Experimental investigation of changing traction force caused by a propagation of vibration for planetary exploration rovers with legs

Abstract: In this study, the supporting force that is increased by providing vibration to the ground is investigated for improving the moving performance of the planetary exploration legged rovers. First of all, the supporting force while the rod is vibrating is investigated. The supporting force is decreased and, the data of one is fluctuated toward every moment while the rod is vibrating. Secondly, the increasing supporting force by vibration under changing vibration time is investigated. When vibration time is short, the longer the vibration time is, the larger the supporting force is. When vibration time is long, the supporting force is not increased by providing vibration. The findings of this study suggest to facilitate further planetary exploration using legged rovers.

脚型探査ローバのための振動伝播を用いた牽引力変化に関する実験的研究

摘要: 本研究では，宇宙探査用の脚型ローバの移動性能を向上させるため，振動を与えた際の支持力の変化に関して調査を行った．まず，常に脚部を振動させた状態の支持力変化について調査を行った．調査の結果，常に振動させた場合では，振動を与えない場合よりも支持力が低くなる，支持力がうねりを伴って増加と減少を繰り返すなど変化を示し，安定して支持力を得られなかった．次に，振動を与える時間の変化による支持力の変化について調査を行った．振動時間と支持力の関係性については，振動時間が増加するほどに支持力は上昇していくが，長時間化していくと支持力はある一定の値に収束する傾向を確認した．これらの結果から，宇宙探査を目的とする脚型ローバの歩行方法に関して有用な知見を得られた．

1. Introduction

In recent years, many missions have been conducted to explore the Moon [1]. Moreover, rovers with leg mechanisms have been focused on as exploration rovers with high running performance [2][3]. The ground of the Moon is covered with loose soil, called regolith. Rovers mainly slip due to deformation of the loose ground because the loose ground is easily deformed by external force. We have addressed this problem. Our study group proposed a walking method for legged rovers that reduces the slip distance on loose ground for planetary exploration legged rovers [4]. In the proposed walking method, it is important that the supporting force is increased by providing vibration to the ground. It is considered that the running performance of the legged rover is related to the supporting force.

In this study, the supporting force that is increased by providing vibration to the ground is investigated in order to improve the proposed walking method. In detail, two topics are investigated. First of all, the supporting force while the rod is vibrating is investigated. Secondly, the increasing supporting force by vibration under changing vibration time is investigated.

In the remainder of this paper, the supporting force while the rod is vibrating is investigated in section 2. In section 3, the increasing supporting force by vibration under changing vibration time is investigated. Finally, this study is summarized in section 4.

The contribution of this study is as follows:

1. The supporting force was decreased and, the data of one was fluctuated toward every moment.
2. When vibration time is short, the longer the vibration time is, the larger the supporting force is. When vibration time is long, the supporting force is not increased by providing vibration.

2. Investigation of the supporting force while the rod is vibrating

The relationship between the supporting force and how to provide vibration to the ground is important information as a design guideline for walking motion. From this importance, the supporting force while the rod is vibrating was investigated.

2.1. Experimental methods

Fig. 1 shows the experimental setup. It consisted of a soil tank, a rod, and a force sensor. Fig. 2 shows the size of the rods. The shape of the rod was a quadrangular prism. The bottom of the rod was a square with sides of 20 mm. Vibration generator (Wave Maker05) propagated vibrations to the rod. The vibratory direction was the same as the towing direction of the rod. The waveform of vibration was a sine wave. The flow of the experiment is illustrated in Fig. 3. First, the ground was mixed and flattened. The rod was filled to 60 mm in the ground. The rod was tracked while vibrating. The force sensor received the value of the supporting force. There are five types of vibrations considered that differ based on the vibratory frequency. Table 1 shows the types of vibrations used. Table 2 shows the conditions of this experiment.

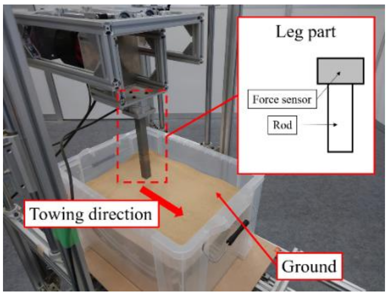


Fig. 1 Environment of measuring supporting force experiment.

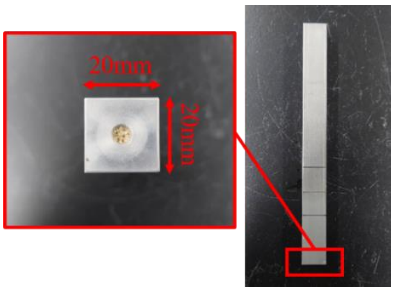


Fig. 2 Overview of rod.

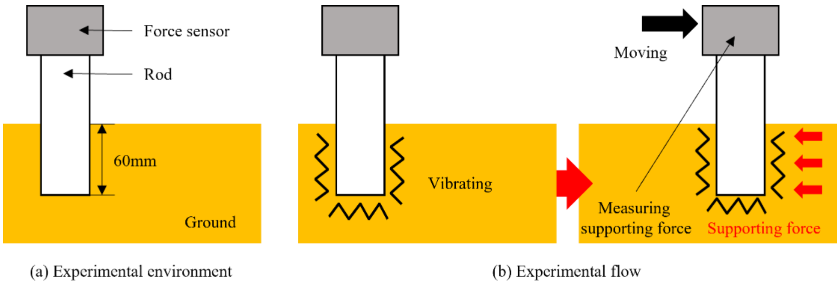


Fig. 3 Flow of supporting force measuring experiment while vibrating.

Table 1 Parameters table of vibration.

Name	Amplitude [mm]	Frequency [Hz]
No vib.	0.0	0
Vib. 1	0.5	10
Vib. 2	0.5	20
Vib. 3	0.5	30
Vib. 4	0.5	40
Vib. 5	0.5	50

Table 2 Conditions for supporting force measuring experiment while vibrating.

Item	Conditions (value)
Number of trial	5
Sinkage	60 mm
Traction speed	0.13 mm/s
Traction distance	13 mm
Kind of sand	Silica No. 5

2.2. Experimental results and discussion

Experimental data was smoothed by applying SMA (Simple Moving Average) because it was noisy by including vibratory force. The formula of SMA is shown in Eq. (1).

$$SMA_m = \frac{p_m + p_{m-1} + \cdots + p_{m-n}}{n} \qquad (1)$$

n is number of data that is averaged. m is number of data that is smoothed. p is value of experimental data. In this investigation, Experimental data was smoothed by applying SMA when n was 10.

Fig. 4 shows supporting force versus traction distance after data was smoothed. In Fig. 4, the supporting force fluctuated toward every moment in case of using the vibration whose frequency was 10Hz. Therefore, the supporting force was unstable in this situation. In case of using other vibrations or without vibration, the supporting force was increased at first of dragging rod. Finally, the increasing supporting force by vibration converged in these experimental conditions. Fig. 5 shows the average supporting force peak value in each experimental condition. This graph shows the standard errors that are calculated from the experimental results of the five trials. In Fig. 5, the supporting force in case of using the vibration whose frequency was 10Hz was biggest in this investigation. The supporting force in case of using other vibrations was smaller than that without vibration. Moreover, values of each the supporting force in case of using other vibrations were almost same.

These experimental results were considered to cause by moving particles of the ground. The supporting force decreased because these particles were moved by imparting vibration to the ground. From these experimental results, it is not suited to obtain the supporting force while the leg is vibrating for the proposed walking method using vibration.

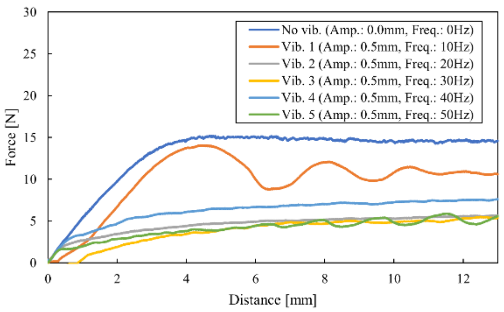


Fig. 4 Result of supporting force measuring experiment while vibrating.

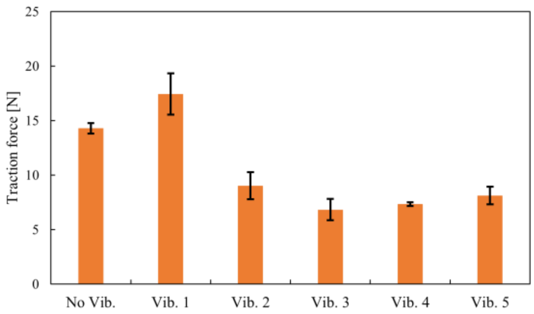


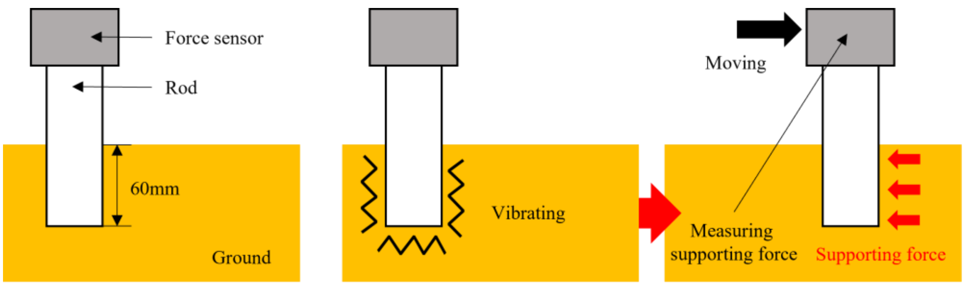
Fig. 5 Comparison of supporting force measuring experiment while vibrating.

3. Investigation of the increasing supporting force by vibration under changing vibration time

The relationship between the supporting force and vibration time is important for shortening walking motion. It is possible to short vibration time in the proposed walking method if this relationship is confirmed. From this importance, the increasing supporting force by vibration under changing vibration time was investigated.

3.1. Experimental methods

The experimental setup was the same as that used in the previous section (Fig. 1). The flow of the experiment is illustrated in Fig. 6. First, the ground was mixed and flattened. The rod was filled to 60 mm in the ground. Next, vibration was generated. The rod was tracked after ceasing the vibration. The force sensor received the value of the supporting force. The shape of the rod is shown in Fig. 2. Table 1 shows the types of vibrations used. Five types of vibration time were considered. There are 25 s, 50 s, 100 s, 150 s, and 200 s. Table 3 shows the conditions of this experiment.



(a) Experimental environment (b) Experimental flow

Fig. 6 Flow of supporting force measuring experiment by changing vibration time.

Table 1 Conditions for supporting force measuring experiment by changing vibration time.

Item	**Conditions (value)**
Number of trial	5
Sinkage	60mm
Vibration time	0 s, 25 s, 50s, 100 s, 150 s, 200 s
Traction speed	0.13mm/s
Traction distance	13mm
Kind of sand	Silica No. 5

3.2. Experimental results and discussion

Fig. 7–11 show the average supporting force peak value in each vibration time. When vibration time was less than 100 s, the longer the vibration time was, the larger the supporting force was. When vibration time was more than 100 s, the supporting force was not increased by providing vibration. From this experimental result, the increasing supporting force by vibration is considered to converge finally. Therefore, it is considered that the vibration that increases supporting force efficiently exists.

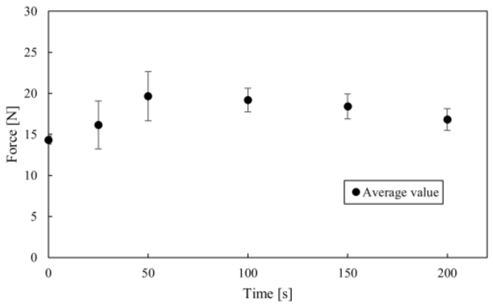


Fig. 7 Time vs supporting force(using vib. 1)

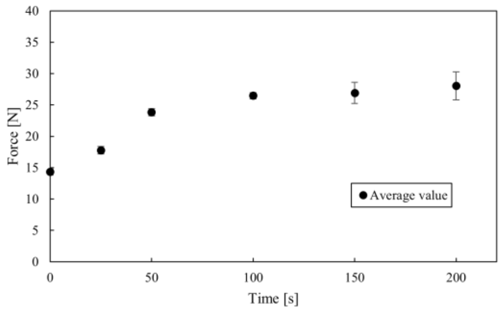


Fig. 8 Time vs supporting force(using vib. 2)

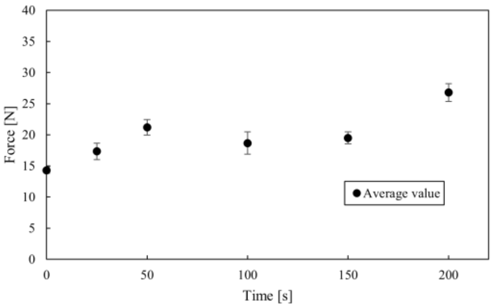


Fig. 9 Time vs supporting force(using vib. 3)

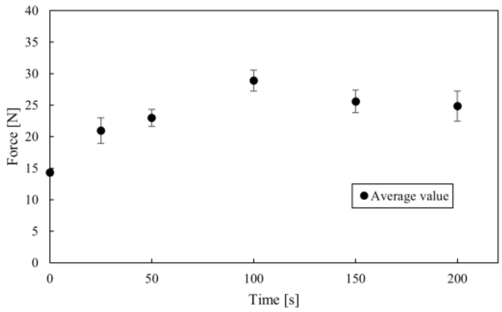


Fig. 10 Time vs supporting force(using vib. 4)

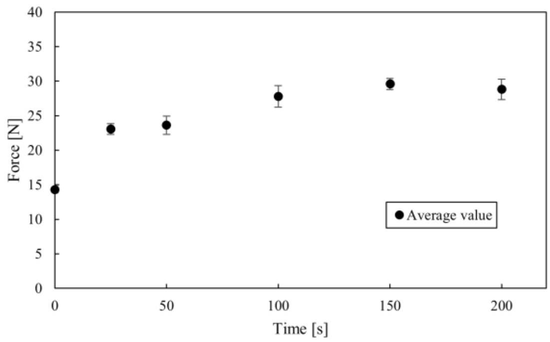


Fig. 11 Time vs supporting force(using vib. 5)

4. Conclusions

In this study, the supporting force that is increased by providing vibration to the ground was investigated for improving the proposed walking method. First, the supporting force while the rod is vibrating was investigated. The supporting force was decreased and, the data of one was fluctuated toward every moment while the rod is vibrating. Therefore, it is not suited to obtain the supporting force while the leg is vibrating for the proposed walking method using vibration. Next, the increasing supporting force by vibration under changing vibration time was investigated. When vibration time was short, the longer the vibration time was, the larger the supporting force was. When vibration time was long, the supporting force was not increased by providing vibration.

In future study, the proposed walking method using vibration will be improved by the knowledge that was obtained in this study. The effectiveness of the improved walking method will be confirmed.

Acknowledgments

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