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15th Triennial World Congress, Barcelona, Spain

DUAL-STAGE ACTUATOR DESIGN FOR HDD SYSTEMS VIA CNF CONTROL

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Abstract: Dual-stage actuator design for hard disk drives via composite nonlinear feedback control is presented, which consists of a primary actuator, the voice coil motor and a secondary actuator, the suspension piezoelectric microactuator. The first is effective in both track seeking and following stages to produce fast rising time and low overshoot and the latter works in track following stage only to help the primary actuator. The implementations show that the dual-stage actuator does yield better performance compared to the single primary actuator. *Copyright ©2002 IFAC*

Keywords: Servo systems, Actuators, Control algorithm, Control application, Nonlinear control.

1. INTRODUCTION

The prevalent trend in hard disk drives (HDD) is towards smaller hard disks with increasingly larger capacities. One of the limitations in the conventional hard disk drives to achieve higher data capacity is its bandwidth. That is, the voice coil motor (VCM) as an actuator has a lot of flexible resonance in high frequencies over 2 kHz. (Workman, 1987), which limits the increase of bandwidth. A possible solution to this kind of problems is to introduce an additional microactuator on top of the conventional VCM actuator to provide a faster and finer response. Dual-stage actuator refers to the fact that there is a small actuator mounted on a large conventional VCM actuator. This small actuator or microactuator will be used only to follow a small data track. Figure 1 shows a simple illustration of a dual-stage actuator HDD servo system used in this paper. The piezoelectric microactuator produces relative motion of the read/write (R/W) head along the radial direction (Evans *et al.*, 1999; Guo *et al.*, 1999) and only the displacement of the R/W head is available as a measurement output.

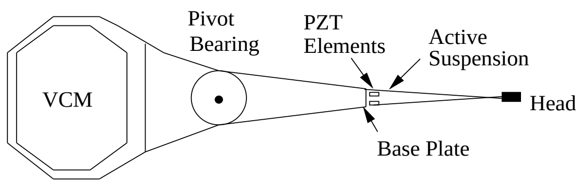

Fig. 1. A dual-stage actuator HDD servo system

Diverse control methods have been reported to design the dual-stage actuator HDD servo system (Guo *et al.*, 1999; Hu et al., 1999). But, much studies on the control methods need to be conducted to achieve better results in HDD servo systems. This paper is focused to design a dual-stage actuator control law using the composite nonlinear feedback (CNF) control technique for HDD servo systems. The CNF control technique proposed by Lin *et al.* (1998) for a class of second order systems with state feedback, has recently been extended by Chen *et al.* (2002) to general linear systems with measurement feedback. In the designed dual-stage actuator HDD servo system, the VCM will be controlled with a control law designed with a modified CNF method and the microactuator will be controlled with a filter, whose input signal is the tracking error of the VCM. The two parts will then be combined to yield a dual-stage actuator control law.

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This paper is organized as follows. In Section 2, the model of the dual-stage actuator HDD servo system will be identified. The modified reduced order measurement feedback CNF (roCNF) will be presented in Sections 3. The dual-stage actuator control law will be designed for the HDD servo system in Section 4. The implementation results will be shown in Section 5, where the closed-loop system in the dual-stage actuator will be compared with that in the single VCM. Finally, conclusions are drawn in Section 6.

2. MODELING OF THE DUAL-STAGE ACTUATOR HDD SERVO SYSTEM

The models of the VCM actuator and the microactuator are identified through frequency response characteristics obtained through experiments to compose the model of the dual-stage actuator HDD servo system. The typical frequency response characteristics of the VCM and the microactuator are respectively shown in Figures 2 and 3. Using the measured data from the actual systems and the algorithms of Eykhoff (1981), a fourth order model is obtained for the VCM actuator,

$$G_v(s) = \frac{6.4013 \times 10^7}{s^2} \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}, \quad (1)$$

where $\zeta = 0.085$, $\omega_n = 1.1309 \times 10^4$ rad/sec and a fourth order model for the microactuator,

$$G_m(s) = \frac{b_0 s^2 + b_1 s + b_2}{s^4 + a_3 s^3 + a_2 s^2 + a_1 s + a_0}. \quad (2)$$

where $b_0 = 1.593 \times 10^9$, $b_1 = 1.708 \times 10^{12}$, $b_2 = 2.512 \times 10^{18}$, $a_3 = 4256$, $a_2 = 3.506 \times 10^9$, $a_1 = 7.496 \times 10^{12}$ and $a_0 = 2.512 \times 10^{18}$. The only measured output, y

$$y = y_v + y_m. \quad (3)$$

where y_v and y_m are outputs of VCM and microactuator respectively. The units are in volts and μm respectively for the input and output in the models. These models compose the model of the dual-stage actuator HDD servo system, which will be used throughout the rest of the paper.

The objective is to design a dual-stage actuator control law for the HDD servo system that meets the following constraint and specifications:

(1) The input signal to the VCM should not exceed ± 3 Volts, and the input signal to the microactuator should be within ± 2 Volts due to physical constraint on the two actuators.

(2) The maximal displacement of the microactuator is about 1μm. It should settle down to zero in steady state so that it can be used further for the next move.

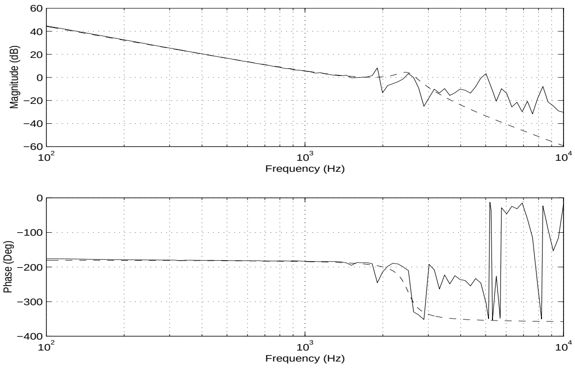


Fig. 2. Frequency response of the VCM actuator

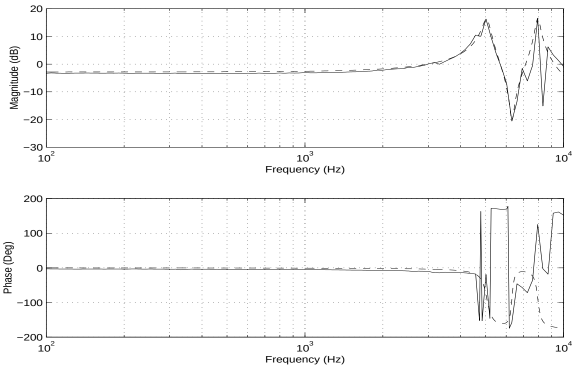


Fig. 3. Frequency response of the microactuator

(3) The overshoot and undershoot of the step response should be kept less than 5% of one track pitch, i.e. 0.05μm, so that the R/W head can write data on to the disk reliably.

3. MODIFIED ROCNF

A modified roCNF will be proposed to design the dual-stage actuator control law for HDD servo systems, which remains the merits of the roCNF (Chen *et al.*, 2002), while takes the additional input to obtain better performance. Consider a linear system with constrained actuators, which briefly outlines the dual-stage actuator HDD servo system, characterized by

$$\begin{cases} \dot{x} &= Ax + B\text{sat}(u_1), \quad x(0) = x_0 \\ y &= C_1 x + D_1 \text{sat}(u_2), \\ h &= C_2 x + D_2 \text{sat}(u_2). \end{cases} \quad (4)$$

where $x \in \mathbb{R}^n$, $u_i (i = 1, 2) \in \mathbb{R}$, $y \in \mathbb{R}^p$ and $h \in \mathbb{R}$ are respectively the state, control inputs, measured output and controlled output of the system (4). $A, B\, C_1, C_2, D_1$ and D_2 are appropriate dimensional constant matrices, and sat: $\mathbb{R} \to \mathbb{R}$ represents the actuator saturation defined as

$$\begin{aligned} \text{sat}(u_1) &= \text{sgn}(u_1) \min\{u_{1\max}, |u_1|\}, \\ \text{sat}(u_2) &= \text{sgn}(u_2) \min\{u_{2\max}, |u_2|\}. \end{aligned} \quad (5)$$

with $u_{1\max}, u_{2\max}$ being the saturation levels of the inputs. The following assumptions on the system matrices are required:

(1) (A,B) is stabilizable,
(2) (A,C_1) is detectable,
(3) D_1 and D_2 are not zero, and
(4) (A,B,C_2) is invertible and has no invariant zeros at $s=0$.

For the given system (4), it is clear that there are p states of the system measurable, if C_1 is of maximal rank. Generally, it is not necessary to estimate these measurable states in measurement feedback. A dynamic control law can be designed with a dynamical order less than that of the given plant. For simplicity of presentation, it is assumed that C_1 is already in the form, $C_1 = [I_p \quad 0]$. Then, the system (4) can be rewritten as,

$$\begin{cases} \begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} &= \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} \mathrm{sat}(u_1), \\ y &= [I_p \quad 0] \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + D_1 \mathrm{sat}(u_2), \\ h &= C_2 \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + D_2 \mathrm{sat}(u_2). \end{cases} \tag{6}$$

$x_0 = (x_{10} \quad x_{20})'$, where the original x is partitioned into two parts, x_1 and x_2 with $\hat{y}_1 = y - D_1 \mathrm{sat}(u_2) \equiv x_1$. Thus, x_1 can be obtained directly from $\hat{y}_1$ and it will need to estimate x_2 only. Next, let F be chosen such that 1) $A+BF$ is asymptotically stable, and 2) $C_2(sI - A - BF)^{-1}B$ has desired properties, and let K_R be chosen such that $A_{22}+K_R A_{12}$ is asymptotically stable. A stabilizing K_R exists as (A_{22},A_{12}) is detectable if and only if (A,C_1) is detectable (Chen, 1991). Then F is partitioned in conformity with x_1 and x_2, $F = [F_1 \quad F_2]$. The modified roCNF control law is given by

$$\begin{cases} \dot{z} &= A_R z + B_{zy}\hat{y}_1 + B_{zy}\,\mathrm{sat}(u_1), \\ u_1 &= F(x_r - x_e) + H r + \rho(r,\hat{h}_1) B' P (x_r - x_e), \\ u_2 &= k_m\, \mu_m\, (r - \hat{h}_1). \end{cases} \tag{7}$$

where $A_R = A_{22} + K_R A_{12}$; $B_{zy} = A_{21} + K_R A_{11} - A_R K_R$; $B_{zu} = B_2 + K_R B_1$; $x_r = (\hat{y}_1 \quad z - K_R\,\hat{y}_1)'$; $x_e = -(A+BF)^{-1}BG\ r$; $G = -[C_2(A+BF)^{-1}B]^{-1}$; $H = [1 - F(A+BF)^{-1}B]G$; r is the step command input; $\rho(r,\hat{h}_1)$ is non-positive scalar function locally Lipschitz in $\hat{h}_1 = C_2\, x_r$ subject to certain constraint to be discussed later; $P > 0$ is the solution to the Lyapunov equation,

$$(A+BF)'P + P(A+BF) = -W_P. \tag{8}$$

Where $W_P \in \mathbb{R}^{n\times n} > 0$. k_m is a gain to be determined; μ_m is a switch defined as follows.

$$\mu_m = \begin{cases} 0 & |r - \hat{h}_1| > e_{\max} \\ 1 & |r - \hat{h}_1| \le e_{\max} \end{cases}, \tag{9}$$

where $e_{\max} \le | D_2 \mid u_{2\max}$. let P be partitioned in conformity with x_1 and x_2, $P = [P_1 \quad P_2]$ and $Q_R > 0$ be the solution to another Lyapunov equation,

$$A_R' Q_R + Q_R A_R = -W_R. \tag{10}$$

where $W_R \in \mathbb{R}^{(n-p)\times(n-p)} > 0$ with minimal eigenvalue greater than maximum of $(a\rho^2 + b\rho + c)$ for $\rho \in [-\rho^\star, 0]$, where $\rho^\star > 0$ is a scalar; b is the minimal eigenvalue of $(P_2BB'PW_P^{-1}PBF_2 + F_2'B'PW_P^{-1}PBB'P_2)$; a and c are the maximal eigenvalues of $P_2BB'PW_P^{-1}PBB'P_2$ and $F_2'B'PW_P^{-1}PBF_2$ respectively. Note that such P and Q_R exist as $A+BF$ and A_R are asymptotically stable. For any $\delta \in (0,1)$, let c_δ be the largest positive scalar such that for all

$$\begin{pmatrix} x \\ z \end{pmatrix} \in X_{R\delta} := \left\{ \begin{pmatrix} x \\ z \end{pmatrix} : \begin{pmatrix} x \\ z \end{pmatrix}' \begin{bmatrix} P & 0 \\ 0 & Q_R \end{bmatrix} \begin{pmatrix} x \\ z \end{pmatrix} \le c_\delta \right\}$$
$$\Rightarrow \left| [F \quad F_2] \begin{pmatrix} x \\ z \end{pmatrix} \right| \le u_{1\max}(1-\delta). \tag{11}$$

Theorem 3.1. Consider the system (4). Then, there exists a scalar $\rho^* > 0$ such that for any non-positive function $\rho(r,\hat{h}_1)$, locally Lipschitz in $\hat{h}_1$ and $|\rho(r,\hat{h}_1)| \le \rho^*$, the modified roCNF control law (7) will drive the controlled output h to asymptotically track the step command input of amplitude r from an initial state x_0 and make the closed-loop system in dual inputs u_1,u_2 have faster settling time than that in single input u_1 provided that x_0, z_0, r. k_m and $e_{\max}$ satisfy

$$\begin{pmatrix} x_0 - x_e \\ z_0 - x_{20} - K_R x_{10} \end{pmatrix} \in X_{R\delta},\ |Hr| \le \delta u_{1\max}, \\ e_{\max} \le |D_2|\, u_{2\max},\ 0 < D_2\, k_m < 1. \tag{12}$$

The proof is skipped due to the space limits.

Remark 3.1. Theorem(3.1) shows that the input u_2 will settle down to zero in the steady state and the closed-loop system in dual inputs u_1,u_2 has faster settling time than that in single input u_1 (i.e. $k_m = 0$).

4. DESIGN OF DUAL-STAGE ACTUATOR HDD SERVO SYSTEM

The only available measurement in the dual-stage actuator HDD servo system is the displacement of the R/W head, the combination of outputs of the VCM and the microactuator. It has to control both actuators using one measurement, which makes difficult to design the dual-stage actuator control law. However, It is possible to design an appropriate filter make the model of the microactuator to be approximated as a constant based on its characteristics. As such, the dual-stage actuator HDD servo system can be modeled like (4). The proposed control strategy is shown in Figure 4, where MA is the microactuator; FTR is the filter; k_s is the static gain of the microactuator; k_m is a feedback gain; y is the only measurable output; r is the step command input; y_v and y_m are the outputs of the VCM and microactuator respectively; $\hat{y}_v$ and $\hat{y}_m$ are the estimated outputs of the VCM and microactuator respectively; u_v and u_m are the input signals to the VCM and microactuator respectively; SW is a switch

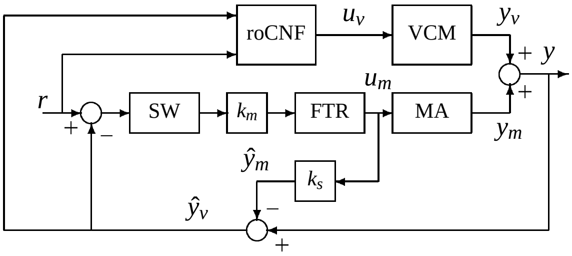


Fig. 4. The schematic representation of dual-stage actuator control

defined as (9). Specifically, the output of the microactuator is estimated directly from its input u_m and then the output of the VCM is obtained from $y-\hat{y}_m$. $\hat{y}_v$ is as a virtual measurement to the roCNF controller. The VCM is a major actuator to be effective in both track seeking and track following stages and the microactuator is a secondary actuator to help the VCM during track following stage. The procedure to design the dual-stage actuator control law is as follows.

(1) Design the roCNF control law for the VCM provided that $\hat{y}_v$ is a virtual output. The procedure can be found in (Chen *et al.*, 2002).

(2) Determine $e_{\max}$ for the switch such that

$$e_{\max} \le |k_s|\, u_{m\max}. \tag{13}$$

where $u_{m\max}$ is the maximum of the input signal to microactuator.

(3) Design an appropriate stable filter with unit static gain, $G_f(s)$ to have the model of the microactuator to be approximated as

$$G_m(s)G_f(s) \approx k_s. \tag{14}$$

Generally, $G_f(s)$ must have a larger bandwidth than that of the closed-loop system in the single VCM.

(4) Choose the gain k_m such that

$$0 < \sigma_{f\max}\, k_m\, k_s < 1 \tag{15}$$

to make the closed-loop system in dual-stage actuator with desired performance, where $\sigma_{f\max}$ is the maximum of $|G_f(j\omega)|$ for $\omega \in [0,\infty)$. The condition means $|u_m| \le u_{m\max}$.

During the design, the model of the dual-stage actuator HDD servo system could be approximated as follows provided that an appropriate filter has been made.

$$\begin{cases} \dot{x}_v &= \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} x_v + \begin{bmatrix} 0 \\ 6.4013\times 10^7 \end{bmatrix} \mathrm{sat}(u_v), \\ y_v &= \begin{bmatrix} 1 & 0 \end{bmatrix} x_v, \\ y_m &= 0.722\, u_f, \\ y &= y_v + y_m. \end{cases} \tag{16}$$

where x_v is the states of the VCM; u_f is the input signal to the filter $G_f(s)$; $\mathrm{sat}(u_v) = \mathrm{sgn}(u_v)\min\{u_{v\max}, |u_v|\}$ with $u_{v\max} = 3$. The dual-stage actuator control law is given by

Table 1. Parameters in the control law

$r(\mu m)$	α	ε	k_m
1	1	1	0.3462
10	1.55	1.7949	0.3462
20	1.55	2.1875	0.2778

$$\begin{cases} \dot{z} &= K_{\mathrm{R}} z - K_{\mathrm{R}}^2 \hat{y}_v + 6.4013\times 10^7 \mathrm{sat}(u_v), \\ u_v &= \kappa_2 z + (\kappa_1 - K_{\mathrm{R}}\kappa_2)\hat{y}_v - \kappa_1 r \\ & \quad + \rho[\kappa_3 z - (K_{\mathrm{R}}\kappa_3 + \kappa_1)\hat{y}_v + \kappa_1 r], \\ u_m &= G_f\, u_f, \\ u_f &= k_m \mu_m (r - \hat{y}_v), \\ \hat{y}_v &= y - \hat{y}_m, \\ \hat{y}_m &= 0.722\, \mathrm{sat}(u_m). \end{cases} \tag{17}$$

where $\mathrm{sat}(u_m) = \mathrm{sgn}(u_m)\min\{u_{m\max}, |u_m|\}$ with $u_{m\max} = 2$; $K_{\mathrm{R}} = -4000$; μ_m is defined as (9);

$$\rho = -1.5820\,\alpha\,(e^{-|1-\hat{y}_v/r|} - 0.3679); \tag{18}$$

$e_{\max} = 1.2\mu m$; $\kappa_1 = -0.0755\varepsilon^{-2}$; $\kappa_2 = -2.0613 \times 10^{-5}\varepsilon^{-1}$; $\kappa_3 = 5.7257\times 10^{-5}\varepsilon^{-1}$. α, ε and k_m are listed in Table 1; $G_f(s)$ is chosen as

$$G_f(s) = \frac{(3000\pi)^2}{s^2 + 4500\pi s + (3000\pi)^2}; \tag{19}$$

When $k_m = 0$, the dual-stage actuator control law (17) becomes the single actuator control law. It is noted that $\hat{y}_m = k_s\, \mathrm{sat}(u_m)$ and not $\hat{y}_m = k_s\, u_f$ as the input signal to the microactuator will be filtered by the filter G_f.

5. IMPLEMENTATION RESULTS

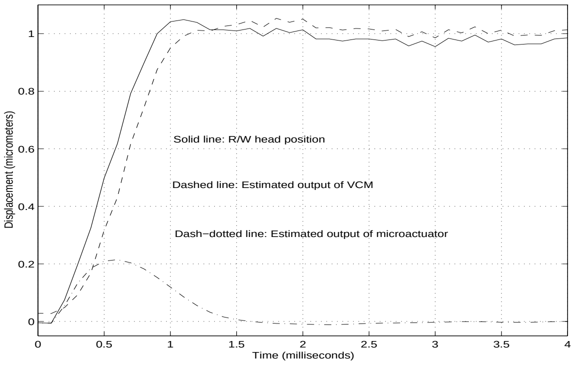
The implementations of the above control algorithm were carried out to verify the design in a sampling rate of 10 kHz. Both track following test and position error signal (PES) test are presented. PES is considered to be a major factor in design of hard disk drive servo systems. The implementations were done on an open hard disk with a TMS320 digital signal processor (DSP). The R/W head position was measured using a Laser Doppler Vibrometer (LDV) and the track pitch was assumed as $1\mu m$.

A. Track Following Test

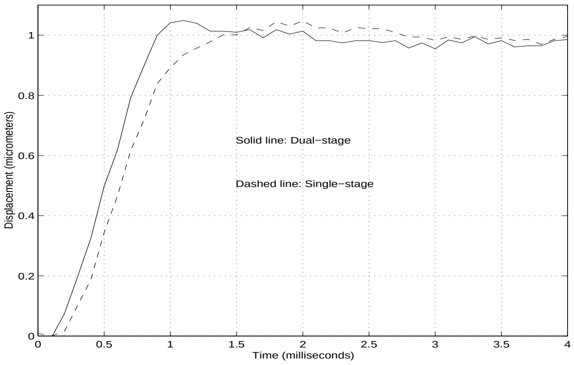
The implementation results for 1 and 10 μm seek lengths for the closed-loop system in the single and dual-stage actuator are shown in Figures 5 and 6. The Table 2 summaries the settling times from the implementations, which shows that the settling time can be reduced up to 27% in the dual-stage actuator than in the single actuator. The settling time means the time to settle the error within 0.05μm around the target track.

B. Position Error Signal Test

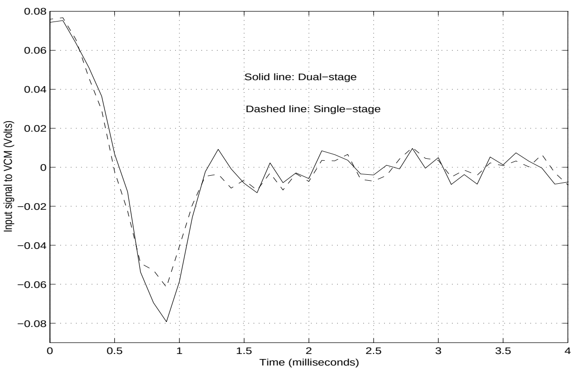
The repeatable runout (RRO) disturbance is considered only to show the performance of the modified roCNF control law against disturbances as it is a major source of track following errors. The



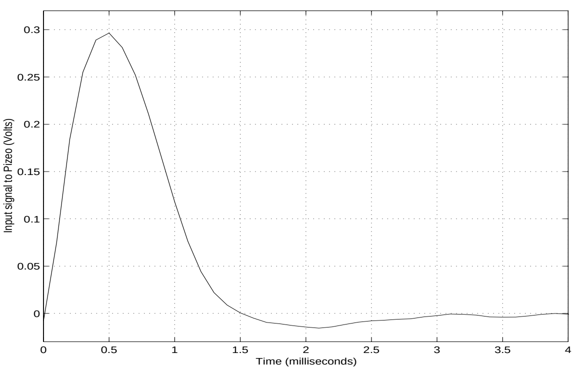
(a) Output response of dual-stage only



(b) Output response

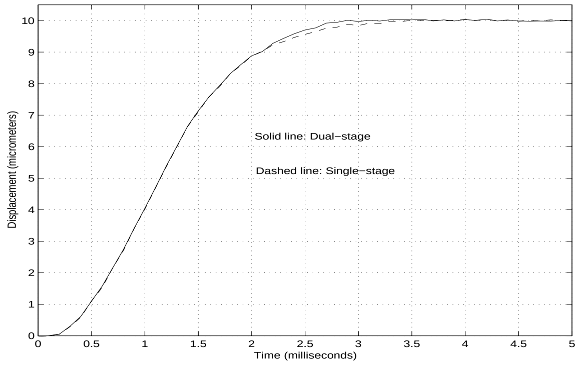


(c) Control signal to VCM

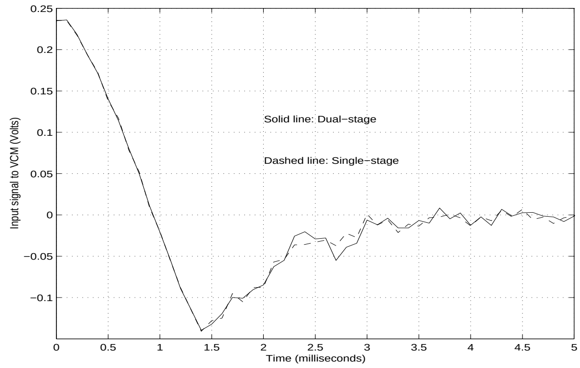


(d) Control signal to microactuator

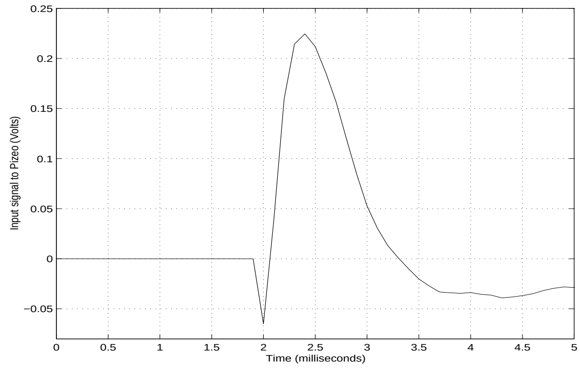
Fig. 5. Experimental results for 1 μm seek length using single and dual-stage actuator



(a) Output response



(b) Control signal to VCM



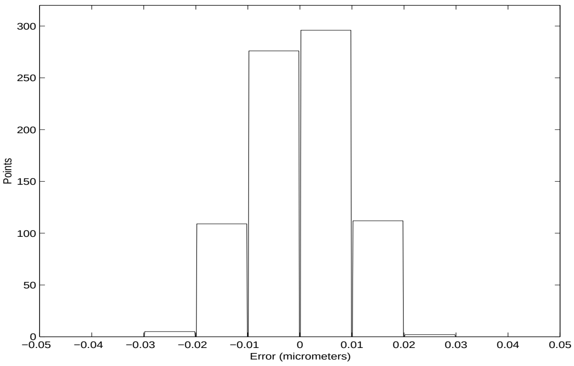
(c) Control signal to microactuator

Fig. 6. Experimental results for 10 μm seek length using single and dual-stage actuator

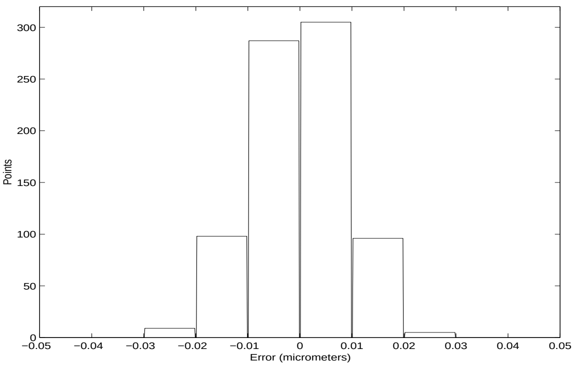
Table 2. Settling time from experimen -tal results

Seek Length (μm)	Settling Time (ms)		Overall Improve -ment(%)
	Single	Dual	
1	1.17	0.85	27
10	3.26	2.81	14
20	4.12	3.87	6

model of the RRO is $w(t) = [0.5 + 0.1\cos(110\pi t) + 0.05\sin(220\pi t)]\mu m.$, which is factitiously added into the measured output. The histograms of the PES are shown in Figure 7 in both single and dual-stage actuator control, where the corresponding 3σ values are 0.0249 μm and 0.0219 μm respectively, which show the RRO was suppressed more effectively 12% in the dual-stage actuator than in the single actuator although



(a) Single actuator



(b) Dual-stage actuator

Fig. 7. Experimental results: Histogram of the PES test

both are within the required margin. 3σ value is the measure of track mis-registration (TMR) in disk drive industries.

6. CONCLUSION

The dual-stage actuator control law has been designed for the HDD servo system, where the VCM is a primary actuator to operate in both tack seeking and following stages and piezo is a secondary actuator to help the VCM in track following stage. The implementations show the dual-stage actuator control decreases the settling time by 27% compared to the single actuator control. The dual-stage actuator is a good idea to improve HDD servo system performance.

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