한국소음진동공학회 창립10주년 기념 소음진동학술대회논문집, pp. 1570~1576.

하드 디스크용 전단형 2단구동기의 동적 해석 및 제어

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Tracking Control of HDD Dual Stage Actuator with Shear Mode PZT Micro-actuator

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Abstract

하드디스크의 고용량화 추세에 따라 헤드의 정밀한 위치제어를 위한 큰 대역폭의 트랙 추적 서보 시스템의 필요성이 대두되고 있다. 이에 작은 신호의 마찰을 제거하고 대역폭을 높이는 방법 중 하나인 2단구동기 트랙추적제어를 실시하여 큰 대역폭의 트랙 추적 서보 시스템을 구성하는 방법에 대해 연구하였다. 2단구동기는 조동구동기(기존 하드디스크의 VCM)와 .전단형 압전체를 부착한 미동구동기로 구성하였다. 미동구동기의 Hinge구조는 트랙 방향의 공진 주파수와 출력변위를 만족시키기 위한 구조로 설계하였다. 제어기는 notch filter와 PI 보상기를 사용하는 조동구동기와 notch filter와 PD 보상기를 사용하는 미동구동기를 다양한 구조로 구성한 것들을 비교하였다. 2단구동기는 VCM만을 사용하여 트랙 추적을 할 때보다 트랙 편심을 잘 추적하며, 기계적 공진과 VCM의 비선형성에 의해 제한된 대역폭을 개선시키는 효율적인 방법임을 확인하였다.

I. Introduction

The areal recording density of HDD (Hard Disk Drives) has been increasing by about 60% a year. To reach high areal density, less track pitch is expected and more servo bandwidth is required. Dual stage actuator and servo controller for HDD have been suggested for achieving high track density as a possible solution.

Several types of dual stage actuators have been proposed such as electromagnetic, electrostatic, or piezoelectric micro-actuator systems. There exist several choices for the location of the micro-actuator. For example the actuator can be placed near the recording head at the tip of the load beam, where it moves only the head or head/slider assembly. In another type, the actuator drives the head suspension assembly [1]. In this paper we use a piezoelectric micro-actuator for dual stage actuator systems, as shown in Fig. 1. Our piezoelectric actuator is based on the shear mode of piezoelectric elements to drive the head

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suspension assembly.

Considering the control algorithm, modern control approach offers a unified approach to disk servos, but it required higher sample and more processor resource. Further, there is no track following performance benefit obtained by modern methods [1]. Thus, we will use rather classical approaches.

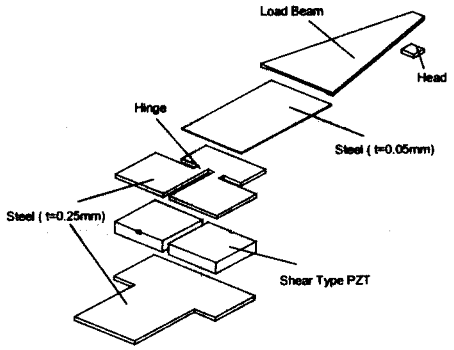

Fig. 1. Shear Mode Piezoelectric Micro-Actuator

II. Piezoelectric Micro-actuator

Two piezoelectric elements of the micro-actuator polarized horizontally in opposite direction generate the displacement. This piezoelectric element model is PIC255 made by PI Ceramic Company.

The displacement generated by the piezoelectric elements is amplified 20 times at the head by the suspension. By applying 30V, the MA (Micro-Actuator) generates 0.25μm displacement. The hysteresis of the displacement is below 10% of a full stroke.

Fig. 2 shows the experimental FR(Frequency Response) of our actuator with a head suspension assembly. The gain is flat to 1.8kHz, and dominant resonance appears at 6.8 kHz.

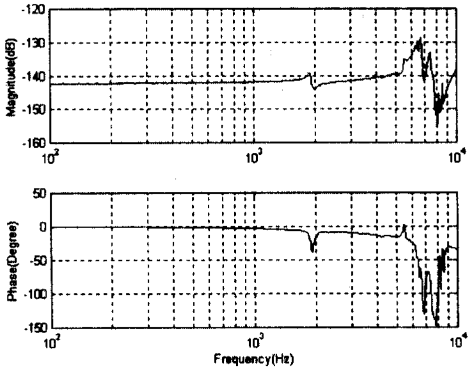

Fig. 2 Experimental Frequency Response

III. Classical Dual-loop Servo Designs

Dual-loop servo system is generally classified into two types. The one is a two-input-two-output system and the other is a two-input-one-output system. If we use an estimator for a two-input-two-output system, it can be converted into two-input-one-output system [3]. The following performance guidelines should be considered in loop [4].

1. High closed loop servo bandwidth.
2. To follow low frequency reference input by VCM
3. To follow high frequency reference input by MA.

In this section several types of control algorithms are studied and they are compared to give an outlook of each one's advantage and disadvantage.

• Parallel Loop System

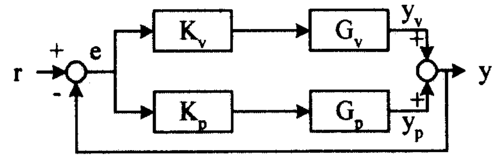

Fig. 3 Parallel Loop

The two-input-one-output system is simple, which is shown in Fig. 3. It needs only one feedback signal, and the closed loop transfer function becomes

$$y=\frac{G_vK_v+G_pK_p}{1+G_vK_v+G_pK_p}r \qquad (1)$$

G_v and K_v are the plant dynamics and the compensator for the voice coil motor (VCM) loop, and G_p and K_p are plant dynamics and compensator for the MA loop.

We used a PI controller with notch filter for the MA controller and VCM controller consists of notch filter and PD controller.

The characteristic equation is

$$1+G_vK_v+G_pK_p=0 \qquad (2)$$

We can see from Equation (2) that the MA loop is not decoupled from VCM loop. It means that the stability of the overall system can't be achieved by stabilizing each individual loop, in other words VCM or MA poles are not overall system poles. Requiring only one feedback is merit of this design [1]. Therefore, this design is useful for dual-loop servo systems that have no feedback for the relative displacement between each actuator.

From the frequency domain results, it is clear that the dual-loop servo system has higher open loop crossover frequency and closed loop BW while maintaining phase and gain margins than those of VCM only system. The comparison is given in Fig. 4 and Fig. 5.

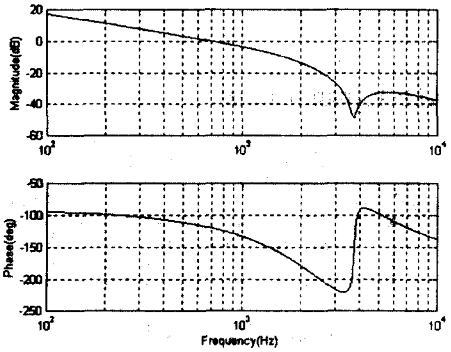

Fig. 4 Open Loop Frequency Response of VCM Only

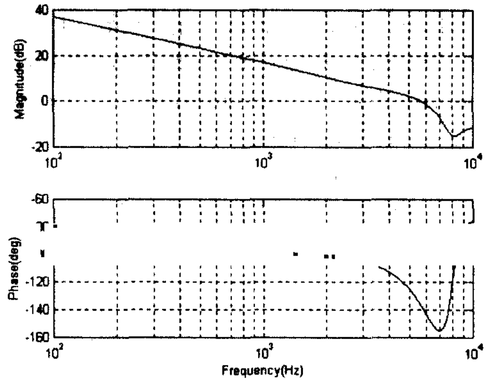

Fig. 5 Open Loop Frequency Response of Parallel Loop

Response of y_v (VCM Output) and y_p (MA output) in the overall system can be denoted as

$$y_p=\frac{G_pK_p}{1+G_vK_v+G_pK_p} \qquad (3)$$

$$y_v=\frac{G_vK_v}{1+G_vK_v+G_pK_p} \qquad (4)$$

and which is shown in Fig. 6.

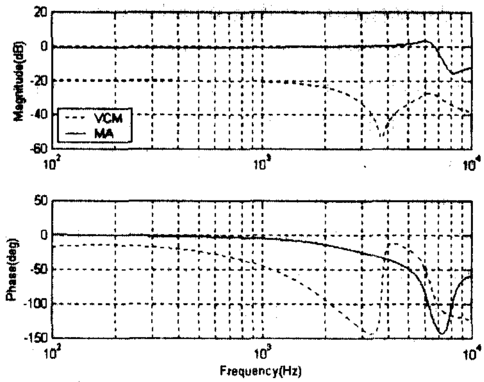

Fig. 6 Relationship between VCM and MA

The simulation result is summarized in Table 1.

Table 1 Simulation Result of Parallel Loop

Closed Loop BW (kHz)	6.8
Open Loop Cross Over (kHz)	5.5
Phase Margin (deg)	46
Settling Time (ms)	0.80

* Master-Slave Loop System

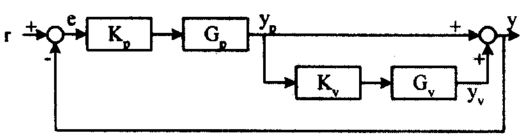

Fig. 7 Master-Slave Loop

The structure of Master-slave loop design is shown in Fig. 7 and the closed loop transfer function of this system is

$$G_{cl}=\frac{(1+G_vK_v)G_pK_p}{1+(1+G_vK_v)G_pK_p} \tag{5}$$

The open loop transfer function is

$$G_{ol}=(1+G_vK_v)G_pK_p \tag{6}$$

The constraints in designing this Maser-slave loop controller are that the term in the open loop transfer function

$$(1+G_vK_v)G_pK_p \Rightarrow G_pK_p, (s\to\infty) \tag{7}$$

and

$$\|(1+G_vK_v)G_pK_p\| \gg \|G_pK_p\|, (s\to 0) \tag{8}$$

Equation (7) points out that the overall system performance needs insensitivity to the variation of the VCM's high frequency dynamics. Equation (8) points out that the contribution of the MA loop at low frequency should be smaller than that of the VCM [3]. These relationships are shown in Fig. 10.

However, from Equation (5) it can be noted that the shaping of the closed loop transfer function cannot be completely decoupled. Additionally, this structure requires two signals, PES and y_P [1]. In other words relative motion between VCM and MA needs to be measured. Low cost dual-stage systems do not have this feedback signal instantly available. One way to solve this problem is to use the MA estimator. In this case, the accuracy of the MA model is very important.

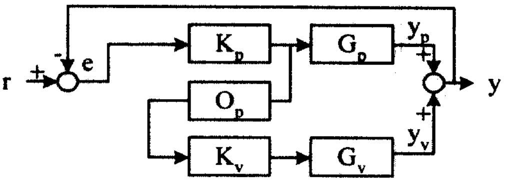

Fig. 8 Master-Slave Loop with Estimator

The Block diagram of the Maser-slave loop system with estimator is shown in Fig. 8. The MA displacement is not observed directly, and thus we need the MA estimator O_P, and simulation result is shown in Fig. 9 ~ Fig. 11 and Table 2.

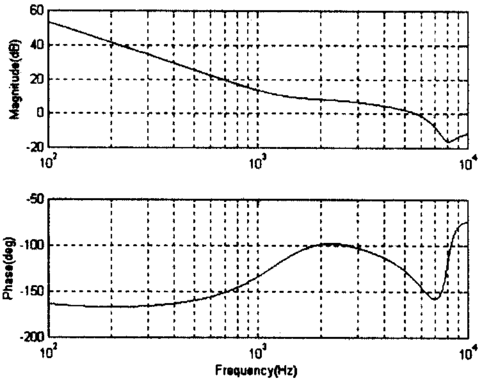

Fig. 9 Open Loop Frequency Response of Master-Slave Loop

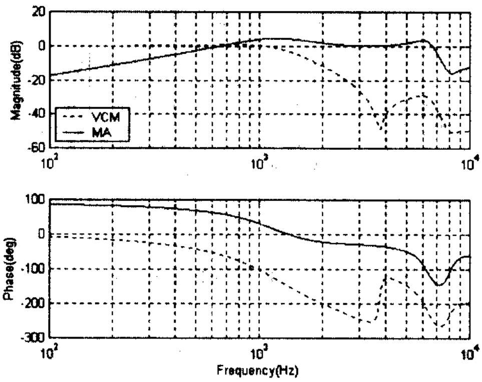

Fig. 10 Relationship between VCM and MA

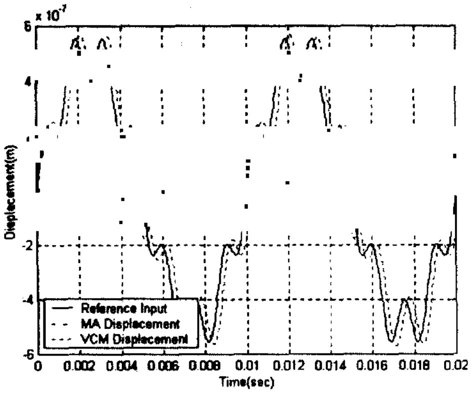

Fig. 11 Displacement of Y_p and Y_v

Table 2 Simulation Result of Master-Slave Loop

Closed Loop BW (kHz)	6.9
Open Loop Cross Over (kHz)	5.48
Phase Margin (deg)	41
Error (μm)	±0.0128
Settling Time (ms)	0.83

Fig. 11 shows that MA responds to the reference input within its stroke range and then VCM reacts against the insufficient displacement

▪ Dual Feedback Loop System

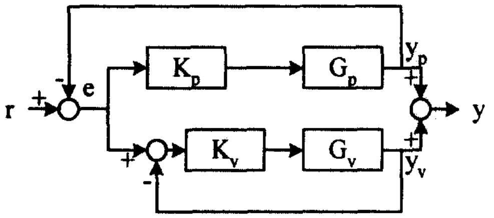

Fig. 12 Dual Feedback Loop

This design uses the displacements of both actuators as feedback signals. The structure is shown in Fig. 12. The closed loop transfer function becomes

$$y = \frac{G_v K_v (1+G_p K_p) + G_p K_p}{(1+G_p K_p)(1+G_v K_v)}\, r \qquad (9)$$

The characteristic equation is

$$(1+G_p K_p)(1+G_v K_v) = 0 \qquad (10)$$

Equation (10) shows that the design of two loops (MA loop and VCM loop) can be completely decoupled [1]. In other words, the overall system is stable when each loop is stable, which is the major advantage of this approach. However, this approach requires both y_p and y_v to be measured. Since only the PES measurement is available, the other signal needs to be estimated.

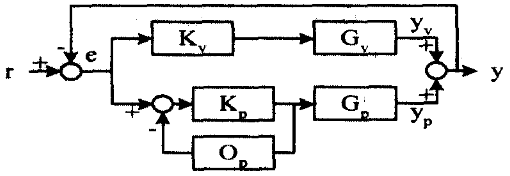

Fig. 13 Dual Feedback Loop with Estimator

A Block diagram of the Dual Feedback loop system with estimator is shown in Fig. 13, and simulation result is shown in Fig. 14 ~ Fig. 15 and Table 3.

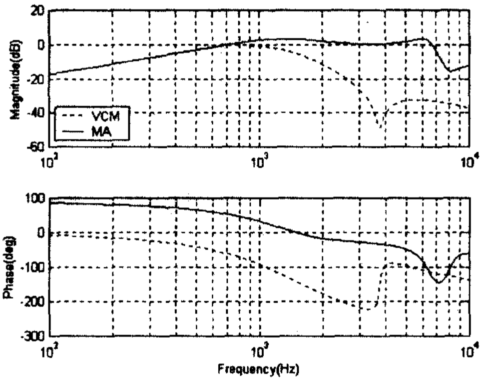

Fig. 14 Relationship between VCM and MA

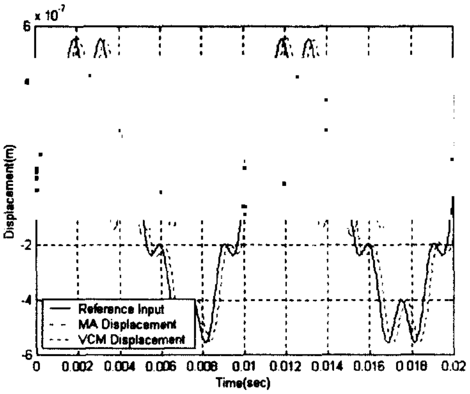

Fig. 15 Displacement of Y_p and Y_v

Table 3 Simulation Result of Dual-Feedback Loop

Closed Loop BW (kHz)	6.9
Phase Margin (deg)	41
Error (μm)	±0.0113
Settling Time (ms)	0.83

These simulation results show that the Dual-feedback loop has the same performance that Master-slave loop has except the error.

* Decoupled Master-Slave Loop System

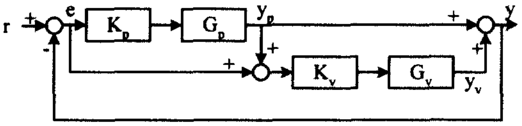

Fig. 16 Decoupled Master-Slave Loop

Fig. 16 shows the block diagram of the Decoupled Master-Slave Loop System. It is modified Master-slave loop system having an added feedforward path [4].

The characteristic equation is

$$(1+G_pK_p)(1+G_vK_v)=0 \qquad (11)$$

It is the same structure as Dual feedback loop, and the additional position sensing or estimation is required.

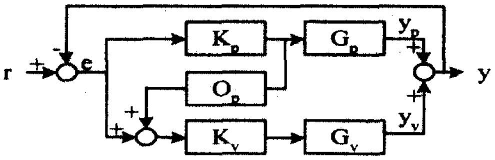

Fig. 17 Decoupled Master-Slave Loop with Estimator

A Block diagram of the Decoupled master-slave loop system with estimator is shown in Fig. 17.

Because the transfer function of Decoupled master-slave loop is identical to that of Dual-feedback loop, the simulation results are the same performance as Dual-feedback loop.

IV. Conclusion

The parallel loop design needs only one feedback signal. However, since the design of the overall system cannot be decoupled, the design of the compensators should be based on overall system stability.

In master-slave loop design, low frequency track following is covered by VCM and high frequency by MA. However, the overall system stability may not be guaranteed because of its coupling.

In dual feedback loop, VCM loop and MA loop can be completely decoupled, and thus overall system is stable when each individual loop is stable.

Decoupled master-slave loop is similar to the master-slave loop design, but it is completely decoupled.

According to this simulation result, if the accuracy of the estimator is correct enough, Dual-feedback loop or Decoupled master-slave loop seems suitable classical control method.

Acknowledgement

This work was funded by the Korea Science and Engineering Foundation (KOSEF) through the Center for Information Storage Device (CISD) Grant No. 2000G0102

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