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Parametric design and analysis on the landing gear of a planet lander using the response surface method

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ABSTRACT

The purpose of this paper is to obtain the design parameter-landing response relation for designing the configuration of the landing gear in a planet lander quickly. To achieve this, parametric studies on the landing gear are carried out using the response surface method (RSM), based on a single landing gear landing model validated by experimental results. According to the design of experiment (DOE) results of the landing model, the RS (response surface)-functions of the three crucial landing responses are obtained, and the sensitivity analysis (SA) of the corresponding parameters is performed. Also, two multi-objective optimizations designs on the landing gear are carried out. The analysis results show that the RS (response surface)-model performs well for the landing response design process, with a minimum fitting accuracy of 98.99%. The most sensitive parameters for the three landing response are the design size of the buffers, struts friction and the diameter of the bending beam. Moreover, the good agreement between the simulated model and RS-model results are obtained in two optimized designs, which show that the RS-model coupled with the FE (finite element)-method is an efficient method to obtain the design configuration of the landing gear.

1. Introduction

Numerous Mars missions from the U.S, Russia and Europe have been carried out to study the planet [1–4]. Until 2014, a long-term goal of sending a human to Mars has been explicitly approved by NASA, and the landmark target is to accomplish a human landing on Mars and safely return to earth [5,6]. The China's Mars exploration plan, approved in 2016, aims to achieve soft-landing on planet Mars, surface mobility with a rover by 2020, and to complete the Mars sample-return mission in 2030. The concept of Mars lander and rover of China Mars exploration was unveiled. The landing gear system is a four-leg landing system, with the inverted-tripod type landing gear [7]. Since the landing gear system brings the vehicle to rest while preventing toppling, absorbing the landing-impact energy, and limiting loads induced into the lander [8,9], it is of utmost importance for the designer to obtain a good design configuration of the lander with good landing performance.

Research on the single landing gear is a necessary and essential task for studying the landing performance and the toppling stability of the whole lander. Examples are the design process of the Apollo lander (US.) [8] and the Chang'e3 lander (China) [10]. However, the research objective of the lander mainly focused on the soft-landing properties (landing dynamics analysis and landing stability analysis) and the conceptual design of the lander [8,9]. Few investigations on the design configuration of the landing gear of the lander were carried out. Moreover, the research methodology of studying the landing gear of the lander can be typically classified into three categories [9,11]. These are the theoretical analysis method [12,13], the simulation analysis (multi-body [14–17] and the finite element method [18,19]), and finally the experimental method [8,10]. In particular, the simulation method is the commonly used method due to savings in cost and improved design efficiency. Therefore, for getting a good design configuration of the lander, it is necessary to find a quick design method for the landing gear of the lander, based on the simulation model.

The response surface method is a collection of statistical and mathematical techniques used for developing, improving, and optimizing processes of industrial production. It also has common applications in the design process of some complex engineering applications

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[20], for examples in vehicles [21,22] and aircraft design [23]. This method can effectively save the extra mathematical effort and reduce the computational expense for analysis and design [24]. The fundamental principle is to construct a simplified model to approximately fit the computationally expensive simulation response, based on the design of experiment (DOE) results of the research model [25]. In fact, in the design process of the Chang'e3 lander and another lander, the RS-method coupled with the multi-body dynamics model was applied. The performance optimization of the lunar lander was carried out to find the best design parameter, based on the multibody dynamics model, which provides a theoretical method for the lander design [26–28]. However, some details cannot be efficiently expressed in the multi-body dynamic model, such as the structural stress and the bending response of the struts, due to the limitation of the multi-body dynamics method. Therefore, it will be an easier acceptable task using the response surface method to analyze the design parameter of landing gear based on the finite element method, since the overall details of the landing gear during lander at touchdown can be efficiently expressed in the finite element method. For this reason, it is necessary that the research on the design parameters of the landing gear be investigated, using the response surface method based on the FE-model.

To acquire the design factor-landing response relation for designing a good configuration with good landing performance quickly, parametric studies on the inverted-tripod type landing gear of the legged lander are carried out using response surface method. The studies are organized into two parts. Section 2 presents the finite element model of the inverted-tripod type landing gear of the four-legged lander constructed in ABAQUS. Moreover, it is validated with the experimental results. Section 3 firstly discusses the parameter setting of the single landing model used for the response surface method. Secondly, Subsections 3.2 and 3.3 present the response surface function for the landing responses and the sensitivity analysis of the parameters, respectively. Moreover, Subsection 3.4 presents two optimization design configurations of the landing gear of the lander to validate the accuracy of the RS-model.

2. Numerical modeling and validation

2.1. Configuration and FE-model

An inverted-tripod type landing gear of the legged lander is modeled in Fig. 1, according to reference [7]. The model consists of the footpad, the two primary struts, and one secondary strut. The primary strut (Fig. 2) includes an outer and inner tube, and the equivalent buffer. The joints in which the primary struts connect the footpad and landing cabin are the spherical and universal joint, respectively. The joints which the secondary strut connects the bending beam and footpad are universal and fixed joint, respectively. The relations among the bending beam, the constraint structure, and the cabin are fixed. The role of the primary struts of the landing gear is to provide the constraint of the whole lander in the vertical direction, in which the crushing force is realized by the plastic deformation of the buffers. The secondary strut consists of one mid-tube, one bending beam, and the constraint structure. The role of the secondary strut is to provide the slipping constraint of the footpad and the rotation motion of the landing gear. The constraint force is provided by the plastic deformation of the bending beam.

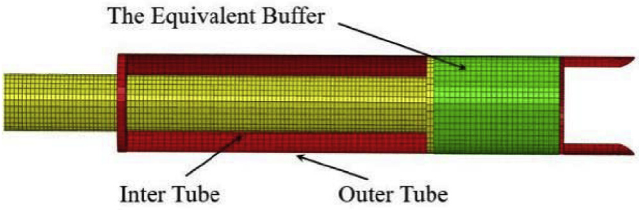

Fig. 2. The primary strut of the landing gear.

All the assemblies in the landing model are modeled in Fig. 3. For simplification of the whole model, the cabin is modeled using the discrete rigid body in ABAQUS, and constrained by a translated joint with a friction relation. The landing surface is modeled using the deformable material. All the struts of the landing gear are modeled using the corresponding element to each component. The element of the tubes in the landing gear is the conventional shell element S4R (a 4-node doubly curved shell element with reduced integration). The detailed model of the connector between the struts of the landing gear was neglected, using the simplified connector to simulate. For example, the universal joints are simulated by the coupled model of the universal connector and a beam type MPC (multi-point constraint) link. The beam type MPC is defining a rigid beam connection to constrain the displacement and rotation of each slave node (on the tubes) to the displacement and rotation of the control point (the joint reference point). Likewise, the spherical joints are simulated by the coupled model of the joint connector and the MPC link.

The properties of tubes, constraint structure, and each buffer in the primary and secondary struts, are illustrated in this paragraph. The material selected for tubes of the landing gear is an aluminum alloy. Since the landing gear should have sufficient stability during the

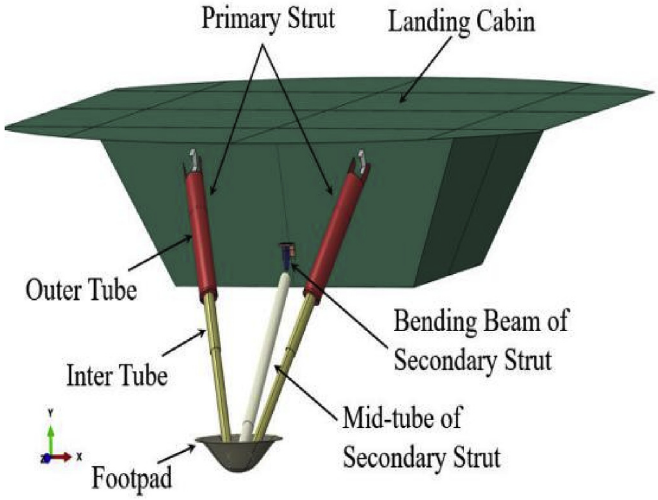

Fig. 1. The single landing gear model.

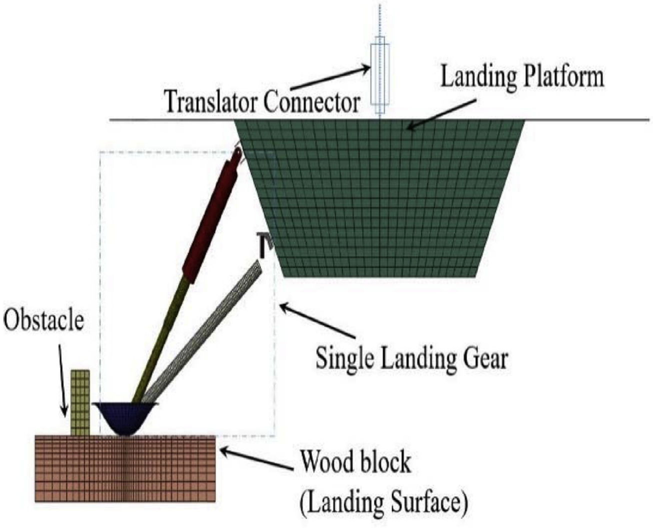

Fig. 3. The validated landing sketch model.