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Design and Analysis of Halbach VCM actuator for 6-DOF active vibration isolation system

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Abstract
In recent years, as nano-precision technologies develop at a fast-growing rate, the ultra-precision measuring instrument requires having high-speed, high-precision and accurate performance. Generally, the bench-top type of 6-DOF active vibration isolation system(AVIS) has been widely used in ultra-precision measuring areas. Although there have been many researches in various AVIS technologies, obtaining a high force constant with compact size is still challenging. In this paper, a novel 6-DOF AVIS based on a Halbach magnet array VCM actuator that have high force constant is proposed. The proposed AVIS based on a Halbach magnet array VCM actuator is optimally designed to provide high power. High power of proposed VCM actuator was verified by comparison with general VCM actuator. A novel AVIS with high power actuator was manufactured with optimally designed parameters, and its performance was evaluated.

V Voice coil motor, active vibration isolation system, vibration isolation

1. Introduction

In recent years, as nano-precision technologies develop at a fast-growing rate, the ultra-precision measuring instrument requires having high-speed, highest precise and accurate performance. Currently, there are many high-precision measuring instruments which have nano-level precision, and these precision measuring instruments are widely used for biotechnology, chemistry, medical science and industiral semi-conductor inspection field [1]. The active vibration isolation systems typically reduce the vibration transmitted to the ultra-precision mechanical system providing managed stiffness and damping. There are many types of active vibration isolation systems in various fields. Especially, in nano-precision measuring instrument field such as atomic force microscope(AFM), scanning probe microscope(SPM), the requirement for isolating of ground vibration has always been of great interest among the researcher. Generally, the bench-top type of 6-DOF active vibration isolation system(AVIS) has been widely used in ultra-precision measuring areas. Because the greater part of AVIS have very similar structures and working principle, the recent researches of AVIS are about control algorithms. Although there have been many researches in various AVIS technologies, obtaining a high force constant with compact size is still challenging. In this paper, a novel 6-DOF AVIS based on a Halbach magnet array VCM actuator that can generate high force constant is proposed. The proposed AVIS based on a Halbach magnet array VCM actuator is optimally designed to provide high power [2]. Figure 1 presents a conceptual design of proposed AVIS. High power of proposed VCM actuator was verified by comparison with general VCM actuator. A novel AVIS with high power actuator was manufactured with optimally designed parameters, and its performance was evaluated.

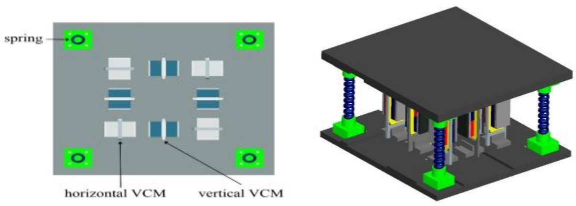


Figure 1. Conceptual design of AVIS

2. Modelling of Halbach VCM actuator

Figure 2. shows the proposed Halbach VCM actuator for the novel 6-DOF AVIS. The Halbach VCM actuator consists of six magnet blocks and a steel yoke. The magnetic flux density of the Halbach magnet array at the air gap can be calculated by applying the charge model and image method.

$$B_{z(block\ 1)}(x,y,z) = +\frac{\mu_0 M_0}{4\pi}\iint_{\substack{magnet\\surface}} \left.\frac{z-z'}{\left(\sqrt{(x-x')^2+(y-y')^2+(z-z')^2}\right)^3}\right|_{(z'=z_2)} dx'dy' - \frac{\mu_0 M_0}{4\pi}\iint_{\substack{magnet\\surface}} \left.\frac{z-z'}{\left(\sqrt{(x-x')^2+(y-y')^2+(z-z')^2}\right)^3}\right|_{(z'=z_1)} dx'dy' \tag{1}$$

Equation (1) provides the z-component field at any point outside the magnet block①. There are six magnet blocks, and the z-component field of the other magnet blocks can be calculated in the same way. The whole field solution is obtained using the superposition of the solutions for the individual magnets. The results of the 3D analytical calculation and 3D FEM simulation are shown in figure 3. The mean errors in the results differ by less than 5 %.

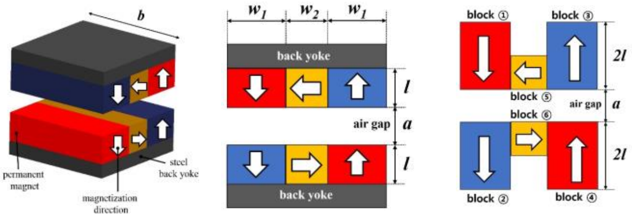
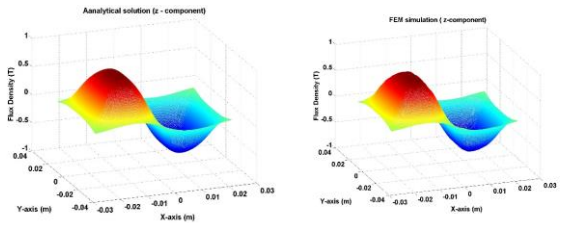


Figure 2. Halbach magnet array of VCM actuator



(a) 3D z-direction flux density from analytical solution

(b) 3D z-direction flux density from FEM simulation

Figure 3. 3D magnetic flux density results

3. Comparison of general NS magnet array

Figure 4 shows a typical NS magnet array for a VCM actuator. The dimensions and coordinates are shown in Figs. 3(b) and (c). There are four magnet blocks, which are sandwiched between equipotential surfaces formed by the steel yokes to produce a high and uniform magnetic flux density at the air gap. The magnetic flux density of the Halbach magnet array at the air gap can be calculated by applying the charge model and image method in the same way as described previously.

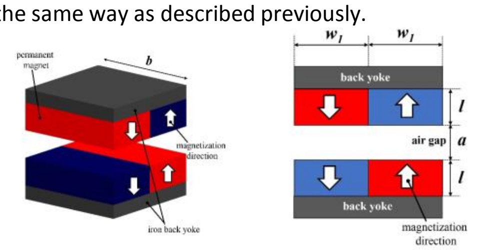
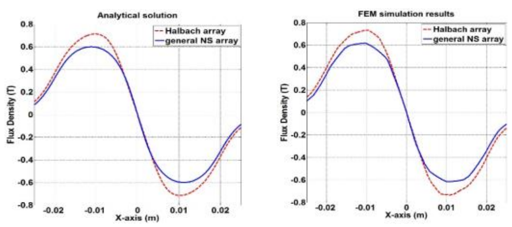


Figure 4. General NS magnet array

For comparison, the field component Bz is presented along the x-axis (y = 0 mm, z = 0 mm). The two-dimensional (2D) plots for the analytic solutions and the FEM simulations are highly similar. Although the NS magnet array and the Halbach magnet array have the same volume, the Halbach magnet array exhibits flux density values approximately 10 % higher, as shown in both plots. The stronger flux density at the air gap means that the VCM actuator generates more force for the same current conditions. Therefore, a VCM actuator with a Halbach magnet array functions more efficiently in a 6-DOF AVIS than one with a typical NS magnet array.



(a) 2D analytical solution (b) 2D FEM simulation

Figure 5. Two-dimensional (2D) x-direction plot for comparison

4. Experiment

Eight actuators and six accelerometers for attenuating upper-plate oscillations were used. Figure 5 shows the experimental setup. For velocity feedback control, acceleration was integrated to velocity [3]. The attenuation performance was examined for payloads of 60 kg. When feedback control was on, the manufactured AVIS shows much improved isolation performance. Many instruments that need AVIS must meet vibration isolation criteria for safety reasons. The transmissibility was determined by sinusoidal excitation of the lower plate and measurement of the velocity of the upper plate.

Figure 6. shows the transmissibilities of the manufactured AVIS for the 60kg payload considered. From low-frequency over 4Hz, appeared vibration isolation performance of 60dB.

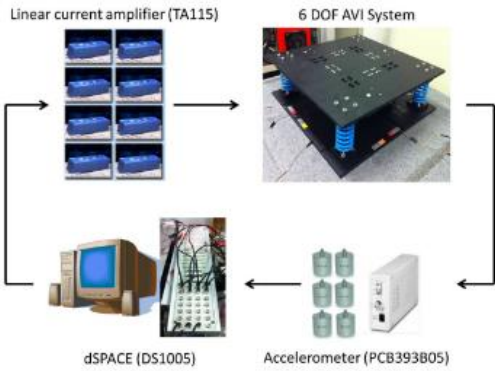


Figure 5. Experimental setup

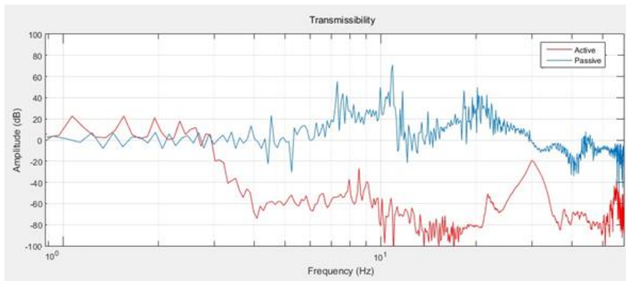


Figure 6. Attenuation of upper plate vibration at 60-kg payload

5. Conclusion

In this paper, a novel VCM actuator for an AVIS that can generate high actuating force was proposed. To maximize the force constant, the proposed VCM actuator uses a Halbach magnet array. The results of the experiments show that effective attenuation of 6-DOF vibration of the upper plate was achieved. The proposed VCM actuator using a Halbach magnet array can increase the energy efficiency of a 6-DOF AVIS.

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