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Research Article

A New Type of Magnetic Actuator Capable of Wall-Climbing Movement Using Inertia Force

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This paper proposes a new type of a magnetic actuator that operates on a resonance energy of a mass-spring model by using an electromagnetic force. The magnetic actuator is moved by the difference in an inertia force during one period of vibration. Experimental result demonstrates that a horizontal speed of the magnetic actuator was 7.4 mm/s with load mass of 50 g. We considered a method of a cable-free movement of the actuator by using two iron rails and four permanent magnets. The magnetic actuator is able to move stably a ceiling plane and a wall plane. This actuator is able to move on the plane of the magnetic materials only a function generator and a power amplifier.

1. Introduction

Under the field and the environmental situation that a human being cannot inspect directly, a robot capable of actual work and inspection is desired at the field of each industry. In a large tank and bridge, periodical inspection is required. In the building, the inspection of the outer wall and the actual work of the wall surface are required.

As an adsorption method for wall surface movement, a method using magnetic attractive force [1–3] and the method to produce negative pressure [4] by using the devices such as a sucker or the pump, the method using van der Waals forces [5], a technique using the adhesive elastomer [6], and the method of magnetic wheel [7] were suggested, and the establishment for principle of locomotion has been accomplished.

However, at the mobile robot as mentioned above, the moving speed is low by problem of controllability and own weight. The development of a superior actuator of lightweight and operability is very important. We demonstrated a cable-free microactuator [8, 9] of vibration type by using an inertia force. In this previous paper, examination of cable-free and downsizing of the actuator were mainly considered. The moving properties of the actuator are not examined.

In this paper, we again propose a new type of a magnetic actuator capable of movement on a magnetic substance such as an iron rail using an inertial force of a mass-spring model. A prototype actuator was fabricated, and it is able to move on the magnetic substance. Experimental result shows that a horizontal speed of the actuator was 7.4 mm/s with load mass of 50 g. In addition, we considered a method of a cable-free movement for the actuator by four permanent magnets and using two iron rails. It was confirmed that this actuator is able to move on the plane of the magnetic materials only a function generator and a power amplifier.

2. Structure of the Magnetic Actuator by Using Inertia Force

Figure 1 is a diagram of the magnetic actuator capable of movement on the magnetic substance. The magnetic actuator consists of a permanent magnet, a translational spring, an electromagnet, a permanent magnet attached at frame bottom, and a frame of triangle shape. The permanent magnet is cylindrical NdFeB and is magnetized in the axial direction. This is 22 mm in diameter and height is 10 mm. The surface magnetic flux density measured due to tesla meter is 480 mT.

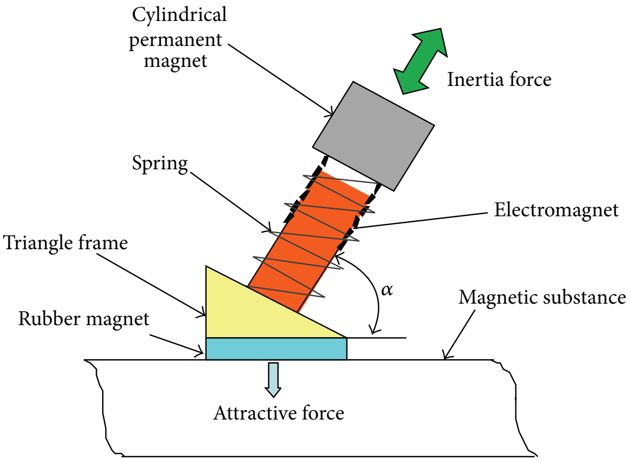

Figure 1: Structure of the magnetic actuator.

The probe surface of the flux meter was in contact with the permanent magnet. The translational spring is the stainless steel compression coil type with an outer diameter of 22 mm, free length of 37 mm, and a spring constant $k = 10150$ N/m. The electromagnet consists of an iron core 12 mm in diameter with 300 turns of 0.2 mm diameter copper wire. The electrical resistance of the electromagnet is 11 Ω. The permanent magnet attached at the triangle frame is a rubber magnet that is magnetized in the axial direction. This permanent magnet has a length of 26 mm, a width of 15 mm, and a thickness of 3 mm. The surface magnetic flux density measured using a tesla meter is 96.6 mT. This electromagnet was inserted in the translational spring. In addition, a clearance between cylindrical NdFeB permanent magnet and the electromagnet is 3 mm. The cylindrical NdFeB permanent magnet also achieves duty of the massof a mass-spring model. The mass-spring model was inclined with angle α from horizontal plane as shown in Figure 1. The actuator has height of 57 mm, width of 25 mm, and total mass of 85 g.

3. Principle of Locomotion

The magnetic actuator is held by an attractive force of the rubber permanent magnet. The principle of locomotion is as follows.

(1) As shown in Figure 2(a), the holding force of the magnetic actuator changes due to inertia force of a vibrating mass m. When the mass m vibrates in the direction of coordinate z, the holding force is decreased because the inertial force is decomposed into a horizontal component and a vertical component. The magnetic actuator is able to slide when the horizontal component of the inertia force produced by the vibrating mass m is bigger than the frictional force between the rubber magnet and the iron rail. (2) On the other hand, the holding force of the actuator is increased due to effect of the inertia force of the vibrating mass m when the mass m moves in the opposite direction of coordinate z. In this case, the frictional force between the rubber magnet and the iron rail becomes quite big compared with the horizontal component of the inertia force produced by the vibrating mass m. Therefore, the magnetic actuator is not able to slide.

(3) The frictional force between the rubber magnet and the iron plate alternately changes during one period of the vibration as mentioned above. As a result, the magnetic actuator is able to slide only in one direction.

4. Locomotion Characteristics of the Magnetic Actuator with Electrical Cable

An experimental test was conducted using the apparatus shown in Figure 3. The magnetic actuator was set on the iron rail. The mass-spring model was driven in resonance frequency by using a function signal generator and an amplifier. The resonance frequency was 103 Hz. The coefficient of friction between the iron rail and the rubber magnet measured by the experiment was 0.8. The frictional force is calculated by multiplying the attractive force and the coefficient of friction, ignoring the self-weight. This coefficient of friction was fixed during the experiment. The tilt angle α of the vibration body on the moving properties of the actuator was examined.

Figure 4 shows the relationship between the speed at horizontal direction of the magnetic actuator and an input power into the electromagnet when the attractive force of the rubber magnet was set to 8.43 N. The tilt angle α of the vibration body is a parameter in this figure. The attractive force was measured by using a force gauge. When inclination angle α of the mass-spring model was 60 degrees, the speed of the magnetic actuator becomes maximum. The maximum speed was 62.5 mm/s when the input power into the electromagnet was 13 W. The case of the inclination angle 75 degrees was not able to move.

Figure 5 shows the relationship between the speed at horizontal direction of the magnetic actuator and the input power into the electromagnet when the attractive force of the rubber magnet was set to 2.48 N. The tilt angle α of the vibration body was considered as the parameter. The speed of the actuator demonstrates maximum value as inclination angle α of the mass-spring model was 60 degrees.

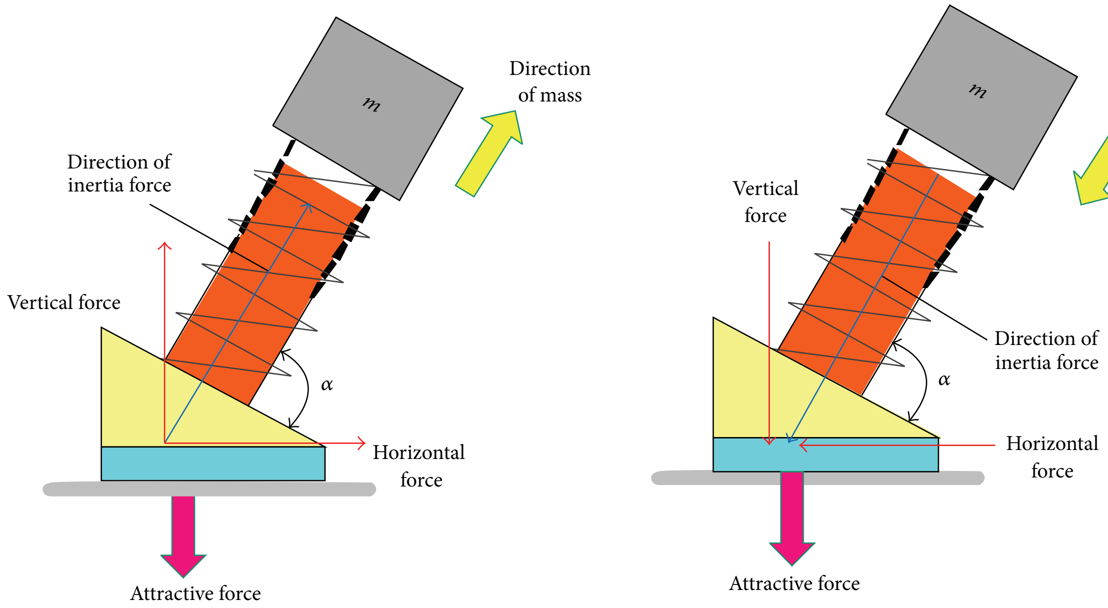

FIGURE 2: Principle of locomotion.

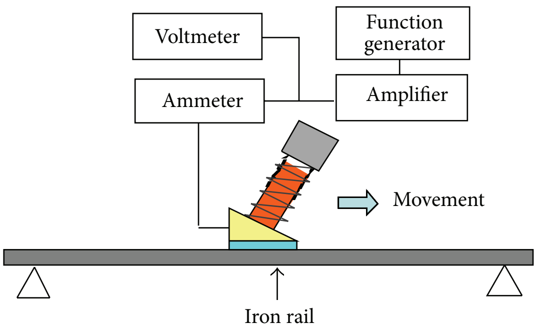

FIGURE 3: Experimental apparatus.

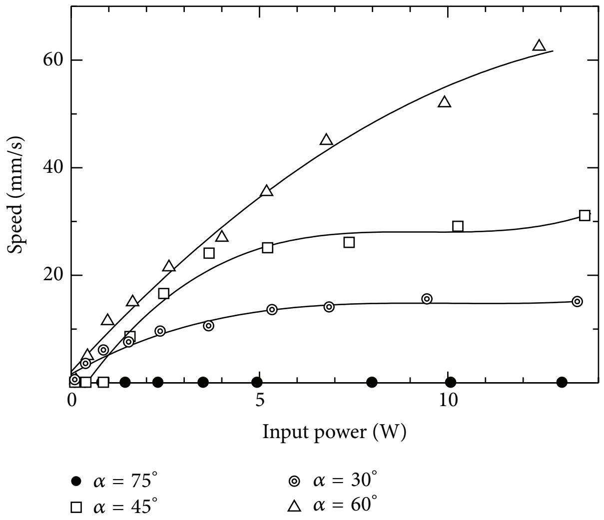

FIGURE 4: Relationship between input power and speed when the attractive force was set to 8.43 N.

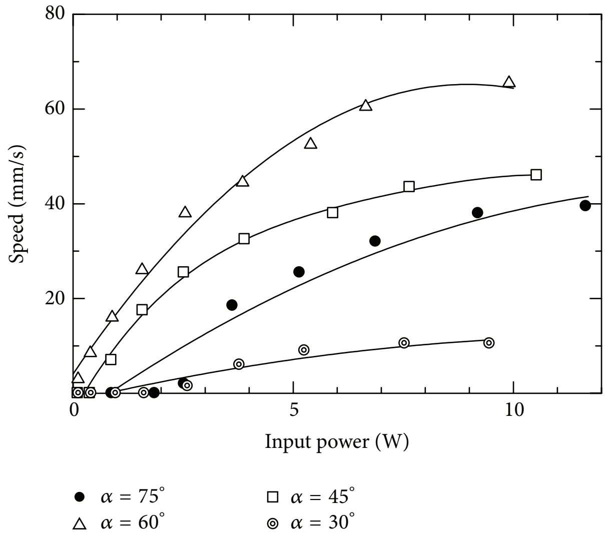

FIGURE 5: Relationship between input power and speed when the attractive force was set to 2.48 N.

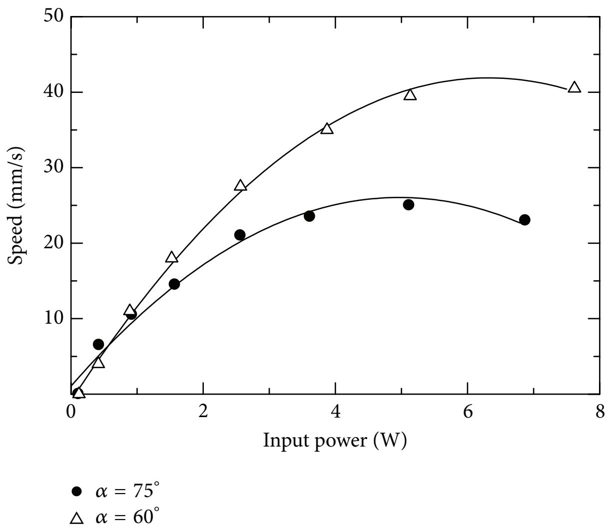

FIGURE 6: Relationship between input power and speed when the attractive force was set to 0.65 N.

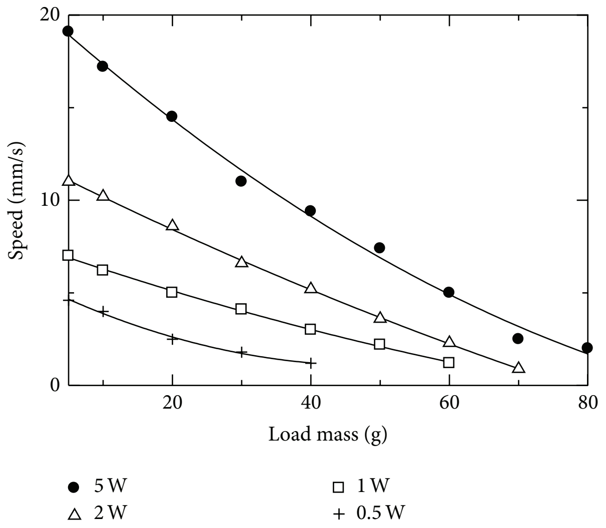

FIGURE 8: Relationship between load mass and speed.

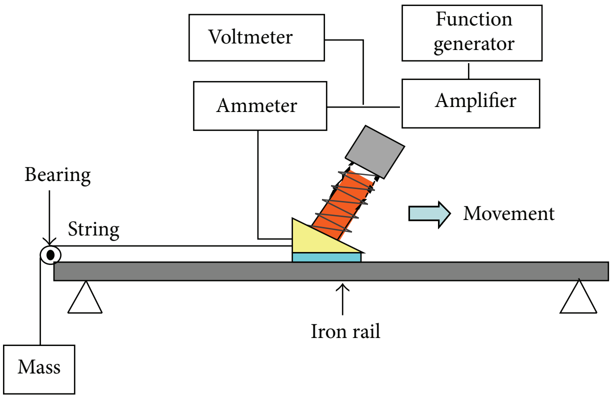

FIGURE 7: Measurement of pulling force.

Figure 6 shows the relationship between the speed at horizontal direction of the magnetic actuator and an input power into the electromagnet when the attractive force of the rubber magnet was set to 0.65 N. The measurement was impossible because the magnetic actuator falls down in the case of the inclination angles 30 and 45 degrees.

Based on these results, the optimal inclination angle α of the mass-spring model was 60 degrees. In the following, the inclination angle α of the mass-spring model was set to 60 degrees. In addition, a moderate attractive force is required so that this actuator moves.

Next, the pulling properties of the magnetic actuator were examined using an experimental apparatus as shown in Figure 7. The load mass was set not to be included in the self-weight of the actuator as shown in this figure.

Figure 8 shows the relationship between the pulling speed of the magnetic actuator and the load mass when the attractive force of the rubber magnet was set to 8.43 N. The input current into the electromagnet was considered as the parameter. The magnetic actuator is able to move 7.4 mm/s pulling load mass of 50 g. When this rubber magnet was used, the magnetic actuator is not able to pull the mass more than 80 g. The rubber magnet slips, and the actuator is not able to move even if input power into the electromagnet was increased.

Figure 9 shows the relationship between the efficiency and the load mass when the input current into the electromagnet was changed. The maximum efficiency of the actuator was about 0.12%. The improvement of the magnetic circuit is necessary to improve efficiency.

5. Magnetic Actuator of Cable-Free Type

Figure 10 shows our proposed cable-free actuator capable of movement on two iron rails. It consists of the magnetic actuator, four NdFeB permanent magnets attached at the triangle frame, and two iron rails. The coefficient of friction between the iron rail and the NdFeB permanent magnet was 0.2. The permanent magnet is cylindrical NdFeB and is magnetized in the axial direction. This is 5 mm in diameter, and height is 2 mm. When four NdFeB permanent magnets were used, the attractive force was 16 N. The input power was supplied to two iron rails using the function generator and the amplifier. While the magnetic actuator moves, the permanent magnet always contacts with the iron rail. The electric current supplied to two rails is supplied to the electromagnet through two permanent magnets. The resistance per unit of length at the iron rail is 0.08 Ω.

Figure 11 shows the relationship between the tilt angle β of the iron rail with the horizontal plane and the speed of the actuator. At this time, the input power into electromagnet was 1.2 W. In measurement, the tilt angle β was varied from -90° (straight downward) to 90° (straight upward) as shown in Figure 12. The moving speed of the horizontal plane is the same as that of a slide-on-ceiling. In this magnetic actuator, the slide-on-ceiling and the wall-climbing are possible.

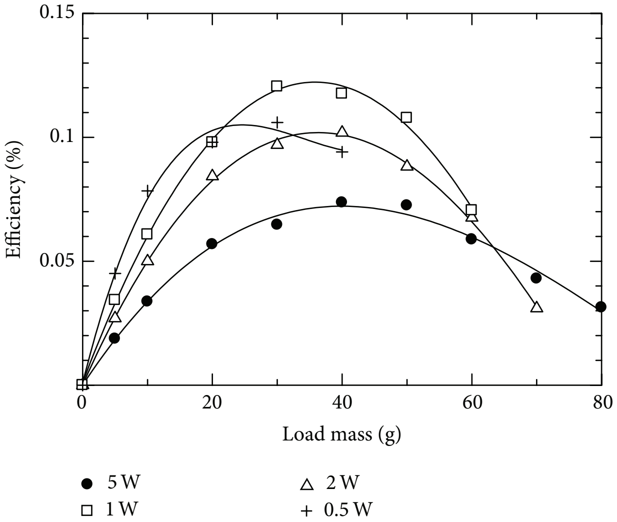

FIGURE 9: Relationship between load mass and efficiency.

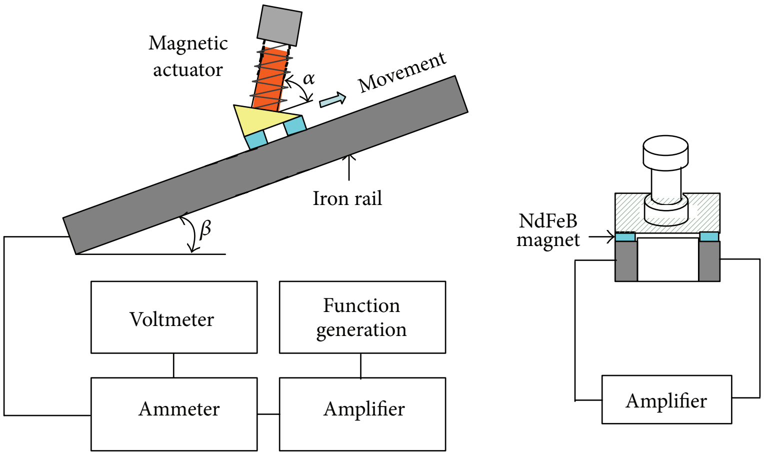

FIGURE 10: Experimental apparatus for cable-free model.

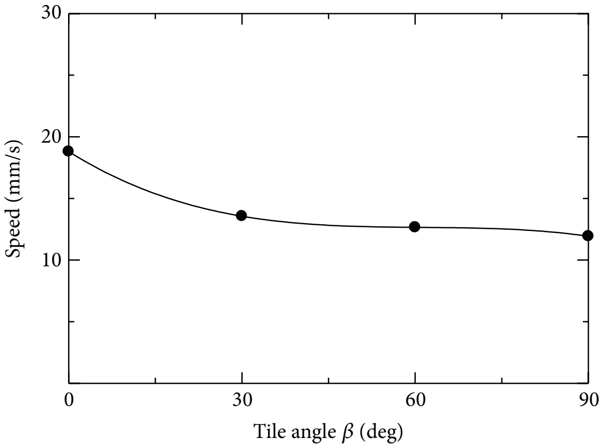

FIGURE 11: Relationship between tile angle β of the iron rail and speed.

6. Conclusion

A new type of a magnetic actuator capable of movement by using an inertia force has been proposed and tested. Based on the measurement results obtained for the cable type model, an optimal leaning angle α of the mass-spring model was 60 degrees. Experimental result shows that this magnetic actuator is able to pull load mass of 80 g. However, the maximum efficiency of the actuator was about 0.12%.

Next, we considered a method of a cable-free movement by using two iron rails and four NdFeB permanent magnets. The magnetic actuator is able to move stably a ceiling plane and a wall plane.

In future, theoretical analysis including a coefficient of friction and improvement of the efficiency by the improvement of the magnetic circuit are necessary. Future research will be directed toward these goals.

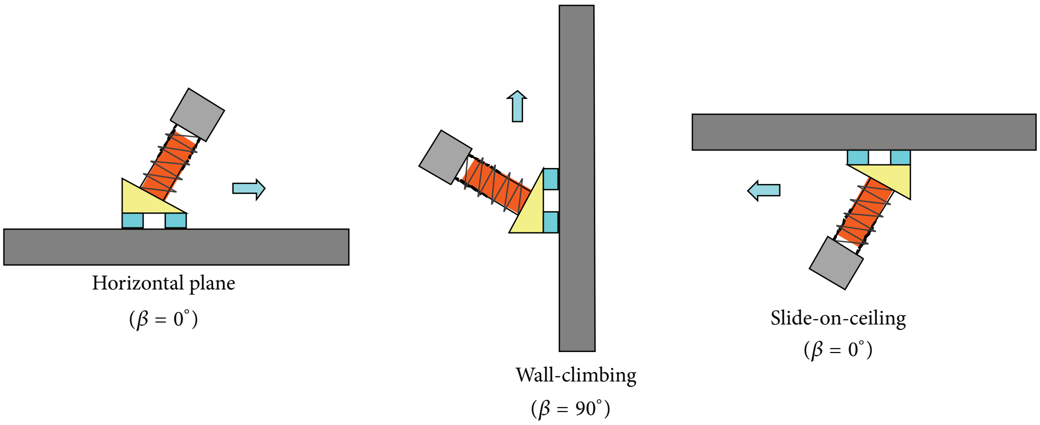

Figure 12: The magnetic actuator moving on iron rail.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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