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Design of a novel fine stage actuated by voice coil motor

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Abstract
Fine stage has been researched for many years and developed in diverse forms. In this paper, design of a novel fine stage actuated by voice coil motors is presented. The fine stage uses voice coil motors as actuators. Total eight voice coil motors are used for actuating six-degree-of-freedom motions: four of them for in-plane motions and four of them for out-of-plane motions. Guiding mechanisms are flexures which support mass of the mover of the fine stage.
The force equation of the voice coil motor can be expressed with current, intensity of magnetic field, and etc. The design variables in the force equation were categorized. After mathematical modelling of the equations, design variables were optimized by mathematical programming. After design variables were derived by the optimization, final 3D geometrical model of the fine stage was virtually made and assembled by computer program. Modal analysis was simulated for finding modal frequencies.

Keywords : nano-positioning, fine stage, voice coil motor, optimal design

1. Introduction

Fine stages have been developed in diverse forms. They have played important role in carrying objects with nano-scale in various industrial fields such as semi-conductor inspection systems, microscopes, etc. In this paper, design of a novel fine stage is presented. The novel fine stage uses rotational symmetric leaf spring type hinge for compensating mass of the mover of the stage. The hinge type flexure has advantage that it can be easily designed with six-degree-of-freedom. The novelty of the structure is that the voice coil motors (VCMs) are located symmetrically, which simplifies actuator kinematics. The simplicity makes mathematical decoupling of six-degree-of-freedom forces more accurate. Furthermore, the height of the horizontal VCMs which generates horizontal forces was chosen in order to correspond to pivoting point of the flexure. This can greatly reduce parasitic motions including rotational motion.

2. Specifications of fine stage

Settling time and maximum stroke are key specifications for the stage. Assuming closed-loop control system of the stage mostly acts like second order system, necessary control bandwidth can be found below [1].

$$\omega_n = \frac{-\ln(\%)}{\zeta \times t_s} \qquad (1)$$

ζ is damping ratio, t_s is settling time that the stage has to satisfy and % is error percentage of target distance. Once the control bandwidth is decided, the stiffness of the flexure can be determined. Forces that voice coil motors should generate are decided by the stiffness of the flexure and maximum stroke with Hooke's law.

3. Mathematical modelling of force of VCM

Since the force of the VCM is important factor to decide the performance of the stage, it should be optimized. In order to optimize the force, it has to be mathematically expressed.

3.1. Lorentz force equation

The VCM is actuated by the Lorentz force. The Lorentz force is mathematically expressed as equation (2).

$$\boldsymbol{F} = \iiint_V \boldsymbol{J} \times \boldsymbol{B}\, dv \qquad (2)$$

$\boldsymbol{F}$ is a three dimensional Lorentz force vector, $\boldsymbol{J}$ is a current density vector of a coil, $\boldsymbol{B}$ is a magnetic field vector applied on infinitesimal volume of the coil and V is entire volume of the coil. Structure of the VCM is shown in figure 1.

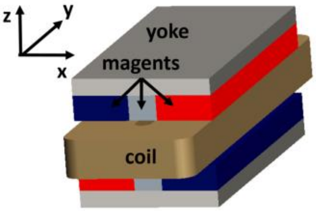


Figure 1. Structure of the VCM

Since the round tip of the coil is not covered by magnet array, volume integral should be calculated over only stretched parts of the coil. Then, the equation (2) changes into surface integral with assumption that the magnetic field distribution does not alter along the stretched part. Since the coil and magnets are symmetric about y-z plane, y and z components of the Lorentz forces are cancelled out, leaving only x component of the Lorentz force. Then the equation can be rewritten as equation (3)

$$F_x = 2\iint_A \left(\frac{I}{A} lB_z \right) dxdz \qquad (3)$$

A is cross sectional area of one side of the wire bundle of the coil on x-z plane, I is current flowing through the area and l is an effective length of the coil which is covered by magnet array. The I is the number of coil turn(n) times current(i) which flows in a single coil wire. The number of coil turn can be expressed with geometrical variables of the coil as written in equation (4)

$$n=\left(\frac{w_c}{d_c}-\frac{1}{2}\right)\left[\frac{2}{\sqrt{3}}\left(\frac{t_c}{d_c}-1\right)+1\right] \qquad (4)$$

w_c, d_c, and t_c are width of coil, diameter of coil wire, and thickness of coil, respectively. Therefore, the final Lorentz force equation can be

$$F_x=2il\left(\frac{w_c}{d_c}-\frac{1}{2}\right)\left[\frac{2}{\sqrt{3}}\left(\frac{t_c}{d_c}-1\right)+1\right]\frac{\iint_A B_z dxdz}{A} \qquad (5)$$

The VCM force is expressed with current, geometrical variables of the coil, and average value of z component of the magnetic field applied on cross sectional area of the coil.

In order for mathematical modeling of the magnetic field intensity on the area, analytic expression of magnetic field based on Biot-Savart's law is used. [2]

3.2. Determination of maximum continuous current

The Lorentz force is proportional to the current. However, if the current flows too much, it can physically damage the coil because heat generated from the coil can melt enamel covering coil wire. Therefore, the heat generation should be mathematically investigated in order for determining allowable maximum continuous current.

In order to determinate the current, heat generated from the coil and heat emitted from the coil should be calculated. The heat generated from the coil can be easily calculated as i^2R where R is electrical resistance of the coil. R is depending on the total length of the coil wire and area of the coil wire.

In order for finding the heat emitted from the coil, the coil is assumed to be cuboid whose every surface is encountering the air, which means the heat is assumed to be dissipated by air convection. Temperature difference is needed for calculating the heat transferred by convection. It is chosen 100 degree because room temperature is 20 Celsius degree and allowable maximum temperature of the coil is 120 Celsius degree. Final equation is

$$i^2\,\frac{4l_c}{{d_c}^2\pi}\le 2h\left(A_{side}+A_{front}+A_{top}\right)\Delta T \qquad (5)$$

where l_c is total length of the coil wire. A_{side}, A_{top} and A_{front} are surface area of side, top and front. Therefore, determination of maximum continuous current depends on geometrical variables of the coil.

4. Flexure design

In order for designing flexure, rotational symmetric leaf spring type hinge is used. Equation used for the fine stage is written below. [3]

$$\begin{bmatrix}\delta_x\\ \delta_y\\ \delta_z\\ \theta_x\\ \theta_y\\ \theta_z\end{bmatrix}=\begin{bmatrix}c_1&0&0&0&c_3&0\\ 0&c_2&0&-c_4&0&0\\ 0&0&c_5&0&0&0\\ 0&-c_4&0&c_6&0&0\\ c_3&0&0&0&c_7&0\\ 0&0&0&0&0&c_8\end{bmatrix}\begin{bmatrix}F_x\\ F_y\\ F_z\\ M_x\\ M_y\\ M_z\end{bmatrix} \qquad (6)$$

5. Optimization of the VCM

The necessary variables for designing the VCM are listed in table 1. They are categorized as three groups.

Table 1 : Variables of VCM

To be optimized	Magnet width / Magnet thickness / Magnet length / Halbach width / Coil width / Coil thickness / Coil diameter / Maximum continuous current
Dependent	Magnet distance / Coil inner length
Prefixed	Coil inner width / Gap between magnet array and coil / Maximum temperature difference

A cost function that should be minimized is chosen as mass divided by force in order to maximize acceleration. Optimization is conducted by MATLAB (Mathworks, US) with SQP method. The predicted performances are listed in table 2.

Table 2 : Predicted performances

Exterior size	464 x 464 x 74.5 (mm^3)	Capable load	5kg
Dimensions of Vertical VCM	60 x 140 x 69.5 (mm^3)	Force of Vertical VCM	43.8N
Dimensions of Horizontal VCM	58 x 160 x 77 (mm^3)	Force of Horizontal VCM	99.7N

Figure 2 shows 3D geometrical model constructed with optimized variables. Finite element method were performed for identifying mode frequencies. Result is shown in figure 3.

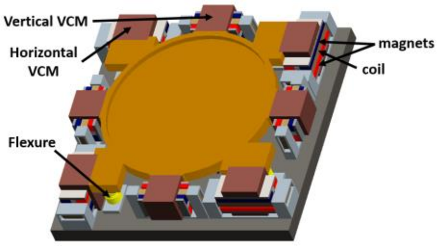
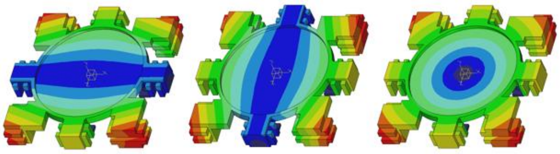


Figure 2. 3D geometrical modelling of the fine stage



1st mode : 86.4Hz 2nd mode : 86.8Hz 3rd mode : 102.4Hz

Figure 3. Modal analysis result of the fine stage

6. Conclusion and future work

The design of the fine stage is studied and optimization were conducted. For optimization, mathematical modelling and heat transfer equation were found. The 3D geometrical model was constructed with optimized variables. Modal analysis was performed for determining control bandwidth. Manufacturing of the fine stage with the optimized geometrical dimensions will be proceeded for future work.

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