3C22

Simulation and Experimental Validation on Touchdown Dynamics of Lunar-Planetary Lander with Controllable Landing Gear

Takao MAEDA*, Masatsugu OTSUKI** and Tatsuaki HASHIMOTO**

* Department of Engineering, The University of Tokyo

7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan

E-mail: takao.maeda@ac.jaxa.jp

** Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency

3-1-1 Yoshinodai, Chuo-ku, Sagami-hara, Kanagawa, 252-5210, Japan

Abstract

This paper presents an actively controlled landing gear system and its experimental validations. Active landing gear uses a variable coefficient damper as a shock absorber. We executed landing experiment with the two dimension lander model which introduced a magnetorheological damper as a shock absorber. Damping coefficient is controlled to reduce attitude disturbance during touchdown based on lander attitude and displacement of landing leg. The result of model experiment indicates that the active landing gear can reduce attitude disturbance which causes the lander overturning.

Key words : Planetary Exploration, Landing Gear, Touchdown Mechanics, Semi-Active Damper.

1. Introduction

To touchdown to the rough but interesting region on moon, mars, and other planet and satellite, not only accurate navigation-guidance system but also robust landing gear system is strongly required. For example, the explorations inside craters, crater central hills, high land regions, and lunar lava tube holes are demanded to achieve unprecedented result that is pivotal in investigating the origin of the Earth and the Solar System (Sakai et al., 2013), (Haruyama et al., 2011). These areas, however, are rough terrains and have many slopes. In order to achieve touch down on rough terrains, we should design a landing system which is adaptable to different kind of slopes, steps and obstacles. However, it is difficult to design a landing system which is applicable to a wide variety of terrains. Recently, some actively controlled landing gear systems are proposed as a solution of this problem. There are different types of actively controlled landing leg systems, (e.g., using the variable coefficient damper (Taguchi et al., 2009), using actuator and control leg's stiffness (Maeda et al., 2012), the momentum exchange impact damper (MEID) (Kushida et al., 2013), ball screw and impedance control (Shigeto et al., 2013), the base-extension separation mechanism (Saeki et al., 2013), or actively using RCS thrusters for anti-rolling (Kajiwarra et al., 2011)).

Authors also proposed an active landing gear system which uses a variable damper. This system control dampers annotation coefficient based on lander attitude and displacement of landing leg. The touchdown simulation with the two dimensional model which express depth symmetric 1/2 lander indicates the feedback of lander angular rate and the direction of displacement of the landing leg is most effective to reduce attitude disturbance during touchdown sequence.

On the other hands, some experimental validations about active landing gear are proposed too. However, the almost all landing experiments are executed with single landing leg and the attitude control of lander did not be considered. Here, our landing experiment system has two landing legs and each leg has magneto-rheological damper which can control damping coefficient. Attitude of lander can be controlled by switching damper coefficient of left and right leg independently.

This paper shows the result of experimental validation about active landing gear system with magneto-rheological damper and its advantages in reducing of the attitude disturbance.

2. Active landing gear system

Active landing gear is one of the types of actively controlled landing system. The feature of shock absorbing of the conventional landing gear is fixed at design phase, and it cannot change after launch. If the damping coefficient is variable, we can select the most suitable parameter to prevent from hazard in final touchdown sequence. For example, in touchdown to steep slope, it seems effective to prevent tip-over that soften first-touch-leg and harden last-touch-leg. Actively variable damper can change its stiffness, so such a damper control will be possible based on lander and terrain state.

In this paper, we apply the magneto rheological fluid variable damping coefficient damper for the landing shock absorber and control its characteristic based on lander attitude as feedback control. In our proposal, we control only the damping coefficient of the landing leg.

To prevent from overturning of lander, each landing legs should be controlled based on lander attitude. The control method for active landing gear was proposed by authors (Maeda et al., 2013). Here, right and left landing legs are controlled independently on the basis of the lander's angular rate and shrinking direction of leg damper.

Here, c_R and c_L are damping coefficient of right and left damper. L_R and L_L mean the length of left and right damper. $\dot{L}_R$ and $\dot{L}_L$ are displacement rate of right and left damper. The controller switches damping coefficient High or Low. The control rule is as follows.

$$c_R = \begin{cases} \text{High} & (\dot{L}_L \omega > 0) \\ \text{Low} & (\dot{L}_L \omega \leq 0) \end{cases}, \quad c_L = \begin{cases} \text{Low} & (\dot{L}_R \omega \geq 0) \\ \text{High} & (\dot{L}_R \omega < 0) \end{cases} \quad (1)$$

Simulation condition is shown in table1. Passive means the result by the fixed parameter damper for landing leg. Active means the result by the controller that is shown in equation1.

Example of touchdown simulation is shown in figure 1. Figure 2 shows the maximum lander attitude angle when the lander touches down on the slope shown in x axis. The result of simulation indicates that the proposed control method has an large advantage in the case of touchdown to slope terrain.

Here, we adopt this controller to the landing experiment system in the following section.

3. Experiment System

Scaled lander model is used for landing experiment. There are the varied sizes of the lunar and planetary landers. The gravity also differs from target planet to another. Therefore, it is difficult to make experiment with a full scale lander. Additionally, magneto rheological damper size which we can get is limited and lander size is decided based on it. For the reasons above, in this paper, landing experiment is executed by scaled lander model.

Figure 3 shows the overview of experimental system with two landing legs. Figure 5 is a schematic of experimental system. In this paper, we consider only the motion of rotation and translation which fixed in a plane. The common lander has four legs. So, this experimental system is equivalent to the half of the original lander. Landing experimental system has two legs. The type of landing leg is swing-arm. Architecture of swing-arm type landing leg is shown in figure 4. A swing-arm leg is hinged at the one side of leg to the lander body and a foot pad is fixed on the other side. A swing-arm leg is suspended by spring and magneto rheological damper to the lander main body.

Lander model parameters are shown in Table 2. In this experiment lander model, the damper and spring are attached close to the body and they are driven by leverage of the swing arm type landing leg. Therefore, the nominal spring constant k and damping coefficient c are identified at the tip of the leg where the foot pad is attached.

The lander main body is fixed on slider on liner guide rail. The slider can move on z and x axis freely, and it is free to rotate about θ axis.

Gyro sensor, angle sensor, acceleration sensor and height sensor are embedded on the lander. An encoder is also embedded on right and left landing leg independently to detect displacement direction of landing leg.

The lander is hold with a magnetic holder above the experimental slope. And release the holder to start experiment. The lander falls freely and touches down on slope experimental terrain.

Fig. 1 Example of touchdown simulation. The lander cannot touch down on 20 degree slope in this case. However, the lander with proposed active landing gear can touch down on the same slope.

Fig. 2 Result of touchdown simulation. The maximum slope angle that the lander can touch down without overturning becomes large by using with the proposed control method. In the case of SLIM class size lander simulation, the lander can land on a slope that is 2.5 times as steep as passive case with the proposed way.

Table 1 Simulation conditions

Parameter		Value	
M	Mass of lander	150	kg
J	Moment of inertia of lander	30	kgm ²
k	Leg spring constant	2.0	kN/m
c	Leg damper constant(Low/High)	0.26 / 2.6	kN/(m/s)
w	Total width of lander	1.2	m
h	Hight of center of gravity (COG) of lander	1.2	m
H	Initial height of COG of lander	3.5	m
μ'	Terrain surface friction	0.8	-

4. Experiment Result

The example image of landing experiment is shown in figure 6. Figure 7(a) ~ 7(e) plots results of experiment. There are four experimental parameters, three passive dampers and one active damper. Passive damper means non-controlled (fixed value) MR damper. Three passive parameters are as follows: Current input: 0.0A, 0.9A and 1.8A. They correspond to SOFT, MIDDLE and HARD dampers. Active means active switching control by proposed method.

Figure 7(a) shows the maximum attitude angle in touchdown sequence. The maximum attitude disturbance of the lander is smallest in HARD on 15 degree slope. However, in case of HARD, attitude disturbance increases with a slope angle. On the other hand, the disturbance of ACTIVE is smaller than any other passive landing gears.

Figure 7(b) indicates that the angular rate of lander becomes small in the condition of small damping coefficient of landing legs. In the case of ACTIVE, it is possible to reduce angular rate in landing on 25 degree slope. On the 15 degree slope, the performance of ACTIVE gets worse. The switching of damping coefficient may be the cause of this.

Figure 7(c) shows the maximum angular acceleration. Maximum angular acceleration becomes small in the case of SOFT damper, and becomes large in the case of HARD. In ACTIVE case, maximum angular acceleration remains in intermediate value between HARD and SOFT.

Figure 7(d) shows maximum vertical acceleration of lander. The case of SOFT has an advantage. The HARD landing

Fig. 3 Overview of touchdown experimental system. The lander model has two landing leg to deal x , z and θ dynamics. The lander body is fixed on liner slider which can move on guide rail, and the body can rotate on the slider freely. Each leg has spring and magneto rheological damper. Gyro, rotation attitude, z -axis and z -acceleration sensors are installed. Leg displacement sensors are also equipped.

Fig. 4 Schematic of swing arm type landing leg. A swing-arm is hinged at the one side of leg to the lander body and a foot pad is fixed on the other side. A swing-arm is suspended by spring and magneto rheological damper to the lander main body.

gear causes large acceleration to body. The maximum acceleration in case of ACTIVE is larger than SOFT case. However it remains smaller value than MIDDLE and HARD case.

Figure 7(e) shows maximum z -axial displacement of lander. The maximum z -axial displacement becomes small under condition of HARD. On the other hand, it becomes large in the case of SOFT. It is indicate that the case of SOFT cannot absorb kinetic energy enough, and it causes displacement to downhill side. In the case of HARD, the displacement becomes small. The active landing gear set the first touch leg soft, so the displacement becomes larger than HARD and MIDDLE condition. However, it remains smaller than condition of SOFT.

From those experimental results, the active landing gear can solve trade-off problems. The SOFT landing gear can reduce maximum angular acceleration and z -axis acceleration. However, it performs poorly on maximum attitude, angular rate, and displacement of lander. On the other hand, the HARD landing gear performs well on maximum attitude, angular rate, and displacement. But angular acceleration and vertical acceleration becomes large. In the case of ACTIVE, the overall performances shown in figure 7(a) ~ 7(e) remain good.

5. Conclusion

The experimental validation of the semi-active landing gear system for the moon and planetary lander is explained in this paper. Especially, experimental validation with actively controlled landing gear system on two or three dimension experimental apparatus had never been executed. This paper showed the first experiment with 2-D limited experiment. The effectiveness of the proposed method was shown in experimentally. The proposed method can solve the trade-off

Fig. 5 Schematic of total laboratory tests. Total signals processed by ds1103/dSPACE. The lander is held by magnet-holder and be released after beginning of experiment.

Table 2 Parameters of experimental lander

Parameter	Value
M Mass of body	9.0 kg
J Moment of inertia of body	0.8 kgm^2
w Width between each footpad	1.0 m
h Height of COG	0.70 m
k Spring constant of leg	1.1 kN/m
c Damping coefficient of leg (variable)	0.1(0.0A) 0.8(0.9A) 1.5(1.8A) kN/(m/s)

problem between the hard and soft landing legs.

As for future works, a comparative verification of experiment with simulation result and modelling of terrain are required. Further, improve experiment apparatus in order to emulate landing dynamics in moon gravity. The effect of nonlinearity of MR-damper should be considered in simulation model and it should be reflected to the control rule for the experiment system to reduce the error of the result of experiment.

Acknowledgement

This work was supported in part by a Grant-in-Aid for Science Research (B) (Grant 23360104) from the Japan Society for the Promotion of Science (JSPS).

References

- Haruyama, J., Sawai, S., Mizuno, T., Yoshimitsu, T., Fukuda, S., and Nakatani, I., Exploration of lunar holes, possible skylights of underlying lava tubes, by smart lander for investigating moon (slim), Proceedings of the 27th International Symposium on Space Technology and Science (2011), Paper No. 2011-k-08.
- Kajiwar, R., Maeda, T., Otsuki, M., and Hashimoto, T., Development of active controlled landing gear experiment system for the lunar-planetary lander, Proceedings of 56th Space Sciences and Technology Conference (2011), pp.128–131, Paper No. B112 (in Japanese).
- Kushida, Y., Hara, S., Otsuki, M., Yamada, Y., Hashimoto, T., and Kubota, T., Robust landing gear system based on a hybrid momentum exchange impact damper, Journal of Guidance, Control, and Dynamics, Vol.36, No.3 (2013), pp.776–789.
- Maeda, T., Kajiwar, R., Otsuki, M., and Hashimoto, T., Proposal of an actively controllable landing leg for lunar-planetary lander, Recent Advances in Space Technologies (RAST), 2013 6th International Conference on (2013), pp.967–971.
- Maeda, T., Hashimoto, T., Otsuki, M., and ichiro Sakai, S., Lunar lander attitude control during planetary surface touchdown, Proceedings of 11th Conference on Motion and Vibration Control (2012), Paper No. 3E01 (in Japanese).

Fig. 6 Example successive photos of landing experiment. Frame late is 60 pictures/sec.

Saeki, N., Susumu, H., Masatsugu, O., Tsubasa, W., and Yoji, Y., Base-extension separation mechanism for planetary exploration spacecraft landing, Proceedings of the 29th International Symposium on Space Technology and Science (2013), Paper No. 2013-d-27.

Sakai, S., Sawai, S., Fukuda, S., Nakaya, K., Sato, E., Kunugi, M., and Yasumitsu, R., Smart lander for investigating moon (slim): Demonstration of smart lunar landing technology with small spacecraft, Proceedings of 57th Space Sciences and Technology Conference (2013), Paper No. 3F06 (in Japanese).

Shigeto, S., Fujimoto, H., Hori, Y., Otsuki, M., and Hashimoto, T., Fundamental research on reduction of impact forces using actively controlled landing gear in lunar/planetary landers, IEEJ Transactions on Industry Applications, Vol.133, No.3 (2013), pp.335–341 (in Japanese).

Taguchi, K., Hashimoto, T., and Otsuki, M., Dynamic touchdown control for safe and precise landing using active landing leg, Proceedings of 53th Space Sciences and Technology Conference (2009), Paper No. 2D05 (in Japanese).

Fig. 7 Result of landing experiment. Three configurations of stiffness and proposed active — HARD, MIDDLE, SOFT and ACTIVE landing gear are tested under experimental condition of 15, 20 and 25 degree slopes. Δ , ∇ and $\square$ markers correspond to HARD, MIDDLE and SOFT landing gear settings. $\star$ means the result of the ACTIVE landing gear that is proposed. Colored markers are average value and colored lines are its variation with slope angle. Those figures includes three results of experiments and their average. In each graph, the smaller is good value.