Single/Dual-rate Digital Controller Design for Dual Stage Track Following in Hard Disk Drives

Jiagen Ding+, Hidehiko Numasato++ and Masayoshi Tomizuka+

+ Department of Mechanical Engineering

University of California at Berkeley, Berkeley, CA 94720-1740, USA

jgding@newton.Berkeley.edu, tomizuka@me.Berkeley.edu

++Data Storage & Retrieval Systems Division, Hitachi, Ltd., Odawara, Kanagawa, 256-8510, Japan

Abstract

This paper presents the design of single rate and dual rate digital controllers for dual stage servo systems. The dual stage actuator system consists of a coarse actuator(voice coil motor) and a fine actuator(peizoelectric transducer, PZT). The design is divided into two steps. In the first step, the stability of the coarse actuator loop is an important consideration. In the second step, the fine actuator loop is designed by loop shaping for superior performance of the overall system. An important consideration in the second stage is to ensure that the phase difference is away from ± 180 degrees between the coarse and fine actuator paths when the magnitudes of the two are close to each other. By loop shaping of fine actuator loop, appropriate contribution of each actuator to the final output is adjusted differently in different frequency range. In the dual rate control, the coarse actuator works at slow sampling frequency and the fine actuator works at fast sampling frequency. Simulation and experimental results justify the proposed design.

1 Introduction

Magnetic hard disk drive storage technology continues to experience a dramatic areal density growth of 60% every year and the density is predicted to reach as high as $10Gb/in^2$ by the year 2001 [1]. Very narrow data tracks are required in order to obtain such high densities. High bandwidth servo is necessary for track following with such a narrow track pitch. Dual stage servo is one way to make the servo bandwidth high. Dual stage disk servo consists of two actuators: coarse and fine actuators. The coarse actuator is low bandwidth with a large stroke, and the voice coil motor (VCM) is the most popular coarse actuator; the fine actuator is high bandwidth with a small stroke, and the piezoelectric transducer(PZT) is a popular fine actuator. Many research groups have proposed and manufactured dual stage actuator prototypes. Research efforts have also been devoted to design a simple and high-performance dual stage servo system [2, 3, 4, 5, 6].

In dual stage servo systems, usually only the total output of the two actuators is available for the servo controller. Namely, the dual stage actuator is a DISO(dual-input/single output) system and the servo controller is a SIDO(single input/dual output) system. The controller design is a special case of multi-input/multi-output system (MIMO) design. MIMO design techniques such as LQG [7], H_∞ and $\mu-$synthesis [8] have been applied to the design of dual stage disk drive systems. Robustness is not explicitly considered in LQG design for MIMO systems. H_∞ and $\mu-$synthesis approaches are advantageous in this sense. However these techniques usually result in high order controllers even after model reduction, which are hard to implement on actual hardware.

The master-slave method[9] is an attempt to treat this MIMO design as a sequence of SISO designs under the assumption that there is very little interaction between the two SISO loops, one for VCM and the other for PZT. In reality, there is interaction between the two SISO loops, which deteriorates performance. The PQ method [10] reduces the problem to two SISO systems while overcoming the disadvantage of the master-slave method. PQ method, however, does not guarantee the stability of the VCM loop. The VCM loop is expected to be stable so that the disk drive still works safely when the microactuator is not activated. In this paper, the VCM loop is first designed to be stable, then the PZT loop is designed to improve the system performance. The bandwidth of the PZT loop will be naturally set higher than that of the VCM loop. This leads us to consider dual rate control: fast sampling rate for the PZT loop and a slow sampling rate for VCM. This approach will reduce the overall computational load on the processor.

The paper first establishes the design criterion for dual stage servo systems, which is analogous to the one used by S.J. Schroceck and W.C. Messner [10]. This paper is organized as follows. Section 2 presents modeling of the dual stage actuator. Section 3 discusses the single rate digital controller design for dual stage servo systems. Section 4 presents the design of dual rate

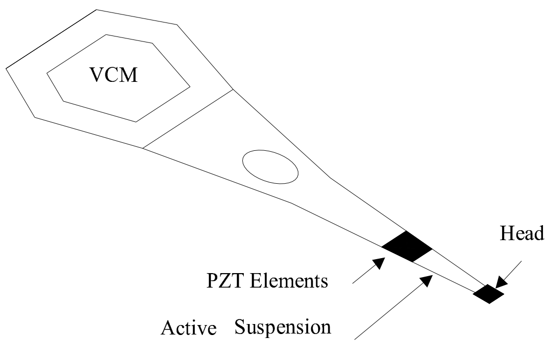

Figure 1: Dual stage model

digital controllers for dual stage servo systems. Section 5 shows a design and analysis example. Section 6 shows exeperimental results. Concluding remarks are given in section 7.

2 Dual Stage Actuator Model

The microactuator considered in this paper is a piezoelectric tansducer(PZT) placed at the carriage end of the suspension load beam(see Figure 1). The PZT elements expand and contract when a voltage potential is applied across their thickness. This results in rotation of the load beam and production of a slider off track motion. Current piezoelectric actuator attains a stroke displacement of about 2 μm. The coarse actuator is a conventional Voice Coil Motor(VCM). Since the inertia and force of PZT are much smaller than those of VCM, and the PZT exhibits the first resonant frequency at $8.2kHz$, which is significantly higher than the bandwidth of VCM , the dual stage system model is decoupled into VCM transfer function G_1 and the PZT transfer function G_2 generating the relative displacement of W/R head. The VCM is modeled as a second order system. The transfer function of which looks like a double integrator at relatively high frequencies but flattens out at low frequencies due to pivot bearing friction effect. High resonant mode is also included in the VCM model. The PZT actuator(including the analog notch filter) is modeled as a second order system with the first resonant frequency at $8.2kHz$. Computational delay is represented by the first order Pade approximation for the two actuators. The transfer function models of two actuators are:

$$G_1(s) = K\_vcm \frac{\omega_1^2}{s^2 + 2\zeta_1\omega_1 s + \omega_1^2} \frac{\omega_2^2}{s^2 + 2\zeta_2\omega_2 s + \omega_2^2} \frac{-0.5D_1 s + 1}{0.5D_1 s + 1} \quad (1)$$

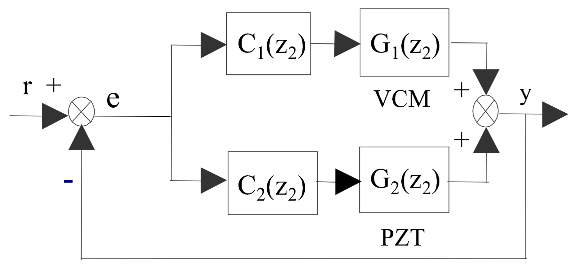

Figure 2: Dual stage single-rate design block

$$G_2(s) = K\_pzt \frac{\omega_3^2}{s^2 + 2\zeta_3\omega_3 s + \omega_3^2} \frac{-0.5D_2 s + 1}{0.5D_2 s + 1} \quad (2)$$

3 Dual Stage Single Rate Controller Design

The VCM controller and the PZT controller are repesptively represented by $C_1(z_2)$ and $C_2(z_2)$ in Figure 2. $G_1(z_2)$ denotes the coarse actuator (VCM, voice coil motor) dynamics and $G_2(z_2)$ the fine actuator (Piezoelectric actuator) dynamics in the discrete time domain. The discrete time models are zero order hold equivalents of the continuous time transfer functions (1) and (2).

From the block diagram, the total output sensitivity function is:

$$S = \frac{1}{1 + (C_1G_1 + C_2G_2)} \quad (3)$$

From this sensitivity function, good output disturbance rejection requires $(C_1G_1 + C_2G_2)$ to be large in the bandwidth of the system. Because of low bandwidth nature of G_1 and high bandwidth but small stroke nature of G_2, C_1G_1 should be large at low frequencies and C_2G_2 should be large at high frequencies. Let $G_0 = C_1G_1 + C_2G_2$, then $G_0 \approx C_1G_1$ at low frequencies and $G_0 \approx C_2G_2$ at high frequencies. When the magnitude of C_1G_1 and that of C_2G_2 are close to each other, the phase difference between C_1G_1 and C_2G_2 should be far from ± 180 degrees; otherwise the two actuators will fight each other resulting in poor control.

The design process is divided into two steps: the first step is to find C_1 for VCM loop, where C_1 should includes those compensators which work mainly in the low frequency range. In this step, the VCM loop is designed to be stable which is not necessary for the system's stability but very helpful for preventing damage of disk drive systems when the microactuator is not activated. The second step is to design C_2. It should include those compensators which work mainly in the high frequency range. So C_1 includes a digital integrator C_i for rejecting constant bias, a notch filter C_{n1}

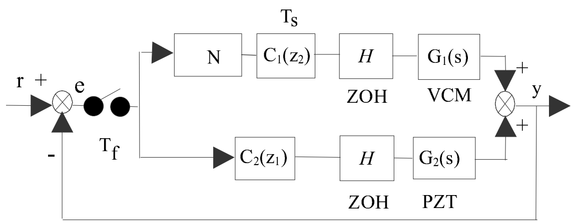

Figure 3: Dual stage dual rate design block

for notching out the resonant peak and a shaping compensator C_{p1} for obtaining appropriate gain and phase margin for the VCM loop. C_2 contains a notch filter C_{n2} (implemented by analog filter because of high resonance frequency at about $8.2kHz$) and shaping compensator C_{p2} in order to satisfy the design specification. C_2 does not include integrator for preventing saturation.

$$C_1 = C_i C_{n1} C_{p1}, C_2 = C_{n2} C_{p2} \tag{4}$$

In order to design C_{p2} , let

$$R = \frac{C_1 G_1}{C_2 G_2} = \frac{C_i C_{n1} C_{p1} G_1}{C_{n2} C_{p2} G_2} \tag{5}$$

From the above analysis, R should be large in the low frequency range and small in the high frequency range. When the magnitude of R is close to one, the phase of R should be far from $\pm 180°$. C_{p2} is chosen by loop shaping to satisfy the requirement on R.

4 Dual Stage Dual Rate Controller Design

Digital dual stage servo system is composed of two parallel paths: VCM path and PZT path. The controller in VCM loop is updated at slow sampling frequency since the VCM works mainly at low frequencies, which can save the computational burden. The controller in PZT loop is updated at high sampling frequency in order to gain better performace at high frequencies. Figure 3 shows the dual rate dual stage system. The PES(position error signal) is obtained at fast sampling frequency(T_f). The PZT controller updates its output every T_f. The VCM controller updates its output at a lower sampling frequency(T_s). From the block diagram(see Figure 3), the PES(sampled at T_f) goes directly to the PZT controller. The PES signal is first downsampled by $N(=T_s/T_f)$ then goes to the VCM digital controller, which works at slow sampling frequecny. The output of VCM digital controller goes to VCM actuator via zero order hold. It is assumed that the PES signal is bandlimited: i.e. the frequency spectrum is contained in the interval $[-1/(2T_s), 1/(2T_s)]$. Let z_1 denote the delay operator for the fast sampling frequency and z_2 denote the delay operator for the slow sampling frequency. The approximate transfer function is derived for VCM path at high sampling frequency in the following manner:

$$PES_s(z_2) = \frac{1}{N} \sum_{k=1}^{N-1} PES_f(z_1 e^{j\frac{2\pi k}{N}})|_{z_1 = z_2^{1/N}} \tag{6}$$

By the assumption that PES signal is bandlimited by $\frac{1}{2T_s}$ the above equation can be simplified as follows

$$PES_s(z_2) = \frac{1}{N} PES_f(z_1)|_{z_1 = z_2^{1/N}} \ (0 \leq \omega \leq \frac{\pi}{T_s}) \tag{7}$$

The output of VCM controller is:

$$U_{vcm}(z_2) = C_1(z_2) PES_s(z_2) \tag{8}$$

The outpupt of VCM controller is directed to VCM actuator via zero order hold. This VCM actuator input signal can be viewed as the sum of delayed upsampled VCM controller outputs, i.e.

$$\begin{aligned} & U_{vcm}(z_1) \\ = \ & U_{vcm(Z_2)}|_{z_2 = z_1^N} (1 + z_1^{-1} + ... + z_1^{-(N-1)}) \\ = \ & \frac{1}{N} PES_f(z_1) C_1(z_1^N)(1 + z_1^{-1} + ... + z_1^{-(N-1)}) \end{aligned} \tag{9}$$

So the equivalent high sampling frequency transfer function for the VCM loop is:

$$(C_1 G_1)_{eq} = \frac{1}{N} C_1(z_1^N)(1 + z_1^{-1} + ... + z_1^{-(N-1)}) G_1(z_1) \tag{10}$$

By the above approximation of VCM loop, the dual rate dual stage servo design is converted to single rate design at high sampling frequency.

5 Design Example

In this section, we presents a design example of dual stage servo for hard disk drives. The design specification is to achieve about $2.0kHz$ bandwidth, $40°$ phase margin and $4dB$ or larger gain margin. The sampling frequency for VCM controller is $10.9kHz$ and the fast sampling frequency for PZT controller is $30.3kHz$. In single rate dual stage control, the two controller work at slow sampling frequency. In dual rate dual stage control, the VCM controller works at slow sampling frequency and the PZT controller at high sampling frequency.

Figure 4 is the Bode plots of VCM and PZT, For the PZT loop, the solid line corresponds to the frequency response under slow sampling frequency and the dash line to the frequency response under fast sampling frequency. The conventional controller for VCM in the single stage servo is:

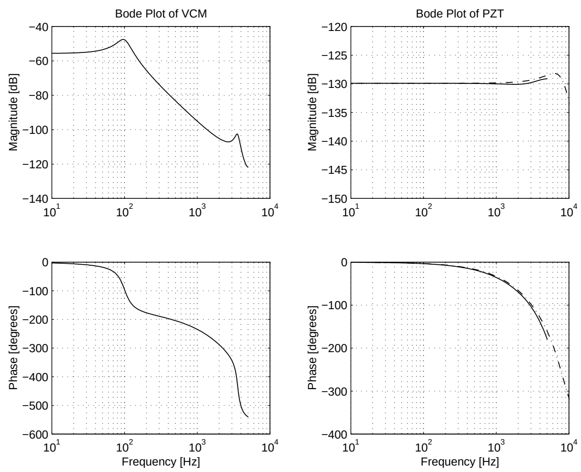

Figure 4: Dual actuator Bode plots

$$C_0 = 8.61e4\frac{(z_2-0.8995)^2(z_2-0.6214)}{(z_2-1)(z_2-0.4594)(z_2+0.3709)} \quad (11)$$

In the present dual stage system, notch filters are implemented by analog filters and they are included respectively in the VCM and PZT plant models. The VCM controller works at low sampling frequency in single/dual rate dual stage design. The same VCM controller is used in the single rate and dual rate design, and it is given by:

$$C_1 = 7.46e5\frac{z_2-0.6214}{z_2-1}\frac{(z_2-0.8556)^2}{(z_2-0.5623)(z_2+0.3709)} \quad (12)$$

In the single rate design, the PZT controller is:

$$C_2 = 2.28e6\frac{(z_2-1)(z_2-0.1247)}{(z_2-0.9938)(z_2-0.9396)} \quad (13)$$

In the dual rate design, the PZT controller is:

$$C_2 = 1.65e6\frac{(z_1-1)(z_1-0.588)}{(z_1-0.9979)(z_1-0.9795)} \quad (14)$$

Figure 5 and 6 are the Bode plots of VCM and PZT open loops for single/dual rate design(notice that VCM loop is designed to be stable). The ratio(R) of VCM over PZT open loop is given in Figure 7. The dash line is the ratio for the single rate design and the solid line is for the dual rate design. From this figure, R is large at low frequencies and small at high frequencies. When the magnitude of R is close to one, the phase is far from $\pm 180°$.

Figure 8 is the total open loop Bode plots for conventional design, single rate dual stage design and dual rate dual stage design. The solid line corresponds to the dual rate dual stage design,the dot-dash line to the

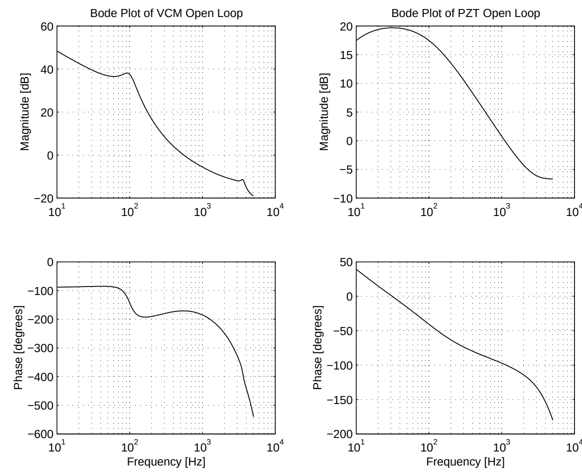

Figure 5: Single rate dual stage open loop

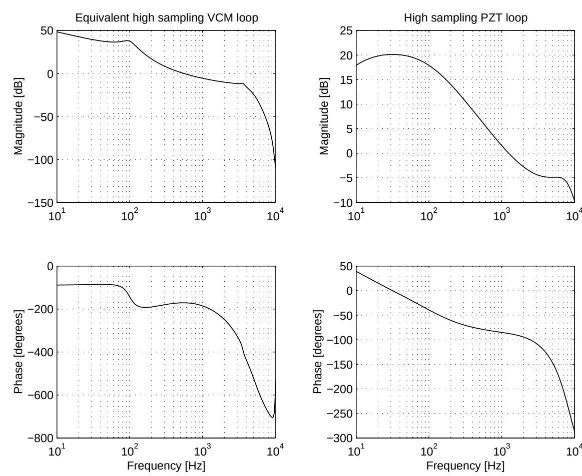

Figure 6: Dual rate dual stage open loop

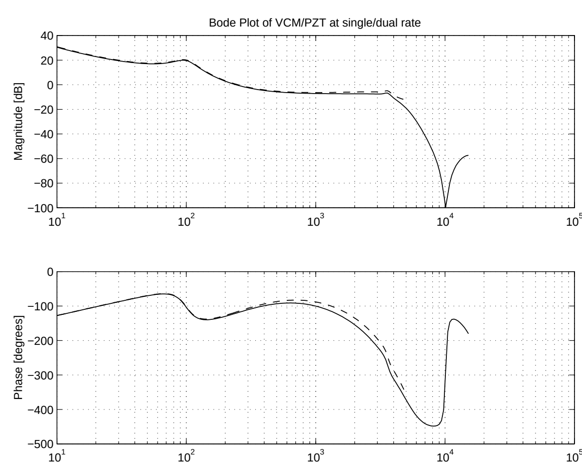

Figure 7: Single/Dual rate R-evaluation plot

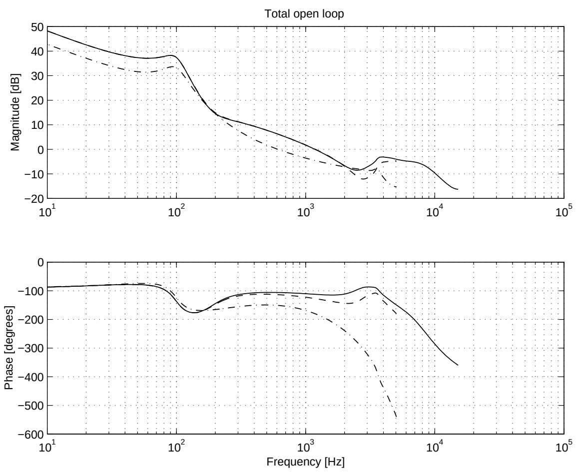

Figure 8: Total open loop

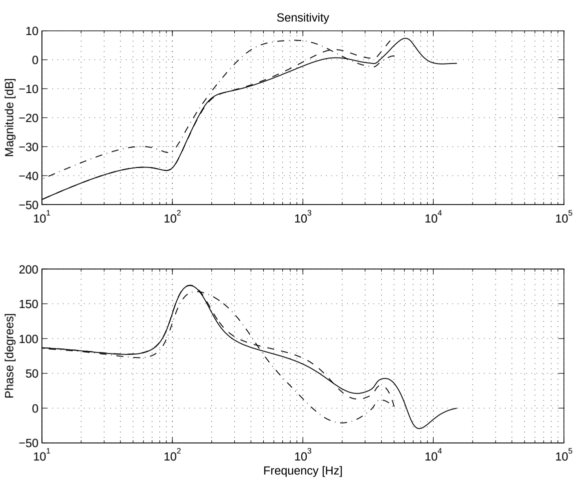

Figure 9: Sensitivity Function

conventional single stage open loop and the dash line to the single rate dual stage design. In the conventional single stage design, the phase margin is $35.7°$ at $620Hz$ and gain margin $5.2dB$. In the dual stage single rate design, the phase margin is $54°$ at $1.3kHz$ and the gain margin is about $12dB$. In the dual stage dual rate design, the phase margin is $65°$ at $1.3kHz$ and the gain margin is about $4.7dB$.

Figure 9 is the plots of sensitivity functions. The solid line corresponds to the dual rate dual stage servo design, the dot line to the conventional single stage design and the dot-dash line to the single rate dual stage design. The dual stage design gains better disturbance rejection compared to conventional design. The dual rate dual stage design has better performance than the single rate dual stage design around $2.0kHz$.

6 Experiment Result

Figure 10 shows the experiment disk drive system. The VCM controller is implemented on the microprocessor

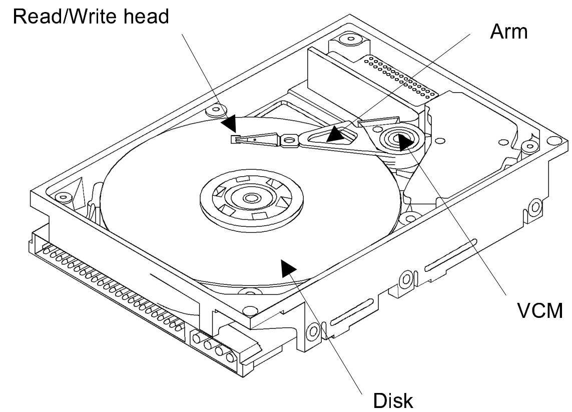

Figure 10: Disk drive schematic

Table 1: Experiment setup specification

Capcity	$18.4GB$
Disks	$5/3.5"$
TPI	$13,000$
Spindle Speed	$7,208rpm$
Sampling Period	$99.1\mu s(slow)/33.0\mu s(fast)$
Average Seek Time	$6.5/7.5ms$(Read/Write)

embedded in the current disk drive system. The PZT microactuator controller is implemented on an external DSP. In current experiment, the analog notch filter is not implemented for VCM, which causes no stability problem in the single stage/dual stage single rate design. In the dual stage dual rate design, this VCM notch filter need to be implemented in order to improve performance significantly at around 2kHz by the high sampling rate PZT controller. The experiment hard disk drive has specifications in the Table 1.

In the experiment disk drive, there are total five disks stacked together and one of the arms has the PZT actuator mounted. First we implemented the conventional single stage design and measured the position error sig-

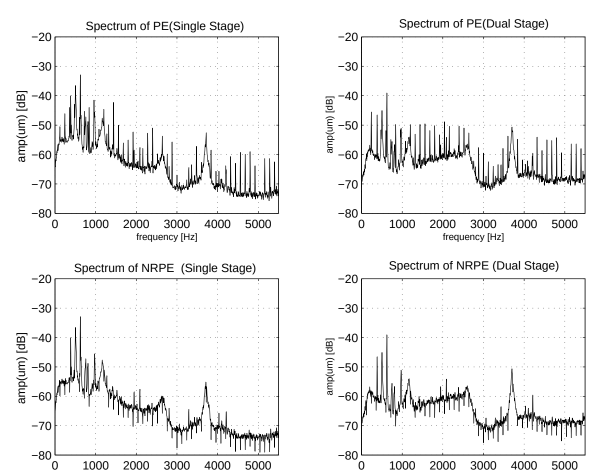

Figure 11: PES spectrum

nal (PES). Then the single rate dual stage design was tested for the dual stage servo and the corresponding PES was measured. Figure 11 shows the PES spectrum for the single stage and dual stage servo. Table 2 shows the standard deviation(STD) of PES composed of NRPE (nonrepeatable position error) and RPE (repeatable position error).

Table 2: PES STD of single stage/dual stage servo

Item	Single Stage	Dual Stage	improvement
NRPE	$0.040\mu m$	$0.024\mu m$	40%
RPE	$0.018\mu m$	$0.013\mu m$	28%

In the experiment, we gained about 40% performance improvement in NRPE STD by single rate dual stage servo over conventional single stage servo. Dual stage dual-rate design was also implemented without notch filter for VCM: In this case, 43% performance improvement was obtained in NRPE STD and same improvement was observed for RPE STD. The experiment is under way for the dual stage dual rate design with an analog notch filer for VCM.

7 Conclusion

Single rate and dual rate controllers are designed for dual stage track following. Natural separation of controller authority was considered between VCM and PZT paths: VCM works mainly at low frequecies and PZT works at high frequencies. The VCM loop is designed to be stable in the dual stage design. A dual rate design scheme has been developed and the design example shows that the dual rate design has better performance at high frequencies. R-evaluation shows the cooperation of the two actuators. Low order controllers are obtained(5 for the VCM actuator and 4 for PZT actuator) for easy implementation. Proposed design is justified by experimental results.

Acknowledgements

This research was conducted at the Computer Mechanics Laboratory(CML) in the Department of Mechanical Engineering, University of California at Berkeley. The authors wish to thank Mr. Craig Smith for discussion.

References

[1] Grochowski and R. Hoyt, "Future trends in hard disk drives", *IEEE Transactions on Magnetics*, vol.32, pp.1850-1854, May 1996.

[2] S. K. Aggarwal, D. A. Horsley, R. Horowitz, and A. P.Pisano, "Micro-actuators for High Density Disk Drives", in *Proceedings of the American Control Conference*, Albuquerque, New Mexico, pp.3979-3984, June, 1997.

[3] R.B. Evans, J.S. Griesbach and W.C. Messner, "Piezoelectric Microactuator for Dual Stage Control",*IEEE Transactions on Magnetics,* vol.35, pp.977-982, March 1999.

[4] S. Koganezawa, Y. Uematsu and T. Yamada, "Dual-Stage Actuator System for Magnet ic Disk Drives Using a Shear Mode Piezoelectric Microactuator",*IEEE Transactions on Magnetics,* vol.35, pp.988-992, March 1999.

[5] D. A. Horsley, N. Wongkomet,R. Horowitz, and A. P. Pisano, "Precision Positioning Using a Microfabricated Electrostatic Actuator",*IEEE Transactions on Magnetics,* vol.35, pp.993-999, March 1999.

[6] D. A. Horsley, D. Hernandez, R. Horowitz, A. K. Packard and A. P. Pisano, "Closed-Loop Control of a Microfabricated Actuator for Dual Stage Hard Disk Drive Servo Systems", in *Proceedings of the American Control Conference*, Philadelphia, PA, June, 1998.

[7] X. Hu, W. Guo, T. Huang and B. M.Chen, "Discrete time LQG/LTR Dual Stage Controller Deisgn and Implementation for High Tracking Density HDDS", in *Proceedings of the American Control Conference*, San Diego, CA, pp.4111-4115, June, 1999.

[8] D. Hernandez, S. S. Park, R. Horowitz, and A. K. Packard, "Dual-Stage Tracking-Following Servo Design for Hard Disk Drives", in *Proceedings of the American Control Conference*, San Diego, CA, pp.4116-4121, June, 1999.

[9] T. Hirano, L.S. Fan, W. Y. Lee, J. Hong, W. Imaino, S. Pattanaik, S. Chan, P. Webb, R. Horowitz , S. Aggarwal and D. A. Horsley, "High-Bandwidth High-Accuracy Rotary Microactuators for Magnetic Hard Disk Drive Tracking Servos", *IEEE/ASME Transactions on Mechatronics*, vol.3, pp156-165, September 1998.

[10] S. J. Schroceck and W. C. Messner, "On Controller Design for Linear Time-Invariant Dual-Input Single-Output Systems", in *Proceedings of the American Control Conference*, San Diego, CA, pp.4122-4126, June 1999.