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Positioning Control of a Redundant Actuator

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Abstract

This paper discusses the solution to the precise positioning control problem applied to a simple model of a dual stage or redundant positioner. The dual stage actuator presented here uses a VCM(Voice Coil Motor) as a coarse actuator and a piezoelectric actuator as a fine actuator. By adopting controllers with two-degree-of-freedom and by optimizing H_2 faster precise tracking can be realized. Experimental and numerical results are presented to demonstrate the control effects.

1. Introduction

A positioner is said to have redundancy if it has more degrees of freedom than are necessary to perform a given task. What are the advantages of redundant positioners? Generally speaking, as in the case of the human arm, they excel in versatility and applicability. More specially, they have the potential to avoid singularities, avoid obstacles, avoid structural limitations, carry out reasonable actions, reach behind an object, crawl into concaves, and so on. Redundancy can also be used to make a positioner more reliable in the sense that it can perform certain takes even after a failure of some actuators. The requirement on the acceleration and range of the servo mechanism dictates a physical size which limits the actuator bandwidth of a single stage actuator to the kilohertz range because of structural resonances. One method of increasing the actuator bandwidth is to mount a fine actuator on top of a coarse actuator. The coarse actuator is usually the conventional rotary or linear actuator. The fine actuator, a much smaller structure limited in range but capable of following high frequency commands, could be a piezoelectric actuator. Of course, redundant positioners have disadvantages too. They have more joints and actuators. This structure is more complex, bulkier, and heavier. More complicated algorithms are required, so the amount of necessary computation increases. Redundant positioners will not be truly beneficial unless these disadvantages are offset by some advantages.

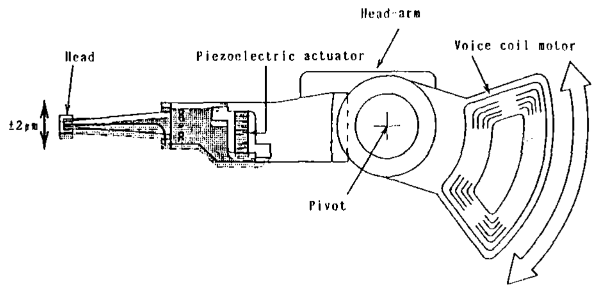


Fig. 1 Dual stage actuator

Dual stage actuators are often used in high performance optical or magnetic disk file systems to improve the tracking performance of the read and write systems. However, in many existing disk systems the fine actuator is locked in a certain position relative to the coarse actuator during a track seek. Thus, in track seeking mode the actuator system is treated as if only a single stage existed. This paper takes into account the motion of the fine actuator when tracking. As a related problem in this field, Yen et al. [1] applied the Linear Quadratic Gaussian optimal control with Loop Transfer Recovery (LQG/LTR) technique to the design of a discrete-time track-following compensator for a compound disk drive actuator. McCormick and Horowitz [2] discussed the solution to the time-optimal control problem applied to a simple model of a dual stage or compound actuator system. Mori et al. [3] described the design of the dual-stage actuator including structural analysis, its static and dynamic characteristics, dual-stage feedback control system. Sampei et al. [4] proposed a controller for plants with redundant degree of freedom using H_∞ control strategy.

This paper discusses the solution to the precise positioning control problem applied to a simple model of a dual stage or redundant positioner. Dual stage refers to the fact that there is a small actuator mounted on a large more conventional actuator. The small actuator will be referred to as the fine actuator and the large actuator will be referred to as the course actuator. The dual stage actuators presented here uses a VCM (Voice Coil Motor) as a coarse actuator and a piezoelectric actuator (PZT) as a fine actuator (Fig. 1). To obtain a good transient response, we adopt the two-degree-of-freedom control scheme. We show that high-speed precise tracking is realized by deriving a function for the evaluation of H_2 optimization in a control system with two-degree of freedom.

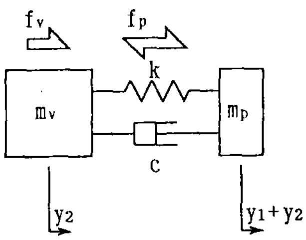


Fig. 2 Redundant actuator model

2. Redundant Actuator Model

Figure 2 shows the redundant actuator model. In this model all passive coupling between the fine and course actuators has been ignored. A redundant actuator is comprised of a high bandwidth fine actuator mounted on top of a large actuator. A high-gain current feedback minor loop minimizes the effect of the motor inductances in the operational bandwidth of the system. A simple model of the redundant actuator consists of two inertias which are actuated by ideal force inputs and which are coupled by a spring-damper system. In this case, the equations of motion of the redundant actuator are written as

$$m_p\left(\frac{d^2y_1}{dt^2} + \frac{d^2y_2}{dt^2}\right) = -ky_1 - c\frac{dy_1}{dt} + f_p \tag{1}$$

$$m_v\frac{d^2y_2}{dt^2} = ky_1 + c\frac{dy_1}{dt} - f_p + f_v \tag{2}$$

where $y_1 + y_2$ is the absolute tip position, y_2 is the relative actuator position, f_v is the coarse actuator force input, f_p is the fine actuator force input, m_v is the coarse actuator mass, m_p is the fine actuator mass, k is the actuator coupling spring constant and c is the actuator coupling damping coefficient. Taking the Laplace transform of eqs. (1)-(2) with respect to t gives

$$\begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} = \begin{bmatrix} \dfrac{1+a}{m_ps^2+(1+a)cs+(1+a)k} & \dfrac{-a}{m_ps^2+(1+a)cs+(1+a)k} \\ \dfrac{-a}{m_ps^2+(1+a)cs+(1+a)k} & \dfrac{m_ps^2+cs+k}{m_vs^2\{m_ps^2+(1+a)cs+(1+a)k\}} \end{bmatrix} \begin{bmatrix} F_p \\ F_v \end{bmatrix} \tag{3}$$

where $a=m_p/m_v$.

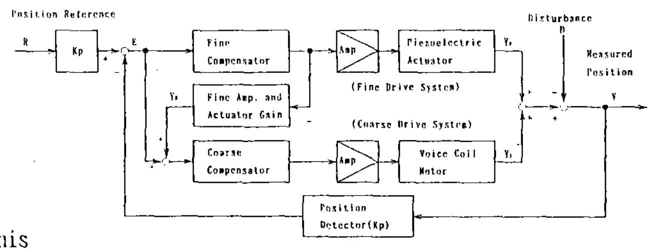


Fig. 3 Block diagram of dual stage servo system

3. Dual Stage Servo Control System

Figure 3 shows a block diagram of the dual stage servo control system which consists of a fine compensator and a coarse compensator. The positional feedback signal is supplied to both compensators. The output of the fine compensator is added to the input of the coarse compensator, which prevents the piezoelectric actuator from going to the end of its stroke. The VCM servo

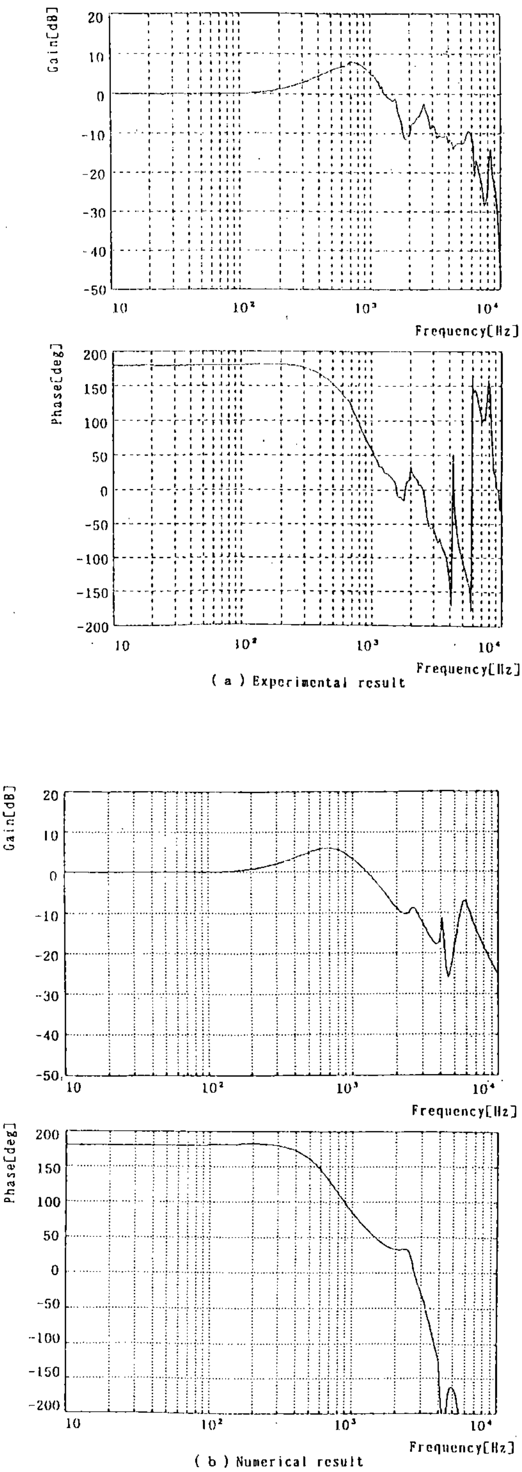


Fig. 4 Frequency response of the closed loop system (one-degree-of-freedom control system)

controller is composed of a lead lag filter, a notch filter and a low-path filter. The piezo servo controller consists of an integrater and a notch filter. The servo system is designed so that the tracking error at 60 Hz decreases 40 dB by both servo system. The bandwidth of the VCM servo system is 450 Hz, and 1 kHz for the piezo servo system. For the implementation of fast controllers we routinely use the TMS320C30 based digital signal processing system along with a set of design and implementation software tools, including an automatic code generator. We carried out the design in the analog domain, and discretized the controller after checking for the effects of discretization, computational delay, AD- and DA-quantization, the signal processor code was generated and downloading. The sampling period was about 50μsec.

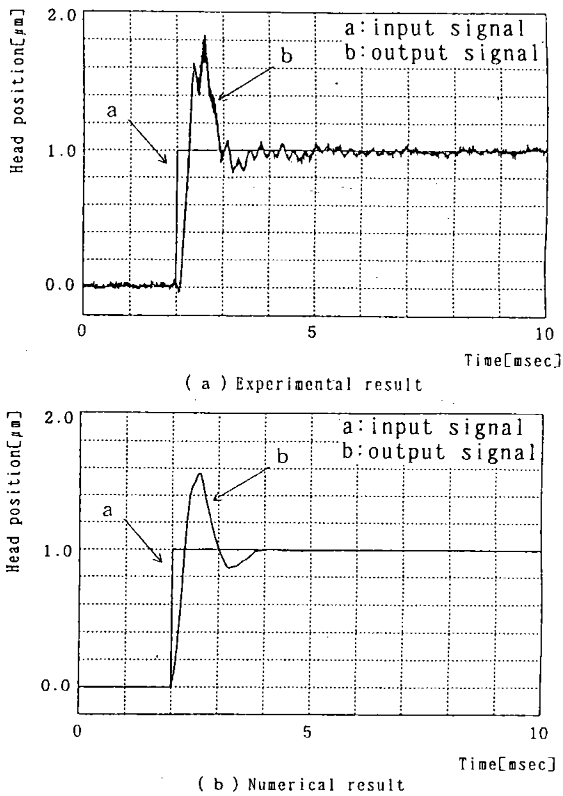


Fig. 5 Step response of the one-degree-of-freedom control system

The frequency characteristics of the dual stage servo control system is shown in Figure 4. Fig. (a) shows the experimental result and Fig. (b) the corresponding numerical simulation result. It is found that the experimental results is in good correspondence with the theoretical one except for higher frequency.

Figure 5 is the step response of the one-degree-of-freedom control system. Fig.(a) is the experimental result and Fig.(b) the theoretical one. It is also noted that the theoretical and experimental results are in good agreement with each other. This means that the theoretical analysis mentioned above is valid for the dual stage servo control system. The step response in Fig.5 shows large overshoot and fast rise time. This might be considered unsatisfactory but is of secondary importance, because the focus is on regulator behavior. The prefilter in the command path could easily eliminate the overshoot while retaining fast rise time.

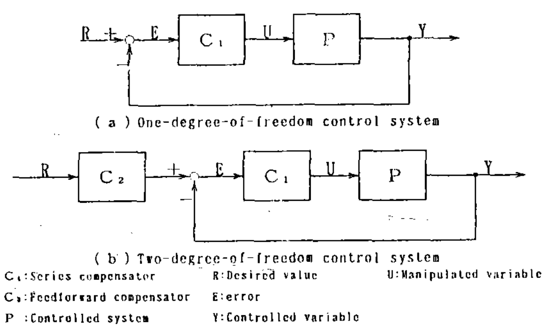


Fig.6 One and two-degree-of-freedom control system

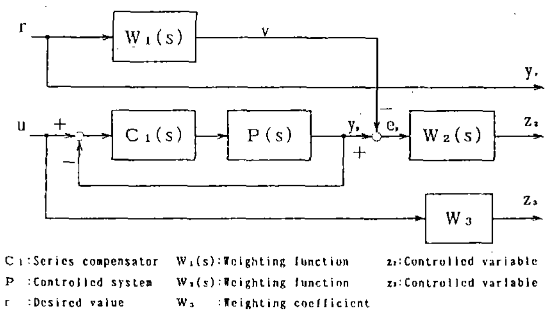


Fig.7 Augmented system for designing two-degree-of-freedom control system

4. Improvement of Tracking Performance with Two-Degree-of-Freedom

In Figure 6 a control system with a single degree of freedom in the feedback characteristics and the following characteristic are determined by controller C_1 alone. On the other hand, in a control system with two-degree-of-freedom the following characteristic and the feedback characteristic can be designed independently. In a two-degree-of-freedom control system, the complementary sensitivity function $T = PC_1/(1+C_1P)$ and the sensitivity function $S = 1/(1+C_1P)$ are determined by C_1, just as in the system with one-degree-of-freedom, but control specifications for the following characteristic can be independently in terms of controller C_2. In this way, the following characteristic can be improved under conditions where the feedback characteristics are strictly specified. Next, a method for the optimal design of controller is considered. That is, stabilized feedback controller C_1 is designed, and the controller C_2 for rapid following time is designed using H_2 optimization. Here, the two-degree-of-freedom controller C_2 is designed based on the augmented plant of Figure 7. The controller C_2 is computed to minimize the H_2-norm of the closed-loop transfer function matrix.

$$\min \left\| \begin{matrix} \{W_1(s) - C_{ry}\}W_2(s) \\ C_2 W_3 \end{matrix} \right\|_2 \qquad (4)$$

where $C_{ry}=PC_1C_2/(1+PC_1)$, $W_1(s)$ and $W_2(s)$ are weighting functions, and W_3 is the weighting coefficient. In Figure 7 minimal realization of the plant and weighting function are performed according to the following equations.

$$G_T(s) = \frac{PC_1}{1+PC_1}$$

$$G_T(s) : \begin{aligned} \dot{x}_T &= A_T x_T + B_T u \\ y_p &= C_T x_T + D_T u \end{aligned}$$

$$W_1(s) : \begin{aligned} \dot{x}_{w1} &= A_{w1} x_{w1} + B_{w1} r \\ v &= C_{w1} x_{w1} + D_{w1} r \end{aligned}$$

$$W_2(s) : \begin{aligned} \dot{x}_{w2} &= A_{w2} x_{w2} + B_{w2} e_p \\ z_2 &= C_{w2} x_{w2} + D_{w2} r \\ z_3 &= W_3 u \;, \quad e_p = y_p - v \end{aligned}$$

The state space expression of the augmented plant is as follows:

$$\begin{bmatrix} \dot{x}_T \\ \dot{x}_{w2} \\ \dot{x}_{w1} \end{bmatrix} = \begin{bmatrix} A_T & 0 & 0 \\ B_{w2}C_T & A_{w2} & -B_{w2}C_{w1} \\ 0 & 0 & A_{w1} \end{bmatrix} \begin{bmatrix} x_T \\ x_{w2} \\ x_{w1} \end{bmatrix} + \begin{bmatrix} 0 & B_T \\ -B_{w2}D_{w1} & B_{w2}D_T \\ B_{w1} & 0 \end{bmatrix} \begin{bmatrix} r \\ u \end{bmatrix}$$

$$\begin{bmatrix} z_2 \\ z_3 \\ y_r \end{bmatrix} = \begin{bmatrix} D_{w2}C_r & C_{w2} & -D_{w2}C_{w1} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_r \\ x_{w2} \\ x_{w1} \end{bmatrix} + \begin{bmatrix} -D_{w2}D_{w1} & D_{w2}D_r \\ 0 & W_3 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} r \\ u \end{bmatrix} \qquad (5)$$

5. Example of Actual Design and Experimental Results

Consider the augmented system shown in Fig. 7. The following set of weighting functions and weighting coefficient were chosen:

$$W_1(s) = \frac{1.9894368\times10^{-5}s + 1.96}{1.9894368\times10^{-4}s + 1} \qquad (6)$$

$$W_2(s) = \frac{1.5915494\times10^{-6}s + 0.4}{3.1830989\times10^{-5}s + 1} \qquad (7)$$

$$W_3 = 0.7 \qquad (8)$$

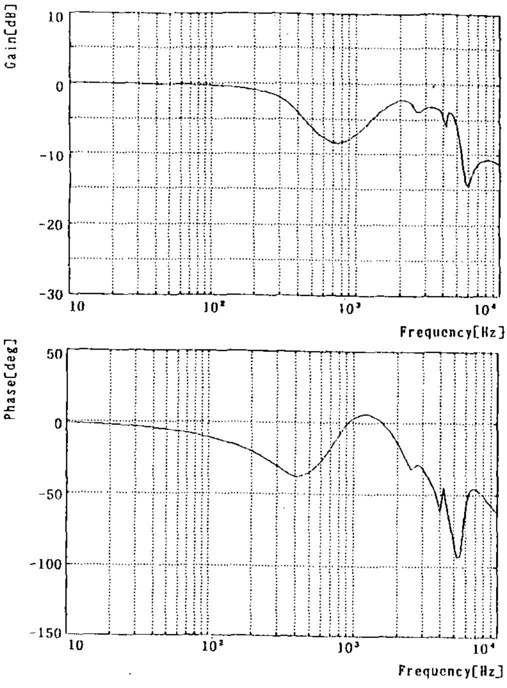


Fig. 8 Frequency response of the reference input filter

The reference input filter design has been carried out using MATLAB Robust Control tool box[5-7]. Fig. 8 is the frequency characteristics of the reference input filter. Fig. 9 shows the frequency response of the two-degree-of-freedom control system. The controller was quantized at the sampling frequency and then equipped with the DSP. Fig. 10 shows the step response of the

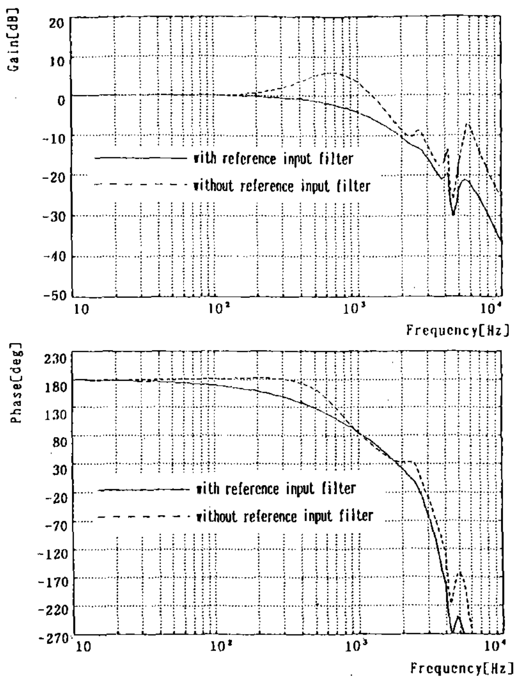
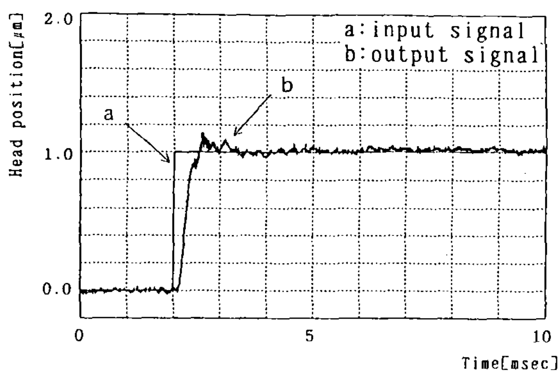
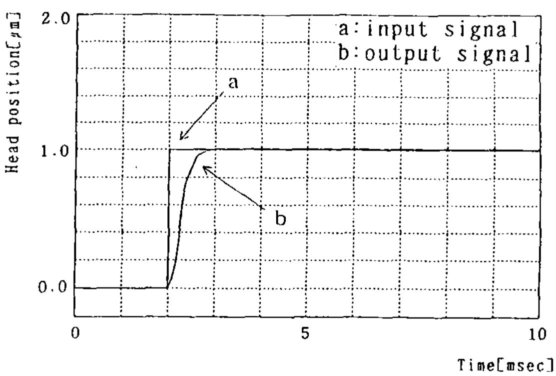


Fig. 9 Closed loop transfer recovery by using the reference input filter



(a) Experimental result



(b) Numerical result

Fig. 10 Step response of the two-degree-of-freedom control system two-degree-of-freedom system. It is found that the experimental and numerical results are in good agreement with each other. Comparing with Fig. 5, by using two-degree-of-freedom control system high-speed settling time with 1 msec are achieved without overshoot.

6. Conclusions

This paper discussed the solution to the precise positioning control problem applied to a dual stage or redundant actuator. The dual stage actuator presented here used a VCM as a coarse actuator and PZT as a fine actuator. Two-degree-of-freedom control system was applied to the positioning control of a redundant actuator. It is shown that the high-speed tracking is realized by deriving a function for the evaluation of H_2 optimization in a control system with two-degree-of-freedom.

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