a constant deviation.

The spring forces of three different cable elements are also shown in Fig. 8. From the spring force of the top element of the cable, it follows that the cable tension is oscillating about 5/6 of the rover weight with an amplitude of 5 N more than that in the case 1.

The normal force between the soil and the rover is also shown in Fig. 9, which oscillates about the target value of 196 N, but with a larger range than in the case 1.

3.3 Simulation of the effects of some parameters

By adjusting the stiffness and the damper of the cable elements, we study the effects of the two parameters on the dynamics of the system for the above Case 2. The parameters are shown in Table 1. A smaller value of the stiffness and the damper means a softer or more flexible cable. The spring force of the top cable element, the normal force between the soil and the rover, and the lateral component force of the spring are shown against different values of the stiffness in Fig. 10–Fig. 12. Because the effects of different values of the damper are very small, the related simulation results are not provided here. The results show that a moderate stiffness is an optimum option for the system, as a very small stiffness is unable to supply enough cable tension and will induce a large lateral vibration under the same conditions, and a very big stiffness means very small oscillating amplitudes of the cable tension.

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4 Conclusion

This paper studies the modeling and simulation of a lunar gravity system based on cable suspension method. The results
月面重力模拟系统恒拉力绳索的动力学研究

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摘要：月面巡视器在未来探月工程中占有非常重要的作用，月球重力场是影响月面巡视器运动性能的重要环境因素，需要对其进行地面模拟试验。文章基于绳索悬挂建立月面重力模拟系统，其关键是对恒拉力绳索进行建模和动力学分析。通过将绳索离散化为一系列集中质量的弹簧阻尼结构，得到多刚体系统来代替连续的弹性系统，用数值计算方法来研究绳索系统的动力学参数（如刚度和阻尼）对月面重力模拟系统的影响，来优化月面重力模拟系统。

关键词：月面重力模拟系统；恒拉力绳索；集中质量的弹簧阻尼结构；多刚体系统；数值计算

院士展望

孙家栋院士：“北斗”卫星导航系统走向商业化应用

“两弹一星”元勋、北斗卫星导航系统总设计师孙家栋院士在第三届中国卫星导航学术年会开幕式上表示，北斗卫星导航系统将迎来最好的应用产业发展期。

孙家栋说，十几年来，卫星导航应用改变着人们的生活方式。互联网信息文明和现代商业模式的快速发展，推动着社会经济形态和信息产业的变革，也为卫星导航的应用创新提供了各种可能。北斗系统的特点源于其独立兼容的体制、定位通信的一体、独具特色的增强、建用相依的政策，将迎来最好的应用产业发展期。

据介绍，当前我国北斗卫星导航系统正按照“质量、安全、应用、效益”的总要求，坚定不移地实施“三步走”总体系规划，形成了突出区域，面向世界，富有特色的发展道路。第一步，于 2000 年建成了北斗卫星导航试验系统，使中国成为世界上第三个拥有自主卫星导航系统的国家。第二步，建设北斗卫星导航系统，2012 年左右形成服务亚太地区的能力。第三步，2020 年左右，北斗卫星导航系统形成全球覆盖能力。随着北斗系统去年 12 月试运行，今年 4 月“一箭双星”成功发射了第十二、十三颗北斗导航卫星，北斗系统定位、导航、授时服务性能不断提升，应用服务逐步拓展到交通运输、气象、渔业、林业、测绘等领域，产生了显著的社会、经济效益，北斗应用呈全面推广和产业化之势。

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