New Linear Oscillatory Actuator Using DC Motor

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Keywords: linear oscillatory actuator, dynamic characteristics, DC motor, resonance, 3-D finite element method

This paper proposes a new structured linear oscillatory actuator that can convert the rotation into linear actuation. Fig. 1 shows the basic construction of the linear actuator. It mainly consists of a DC motor, two magnets with yokes, resonance springs, shaft, and bearings. A couple of multi-poles permanent magnets of a rotor and an armature are opposite together with an initial gap of 1.6 mm. The rotor is directly connected to the shaft of a DC motor, and the armature is connected to the resonance spring.

The operating principle of this actuator is that the armature linearly moves in direction of z-axis as the attractive or repulsive force acts on the armature according to the rotation of the rotor. Because the armature is restricted to linear motion by the sliding guide, it reciprocates twice while the rotor travels around when you use a couple of four poles permanent magnets as shown in Fig. 2. Frequency and amplitude of this actuator can be arbitrary controlled by changing the gap, resonance spring constant, and number of poles of permanent magnets.

Fig. 3 shows the measured thrust characteristics compared with the calculated ones by 3-D finite element analysis. As it can be seen, both results are in good agreement.

Fig. 4 shows the measured amplitude and current when the frequency of this actuator is varied from 190 to 225 Hz by changing the rotation speed of the motor. From this figure, it is found that the amplitude (peak to peak) of the actuator greatly increases and becomes more than 1.8 mm when this actuator is operated at near the resonant frequency.

In this study a model with a couple of six poles magnets is also investigated. Theoretically, the operating frequency is 1.5 times as high as that of the model with a couple of four poles magnet. As a result, the amplitude of six poles magnet model becomes 22% compared with that of the four poles magnet model because of the serious decrease of thrust. In order to improve the amplitude, the gap length should be shortened from 1.6 mm to 1.2 mm, obtaining the same maximum thrust as four poles magnet model. Then, the amplitude of this model increases up to 1.0 mm at the frequency of 312 Hz.
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This paper proposes a new structured linear oscillatory actuator that can convert the rotation into linear actuation by the attractive and repulsive forces of two multi-poles permanent magnets, one is connected to the linear motion armature and the other is to a DC motor, respectively. The basic construction and the operating principle of this actuator are described. The effectiveness of this actuator is verified by the measurement.

Keywords: DC motor, linear oscillatory actuator, finite element method

1. Introduction

Generally the linear actuation mechanism for small sized electric and electronic equipments has been accomplished by employing movement conversion gears in conjunction with traditional rotary motor. However, this kind of movement conversion system has typically demonstrated unfavorable characteristics including significant vibration, noise, size constraints, and limitations on operating speed. As a result, alternatives to the rotary and gears model to achieve linear actuation are a topic of great interest. Then, various kinds of linear actuators have been studied(1)–(4). These actuators give a lot of merits; high frequency, low vibration, low power consumption, size, and so on, however, they are costly as compared with the conventional mechanism.

This paper proposes a new structured linear actuator(5) that can convert the rotation into linear actuation by the attractive and repulsive force of a couple of multi-poles permanent magnets which are connected to the armature and DC motor, respectively.

The basic construction and the operating principle of this actuator is described. The thrust of the prototype is measured to compare with the computed results by the 3-D finite element method (FEM). Both results show good agreement. Furthermore, the effectiveness of the actuator is verified through the measurement of dynamic characteristics.

2. Basic Construction and Operating Principle

Fig. 1 shows the basic construction of the new structured linear actuator. It mainly consists of a DC motor, two magnets with yokes, resonance springs, shaft, and bearings. A couple of multi-poles permanent magnets of a rotor and an armature are opposite together with an initial gap of 1.6 mm. The rotor is directly connected to the shaft of a DC motor, and the armature is connected to the resonance spring.

The operating principle of this actuator is that the armature linearly moves in direction of z-axis as the attractive or repulsive force acts on the armature according to the rotation of the rotor. Because the armature is restricted to linear motion by the sliding guide, it reciprocates twice while the rotor travels around when you use a couple of four poles permanent...
magnets (NdFeB $Br = 1.4$ T) as shown in Fig. 2. Frequency and amplitude of this actuator can be arbitrary controlled by changing the gap, resonance spring constant, and number of poles of permanent magnets.

3. Thrust Calculation

Fig. 3 shows the computed thrust and torque with the gap of 1.6 mm against the rotation angle employing 3-D FEM. It is found that the armature reciprocates twice while the rotor travels around. The waveforms of the thrust and torque are shifted with 45 degree each other. In actual operation, the gap is varied caused by the thrust (attractive and repulsive force) and spring force according to the rotation angle of the rotor.

Fig. 4 shows the peak value of the thrust and the torque when the gap is varied from 1 to 2 mm in steps of 0.2 mm. As shown, the thrust nonlinearly drops as the increase of gap length. Fig. 5 shows the comparison between the computed and measured maximum thrust characteristics. As can be seen, both results are in good agreement. Fig. 6 shows the prototype actuator used in this study. The approximation functions of the thrust and the torque are expressed in equations (1) and (2).

$$F = 7.01x^{-1.61}$$  
$$T = 12.59x^{-1.40}$$  

Where $F$ is the thrust, $T$ is the torque, and $x$ is the gap length.

4. Dynamic Characteristics

This armature has the mass of 11.5 g and the spring constant of 26.3 N/mm so that it is operated at the resonance frequency of 240 Hz. Fig. 7 shows the characteristics of rotation speed and current versus input voltage of the used DC motor. It is found that the rotation speed linearly increases according to the increase of input voltage, and is operated at the frequency range from about 190 to 370 Hz when the input voltage is varied from 0.9 to 1.8 V.

Fig. 8 shows the characteristics of the rotation speed and the current versus input voltage when this actuator is composed of above mentioned DC motor. The rotation speed
gradually increases without the current increase when the input voltage is increased under the voltage of less than 1.1 V. On the other hand, it keeps constant even if great current flows according to the increase of input voltage under the voltage of more than 1.1 V. This is because the amplitude increases as the operating frequency approaches the resonance frequency, and the load to DC motor greatly increases because the minimum gap length becomes too small. As the result, the rotation speed of the motor does not increase even if large input voltage is applied. The rotation speed drops from 7140 to 6730 rpm under the voltage of 1.2 V as compared with DC motor.

Fig. 9 shows the amplitude and current when the frequency of this actuator is varied from 190 to 225 Hz by changing the rotation speed of the motor. From this figure, it is found that the amplitude (peak to peak) of the actuator greatly increases and becomes more than 1.8 mm when this actuator is operated at near the resonant frequency. Then, the input current increases up to 0.6 A.

It is also confirmed that the rotor and armature are opposite together with the different magnetic poles at the minimum gap and are opposite with the same magnetic poles at the maximum gap using a high-speed camera.

5. Effect of Number of Magnet Poles on Speed

In order to operate this actuator at higher frequency, number of poles of magnets should be increased. In this study a model with a couple of six poles magnets is investigated as shown in Fig. 10. Theoretically, the operating frequency is 1.5 times as high as that of the model with a couple of four poles magnet model mentioned above. Fig. 11 shows the comparison of thrust characteristics between four poles and six poles magnet model with the gap length of 1.6 mm. It is found that the armature reciprocates three times while the rotor travels around. Figs. 12 and 13 show the comparison of peak values of the thrust and torque between four poles and six poles magnet models when the gap length is changed from 1 to 2 mm in steps of 0.2 mm. The peak values of both thrust and torque are greatly decreased. This is because the magnitude of magnetization of the magnet becomes weak at the boundary part of magnetization.

Nextly, dynamic characteristics are evaluated by the measurement of the prototype with six poles magnet. This actuator has the mass of 11.5 g and the spring constant of 58.8 N/mm so that it is operated at the resonance frequency of 360 Hz. The initial gap length is the same as four poles model.

Fig. 14 shows the comparison of characteristics of the amplitude and the current versus operating frequency between four poles and six poles magnet models. In both models, the amplitude and current rapidly increase when the operating frequency approaches resonance frequency. The six poles magnet model has the maximum amplitude of 0.4 mm when the operating frequency is 311 Hz in spite of large current
of 1.0 A. The amplitude of six poles magnet model becomes 22% compared with that of the four poles magnet model. This is because the peak value of the thrust at the gap of 1.6 mm drops from 3.39 to 1.87 N.

In order to improve the amplitude, the gap length should be decreased from 1.6 mm to 1.2 mm to obtain the same maximum thrust as four poles magnet model. Fig. 15 shows the comparison of characteristics of the amplitude and the current versus operating frequency of six poles magnet models with the initial gap of 1.2 mm and 1.6 mm. As shown, the amplitude increases up to 2.5 times by the decrease of the gap length of 0.4 mm. Thus, the maximum amplitude of this model becomes 1.0 mm with the current of 1.0 A when it is operated at the frequency of 312 Hz. However, this amplitude is 55% as compared with that of four poles magnet model. It is thought that the average thrust of this model is 3.9 N while that of four poles model is 4.7 N.

6. Conclusions

This paper presented the new structured linear oscillatory actuator that can convert the rotation into linear actuation by the attractive and repulsive forces of two multi-pole permanent magnets, one is connected to the linear motion armature and the other is to a DC motor, respectively. The effectiveness of this actuator was verified by the measurement.

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References


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