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Design and landing dynamic analysis of reusable landing leg for a near-space manned capsule

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ABSTRACT

To improve the landing performance of a near-space manned capsule under various landing conditions, a novel landing system is designed that employs double chamber and single chamber dampers in the primary and auxiliary struts, respectively. A dynamic model of the landing system is established, and the damper parameters are determined by employing the design method. A single-leg drop test with different initial pitch angles is then conducted to compare and validate the simulation model. Based on the validated simulation model, seven critical landing conditions regarding nine crucial landing responses are found by combining the radial basis function (RBF) surrogate model and adaptive simulated annealing (ASA) optimization method. Subsequently, the adaptability of the landing system under critical landing conditions is analyzed. The results show that the simulation effectively results match the test results, which validates the accuracy of the dynamic model. In addition, all of the crucial responses under their corresponding critical landing conditions satisfy the design specifications, demonstrating the feasibility of the landing system.

1. Introduction

Due to the development of science and technology, near-space flight vehicles have attracted increasing attention all over the world [1]. In recent years, with the concept of commercial use for near-space flight vehicles being brought up, near-space manned capsules have been widely researched. Near-space manned capsules are capable of carrying several passengers to altitudes of 20–40 km using helium balloon lifting systems to experience beautiful views. After that, it returns to the ground. Of all the recovery steps, landing is one of the most crucial because a slight malfunction could result in failure of the entire trip. Many corporations have designed and experimented with near-space vehicle landing systems. The World View's near-space vehicle achieves soft-landings using parafoil and landing legs after cutting off the helium balloon. This scheme has been partly verified by experiments. The “traveler” near-space vehicle designed by Kuang-Chi returns to the ground by deflating a helium balloon under nominal conditions or opening a parachute system under failure conditions. It then relies on the landing system to implement a successful soft landing. This scheme also has been verified in some experiments [2]. Considering the uncertainties of initial landing conditions and reusability of the capsule, it becomes crucial to design a reusable landing system that can improve landing stability as well as reduce landing impact overloads.

Based on the above motivations, this paper proposes a novel reusable landing system configuration for a near-space manned capsule to address different initial landing conditions. The landing system employs a double chamber damper in the primary strut and two single chamber dampers in corresponding auxiliary struts. Various types of dampers have been studied in the past. Crushable metal dampers are widely used. Zupp [3] investigated the stroking behavior, internal load distributions and landing dynamic response of a lander with crushing honeycomb using a multi-body dynamic model. Chen [4], Wei [5] and Van Lai Pham [6] studied the influences of different initial conditions on honeycomb attenuation capability and landing stability through dynamic simulations and drop experiments. Liu [7] and Yue [8] undertook multi-objective optimization of a honeycomb damper used in a lander and oleo-honeycomb damper used in a vertical landing vehicle, respectively. Witte [9] studied the probability of landing failure of planetary landing systems with energy-absorbing honeycomb. Han [10] studied landing performance of a damper that used metal deformation or friction to absorb energy. When compared with crushable metal dampers, the advantages of the damper in this paper are that it is reusable and can recover vehicle altitude. Hydraulic dampers or single chamber oleo-pneumatic dampers [11,12] compose another type of

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widely used damper for vehicle landings. When comparing these dampers, the double chamber damper in this paper can provide good attenuation performance under both nominal and severe landing conditions. In addition, active and semi-active dampers have also been broadly researched for vehicle landings. Wang [13,14] undertook research on the feasibility of using magneto-rheological fluid dampers on a lander and built a soft-landing mathematical model to analyze its performance. Choi [15] developed a design analysis and control of a magnetorheological damper for shock mitigation in a helicopter, and experiments were conducted to validate the analysis. Sivakimar [16] investigated the active landing gear system of an airplane using proportional integral derivative controllers. Although active and semi-active dampers can be more adaptable than the landing system in this paper under different landing conditions, they are usually much heavier, more expensive and have more complex structures, causing them to be less reliable. Other types of dampers have been recently studied by researchers, such as the electromagnetic shock absorber used in the landing leg of the Mars hopper [17] and the momentum exchange landing leg in a planetary lander [18,19]. These dampers are still at the stage of laboratory research and small-scale experiments, and there is limited knowledge regarding their practical attenuation performances under various landing conditions.

Based on the novel landing system in this paper, landing dynamic model is established and damper parameters are determined employing the design method. The dynamic model is experimentally validated and the adaptability of this landing system is analyzed. By using a radial basis function (RBF) model as a surrogate for the landing responses of the dynamic model under different landing conditions in the adaptability analysis [20], the calculation efficiency can be improved. The adaptive simulated annealing (ASA) global optimization method is also introduced to search for the extreme landing responses and their corresponding initial conditions, which are used to demonstrate the landing system's adaptability.

The paper consists of the following parts. Section I presents an overview of the publications related to the topics in this paper. Sections II and III focus on the mathematical modeling of vehicle landing with the new landing system. Section IV provides a design method for determining the damper parameters. The description of the experiments and validation of the dynamic model are presented in section V. Section VI investigates the adaptability of the landing system under different critical landing conditions.

2. Dynamic landing model of capsule

2.1. Overall scheme

The landing system of the capsule primarily consists of one primary strut, two auxiliary struts and a footpad. The primary strut contains a double chamber damper, which is primarily used for absorbing the landing energy in the vertical direction. The auxiliary strut contains a single chamber damper, which has the following functions.

(1) It can absorb the landing energy in the horizontal direction.
(2) It can compress to ensure the compression for the primary struts when the footpad cannot move due to the large contact friction force.
(3) It can absorb part of the landing energy in the vertical direction when the force-transfer path from the ground to capsule is changed with initial landing pitch angles.

The overall scheme of one landing leg is shown in Fig. 1.

To make the simulation results consistent with real conditions and maintain model calculation convenience and efficiency, the following assumptions are made for this study.

(1) The capsule is divided into one upper mass and four lower masses.

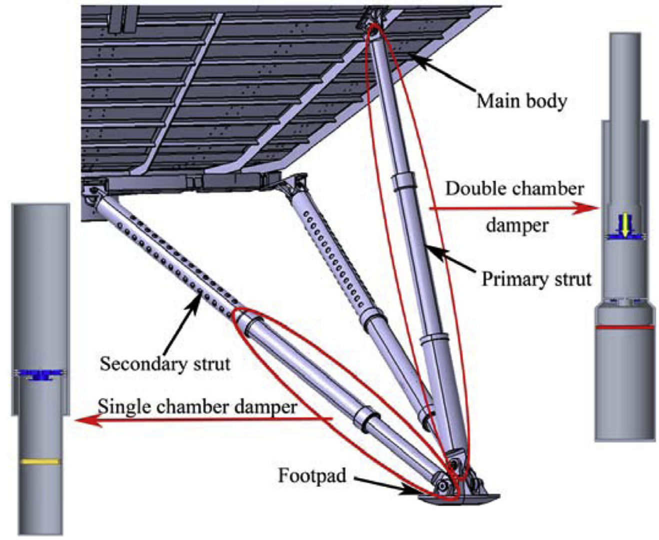

Fig. 1. Overall scheme of one landing leg.

The upper mass includes the main body, primary struts pistons and auxiliary struts envelopes. The lower mass in each landing leg consists of the envelope of the primary strut, the pistons of the two auxiliary struts and the footpad.

(2) The upper mass, which is concentrated at the center of gravity of the main body, has six degrees of freedoms including three translational and three rotational movements. For the lower masses, which are concentrated on gravity center of each footpad, the three rotational movements are ignored to simplify the model. The lower mass is recognized as a load on the spherical hinge joint of the footpad [21].
(3) The footpad is taken as a rigid body, and therefore only the deformation of the ground is considered in the analysis of the landing process. The contact force passed from the ground to the main body through the footpad.

2.2. Definitions of the coordinate systems

A total of 18° of freedom (DOF) are used in the dynamic model, and they included the motions of the main body (6 DOF) and four footpads (3 DOF for each). As shown in Fig. 2, three different right-handed

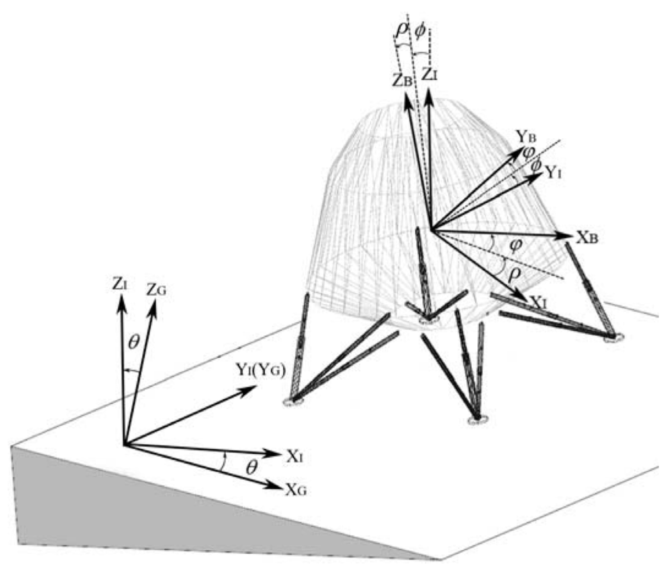

Fig. 2. The relationships among the different coordinate systems.