Acta Astronautica 105 (2014) 407–416

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Study on passive momentum exchange landing gear using two-dimensional analysis

Tsubasa Watanabe [a], Susumu Hara [a,*], Masatsugu Otsuki [b]

[a] *Department of Mechanical Science and Engineering, Graduate School of Engineering, Nagoya University, Japan*
[b] *Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Japan*

ARTICLE INFO

Article history:
Received 14 March 2014
Received in revised form
2 September 2014
Accepted 13 October 2014
Available online 22 October 2014

Keywords:
Shock
Spacecraft
Landing
Lunar exploration
Momentum exchange

ABSTRACT

This paper discusses a landing response control system based on the momentum exchange principle for planetary exploration spacecraft. In the past, landing gear systems with cantilever designs that incorporate honeycomb materials to dissipate shock energy through plastic deformation have been used, but once tested before launch, the system cannot be used in a real mission. The sky crane system used for the Mars Science Laboratory by NASA can achieve a safe and precise landing, but it is highly complex. This paper introduces a momentum exchange impact damper (MEID) that absorbs the controlled object's momentum with extra masses called damper masses. The MEID is reusable, which makes it easy to ensure the landing gear's reliability. In this system, only passive elements such as springs are needed. A single-axis (SA) model has already been used to verify the effectiveness of MEIDs through simulations and experiments measuring the rebound height of the spacecraft. However, the SA model cannot address the rotational motion and tipping of the spacecraft. This paper presents a two-landing-gear-system (TLGS) model in which multiple MEIDs are equipped for two-dimensional analysis. Unlike in the authors' previous studies, in this study each MEID is launched when the corresponding landing gear lands and the MEIDs do not contain active actuators. This mechanism can be used to realize advanced control specifications, and it is simply compared with previous mechanisms including actuators, in which all of the MEIDs are launched simultaneously. If each MEID works when the corresponding gear lands, the rebound height of each gear can be minimized, and tipping can be prevented, as demonstrated by the results of our simulations.

1. Introduction

The construction of a lunar base has become one of the greatest goals of space development projects around the world. Lunar bases have many benefits, such as facilitating long-duration manned exploration missions. Detailed lunar exploration is a prerequisite for determining the location in which a lunar base is to be built. Thus, improving technology to land on the moon is important, since lunar exploration spacecraft will need to be able to land in all kinds of environments. The landing terrain is not always flat, and can sometimes be very rocky and bumpy. Restricting landing sites to flat locations is technically too difficult, because the lunar surface has not yet been fully mapped, and navigation errors may occur. When a spacecraft lands on unstable terrain, tipping over may occur; thus, systems to prevent this tipping must be developed. In particular, for a spacecraft to land at any location, landing gear that prevents tipping over is indispensable.

Several types of landing gear have been used in lunar exploration spacecraft. The Apollo missions in the 1960s

---

[*] Corresponding author. Tel.: +81 52-789-5582.
E-mail addresses: haras@mech.nagoya-u.ac.jp (S. Hara), otsuki.masatsugu@jaxa.jp (M. Otsuki).

http://dx.doi.org/10.1016/j.actaastro.2014.10.020
0094-5765/© 2014 IAA. Published by Elsevier Ltd. All rights reserved.

and 1970s used a cantilever design incorporating an aluminum honeycomb material [1]. When a spacecraft with this mechanism lands on the moon, this mechanism dissipates the shock energy through plastic deformation. This mechanism has been studied well until now, for example, recently, Nohmi et al. applied this mechanism to a four legged lunar lander and simulated its performance using mechanical dynamics software [2]. However, this mechanism can be used only once; if tested before launch, the mechanism cannot be installed in a spacecraft. To ensure reliability, many specimens are made and tested many times before launch, which is a difficult process. As another example, the sky crane system used for the Mars Science Laboratory by NASA can achieve a safe and precise landing [3]. This system is divided into the descent stage and the rover. When the descent stage is slowed to nearly zero velocity by its steering engines, the rover is released from the descent stage, and a bridge and umbilical cord lower the rover to the ground. Then, after the rover lands softly, the bridge is cut, and the descent stage then fly away from the rover. However, maintaining the altitude of the descent stage is difficult, and this mechanism is complex. From these points of view, development of new landing gear that can achieve safe landings is needed.

As a different approach to safe landings, a low-cost mechanism based on momentum exchange principles has been proposed [4]: the momentum-exchange-impact-damper (MEID). This system can be explained using billiards as an example, as shown in Fig. 1: the momentum that the controlled object receives from the impact source is exchanged for another mass's momentum. This mass is called a damper mass. For spacecraft applications, the damper mass is thrown upward after the spacecraft rebounds, which can reduce the rebound of the spacecraft. MEID systems are classified into three types according to the mechanism of this momentum exchange: passive-MEID (PMEID) systems, which comprise only passive elements such as linear springs; active-MEID (AMEID) systems, which comprise only active elements such as actuators; and active/passive-hybrid-MEID (HMEID) systems, which comprise passive and active elements.

Until now, the effectiveness of MEIDs has been demonstrated with simulations and experiments based on a single axis (SA) [5–8], and the effectiveness of MEIDs in a double-axis scenario has been verified only for AMEID systems [4]. However, actuators increase the overall mass of the system, and may lead to control errors. Therefore, the purpose of this paper is to demonstrate the effectiveness of a PMEID in a double-axis situation. If a PMEID can be used to prevent tipping of the spacecraft, it will open up various opportunities such as an increase in the payload ratio. This paper discusses only by the simulations because this is the first study with two-dimensional analysis using a PMEID. The two-landing-gear-system (TLGS) model, in which multiple MEIDs are equipped, is examined in this paper to analyze the two-dimensional motion of a spacecraft, and the effectiveness of a MEID in suppressing rotational motion is simulated. The scheme for the TLGS model is shown in Fig. 2. In the previous system including AMEIDs, all of the MEIDs were launched simultaneously. However, in this paper, the authors presume that each MEID works when the corresponding gear lands to realize effective momentum exchange. This approach can minimize the rebound height of each gear and also prevent tipping. The details of the PMEID systems and the TLGS model are explained in Section 2. In particular, the advantages of the MEID mechanism for realizing an ideal landing response are demonstrated. This paper compares the simulation results for systems: without MEIDs (model without MEIDs), with one MEID (1-MEID model), and with two MEIDs (2-MEID model).

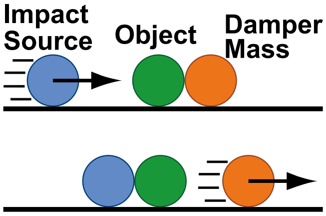

Fig. 1. Conceptual diagram of the MEID.

2. Landing response control method

Three models are considered in the two-dimensional analysis, called the model without MEIDs, 1-MEID model, and 2-MEID model, as mentioned above. In the 1-MEID model, the damper mass is placed on the top of the left or right leg. In the 2-MEID model, the damper masses are placed on top of both legs. The damper mass at the top of the left leg is called the “left damper mass,” and the damper mass at the top of the right leg is called the “right damper mass.” Each damper mass is connected to the spacecraft with a spring and damper material. The damper material in the model represents the damping elements of the spring. Moreover, the authors presume that before the damper masses are separated, they can move only along the axis parallel to the legs.

If the landing ground is inclined downward to the right, the overall TLGS model is divided into six states described by different models of the system:

(i) the 2-MEID model with the constraint,
(ii) the 2-MEID model without the constraint,
(iii) the left MEID model,
(iv) the right MEID model with the constraint,

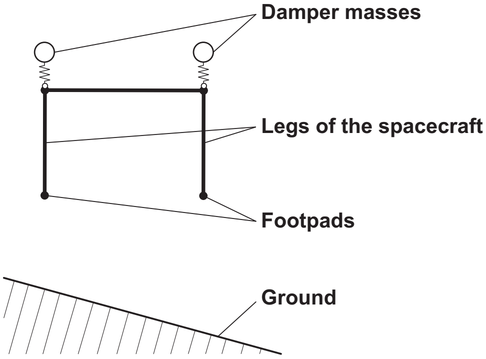

Fig. 2. Scheme of the TLGS model.