VIBRATION ACTUATOR SYSTEM FOR INTERNAL INSPECTION OF LARGE COMPLEX IRON STRUCTURES

* Hiroyuki Yaguchi1 and Yusuke Itoh[1]

[1]Faculty of Engineering, Tohoku Gakuin University, Japan

ABSTRACT: In recent years, many large structures have been constructed all over the world due to economic development. Especially in Japan, more than 50 years have passed since the intensive construction of large structures during the period of high growth known as the Japanese economic miracle. As these structures age, they need to be inspected, and numerous robots have been proposed for structural inspection. However, the technology for inspection of large structures by robots remains immature. This paper proposes a vibration actuator system that can move a robot over an iron structure having a complicated surface, such as a stepped surface. A prototype vibration actuator system was built, in which four vibration actuators and wheels containing magnets were combined with flexible silicone rubber "backbone." Actual climbing tests showed that this actuator system can move smoothly over vertical steps. Further, this system can be equipped with an automatic tapping device, which might allow it to inspect the main towers of a large bridge.

Keywords: Vibration, Actuator system, Inspection, Magnetic wheel, Complex iron structure.

1. INTRODUCTION

In recent years, many large structures have been constructed in every country due to economic development. Especially in Japan, more than 50 years have passed since the intensive construction of large structures during the period of high growth known as the Japanese economic miracle. Therefore, the maintenance requirements for these structures have increased since 2010. Within 20 years, it is expected that more than 50% of Japan's social infrastructure will be more than 50 years old. Old infrastructure was built without seismic standards, so there is a risk of collapse in the event of a major disaster. For this reason, inspection and maintenance of social infrastructures, such as large bridges and storage tanks, is extremely important. In particular, there is a high demand for inspection at the cable joint of a cable-stayed bridge having a height of the main tower over 200 m.

Numerous robots have been proposed for structural inspection. Adhesion methods for wall surface movement include the following proposed techniques: mimicking of a living leech [1], roller structure with a belt and suction cups [2], van der Waals forces [3], negative pressure produced by a pump [4], adhesive materials [5], and a claw gripper [6]. Multiple actuators are always mounted on the drive unit of these robots. Additionally, these methods involve complicated mechanisms and require the adhered device to have a relatively large weight. In recent years, robots that apply

drone technology have been developed. However, drone inspection technology has not advanced because it requires skill in investigations due to the effects of strong winds and thunderstorms.

The authors previously proposed an actuator capable of movement on a ferromagnetic material by coupling an electromagnetic force and a mechanical vibration [7 - 9]. Although this actuator can climb vertically, it cannot move over a stepped surface. Therefore, it cannot be used for the inspection of iron structures having a complicated shape. The proposed actuator system [10] is also capable of movement on the stepped surface, it cannot be equipped with a heavy sensor, such as an automatic tapping device.

This paper proposes a vibration actuator system that can move over an iron structure having a complicated surface with, for example, steps. First, the movement characteristics of the vibration actuator were examined. Next, a vibration actuator system prototype was built having four vibration actuators and magnetic wheels combined with flexible silicone rubber. Actual climbing tests showed that this actuator system can move smoothly over a stepped surface. This actuator system can be equipped with an automatic tapping device, and it has been shown that it may apply to inspection of large iron structures.

2. STRUCTURE OF VIBRATION ACTUATOR

Fig. 1 shows a diagram of the vibration actuator capable of movement on ferromagnetic material. The vibration actuator consists of a permanent magnet, a translational spring, an electromagnet, a triangular acrylic frame, a second permanent magnet attached to the bottom of the frame, and a natural rubber sheet. The upper permanent magnet, which made up the mass of the vibration component, was cylindrical and was composed of NdFeB magnetized in the axial direction. This magnet was 15 mm in diameter and 6 mm in height. The surface magnetic flux density measured using a tesla meter was 380 mT. The translational spring was a stainless-steel compression coil having an outer diameter of 14 mm, a free length of 30 mm, and a spring constant k of 4,812 N/m. The electromagnet consisted of an iron core having a diameter of 5 mm and a length of 25 mm with 1,000 turns of 0.2-mm-diameter copper wire. This electromagnet was inserted into the translational spring.

The permanent magnet attached to the bottom of the frame had a diameter of 12 mm and a thickness of 5 mm. The average surface magnetic flux density was 383 mT. A natural rubber sheet of 1 mm in thickness was attached to this permanent magnet to increase the frictional force. The vibration component was inclined at an angle α from the horizontal plane. The vibration actuator had a height of 42 mm, a width of 15 mm, and a total mass of 30 g.

The angle α of the vibration component was set to 60° based on the results obtained in a previous study [8]. The attractive force generated by the permanent magnet attached at the support part acts on the vibration actuator when it is placed on a ferromagnetic material, as shown in Figs. 2(a) and 2(b). The frictional force between the rubber sheet and the magnetic substance alternates periodically during one cycle of vibration. Because the horizontal component of the inertial force exceeds the frictional force, the vibration actuator
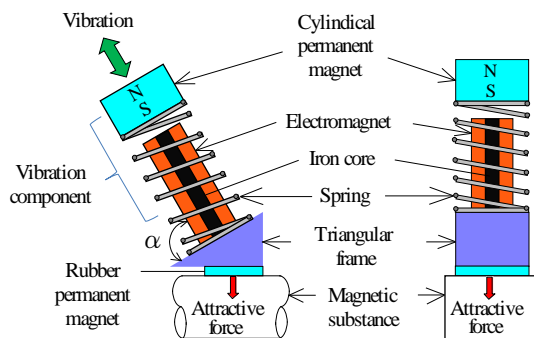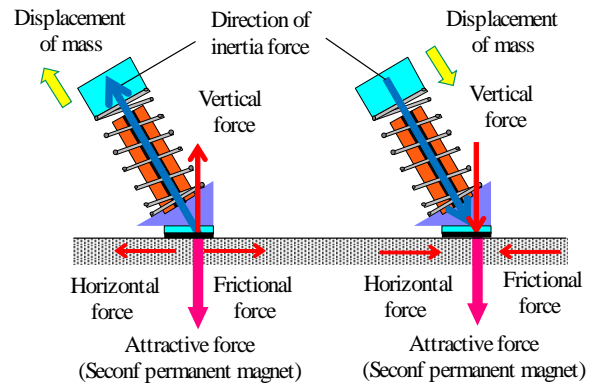

(a) Sliding   (b) No sliding
Fig. 2. Principle of locomotion.

is propelled by the difference between the frictional forces in the forward and backward directions acting on the rubber sheet, as shown in a previous study [8].

3. LOCOMOTION CHARACTERISTICS OF VIBRATION ACTUATOR

An experiment was conducted using the vibration actuator shown in Fig. 3. An iron rail with a width of 50 mm, a thickness of 50 m, and a length of 1,000 mm were used as the target magnetic structure. The vibration component was driven at a resonance frequency of 106 Hz using a signal generator and an amplifier. The attractive force F between the actuator unit and the iron rail was 8 N. The coefficient of friction between the iron rail and the natural rubber as measured in the experiment was 0.67. Fig. 3 also shows a photograph of the vibration actuator.

Fig. 4 shows the relationship between the load mass and the vertical upward speed of the actuator when the input power was 0.6, 0.9, and 1.4 W. In this figure, the actuator can move upward at a speed of 24.1 mm/s even with a load mass of 650 g.

Fig. 5 shows the relationship between the load mass and the self-propulsion efficiency of the actuator. The efficiency η is expressed:

Fig. 1. Structure of the vibration actuator.
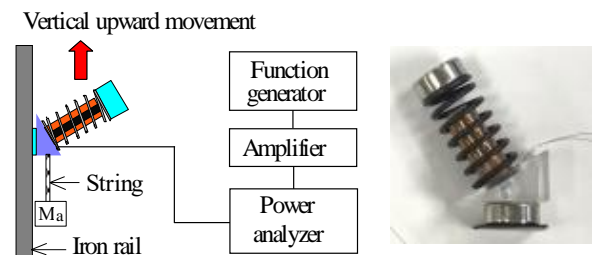
(a) Schematic   (b) Photograph
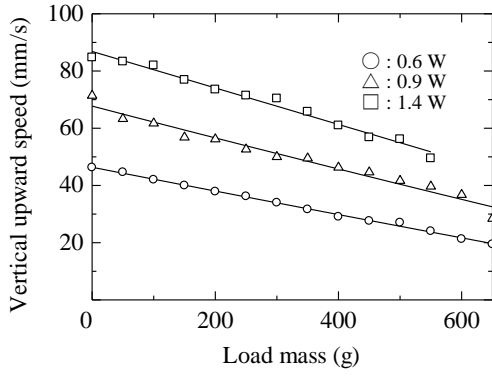Fig. 3. Experimental apparatus and actuator.

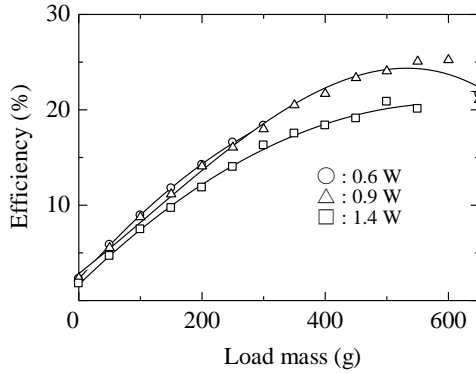Fig. 4. Relationship between load mass and vertical upward speed for the single actuator.

Fig. 5. Relationship between load mass and efficiency for the single actuator.

$$\eta\,[\%] = \left(M_a + M_m\right) v_{up}\, g \times 100 / P_I\,, \qquad (1)$$

where M_a is the total mass of the actuator, M_m is the load mass, v_{up} is the vertical upward speed, g is the acceleration due to gravity, and P_I is the input power. It was observed that the maximum efficiency of this actuator is about 25.2 %.

4. VIBRATION ACTUATOR SYSTEM CAPABLE OF MOVEMENT OVER A STEP

To move on a complex iron structure having a stepped surface, the new vibration actuator system has a flexible frame capable of deformation over uneven parts of the structure surface. Silicone rubber was used for the flexible frame, and the attractive force was generated by multiple permanent magnets.

Fig. 6 shows a vibration actuator system in which four actuators (A, B, C, D) capable of movement are connected by a flexible silicone rubber frame. The silicone rubber is divided into five segments. The lengths of silicone rubber segments A, B, C, D, and E are L_1, L_2, L_3, L_4,

and L_5, respectively. A magnetic wheel is attached to opposite ends of silicone rubber segments A and E. By attaching a magnetic wheel to the tip of the actuator system, it is possible to exert an appropriate attractive force on the iron structure and provide a guide for movement over a step. The magnetic wheel has a three-layer structure in which a ring-type permanent magnet is sandwiched between two acrylic disks having outer diameters of 30 mm and a thickness of 2 mm. In addition, auxiliary permanent magnets are placed at distances x_1, x_2, x_3, x_4, and x_5 from the origin O to adhere to an iron structure during movement over a stepped surface.

The longitudinal stiffness of the silicone rubber connecting the four actuators has a significant effect on the traction and movement over a step. Furthermore, the attractive force exerted by the magnetic wheel also affects the movement over the step. Because there are countless combinations of parameters for designing the actuator system, the following four criteria were introduced:

1) The total length of the actuator system is approximately 700 mm to allow portability.
2) Considering long cable traction over 200 m, the traction force for the actuator system is more than 15 N (load mass of 1,500 g).
3) In the future, an automatic tapping device mass weighing 260 g can be installed in the center of the actuator system.
4) The height of the step-over which the actuator system can move does not exceed 25 mm in the vertical plane.

Preliminary experiments were conducted to satisfy the above design criteria. By trial and error, the dimensions of the silicone rubber material were determined. All silicone rubber segments A, B, C, D, and E had a thickness of 5 mm. In addition, the width B and length L of the silicone rubber were set to B = 20 mm and L_1 = 120 mm, L_2 = 140 mm, L_3 = 140 mm, L_4 = 140 mm, and L_4 = 120 mm. As the auxiliary attractive force, cylindrical permanent magnets were arranged at x_1 = 0 mm, x_2 = 165 mm, x_3 = 305 mm, x_4 = -165 mm and x_5 = -305 mm in segments A, B, C, D, and E. Cylindrical permanent magnets with an outer diameter of 15 mm and a thickness of 6 mm were attached at these positions. The attractive force on the iron rail for this magnet was 1.8 N.

The ring-shaped permanent magnet for the magnetic wheels had an outer diameter of 16.5 mm, an inner diameter of 8.5 mm, a thickness of 4 mm, and a magnetic flux density of 356 mT. A three-layered wheel with a shaft with an outer diameter
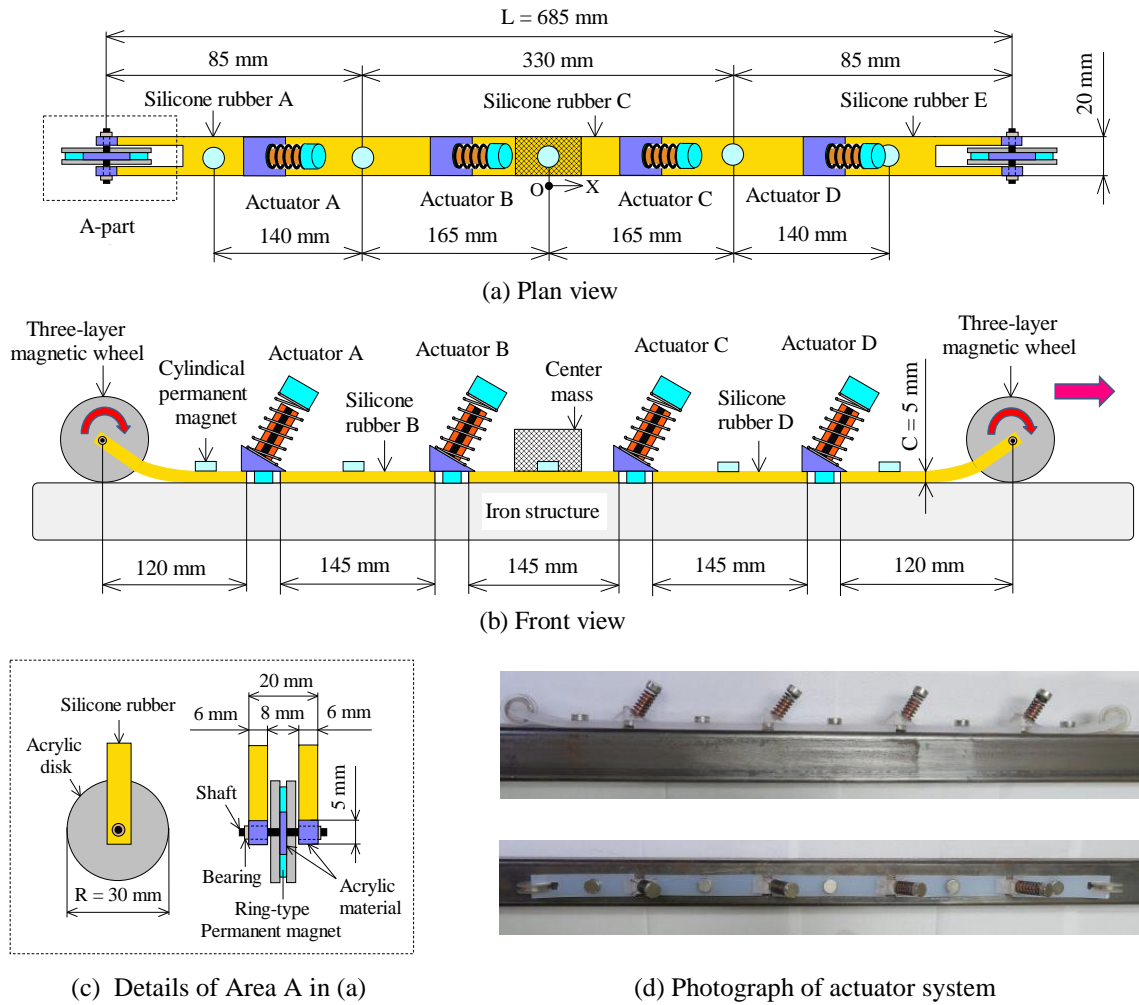
(a) Plan view

(b) Front view

(c) Details of Area A in (a)

(d) Photograph of actuator system

Fig. 6. Vibration actuator system capable of movement over a step.
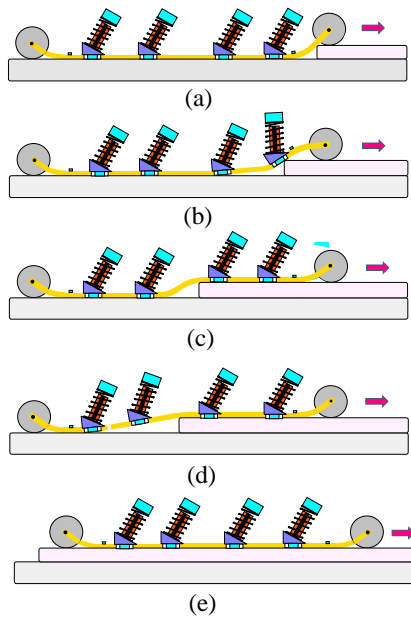

(a)

(b)

(c)

(d)

(e)

Fig. 7. Movement overstepped surface by vibration actuator system.

of 1 mm in the center was attached to the silicone rubber via bearings. The attractive force for the magnetic wheel was 0.9 N.

The overall length of the actuator system was 715 mm, and the distance between the magnetic wheels was L = 685 mm. The width, height, and total mass of the actuator system were 20 mm, 42 mm, and 250 g, respectively. In this system, the attractive force F for each vibration actuator was set to 8 N. Fig. 6(d) shows photographs of the vibration actuator system.

Fig. 7 shows an image of the vibration actuator system moving over a step.

5. LOCOMOTION CHARACTERISTICS OF VIBRATION ACTUATOR SYSTEM

Measurements were performed using the experimental apparatus shown in Fig. 3. In the measurement, a square iron pipe with a width and height of 50 mm, and a total length of 2,000 mm

was used. The traction characteristics of the prototype actuator system were measured experimentally for the two load mass patterns shown in Figs. 8(a) and 8(b). For the load mass pattern in Fig. 8(a), Fig. 9 shows the relationship between the central mass (mock automatic tapping device) mounted in the actuator system and the
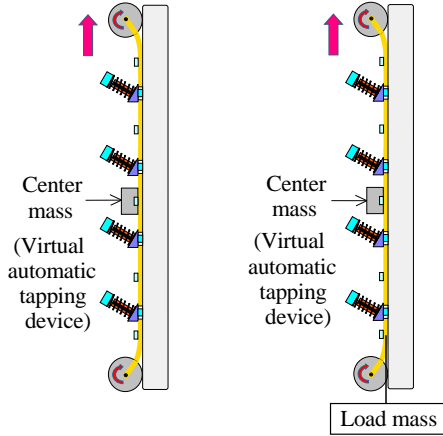
(a) Central mass   (b) Central and load masses
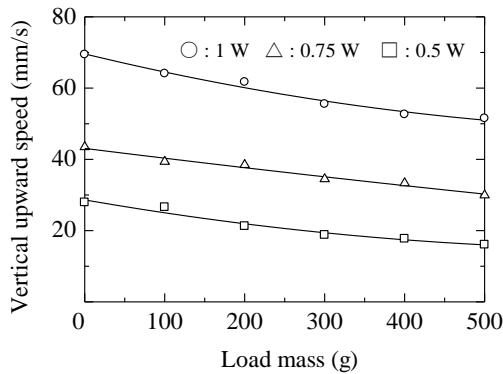Fig. 8. Two load mass patterns for climbing iron structures.

Fig. 9. Relationship between load mass and vertical upward speed with a central mass of 500 g.
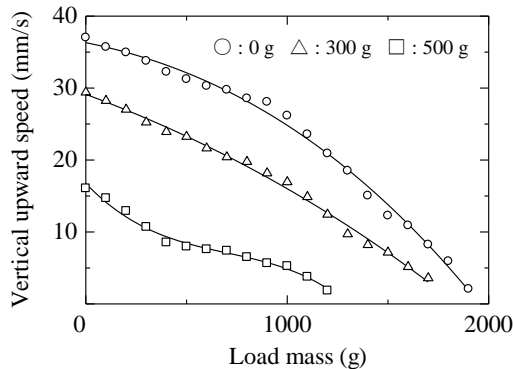

Fig. 10. Relationship between load mass and vertical upward speed with different central masses.

vertical upward speed for different power inputs to one actuator. When 1 W is input to each actuator, it is possible to ascend vertically at a speed of 51.5 mm/s while pulling a central mass of 500 g.

For the load mass pattern in Fig 8(b), Fig. 10 shows the relationship between the load mass and the vertical upward speed for central masses of 0, 300, and 500 g with a 1 W input to each actuator. The load mass was attached to the silicone rubber with a string. When a central mass of 300 g, which is heavier than a tapping device (260 g), was mounted on the actuator system, a vertical upward motion was possible at a speed of 7.2 mm/s even when the maximum design load mass of 1,500 g was attached to the main body.

6. STEP MOVEMENT CHARACTERISTICS OF VIBRATION ACTUATOR SYSTEM

As shown in Fig 11, the locomotion characteristics of the vibration actuator system for two-step patterns were measured. First, as shown in Fig. 11(a), an iron structure having a single step with an infinite length was examined. In these experiments, the measurement distance was set to 750 mm. The power input to each actuator was 1 W.

Fig. 12 shows the relationship between the load mass of the actuator system and the vertical upward speed for a single step with a height of 25 mm by varying for central masses of 0, 200, 300, 400, and 500 g. It was found that even with a central mass of 300 g, a traction force of 5 N (load mass of 500 g) was generated. However, the speed was only 6 mm/s. In the future, it will be necessary to take measures to increase the speed, such as changing the magnetic circuit in the vibration component.

Fig. 13 shows the relationship between the load mass of the system and the vertical downward speed for a single step with a height of 25 mm and central masses of 0, 200, and 300 g. For downward movement, the results show that the speed increases as the load mass increases.

Furthermore, as shown in Fig. 11(b), the complex iron structure has two steps (defined as a single step of finite length, where the actuator system must crawl up the step where it begins and down the step where it ends) was examined. The power input to each actuator was 1 W. In the experiment, the step height was fixed at 25 mm, and the effect of the step length L on the movement of the actuator system with no load mass was investigated. The step length L was varied from 50 to 550 mm at intervals of 50 mm,
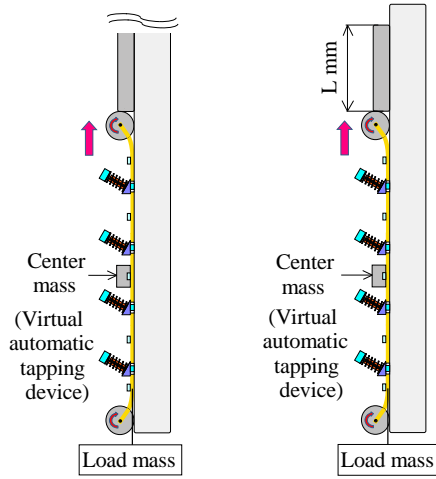
(a) Single infinite step   (b) Two steps
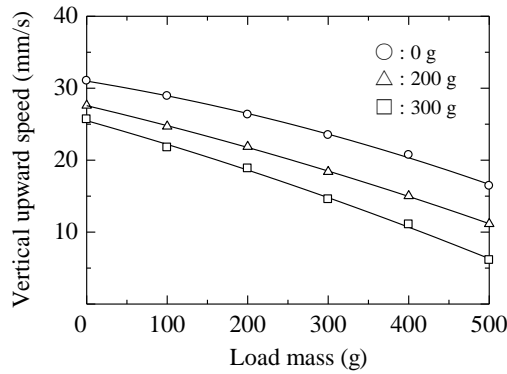Fig. 11. Two-step patterns for iron structure.

Fig. 12. Relationship between load mass and vertical upward speed for single infinite step.
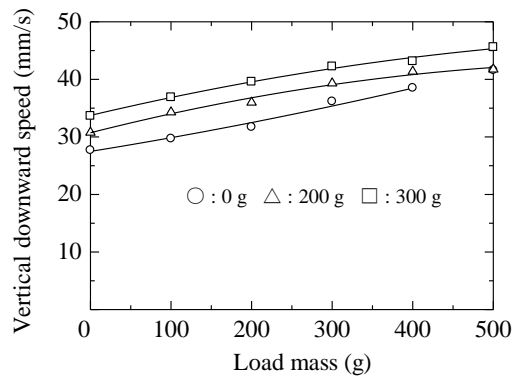

Fig. 13. Relationship between load mass and vertical downward speed for single infinite step.

and the vertical upward speed was measured. The step lengths over which the actuator system could move were 350, 500, and 550 mm or more. This is due to the placement interval of the vibration actuators in the system. An arrangement of vibration actuators that can handle any step length is an issue for the future.

The speed of the actuator system for the two-step case shown in Fig. 11(b) was measured. In these experiments, the step length was set to 500 mm. The power input to each actuator was 1 W.

Fig. 14 shows the relationship between the load mass and the vertical upward speed for a finite-length step 25 mm in height and central masses of 0, 200, and 300 g. Even for a central mass of 300 g, the system could move over the vertical surface while generating a traction force of 5 N.

Fig. 15 shows the relationship between the load mass and the vertical downward velocity for a finite-length step 25 mm in height for central masses of 0, 200, and 300 g. This actuator system proved capable of moving downward on a vertical surface with steps.

Compared to the infinite-length step (single step), the speed in the case of a finite-length step (two steps) was considerably reduced. This is because three actuators required large propulsive forces to overcome the attractive force between the permanent magnet in the holding part of one actuator and the stepped part of the iron structure. In the future, it will be necessary to improve the
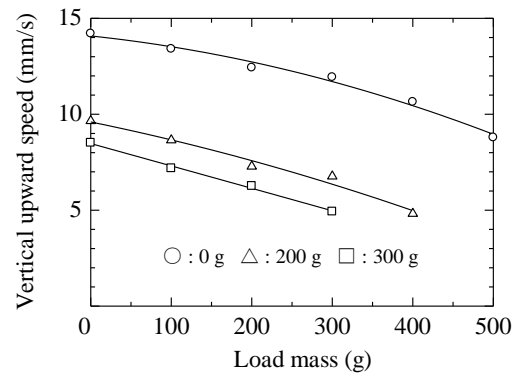

Fig. 14. Relationship between load mass and vertical upward speed for finite double step.
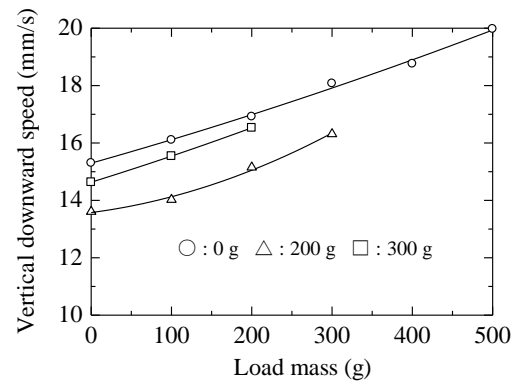

Fig. 15. Relationship between load mass and vertical downward speed for finite double step.

holding part using a design that combines a permanent magnet and an electromagnet. This will allow control of the attractive force according to the movement conditions.

In addition, this actuator system cannot switch the movement direction. To solve this problem, it is necessary to change the actuator to a structure that uses a vibration phase difference, as previously proposed by the author [9].

7. CONCLUSION

The demand for inspection of structures is increasing all over the world. However, it is very difficult to move on a complex iron structure having a step on a vertical surface. In this paper, a new vibration actuator system for the inspection of complex iron structures has been proposed.

At first, a single vibration actuator was prototyped and measured. The experimental results revealed that this vibration actuator was able to move with a load mass of 650 g. It is a maximum efficiency of about 25.2 % for the case of carrying only its weight.

Next, to move on a complex iron structure having a stepped surface, the vibration actuator system was prototyped with four vibration actuators and magnetic wheels combined with a flexible silicone rubber frame. The actuator system produced a traction force of 19 N. In addition, even for a load mass of 300 g, the approximate weight of an automatic tapping device, the system could move vertically over a step 25 mm tall. Thus, this actuator system can move on a complex iron structure which is difficult even for a robot equipped with a complicated control system. However, this actuator system cannot switch its direction of movement. To solve this problem, it is necessary to change the actuator to a structure that uses a vibration phase difference, as previously proposed by the author [9].

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