Design of a VCM actuator for dual servo system

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Abstract: In this study, Dual servo mechanism with VCM(Voice Coil Motor) and PZT is designed for a high precision force and position control. We designed the VCM actuator and dual servo mechanism with leaf spring. VCM actuators, with their high linearity, simple structure, low weight, and high efficiency, are increasingly being used in micro-positioning applications. There are many kinds of VCM with a structure. VCM actuators are divided into two types by moving parts. One is moving magnet type and the other moving coil type. We described the properties of these two types of VCM. Design parameters of VCM are defined through the FEM simulation analysis of magnetic field and dynamic model of dual servo mechanism. These researches help to for decreasing loss in the air gap of VCM. We present dual servo mechanism is effective mechanism for a force control in high precision, properties of designed VCM.

Keywords: VCM, Dual servo control, Nanoindentation, PQ method, PZT.

1. INTRODUCTION

A growing number of motion control application require sub-micron positioning accuracy. The high precision position control technique is used in many fields of industry. There are many kinds of a system structure for getting the high precision and dynamic performance such as high bandwidth, high robustness, and fast response.

It is difficult to satisfy high precision and large motion range simultaneously. Dual servo mechanism has been used for such cases. It is constructed with fine motion mechanism and coarse one. So the dual servo system contains two actuators that act in serial or parallel. One is the fine actuator that covers the short moving-range of sub-micrometer accuracy and high bandwidth. The other is the coarse actuator that is low bandwidth and large stroke. These actuators serve each other; so dual servo system can get both high precision and large stroke.[1]

In many cases, the PZT and VCM (Voice Coil Motor) are used for high precision position control. The fine actuator, PZT is applied in fine motion stage for actuator, and VCM is used for driving the coarse stage in dual servo system.

Piezoelectric translator(PZT) actuators, with their high stiffness, fast frequency response, and high resolution, are increasingly being used in fine positioning application.[2] VCM has a wide moving range and low bandwidth than PZT.

Many research projects have been done exploring positioning methods for nanometer resolution with large moving range and dynamic properties. Ro and Hubbel[3], using a lead-screw-driving translation table, approached this issue by designing adaptive controllers around two stages of positioning. Norbert C. Cheung and et. al., using the two VCM, proposed the linear positioning system.[1] Lichuan Li proposed the dual system for cooper loss reduction of a VCM using an auxiliary rotary motor[5]

In this paper, we designed dual servo system for developing the positioning control. VCM and PZT actuator are used in this mechanism. VCM is designed as a coarse actuator. The controller is designed with PQ method. With the designed controller and system, the high precision and robustness were achieved.

Section 2 develops the mechanism of dual servo system and actuator model. Section 3 describes the controller design, and section 4 shows an experiment result. Finally section 5 contains the conclusion.

2. MECHANISM DESIGN

2.1 Mechanism model

Proposed dual servo system mechanism consists of mechanical parts that is moving body and leaf spring, and actuator parts that is VCM actuator and PZT. The proposed dual servo mechanism has two moving body. One is for the coarse motion and another body is for the fine motion. The fine motion body is a PZT actuator end point, so weight of fine motion body is negligible. The PZT is rigidly fixed to a coarse motion body. The stiffness between the coarse body and PZT is too high. So the interference behavior between the coarse motion body and the fine one can be ignored. The mechanical system is modeled as a Fig.1. Equation (1) is the dynamic model of dual servo system.

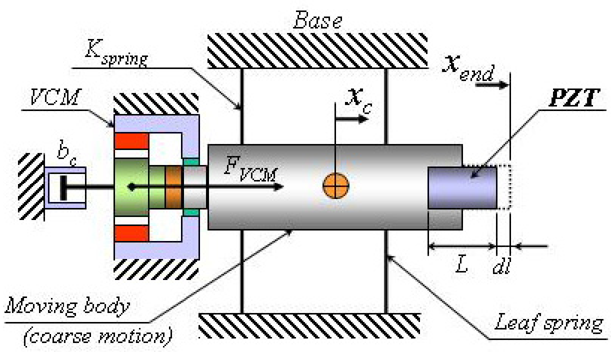

Fig. 1 The caption should be placed after the figure.

$$m_c\ddot{x}_c + b_c\dot{x}_c + k_{spring}x_c = F_{VCM}$$
$$dl = d_{33}\cdot L\cdot V_{input}(t) \qquad (1)$$
$$x_{end} = x_c + dl$$

where,

x_c : *Coarse body displacement*

m_c : *Mass of coarse body* $\quad b_c$: *Damping coefficient*

K_{spring} : *Leaf spring stiffness*

dl : *PZT actuator displacement*

x_{end} : *End point displacement*

F_{VCM} : *VCM force*

d_{33} : *Strain coefficient* $\quad V_{input}$: *Input voltage*

L : *PZT actuator length*

2.2 PZT actuator

PZT translators have a high precision and stiffness. However, they are needed several considerations. Preload is applied for installing the PZT stack between mechanisms, and lateral force or torque is able to give damages PZT. In this study, we make preload with set-screw, and flexible tip is applied to decouple lateral force and torque. Fig.2 is picture of used PZT stack.

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PZT is controlled with power amp that has 0V-100V output voltage and is designed for open loop operation. Table 1 is the specification of PZT translator.

Table 1 The caption should be placed before the table.

Travel range	15 ㎛
Push/Pull force	3000 / 20 N
Dimensions(W*H*L)	12*12*18mm
Resonant frequency	29 kHz
Electrical capacitance	7.2 μF

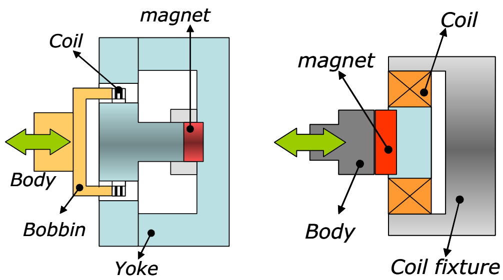
2.3 VCM actuator

VCM actuators are configurated by permanent magnet, coil, bobbin, and yoke. There are many kinds of VCM. We can divide VCM to moving magnet type and moving coil type by moving object.

Moving coil type, using the yoke as loop for magnetic flux stream, has low level loss and uniform magnetic flux density in air gap. However, coil size of moving coil type is limited, because a big size coil is too heavy for high dynamic range, and a stiffness of coil-lead for current supply increases the nonlinearity.

Moving magnet type is magnet is fixed on moving stage, and coil is installed base structure. There is no interference of coil lead stiffness, and designer can use big size coil. However, In this type, Air gap is lager than the other type, so energy loss is increased.

Fig 3 is schematic of two types VCM.



(a)Moving coil type (b)Moving magnet type

Fig.3 Two type of VCM structure

2.4 VCM design

The dynamic model of coarse part consists of the governing equations which are electromagnetic part and mechanical part. The governing equation of electromagnetic part is shown as Equation (2).

$$L_C(dI_C/dt) + R_C I_C = V_C - e_T(dX_{VCM}/dt) \qquad (2)$$
$$e_T = NBl$$

where L_C and R_C are the inductance and the resistance of the coil, respectively, I_C is the driving current, V_C is the driving voltage of VCM, N is the turn number of coil, B is the magnetic flux density in the air gap between yoke and moving coil, l is the effective average coil length of one turn, X_{VCM} is the displacement of the moving coil. The back electromotive force(BEMF) is expressed as $e_T\ (dX_{VCM}/dt)$. The governing equation of mechanical part results in the following Eq.(3).

$$m_c\ddot{x}_c + b_c\dot{x}_c + k_{spring}x_c = e_T I_C \qquad (3)$$

Applying the Laplace transform to the above equations, a system dynamic of the coarse part is represented as Eq.(4).

Fig.4 illustrates the schematic of VCM that has both electromagnetic part and mechanical part.

$$X_1(s) = G(s)\, V_c(s) \qquad (4)$$

$$G(s) = \frac{e_T}{m_c s^2 + \left(b_c + \left(\frac{e_T^2}{L_C s + R_C}\right)\right)s + k_{spring}}\cdot\frac{1}{L_C s + R_C}$$
$$= \frac{e_T}{m_c L_C s^3 + \alpha s^2 + \beta s + k_{spring}R_C}$$

where, $\alpha = m_1 R_C + b_c L_C + L_C e_T^2$

$\beta = b_c R_C + R_C e_T^2 + k_{spring} L_C.$

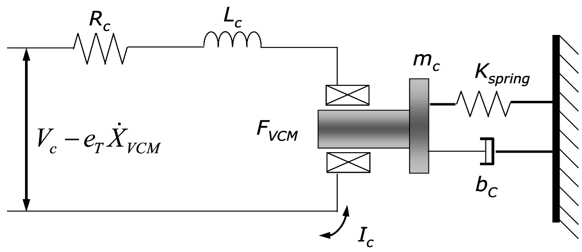


Fig.4 The schematic of VCM model and hinge mechanism

2.3 VCM actuator

In the many field, VCM is used for variety usage. This is simple structure, and has a good linearity. However, while adequate driving force can be provide by a VCM, the copper loss or temperature rise of the VCM may be high. These will be change the character of VCM such as a resistance, efficiency, and decrease the life time of coil. For the prevent the increasing the coil temperature, the VCM coil is located in out side of magnet, so that thermal energy of coil is dissipated more than coil is located between the permanent magnet or yoke. Fig.5 shows the cross section view of VCM. In VCM design, yoke design is important for getting desired performance of VCM. It is direct effective design parameter, so the shape and material of a yoke effect on the linearity, power, efficiency, motion range. Electromagnetic simulation help to define the yoke design parameter mere easily. We used the Maxwell® that is commercial FEM software for electromagnetic analysis.

VCM is designed for generating the force 2N that is value of force for 1mm moving stroke. Yoke and coil is designed with FEM simulation of magnet filed. Max input current of VCM is 5A. e_T is approximately 0.4. Fig.6 shows result of simulation of magnetic field at VCM coil. It shows that the magnetic field has the orthogonal direction about that current direction of coil

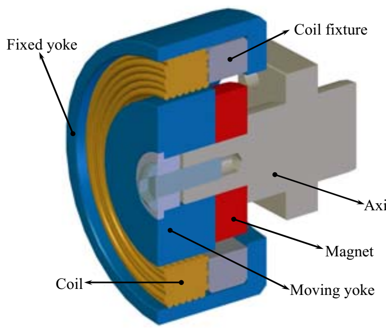


Fig.5 Structure of moving magnet type VCM

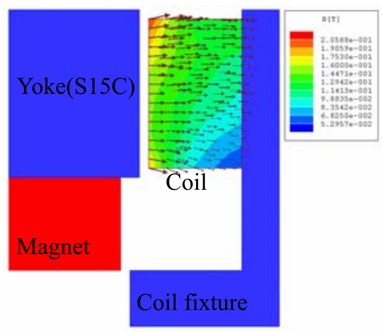


Fig.6 Simulation result of magnetic field at VCM air gap

3. CONTROL SYSTEM MODEL

3.1 System model

The response of a third order system can be approximated by the dominant roots of the second order system as long as the real part of the dominant roots is less than 1/10 of the real part of the third root. Because the third root is more than 10 times of the dominant roots such as Fig.7, *G(s)* is approximated to second order system. Therefore, both inductance of the coil and BEMF are eliminated by the dominant roots. The second order system approximated of *G(s)* is represented as Eq.(5):

$$G_n(s) = \frac{NBl}{m_c s^2 + b_c s + k_{spring} s} \cdot \frac{1}{R_C} \qquad (5)$$

The bode plot of both *G(s)* and $G_n(s)$ is shown in Fig.8. The bode plot of the second order system is similar to third order system, so this model is used to design the controller for a real system.

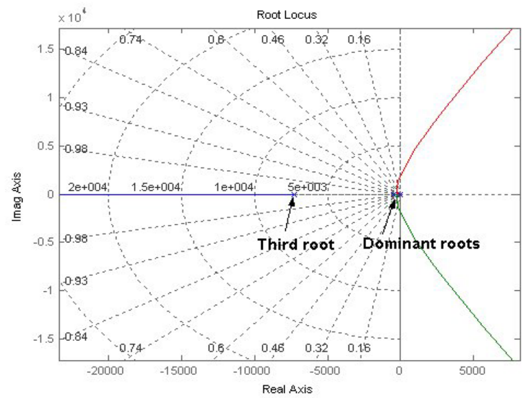


Fig.7 Root locus of G(s)

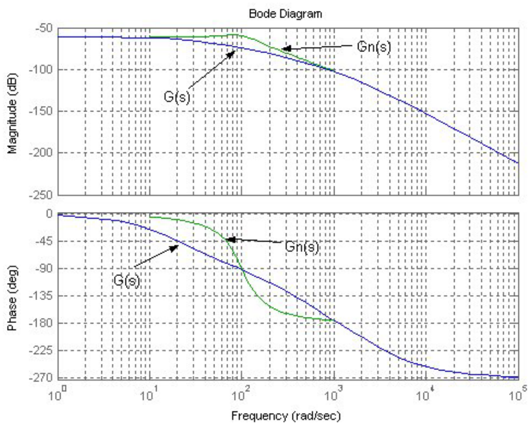


Fig.8 Frequency response G(s) and $G_n(s)$

3.2 Dual servo controller design

The objective of controller about dual servo system is at least 1700(rad/s) crossover frequency and more than 45° of phase margin. Fig.9 is shown the control system block diagram. G_1 is PZT and G_2 is transfer function of VCM. The frequency responses of G_1 and G_2 are shown in the Fig.10 and Fig.11.

According to specification of PZT and VCM, we design a 270(rad/s) crossover frequency of PQ and select a 74° phase margin. The transfer function of P and Q is Eq.(6), and the bode plot of PQ is shown in Fig.12.

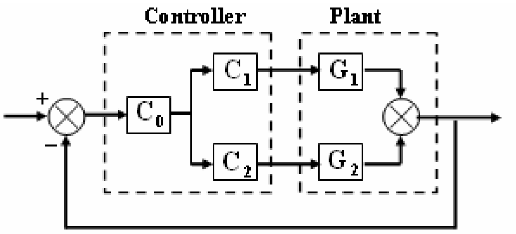


Fig.9 Control system block diagram

$$P = \frac{G_2(jw)}{G_1(jw)}$$
$$Q = \frac{C_2(jw)}{C_1(jw)} = 2.87\frac{0.00885\ S\ +\ 1}{0.0016\ S\ +1} \qquad (6)$$
$$G_{SISO}(jw) = C_1(jw)G_1(jw) + C_2(jw)G_2(jw)$$

C_1=1 and C_2=Q are a reasonable choice from PQ method. The controller C_0 for G_{SISO} consists of both lead compensator and notch filter. C_0G_{SISO} can achieve a high bandwidth, and a high robustness. C_0 is shown as Eq(10).

$$C_0 = \left(\frac{0.0108S+1}{0.006S+1}\right)\left(\frac{S^2+63S+9025}{S^2+114S+9025}\right) \qquad (10)$$

Bode plot of C_0G_{SISO} is shown as Fig.13. The crossover frequency, and the phase margin of C_0G_{SISO} are 1989(rad/s) and 64° respectively. These satisfied the design object of controller. Fig.14 represents sensitivity of both a dual servo system and a single servo system. In simulation result, the dual servo system is less sensitive than a single servo system.

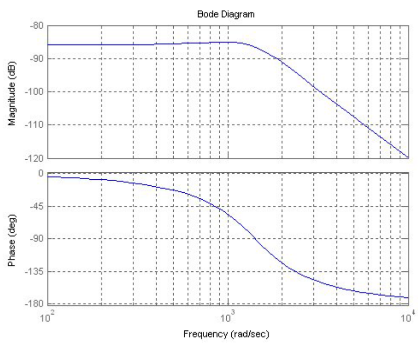


Fig.10 Bode plot of G_1(Fine, PZT)

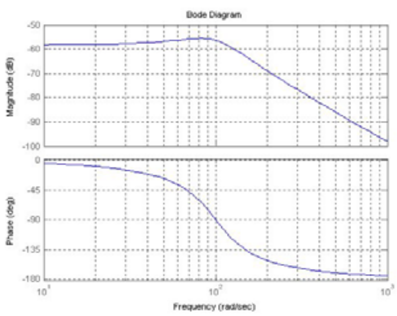


Fig.11 Bode plot of G_2 (Coarse, VCM)

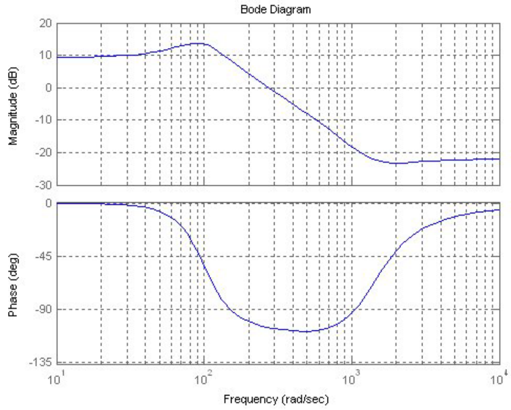


Fig.12 Bode plot of PQ

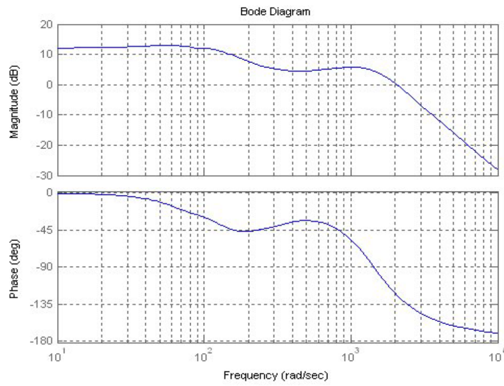


Fig.13 Bode plot of C_0G_{SISO}

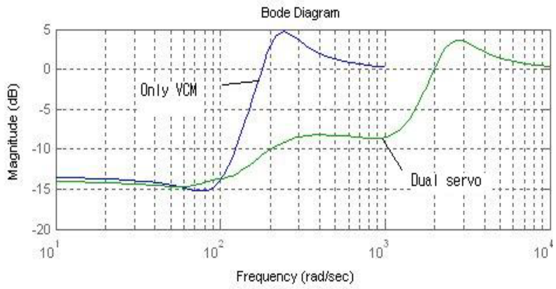


Fig.14 Sensitivity function of dual and single servo system

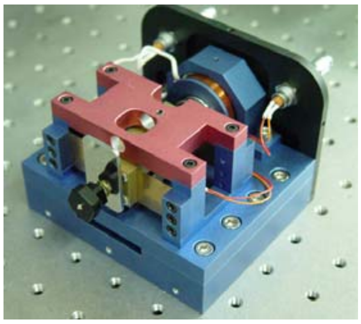


Fig.15 Cross section view of mechanism

4. EXPERIMENTAL RESULTS

4.1 Experimental system

The experimental dual servo system is developed with VCM and PZT actuators.(Fig 15) The capacitive sensor is used for measuring the displacement of the end point.

Proposed mechanism push and measure the installed load-cell. We input the desired target value of force into controller. The load cell measured the press force. Experimental system layout is shown in Fig.16. This system is tightly fastened to the vibration isolation table.

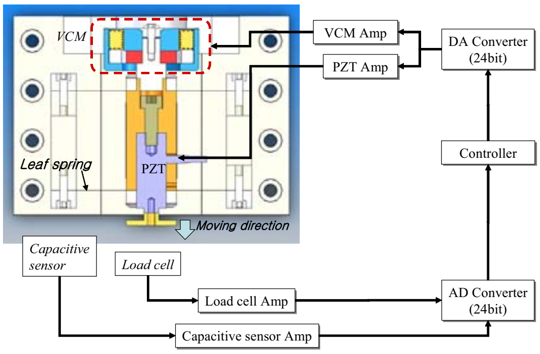


Fig.16 Schematic of experimental system

4.2 Experiment result

Linearity of Designed VCM is measured. Fig.17 shows the VCM linearity. At maximum current 8A, VCM force is about 3N.

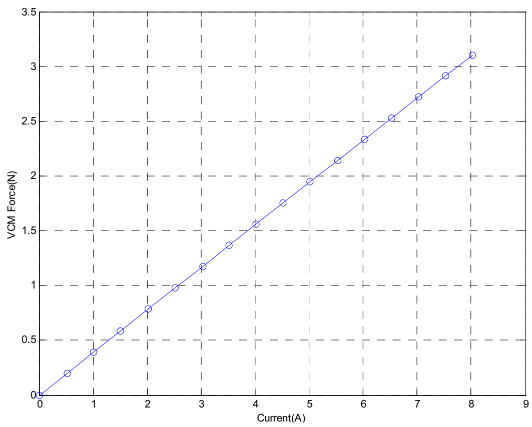


Fig.17 Measured force of VCM

Fig. 18 shows the experiment result that is response of harmonic motion with sine wave and DC offset. Sine wave frequency is 200Hz, and moving range is 500µm. This indicates the property of tracking performance and moving range.

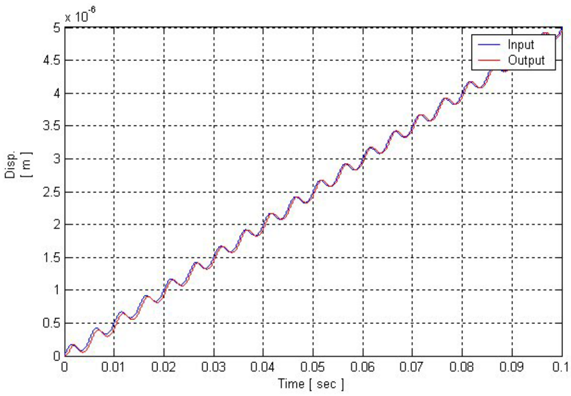


Fig.18 Measured displacement of Sin + DC offset input

We measured the repeatability of the designed system. Input command was a step input that has the amplitude of 40 µm. It was ten times to test and measure the position error. 40 times experiments was operated for each test that is moving from initial position to 40µm. Average of displacement was 40.01µm and standard deviation was about 8.9% of the average, which was cause by the measurement errors measuring displacement with capacitive sensor. Fig. 17 shows the experiment result that is a measured displacement average and error.

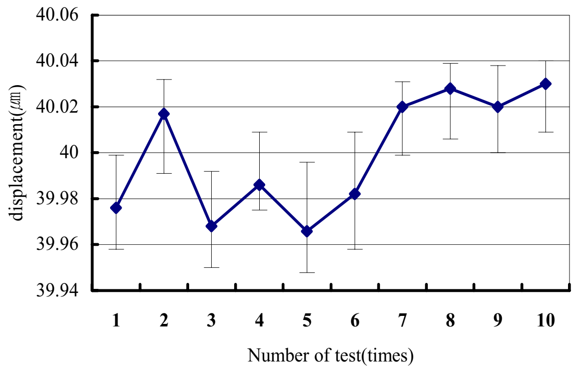


Fig.19 Result of repeatability test

With a step input of 50mN, Dual servo system performance is shown Fig 20. We input command signal that generate 50nN.

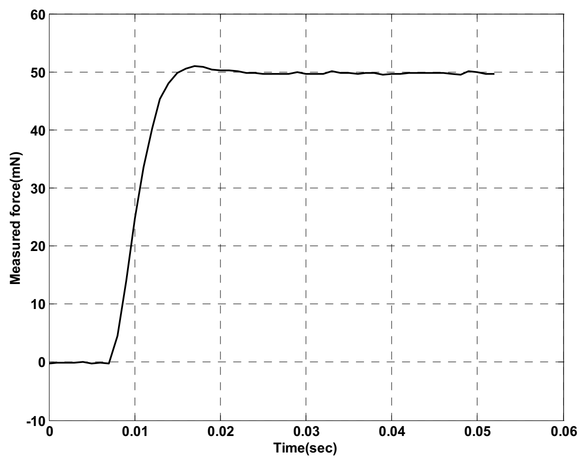


Fig.20 Result of step response with command signal 50mN

5. Conclution

This paper has describes a VCM actuator and dual actuator servo system for a high precision position control. For wide moving range and high precision, we use a PZT and VCM for actuator. Dual servo controller is designed with PQ method.

Controller consists of both lead compensator and notch filter. The bandwidth and robustness of system are improved with designed controller.

The designed dual servo system obtains higher bandwidth, less sensitive about the disturbance, faster response than the single servo system.

We concluded that the dual servo mechanism has higher precision, robustness, and more wide motion range than the single servo mechanism.

ACKNOWLEDGMENTS

This work was financially supported by MOCIE(Ministry of Commerce, Industry and Energy) under project named as "Milli-Structure manufacturing technology. ".

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