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New Electro-Magnetic Actuator for Active Vibration Isolators

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Vibration limits the performance of the ultra-precision machine in numerous applications, thus the need to dissipate the effect of vibration has become crucial. This paper proposes a new design for a voice coil motor (VCM) actuator that can be used in the vibration isolators to dissipate the fluctuation in the broadband frequency. The VCM was designed to produce a proper force for the isolation of fluctuation. The magnetic flux modeling and force calculation were conducted. Obtained simulation results using finite element method were verified by comparison with experimental results. Comparing these two results, we demonstrated that proposed VCM actuator was constructed properly.

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NOMENCLATURE

N = coil turn numbers
B = magnetic flux density (T)
i = effective current (A)
l = effective length of coil in magnetic field (m)
R = resistance
L = inductance of coil
F_a = force in actuator
d_a = damping coefficient of actuator
k_a = stiffness of actuator
k_t = electric damping coefficient

1. Introduction

During the last decade, there has been an increasing interest in the development of precision measuring equipments such as scanning electron microscopy (SEM), scaning probe microscope (SPM), atomic force microscope (AFM), etc.,. Precision measuring equipments are negatively influenced by acoustic noise and direct mechanical fluctuation that can cause poor performance.[1,5] Thus, the dissipation of such fluctuation is a essential task for accurate and precision measurement. To solve fluctuation isolation problem, an isolator using the spring and damper have been proposed. Such isolator works as a low pass filter to dissipate vibration transmitting to the precision measuring equipments. A passive isolator was widely used to isolate these fluctuations from base of precision machine. However, the conventional passive isolator is good for vibration isolation at high frequencies. Recently, a hybrid active passive isolator which use an active isolator in combination with a passive isolator have been proposed. This isolator can actively control the fundamental mounted resonance without deterioration in the good high frequency attenuation performance.[2-4,6-9]

To control active vibrations at nanometer or micron scale resolution, various actuators such as electromagnetic motor, electrical linear motor, piezoelectric actuators, pneumatic springs, mechanical mechanism are applied on the isolator systems. Among these, with the high stiffness and accuracy, piezoelectric actuators are often used to obtain the good attenuation control and good positioning accuracy. On the other hand, because the stiffness of piezoelectric actuator is significantly higher than that of spring, the isolation efficiency is decreased when springs and actuators are located in parallel. In this paper, a new design for a voice coil motor (VCM) on active vibration isolator that undertakes to manage the fluctuation in the broadband frequency is proposed. The

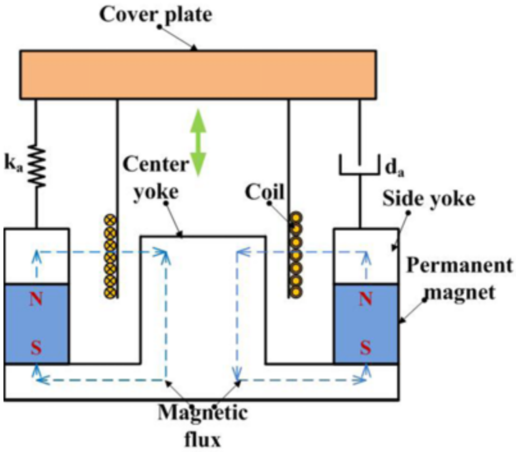

Fig. 1 Proposed VCM actuator

actuation force of the VCM was calculated for the vibration isolator. The magnetic flux modeling and magnetic force calculation were conducted. Obtained results were verified by comparison with electromagnetic finite element method simulation results.

2. Theoretical Analysis of the Voice Coil Motor

The voice coil motor consists of a permanent magnet, a coil assembly, a yoke which gives the magnetic flux path and a moving plate. The generated actuation force is governed by the Lorentz force. Also, the direction of the actuation force is determined by the Fleming's left hand rule. Moreover, its simple structure makes it easy to maintain. It can provide superior acceleration and deceleration via the magnetic force. The schematic diagram of VCM actuator is represented in Fig. 1.

The electromechanical conversion mechanism of the VCM is governed by Lorentz Force Principle. When a conductor of length l carrying current i is placed in magnetic field of uniform flux density B, the conductor experiences a force given by.[10]

$$F = NBil \tag{1}$$

Where N is the turn number of the coil, B is the magnetic field density (T), i is the effective coil current (A), and l is the effective coil legnth (m).

The coil current flowing in the VCM actuator is governed by equation as below.

$$V = Ri + L\frac{di}{dt} + k_b\dot{x} \tag{2}$$

Where R is a coil resistance, L ($L=N^2/R$) is a coil inductance, and $k_b\dot{x}$ is an electro-motive force generating by the moving part.

The equation of motion for moving part is given as the follows.

$$m_a\ddot{x} + d_a\dot{x} + k_a x = F_a \tag{3}$$

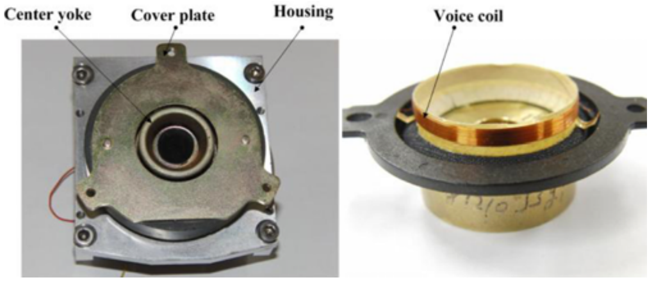

Fig. 2 Model of voice coil motor

Where F_a is the force in actuator, d_a is the damping coefficient of actuator, k_a is the stiffness of actuator.

F_a is the same as force described by Lorentz Force. From Eq. (1) the motion equation for moving part can be written as.

$$m_a\ddot{x} + d_a\dot{x} + k_a x = F_a = NBil = k_t \tag{4}$$

Where the electric damping coefficient is given by

$$k_t = NBl = k_b$$

By using the Laplace transformations for Eqs. (2) and (4), it can be written as

$$m_a S^2 X(s) + d_a sX(s) + k_a X(s) = NBlI(s) \tag{5}$$

$$LsI(s) + RI(s) = V(s) - k_b sX(s) \tag{6}$$

Taking values of $I(s)$ from Eq. (5) and then inserting it to Eq. (6) and rearrange the left side. The final transfer function of the whole system is derived as follows:

$$\frac{X(s)}{V(s)} = \frac{NBl}{m_a Ls^3 + (d_a L + m_a)s^2 + (k_a d_a + d_a R + k_b NBl)s + k_a R} \tag{7}$$

Eq. (7) shows that it changes the numerator and denominator of the close-loop tranfer function to use Eq. (2) as the feedback signal, so it can control the resonance frequency and the transmissibility under the resonance frequency using this signal. In addition, the dynamic characteristic coefficient of the eletric-magnetic actuator ($\tau = \mathrm{L/R}$) affects the attenuation performance, and then it will induce the change of magnitude and phase of the control force under the excitation frequency.

The photograph of the fabricated VCM is presented in Fig. 2. As the current is applied in the coil under magnetic field, the electro-magnetic actuation is created in the upward/downward directions. This force is proportional to the product of the coil current, the magnetic flux intensity, and the effective coil length. Fig. 3 shows flux direction of proposed VCM. The magnetic flux direction is always directed at the center of VCM.

The iron yoke of actuator is attached to a permanent magnet. The characteristics of the VCM actuator depend significantly upon the structure of yoke, thus selecting proper yoke structure is very important. The most important parameter of the yoke is the material which used in its construction. The used material must have a high saturated

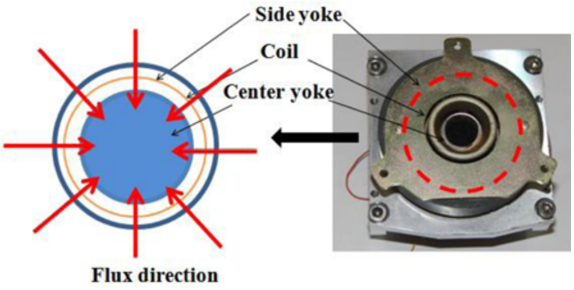

Fig. 3 Magnetic flux direction

Table 1 Summary of the parameters used in simulation

Variables	Input value
Magnetic flux of permanent magnet (*B*)	0.14 (T)
Coercive force of permanent magnet	400,000 (A/m)
Turns of coil	40
Applied current	0.5 (A)
Effective area of current (conducting area)	300

Table 2 Simulation results

Simulation	Results
Generated electronic force	6.4 (N)
Magnetic flux density in the air gap	0.14 (T)

magnetic flux density to generate the high eletrical force and improve the performance of VCM. The material and specification of proposed VCM is listed in Table 1. The relationship between the magnetic permeability and magnetic flux density is given by

$$B = \mu H \tag{8}$$

In addition, the piezo-ceramic with high capacitance was used to make a good performance. The capacitance represents the ability of the piezo sensor to store electricity. The acceleration sensor can generate a high voltage at the same pressure when the piezo sensor has a larger capacitance.

3. Simulation and Experiment Results

The model of the proposed VCM is simulated via the finite element method (FEM). Fig. 4 shows the FEM analysis result. The magnetic force is produced in the upward as shown in Fig. 4a. The magnetic flux density is 0.14 T as shown in Fig. 4b. Fig. 4c shows the current flow in coil of the VCM. The simulation results are shown in Table 2.

The proposed VCM was analyzed using a frequency response function (FRF) based on the obtained results in Table 2. The natural frequency of VCM actuator is 47 Hz. The phase transition was occurred in this natural frequency. Fig. 5 presents the frequency reponse function of VCM actuator. Then we calculated the transfer function about VCM. The parameters for transfer function are descibed following Table 3. The experimental results and theorerical results are in good agreement. Fig. 6 shows the simulation result using MATLAB.

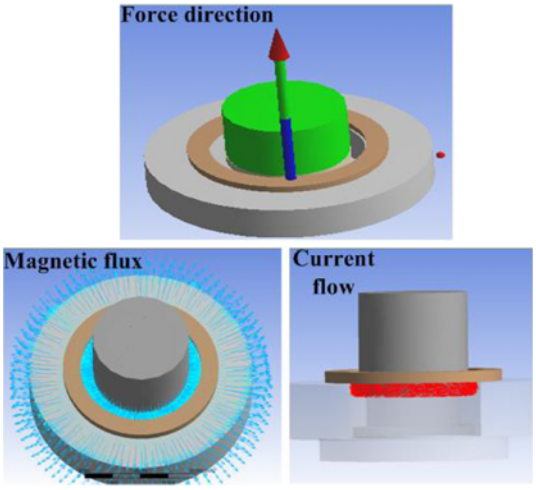

Fig. 4 FEM analysis result

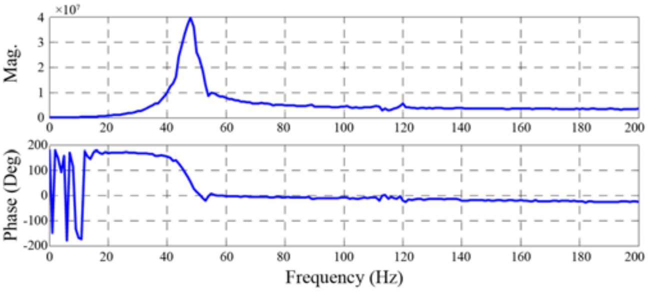

Fig. 5 Frequency response function

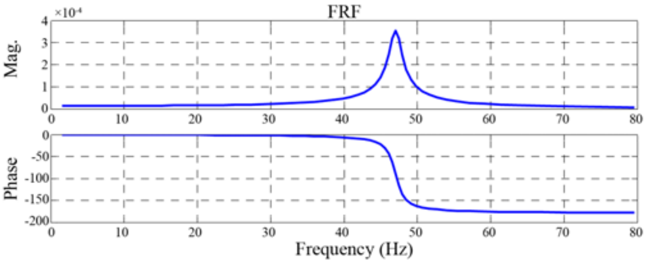

Fig. 6 Simulation results using MATLAB software

Table 3 Parameters for Bode plot

Parameters	Values
m_a	0.04697(kg)
L	3.0843x10^{-7} (H)
d_a	0.5 (kg/s)
R	6.8 (Ù)
k_a	4100 (N/m)
k_b	0.3142 (N/m)

To show the tracking performance of the VCM actuator, we used the sine tracking test. The results are shown in Fig. 7. It can be seen that there is in good agreement between input and output response of actuator. Such response indicates the satisfaction of proposed VCM actuator.

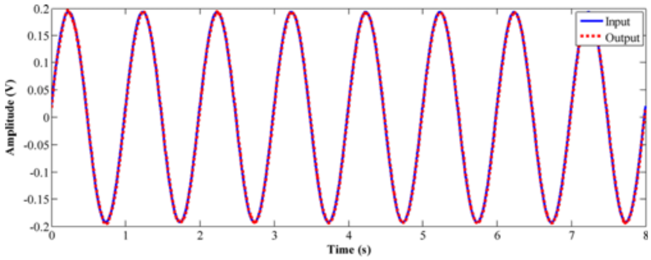

Fig. 7 Sine tracking response of actuator

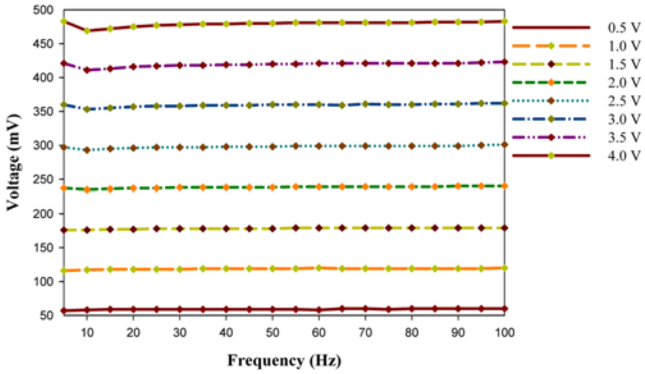

Fig. 8 Output voltages versus frequency

The piezo-ceramic acceleration sensor was investigated. Fig. 8 shows the output voltages versus the frequency. Although the frequency changed, the performance did not change. The output voltages increased because the input voltages increased.

4. Conclusions

In this research, a new electro-magnetic actuator for active isolator system was proposed. The theoretical modeling is obtained by using the Lorentz force equation, the ohm's law and the Newton's 2nd law of motion. The final transfer function between the voltage input and the mechanical velocity is derived. The finite element analysis was performed to ensure the accuracy of the derived theory. The calculated force is in good agreement with the simulated result (6.4N).

We evaluated the VCM actuator's performance with a capacitive sensor. The sine tracking experiments reveals the good tracking performances of the VCM actuator. The measured first resonant frequency (47 Hz) is in good agreement with the simulation result.

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REFERENCES

1. Kim, M. H., Kim, H., and Gweon, D. G., “Design and Optimization of Voice Coil Actuator for Six Degree of Freedom Active Vibration Isolation System using Halbach Magnet Array,” Review of Scientific Instruments, Vol. 83, No. 10, Paper No. 105117, 2012.

2. Banik, R. and Gweon, D. G., “Design and Optimization of Voice Coil Motor for Application in Active Vibration Isolation,” Sensors and Actuators A: Physical, Vol. 137, No. 2, pp. 236-243, 2007.

3. Chen, Y. D., Fuh, C. C., and Tung, P. C., “Application of Voice Coil Motors in Active Dynamic Vibration Absorbers,” IEEE Transactions on Magnetics, Vol. 41, No. 3, pp. 1149-1154, 2005.

4. Flint, E. M., Flannery, P., Evert, M. E., and Anderson, E. H., “Cryocooler Disturbance Reduction with Single and Multiple Axis Active/Passive Vibration Control Systems,” Proc. of SPIE's 7th Annual International Symposium on Smart Structures and Materials, Vol. 3989, pp. 487-498, 2000.

5. Hauge, G. and Campbell, M., “Sensors and Control of a Space-based Six-Axis Vibration Isolation System,” Journal of Sound and Vibration, Vol. 269, No. 3, pp. 913-931, 2004.

6. Mizuno, T., Toumiya, T., and Takasaki, M., “Vibration Isolation System using Negative Stiffness,” JSME International Journal Series C, Vol. 46, No. 3, pp. 807-812, 2003.

7. Huang, X., Elliott, S. J., and Brennan, M. J., “Active Isolation of a Flexible Structure from Base Vibration,” Journal of Sound and Vibration, Vol. 263, No. 2, pp. 357-376, 2003.

8. Kerber, F., Hurlebaus, S., Beadle, B. M., and Stöbener, U., “Control Concepts for an Active Vibration Isolation System,” Mechanical Systems and Signal Processing, Vol. 21, No. 8, pp. 3042-3059, 2007.

9. Kim, Y., Kim, S., and Park, K., “Magnetic Force Driven Six Degree-of-Freedom Active Vibration Isolation System using a Phase Compensated Velocity Sensor,” Review of Scientific Instruments, Vol. 80, No. 4, Paper No. 045108, 2009.

10. Chai, H. D., “Electromechanical Motion Devices,” Prentice Hall, Chap. 5, 1998.