Intelligent and Robust Control of Dual Stage Actuator Arm using GA based Fixed Structure Robust Loop Shaping Control

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Abstract
Since the aerial density of Hard Disk Drive (HDD) is increasing at very impressive rate, conventional techniques for controlling HDD servo system can no longer meet the necessary tracking performance and robustness; a new class of servo controller will be required to address this issue. H_∞ robust controller is one of the most popular techniques for designing a robust controller and it provides necessary robustness and performance even under perturbed plant conditions. However, the order of controller designed by this technique is usually higher than that of the plant, making it difficult to implement practically. To overcome this problem, this paper proposes a new technique for designing a robust controller for HDD with Voice Coil motor (VCM) and micro actuator called dual stage actualtor. The proposed technique does not only solve the problem of complicated and high order controller but also still retains the robust performance of conventional H_∞ control technique. Simulation results show the effectiveness of our proposed technique..

Keywords: *HDD servo system, Robust control, H-inf loop shaping Genetic Algorithm*

1 Introduction

It is well known that the recording density is increasing at an impressive annual rate of 40%. The access time is decreasing; very soon the storage density might cross 1 Terra bit per square inch. It is expected that for the necessary track density for 1 Terra-bit per square inch, the required TPI should be 500,000 and it also requires a track mis-registration (TMR) budget of less than 5nm (3-sigma value) [1]. Currently, HDD uses combination of control techniques such as lead lag compensators, PI compensators, robust control and notch filters. However, some classical methods for controlling HDD servo mechanism can no longer meet the demand of higher performance of HDD. The VCM actuator used in conventional disk drives has hundreds of flexible resonances at high frequencies, which limits the increase of bandwidth and hence the positioning accuracy. In order to develop high band width (track-following) servo systems, dual-stage actuation has been proposed as a possible solution to this problem. In Dual-stage actuator, there is a micro-actuator mounted on a large conventional VCM actuator. Thus, the VCM actuator will be mainly used for seeking control and rough positioning, while the micro-actuator is used to provide fine positioning. The remainder of this paper is organized as follows. Section 2 provides the detailed descriptions of micro-actuator model. Section 3 describes the topology design. In this section, the design a direct control using multi input single output (MISO) technique is described. The drawbacks of the conventional Parallel and Decoupled Master slave controller, and how the MISO controller overcomes the mentioned drawbacks are shown in this section. Finally, Section 4 describes the simulation results and Section 5 concludes the results.

2 Modelling for a dual stage actuator

The VCM actuator and micro-actuator are used to construct a Dual-Stage actuator which contain a fine positioner based on the piezoelectric based suspension mounted on the end of the primary VCM arm. The micro-actuator produces the relative motion of the read/write head along the radial direction [2].

VCM model

Dynamic model of HDD servo system (VCM) can be characterized as a double integrator cascaded with some high frequency resonance modes, which will reduce the system stability if neglected. There are some bias forces in the HDD system that cause steady-state errors in tracking performance. Moreover, there is also some non linearity in the system at low frequencies, which are primarily due to the pivot-bearing friction. All these factors have to be taken into consideration when considering the design of a controller for the VCM actuator. For the purpose of developing a model, we have to compromise between accuracy and simplicity. The dynamic model of an ideal VCM actuator can be formulated as a second order state space model as follows [19].

$$\begin{pmatrix} \dot{y} \\ \dot{v} \end{pmatrix} = \begin{bmatrix} 0 & k_y \\ 0 & 0 \end{bmatrix} \begin{pmatrix} y \\ v \end{pmatrix} + \begin{pmatrix} 0 \\ k_v \end{pmatrix} u \qquad (1)$$

Where u is the actuator input (in volts), y and v are the position (in tracks) and the velocity of the R/W head, K_y is the position measurement gain, $K_y = \frac{K_t}{m}$, K_t is the current/force conversion coefficient, and m is the mass of the VCM actuator. Consequently, the transfer function of an ideal VCM actuator model can be written as a double integrator. However, if the high-frequency resonance modes are considered, a more realistic model for the VCM actuator will be [2]:

$$G_v(s) = \frac{k_v k_y}{s^2} \prod_{i=1}^{N} G_{r,i}(s) \qquad (2)$$

Where N is the number of resonance modes, $G_{r,i}(s)$ is the ith resonance mode term which can be modeled as:

$$G_{r,i}(s) = \frac{a_i . s^2 + b_i s + \omega_i^2}{s^2 + 2\xi_i \omega_i s + \omega_i^2} \qquad (3)$$

Where a_i, b_i, ξ_i and ω_i are coefficients of ith resonance mode dynamic. For example in this paper, a HDD servo system with the model shown in Table 1 is studied. Table 1 describes the parameters and the uncertainties considered for this VCM model [2, 3].

Table 1: VCM parameter with tolerances

Parameter	Value	Tolerance
M	.200Kg	-
k_t	20	-
k_v	6.4013*e5	-
ω_1	$2.\pi.1905$	3%
ω_2	$2.\pi.2511$	5%
ω_3	$2.\pi.5011$	5%
ω_4	$2.\pi.8317$	5%
ξ_1	.015	10%
ξ_2, ξ_3, ξ_4	0.025	10%
a_1	0.912	-
a_2	0.7286	-
b_1	457.4	-
b_2	962.2	-
a_3, b_3, a_4, b_4	0	…

From Table 1, we can see that this VCM actuator have four resonance modes at resonance frequencies 1905, 2511 5011 and 8317 Hz. In order to reduce the effect of high frequency resonance mode, notch filter is added. The notch filter can be modeled using (4) and (5). For example, three notch filters described in Table 2 h/as been used to compensate the plant resonances. From the table, we can see that in order to compensate 4 resonance modes, we use 3 notch filters.

$$N_r(s) = \prod_{i=1}^{N} N_{n,i}(s) \qquad (4)$$

Where

$$N_{r,i}(s) = \frac{s^2 + 2\xi_{ni}\omega_{ni} s + \omega_{ni}^2}{s^2 + 2\xi_{ni+1}\omega_{ni} s + \omega_{ni}^2} \qquad (5)$$

Table 2 : VCM notch parameters

Notch	ξ_{ni}	ξ_{ni+1}	ω_{ni}
1	0.01	0.10	$2.\pi.1900$
2	0.01	0.10	$2.\pi.2500$
3	0.01	0.20	$2.\pi.5000$

By (1)-(3) and Table 1, the plant which is 10th order can be derived and by (4), (5) and Table 2, we can obtain the notch filter.

Micro-Actuator Model

Followings describe the model of micro-actuator. The higher bandwidth of the micro-actuator allows the R/W heads to be positioned accurately. The two most fundamental choices in a dual-stage system are the actuator configuration and the control algorithm. They have been proposed for different kinds of micro-actuators such as electromagnetic, electrostatic, piezoelectric, shape memory and rubber micro-actuators etc, each with their own advantages and disadvantages. In this paper, we focus on the design of HDD servo systems with a dual-stage actuator with a piezoelectric actuator in its second stage (see Figure 2.2).The micro-actuator model is described in this section is a 10th order model given by [2].

$$G_m(s) = 0.5.\prod_{i=1}^{5} G_{m,r,i}(s) \qquad (6)$$

Where $G_{r,i}(s)$ is the i^{th} resonance mode term which can be modeled as:

$$G_{m,r,i}(s) = \frac{a_i.s^2 + b_i s + \omega_i^2}{s^2 + 2\xi_i \omega_i s + \omega_i^2} \qquad (7)$$

Where a_i, b_i, ξ_i and ω_i are coefficients of i^{th} resonance mode dynamic. HDD servo system with the model shown in Table 3 is studied. Table 3 describes the parameters and the uncertainty considered for this VCM micro-actuator model [2].

Table 3: Micro-actuator parameter with tolerance

Parameter	Value	Tolerance
ω_1	$2.\pi.5488$	-
ω_2	$2.\pi.6376$	-
ω_3	$2.\pi.6832$	-
ω_4	$2.\pi.7408$	5%
ω_5	$2.\pi.7758$	5%
ξ_3	0.0125	5%
$\xi_1, \xi_2, \xi_4, \xi_5$	0.005	5%
a_1	0.7938	10%
a_2	0.955	10%
a_3	0.8912	-
a_4	0.9772	-
b_1	767.9	
b_2	978.6	-
b_3	1013	-
b_4	460.1	
a_5, b_5	0	…

From (6), micro-actuator model along with its resonance modes is of 10 orders. As seen in the bode plot in Fig. 1, the phase starts from 0 degree at lower frequencies and it reaches to 180 degree at high frequencies. Thus, a propositional controller is sufficient to shape this plant.

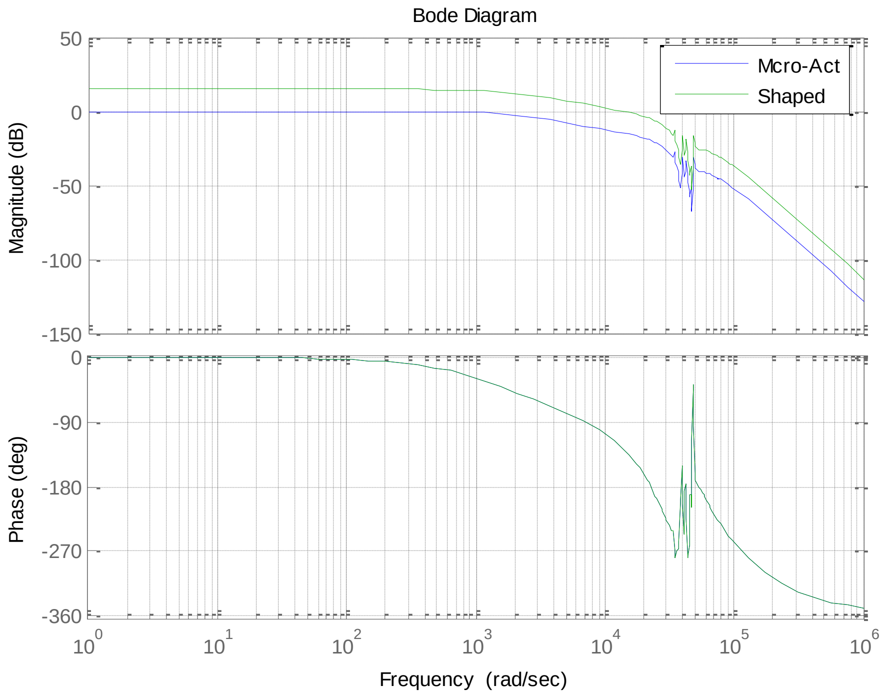

Figure 1: Bode plot with proportional controller for Micro-actuator

3 GA based Fixed-Structure Robust Loop Shaping Control

In the proposed technique, GA is adopted in control synthesis. Genetic algorithms are well known as a biologically inspired class of algorithms applicable to any nonlinear optimization problems. This algorithm applies the concept of chromosomes and the genetic operations of crossover, mutation and reproduction. A chromosome is an individual sample in a population. Each individual is assigned a fitness based on evaluation and objective function. At each step, called generation, fitness values of all individuals in a population are calculated. Individual with maximum fitness value is retained as a solution in the current generation and passed to the next generation. To form a new population of the next generation, crossover, mutation, and reproduction are used. Crossover randomly selects a site along the length of two chromosomes and then splits the two chromosomes at the crossover site. New chromosomes are then formed by matching the head of one chromosome with the tail of the other. Mutation forms a new chromosome by randomly changing a single bit in the chromosome. Reproduction forms a new chromosome by copying the old chromosome. The process of these operations is illustrated in the Figure 3.2 given below. Chromosome selection in genetic algorithms depends on the fitness value. High fitness means a high chance of being selected. Mutation, reproduction, or crossover depends on the pre-specified operation's probability. Individual samples in the genetic population are coded in binary. For real numbers, decoding binary to floating-point numbers is used [4]. In this paper, the genetic searching algorithm is also adopted to solve the Fixed-Structure H_∞ Loop Shaping Optimization problem. Although the proposed controller is structured, it still retains the entire robustness and performance guarantee as long as a satisfactory uncertainty boundary ε is achieved. Assume that the predefined structure controller $K(p)$ has specified parameter p, based on the concept of $H\infty$ loop shaping, optimization goal is to find parameter p in the controller $K(p)$, that minimizes infinity norm from disturbances w to states z, $\|T_{ZW}\|_\infty$. Based on the conventional, assuming that W_1 and W_2 are invertible, then $K_\infty = W_1^{-1}K(p)W_2^{-1}$. Substituting this equation into (3.6), the ∞-norm of the transfer function matrix $\|T_{ZW}\|_\infty$ which is subjected to be minimized can be written as:

$$J_{\text{cost}} = \gamma = \|T_{ZW}\|_\infty = \left\| \begin{bmatrix} I \\ W_1^{-1}W_2^{-1}K(p) \end{bmatrix} (I + G_s W_1^{-1} W_2^{-1} K(p))^{-1} M_s^{-1} \right\|_\infty \quad (8)$$

The optimization problem can be written as:

Minimize $\left\| \begin{bmatrix} I \\ W_1^{-1}W_2^{-1}K(p) \end{bmatrix} (I + G_s W_1^{-1} W_2^{-1} K(p))^{-1} M_s^{-1} \right\|_\infty$

subject to $p_{i,\min} < p_i < p_{i,\max}$ where $p_{i,\min i}, p_{i,\max}$ are lower and upper bounds of the parameter p_i in controller $K(p)$ respectively. The fitness function in the controller synthesis can be written as following

$$Fitness = \begin{cases} \left(\left\| \begin{bmatrix} I \\ W_1^{-1}W_2^{-1}K(p) \end{bmatrix} (I + G_s W_1^{-1} W_2^{-1} K(p))^{-1} M_s^{-1} \right\|_\infty \right)^{-1} & \text{If K(p) stabilizes the plant.} \\ 0.00001 & \text{Otherwise} \end{cases} \quad (9)$$

The fitness is set to a small value (in this case is 0.00001) if *K(p)* does not stabilize the plant. Our proposed algorithm is summarized as follows. The flow chart of the proposed technique is given in Figure 2.

Step 1 Follow steps 1 and 2 in the conventional H_∞ Loop Shaping Optimization to select the weights. Specify the genetic parameters such as initial population size, crossover and mutation probability, maximum generation, etc.

Step 2 Select a controller structure *K(p)* and randomly initialize several sets of parameters p as population in the 1st generation.

Step 3 Evaluate the fitness value of each chromosome using (3.11). Select the chromosome with maximum fitness value as a solution in the current generation. Increment generation for a step.

Step 4 While the current generation is less than the maximum generation, create a new population using genetic operators and go to step 3. If the current generation is the maximum generation, then stop.

Step 5 Check performances in both frequency and time domains. If the performance is not satisfied such as too low ε (too low fitness function), then go to step 2 to change the structure of controller.

4 Simulation Results

The block diagram of MISO controller given in Figure 2 is used for our design. Cmiso controller will provide two inputs, one for the VCM PLANT and the other for the micro-actuator plant. The outputs of both the plants are added to get the final output which is fed back via to the sensor of the system.

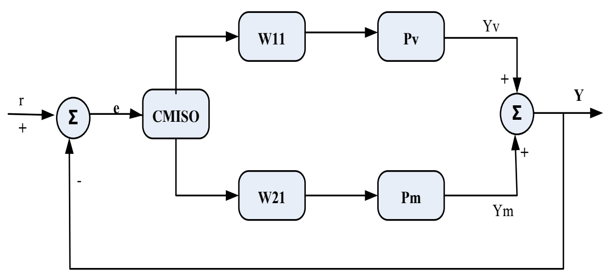

Figure 2: MISO Controller design block

Here Pv is the VCM plant Transfer function; Cv is the VCM controller transfer function; CMISO is the multi input single output controlle.

The model of the dual-stage actuator is

$$y = [G_m \quad G_v] \begin{bmatrix} u_m \\ u_v \end{bmatrix} \quad (10)$$

Where G_m and G_v are the plant dynamics with notch filters of micro-actuator and VCM, respectively. The MISO plant in (10) can be shaped with two weights, W11 and W21 as the followings.

$$W = \begin{bmatrix} W11 \\ W21 \end{bmatrix}$$
$$W11 = \left\{ 4.7787 \frac{(s+389.89)(s+51.87)}{(s+134600)(s+300)} \right\}$$
$$W21 = \{ 5.5 \} \quad (11)$$

First, the robust controller based on the concept of classical H_∞ loop shaping method is designed. The controller order is 35th and it can control the DSA MEMS actuator very well. The infinity norm from disturbances to states obtained from this designed controller is γ = 1.7653 and the stability margin obtained is 0.5205. This indicates that the controller achieved here is robust. Since this controller is difficult to implement, the order of controller can be reduced from 35th order to 7th order (in association with the weighting function W11 and W21 (5.4) and (5.5)) using Hankle Norm model reduction technique. The new reduced order controller is given below. With this controller, the stability margin 0.3917 is obtained. Followings are the state space model of the designed reduce order controller. Next, a fixed-structure robust controller using GA for MISO system is designed. The structure of the controller is fixed as the following state space model.

$$A_{GA\ CONTROLLER} = \begin{bmatrix} K_1 & K_2 \\ K_3 & K_4 \end{bmatrix}$$

$$B_{GA\ CONTROLLER} = \begin{bmatrix} K_5 \\ K_6 \end{bmatrix}$$

$$C_{GA\ CONTROLLER} = \begin{bmatrix} K_7 & K_8 \end{bmatrix}$$

$$D_{GA\ CONTROLLER} = 0 \tag{12}$$

In the optimization, the ranges of the search parameters, and GA parameters are set as follows. $k_1 \in$ [-85000 0]; k_2 = [0 20000]; $k_3 \in$ [-30000 -10000]; $k_4 \in$[-1000 -100]; $k_5 \in$ [0 500] ; $k_6 \in$[0 100]; $k_7 \in$[-500 0]; $k_8 \in$[0 100];. Population size=100; crossover probability =0.6; mutation probability=0.1; maximum generation = 30. When running GA for 27 generations, an optimal controller can be found as.

$$A_{GA\ CONTROLLER} = \begin{bmatrix} -81615 & 1151 \\ -10167 & -364 \end{bmatrix}$$

$$B_{GA\ CONTROLLER} = \begin{bmatrix} 242.9924 \\ 25.9629 \end{bmatrix}$$

$$C_{GA\ CONTROLLER} = \begin{bmatrix} -117.2772 & 25.7505 \end{bmatrix}$$

$$D_{GA\ CONTROLLER} = 0 \tag{13}$$

As seen in the model, the order of the controller is 2. Figure. 3 shows a plot of convergence of fitness function (stability margin versus generations) by genetic algorithm. As shown in the figure, the optimal robust controller with our proposed structure provides a satisfied stability margin at 0.4289. The order of this final controller is 4 because it needs to be used in association with weights W11 and W21.

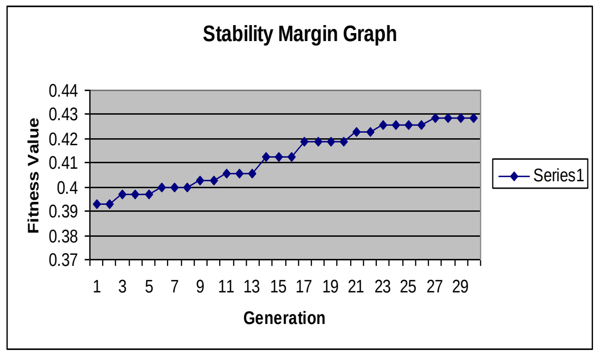

Figure 3 : Convergence of fitness value

The step responses from the H∞ loop shaping controller, the reduced order controller and GA based controller are given in Figure 4. Performance comparison for all controllers has been given in Table 4.

Table 4 : Performance comparison

Controller	HLS CONTROLLER	REDECED CONTROLLER	GA based CONTROLLER
ORDER	35	7	4
Stability Margin	0.52	0.39	0.42
Over shoot	4%	4%	4%
Settling Time	1.9ms	2ms	2ms

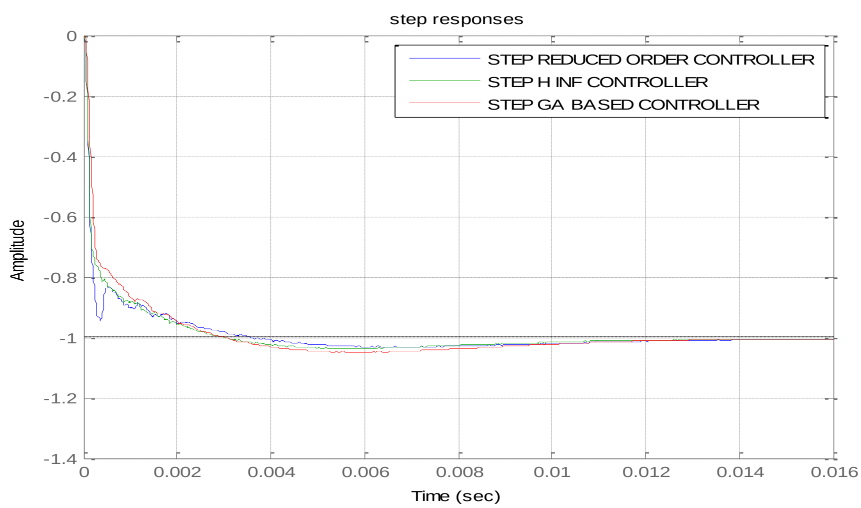

Figure 4: Step response of the system with MISO H-∞ controller, reduced order controller and the proposed controller.

From the Table 4, we can see that even the order of GA based controller is lower than the reduced order controller, it has a better stability margin than the reduced order controller. This indicates that it is more robust than the reduced order controller. Fig 4 shows that it provides smoother step response than the reduced order controller. In addition, its step response is comparable to the H_∞ loop shaping control. Though the stability margin of H_∞ controller is better than GA based controller, but its order is 35 which is difficult to be implemented in actual practice as on HDD the interrupt service routine has hard deadlines and every task must be finished within that.

5 Conclusions

In this paper, the design of high-performance and robust controller for HDD MEMS DSA actuators using the conventional H-∞ loop shaping technique, the reduced order controller and the GA based controller have been proposed. Among those three techniques, the GA based controller has significant advantages as lower order and well performance compared to the other reduced order technique. Although the stability margin obtained from the classical H-∞ controller is slightly better than the proposed controller; however, the order of the proposed controller is much lower than that of the full order controller. Considering this aspect, the proposed controller is easy to be implemented.

Acknowledgment

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