Design and Control of High Precision 3D Pickup Actuators for Near Field Recording System

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Abstract — *In the NFR system, since the gap between SIL and disc is under 100nm, the precise control of actuator is required. For the stable gap control, performance of actuator should be improved. When the mass center and centroid of actuator is not coincide with each other, coupling between linear and rotational motion appears and in near field recording system, it affects directly readout performance.*

Therefore, by constructing general mathematical model of actuator which can reflect coupling motion, quantity of coupling was analyzed. Moreover, by sensitivity analysis, critical variables which affect coupling motion were selected and by applying optimal value to the system, coupling effect was decreased effectively. By measuring transfer function of actuator, analytic approach was verified .

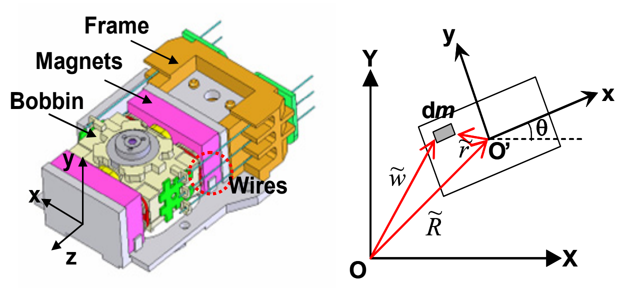
Index Terms — Near field recording, 3-axis actuator, Compensation, Coupling analysis, Transfer function, Sensitivity analysis.

I. INTRODUCTION

Over the past few years, SIL actuating NFR system has only evolved towards high capacity and high density. Another mainstream in NFR research, which is very important in terms of system realization, is the improvement of reliability. In order to become the candidate of mass data storage systems, collision of SIL (Solid immersion lens) to disc by insufficient mechanical margin should be overcome for commercialization. To enlarge mechanical margin between SIL and disc, rotational compensation should be applied and 3-axis wire type actuator is commonly used[1][2]. However, by mis-alignment of component and lack of optimal design process, coupling motion between linear and rotational motion could be observed and it affects directly to the system stability. In here, to reduce coupling effect of actuator motion, generalized actuator modeling was constructed and by analyzing sensitivity function in frequency range, optimal variable range was suggested and by performing experiments, validity of design process was confirmed.

II. MODELING OF ACTUATOR

In this study, 3-axis wire type actuator was concerned and coordinate of bobbin is shown in Fig.1(a). X for tracking direction, Y for focusing direction, θ_z for rolling direction. Traditionally, 3-axis actuator is modeled by simple mass-damp-spring system[3] and it was considered as non-coupled dynamics for each directions. However, if mass center is not coincide with centroid of actuator and 1st mass moment of inertial for focusing and tracking direction is not assumed 0, coupling motion could be appeared. To observe coupling motion between linear and rotational motion, it requires generalized equation of motion of 3-axis actuator depicted in Fig.1(b).



(a) (b)

Fig. 1. Schematic view of actuator system and notation of 3-degree of freedom. X for tracking, Y for focusing, Rotation along Z axis for rolling(a) and schematics of actuator bobbin for mathematical modeling(b).

Here, it is taken into account that the mass center does not coincide with the centroid and to derive generalized equations of motion for actuator, the displacement vector $\boldsymbol{w}$ of a typical point on the bobbin (the moving part of actuator) is first found with respect to the origin of the inertial XYZ co-ordinate frame as follows:

$$\tilde{w} = \tilde{R} + [C]\cdot\tilde{r},\ where\ \tilde{R} = [X\ Y\ 0],\ \tilde{r} = [x\ y\ \theta]$$
$$C = \begin{bmatrix} c\theta & -s\theta & 0 \\ s\theta & c\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

where $\tilde{R} = [X\ Y\ 0]^T$ is the position vector of the centroid from the origin O, and $\boldsymbol{C}$ is the rotation matrix between the two frames, $\tilde{r} = [x\ y\ \theta]^T$ is the position vector of the typical point from the centroid o in Fig.1(b). Considering the time derivative of (1), we can get the

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kinetic energy expression as follows:

$$T=\frac{1}{2}m(\dot{X}^2+\dot{Y}^2)+\frac{1}{2}I_{OZ}\dot{\theta}^2-\dot{X}\dot{\theta}(S_x\sin\theta+S_y\cos\theta)+\dot{Y}\dot{\theta}(S_x\cos\theta-S_y\sin\theta) \quad (2)$$

where I_{oz} is the mass moment of inertia of the bobbin about its centroid while $S_x=\int_m xdm$ and $S_y=\int_m ydm$ are first mass moments of inertia. In (2), 1st derivative term of vector **r** is not included since derivative of constant distance is 0. In here, those first mass moments of inertia do not vanish as long as the centroid is not coincident with its mass center as mentioned before. Next, the potential energy can be derived as:

$$V=\frac{1}{2}(k_xX^2+k_yY^2+k_\theta\theta^2)+mgY \quad (3)$$

where k_x , k_y and k_θ express spring stiffness in each direction, and g denote the gravitational acceleration. Finally, the non-conservative virtual work which was induced by Lorent'z force by electro-magnetic loop of actuator is obtained as follows:

$$\delta W=(F_x\cos\theta-F_y\sin\theta)\delta X+(F_x\sin\theta+F_y\cos\theta)\delta Y+F_\theta\delta\theta \quad (4)$$

where F_x,F_y and F_θ represent the actuator forces resulting at the centroid respectively in the tracking, focusing and rolling directions. When we replace (2) through (4) to the standard Lagrangian equation, the equations of bobbin motion can be obtained as follows:

$$[M]\ddot{\tilde{q}}+[C]\dot{\tilde{q}}+[K]\tilde{q}+[N]+[G]=[T]\cdot\tilde{F} \quad (5)$$

Coupled term

$$[M]=\begin{bmatrix} m & 0 & -(S_xs\theta+S_yc\theta) \\ 0 & m & (S_xc\theta-S_ys\theta) \\ -(S_xs\theta+S_yc\theta) & (S_xc\theta-S_ys\theta) & I_{OZ}\end{bmatrix}$$

$$[C]=diag[c_x,c_y,c_\theta]\ ,\ [K]=diag[k_x,k_y,k_\theta]\ ,$$

$$\tilde{F}=\begin{bmatrix}F_x & F_y & F_\theta\end{bmatrix}^T\ ,\ [G]=\begin{bmatrix}0 & mg & 0\end{bmatrix}^T$$

$$[N]=\begin{bmatrix} -\dot{\theta}^2(S_xc\theta-S_ys\theta) \\ -\dot{\theta}^2(S_xs\theta+S_yc\theta) \\ -\dot{X}\dot{\theta}(S_xc\theta-S_ys\theta)-\dot{Y}\dot{\theta}(S_xs\theta+S_yc\theta)\end{bmatrix}$$

where **q=[X Y θ]^T** is the generalized co-ordinate, ***M*** and ***K*** are overall mass and stiffness matrices, ***N*** is the centrifugal and Coriolis force term, and ***F*** is the actuator force vector.

To design a linear controller and identify system parameters based on the frequency response functions (FRF), the equations of motion need to be linearized. Hence, by assuming θ to be small enough and neglecting second and higher order perturbation terms as (6), (5) can be simplified as (7):

$$\sin\theta\approx 0,\ \cos\theta\approx 1,\ \theta^2\approx\dot{X}\dot{\theta}\approx\dot{Y}\dot{\theta}\approx\dot{\theta}^2\approx 0 \quad (6)$$

$$[M]\ddot{\tilde{q}}+[C]\dot{\tilde{q}}+[K]\tilde{q}+[G]=\tilde{F},\ \tilde{q}=[X\ Y\ \theta] \quad (7)$$

$$[M]=\begin{bmatrix} m & 0 & -S_y \\ 0 & m & S_x \\ -S_y & S_x & I_{OZ}\end{bmatrix} \qquad [C]=\begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & c_\theta\end{bmatrix}$$

$$[K]=\begin{bmatrix} k_x & 0 & 0 \\ 0 & k_y & 0 \\ 0 & 0 & k_\theta\end{bmatrix} \qquad [F]=\begin{bmatrix} f_x \\ f_y \\ f_\theta\end{bmatrix}$$

where the damping term is the effect of the visco-elastic materials, and the centrifugal and Coriolis terms have disappeared by (6).

From (7), it seems clear that the non-zero S_x and S_y quantities play the role of coupling between focusing, tracking and rolling motions. Hence, to reduce the undesirable linear motion caused by rotational motion and vise versa, their values should be minimized to suppress coupling motion. To clarify the role of non-zero S_x and S_y term, motion under various frequency range should be observed. Therefore, by taking Laplace transform to (7), we can get following transfer function for each direction:

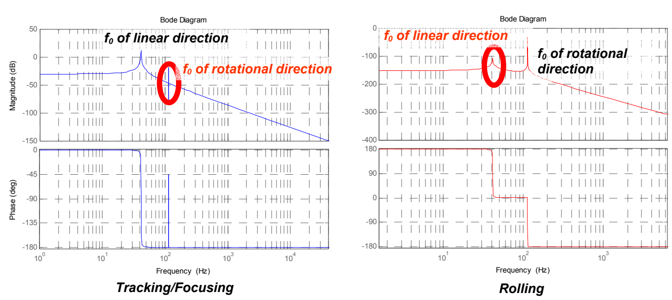
$$G_{X,Y,\theta}(s)=\frac{N_{X,Y,\theta}(s)}{D_{X,Y,\theta}(s)}=\frac{Order(s^4)}{Order(s^6)} \quad (8)$$

$$N_{X,Y}(s)=\{(mI_{oz}-S_{y,x}{}^2)s^4+(mc_\theta+c_{x,y}I_{oz})s^3+(mk_\theta+c_xc_\theta+k_{x,y}I_{oz})s^2+(k_\theta c_{x,y}+k_{x,y}c_\theta)s+k_{x,y}k_\theta\}$$

$$N_\theta(s)=m^2s^4+(mc_x+mc_y)s^3+(mk_x+mk_y+c_xc_y)s^2+(k_xc_y+k_yc_x)s+k_xk_y$$

$$\begin{aligned}D_{X,Y,\theta}(s)=&\,m(mI_{oz}-S_y{}^2-S_x{}^2)s^6+(-c_yS_y{}^2-c_xS_x{}^2+mc_yI_{oz}+mc_xI_{oz}+m^2c_\theta)s^5\\&+(c_xc_yI_{oz}+mk_yI_{oz}+mk_xI_{oz}+m^2k_\theta+mc_xc_\theta+mc_yc_\theta-k_yS_y{}^2-k_xS_x{}^2)s^4\\&+(c_xc_yc_\theta+mk_xc_\theta+mk_yc_\theta+k_xc_yI_{OZ}+mc_xk_\theta+k_yc_xI_{OZ}+mc_yk_\theta)s^3\\&+(k_xk_yI_{oz}+mk_xk_\theta+mk_yk_\theta+k_xc_yc_\theta+k_\theta c_xc_y+k_yc_xc_\theta)s^2\\&+(c_xk_yk_\theta+c_yk_xk_\theta+c_\theta k_xk_y)s+k_xk_yk_\theta\end{aligned}$$

From (8), we can plot the frequency response function for each direction and it was depicted in Fig.2.



(a) (b)

Fig. 2. Transfer function for linear(tracking/focusing) and rotational direction. Under circle, sub-resonance by coupling effect can be observed in each direction.

In Fig.2, coupled frequency response was observed at 100Hz for linear motion and 45Hz for rotational motion.

Especially, since actuator servo range is over 1st natural frequency, coupled effect observed in linear motion by rotational motion-Fig.2(a) gives most serious effect in servo performance. Therefore, we focused on decreasing coupled effect in linear motion as was depicted in Fig.2(a).

To decouple these linear-rotational coupled motion, difference between mass and force center should be minimized by trial and error or variables which affects coupled motion should be selected and optimized. In this paper, to suggest reasonable design approach, we focused on later case and tried to analyze variable sensitivity under frequency range.

II. Sensitivity Analysis for Coupled Motion

To analyze sensitivity of design variables, proper method should be selected. In this paper, to know the effect in frequency range, logarithm sensitivity by John Y. Hung[4] was applied. Logarithm sensitivity was defined as:

$$S_{\delta}^{G}(s) = \frac{d(\ln G)}{d(\ln \delta)} = \frac{\delta}{G}\left(\frac{dG}{d\delta}\right) \qquad (9)$$

Equation (9) can offer variation of transfer function in frequency range as changing the design variables and the higher peak level in sensitivity function means higher sensitive for derivative variable term. Therefore, by analyzing sensitivity for linear direction, critical variables which affect coupling motion could be selected.

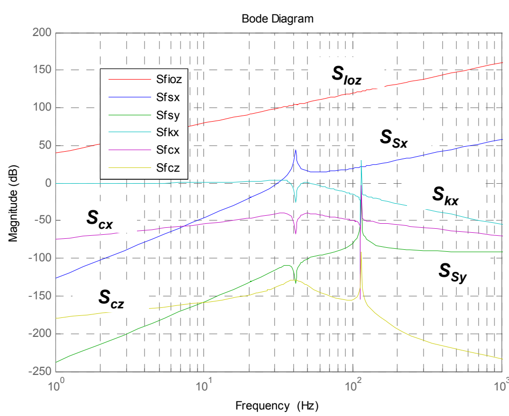


Fig. 3. Sensitivity analysis for linear direction. I_{oz} has the highest level through all frequency range.

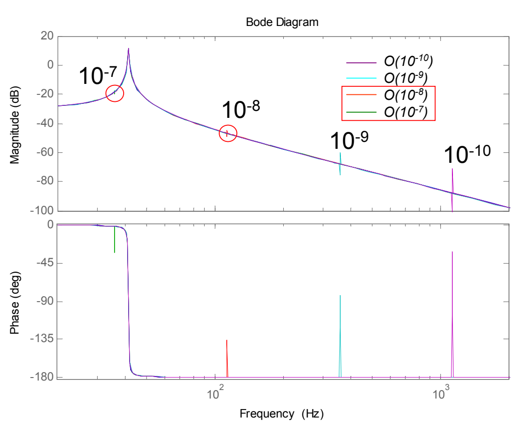


Fig. 4. The tendency of transfer function by changing the order of I_{oz}

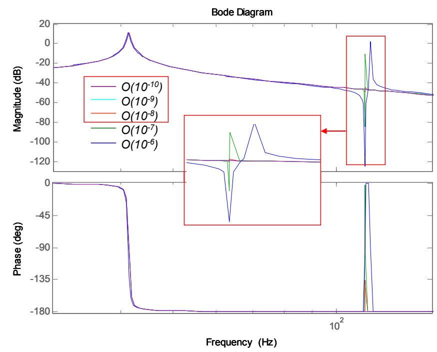


Fig. 5. The tendency of transfer function by changing the order of S_x

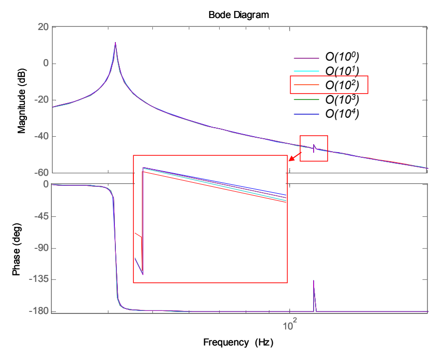


Fig. 6. The tendency of transfer function by changing the order of k_x

In Fig.3 sensitivity functions for linear direction was depicted and in the order of their peak level, I_{oz}, S_x, k_x were selected as critical variables which can affect transfer function shape of actuator. In case of linear motion, since I_{oz} is most sensitive variables from the Fig.3, its effect was verified first of all. When we observe Fig.4, I_{oz} with the range of 10^{-8}~10^{-7} [kg·m^2] order can effectively reduce sub-resonance peak by rotational motion, and from Fig.5 S_x under 10^{-8}[kg·m] gives good reduction of sub-resonance peak. Also, when we control k_x near 10^2[N·m], sub-resonance has minimum peak level as Fig.6.

III. Experimental Result

By using optimal variables which was selected in previous section, actuator was designed and its transfer functions were measured by laser doppler vibrometer under sinusoidal signal sweeping from 0Hz to 50kHz.

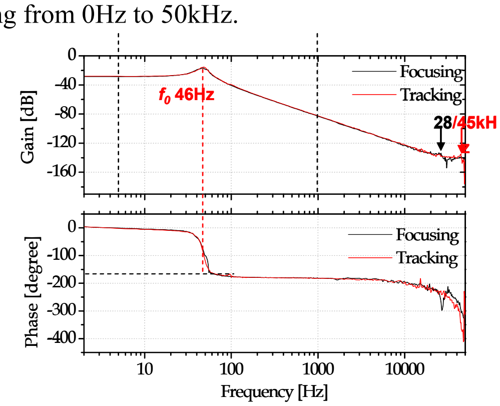


Fig. 7. Linear directional transfer function measured by LDV. No sub-resonance peak was found in all frequency range.

In Fig.7, transfer functions for focusing and tracking directions were depicted and it is noteworthy that coupling effect by rotational motion was not observed in all frequency range.

IV. CONCLUSIONS

Optimal 3-axis actuator was designed by constructing generalized mathematical modeling of coupling motion and by analyzing sensitivity of transfer function, critical variables which affect coupling motion was selected and their optimal range was found by simulation. Considering these optimal variable ranges to the design process, actuator was assembled and analytical validity was confirmed by experiment.

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