Iterative Feedback Tuning (IFT) of Head Positioning Servomechanism in Hard Disk Drive

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Abstract — Actuators used in hard disk drives (HDD) are produced en mass and therefore their dynamic properties vary within a given tolerance bound. A nominal model representing the batch of actuators is used to design the head positioning servomechanism. Equal performance can not be expected for all actuators when such controller is used. Disk drive servomechanism is expected to provide performance with increasingly tighter tolerance as the demand for higher storage capacity continues. Moreover, physical properties of any actuator may change over time causing the degradation of performance. All these issues demand for good on-line tuning of controller. This paper explores the usage of Iterative Feedback Tuning (IFT) in HDD servomechanism. Improved performance of the tuned controller is demonstrated using simulation and experimental results.

***Keywords*—HDD Servomechanism, Iterative Feedback Tuning, PID controller, Voice Coil Motor**

I. INTRODUCTION

Demand for higher storage capacity and, therefore, for denser layout of data tracks, continues to set the performance specifications of hard disk drive (HDD) head positioning servomechanism to higher level [1]. Meeting this ever-increasing demand always remains a challenge; variations in actuator properties make the challenge more difficult. Properties of the HDD actuators, which are mass produced, vary within some given tolerances. If the controller is designed using a nominal model of this family of actuators, same level of performance is not achievable for all cases. The disparity between performances is widened with usage due to the changes in actuator properties inflicted by physical and environmental changes as well as wear and tear. It is, therefore, necessary to tune the controller for each HDD not only at the time of manufacturing but also on a regular basis when it is used in a system. The well-known iterative feedback tuning (IFT) is used in our work to select the control parameters of the HDD head positioning servomechanism. This enables the mass produced actuator to perform at its best and to maintain the level of its performance over time.

Section II of this article provides background information on HDD head positioning servomechanism and on IFT. Identification of the model of a voice coil motor (VCM) actuator from its frequency response and the design of the nominal controller is presented in Section III. Since auto-tuning is at the focal point of this article, we do not optimize the nominal PID controller. Effectiveness of IFT in finding the optimal controller gains is first shown using simulation of the closed loop servomechanism and the results are presented in Section III while the implementation results are shown in Section IV.

II. Background

A. HDD Head Positioning Servomechanism

Head positioning servomechanism plays a very important role in achieving high data density on disks of HDD. Number of bits recorded per surface of disk can be increased by a variety of means including (i) smaller distance between two adjacent bits on a data track and (ii) reduced separation between any two of the thousands of concentric data tracks created on the disk surface. The first is achieved by using improved materials for recording head and medium and by making the dimensions of head as small as possible. Accurate and precise positioning of the head, on the other hand, is the key to achieving high track density, i.e., small track-to-track separation.

A VCM actuator is used to move the read/write heads over the surface of the rotating disk. The read head and write head are fabricated on a single piece of slider which is attached to a thin, light weight, stainless steel suspension arm. The suspension, in turn, is attached to the VCM actuator. Aerodynamic shape of the slider makes it float above the rotating disk. Movement of actuator in the direction parallel to disk surface is required for both positioning of the read-write head from one track to another and following the center of rotating tack. Small degree of movement in the direction perpendicular to disk surface is also necessary to avoid collision between the slider and uneven bumps on the disk. This is the reason for not using a 100% rigid structure for the slider-suspension assembly. Flexible modes of suspension arm appear as an obstacle to concurrent fulfillment of the requirements of ultra precision and fast motion.

A typical HDD in the current market has track-to-track separation of 6~10 μin or 170~250 nm. The head must be held near the center of a track while data is being read or written. Typical tolerance of wandering of the head is 10~15% of track pitch which translates into an error tolerance as small as 17~25 nm. Challenging task of getting such precision is further intensified by the noise and disturbances present in the system which are contributed by variety of factors like eccentricity of disk motion, wind-induced vibration of the slider and suspension, environment-induced vibration etc. Component designers do their best to make these disturbances smaller through better design, engineering and manufacturing. However, for the given error tolerances, the ratio between marginal improvement and increase in cost is not very attractive. A well designed feedback controller is very crucial in meeting the specifications on error tolerance. Interested readers may refer to [2] for a comprehensive overview of HDD servomechanism and the associated challenges. Small variation in the properties of the actuator or any other component involved in the servomechanism has severe detrimental effects on the performance of servo loop and hence on the achieved storage density. However, it is impractical to design tailor-made controller for each and every actuator. This is where tuning of the controller becomes important.

B. Iterative Feedback Tuning

Iterative Feedback Tuning (IFT), a method initially proposed in [3]-[4] for tuning controller parameters, does not need an explicit model of the system to be controlled. This method improves the performance of a stable, operating controller on the basis of closed loop data. The fact that controller parameters can be changed iteratively with improved performance in successive iterations without ever opening the loop makes this method particularly appealing to process control engineers. The method has been successfully applied to many practical applications – both mechanical systems and chemical processes. Interested readers may refer to [5]-[11] to find more about these applications. The method has also been extended to nonlinear systems [12]-[14] and MIMO systems [15]-[16]. This tuning algorithm can be formulated for various specifications, e.g., settling time [17] or absolute error [18]. Comparison between different methods of PID tuning, including IFT, is reported in [19] which shows that IFT performs as good as or better than other tuning methods.

Advantages of tuning controller gains through IFT include among others - (i) no model of the plant is required and (ii) tuning algorithm can be executed with closed loop control uninterrupted. The algorithm works on manipulation of input-output data obtained from specially conducted closed loop experiments. It is assumed that a nominal controller stabilizes the system and parameters of the controller are further tuned to achieve improved performance. IFT algorithm can be used to tune any number of control parameters; it is not restricted to 3-parameter PID control only. Increased number of control parameter means more manipulations of the input-output data. However, these manipulations are performed outside the closed loop operation. These features make IFT an attractive solution for tuning of the HDD servomechanism. It can be applied to many different types of controller suggested in the published literature [2], [20]-[23]. As explained later in this section, the IFT technique utilizes the error signal to adapt the controller parameters such that response improves from iteration to iteration. Tuning of controller parameters can be realized in closed loop without causing any disruption to the normal operation of the head positioning servomechanism of HDD.

Iterative Feedback Tuning (IFT) was first proposed in [3] for a general two degree-of-freedom controller used to control unknown, linear and time-invariant (LTI) system shown in Fig. 1, where, G represents the LTI plant and $\{r_k\}$ and $\{y_k\}$ are reference and output signals, respectively, with k representing discrete time instants. Disturbance $\{v_k\}$, which is not measurable, is assumed to be a zero-mean weakly stationary random process. The plant is controlled by a two-degree-of-freedom (2DOF) controller where $C_r(\rho)$ and $C_y(\rho)$ are LTI transfer functions parameterized by the parameter vector ρ. The external reference signal $\{r_k\}$ is deterministic and independent of $\{v_k\}$. The subscript k is dropped in the remaining part of this paper to avoid using too many subscripts and superscripts; we also assume that all signals are in discrete time.

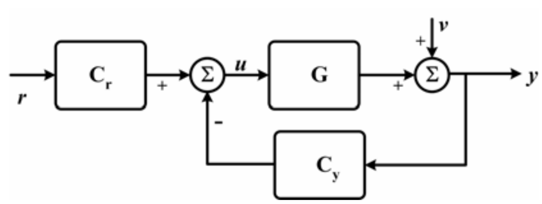


Fig. 1: Block diagram of 2-DOF controller

If $y^d = T_d r$ is the desired output response to a given reference signal r, then the error between the achieved and desired response is

$$\tilde{y}(\rho) \overset{\Delta}{=} y(\rho) - y^d = \left(\frac{C_r(\rho)G}{1 + C_y(\rho)G} - T_d \right) r + \frac{1}{1 + C_y(\rho)G} v . \tag{1}$$

This error is contributed by two factors – incorrect tracking of reference input and influence of external disturbance. The controller can be tuned by finding the solution of an optimization problem that minimizes some norm of this error over the controller parameter vector ρ. One can consider the quadratic criterion,

$$J(\rho)=\frac{1}{2N}E\left[\sum_{k=1}^{N}(L_y\tilde{y}_k(\rho))^2+\lambda\sum_{k=1}^{N}(L_u u_k(\rho))^2\right]. \tag{2}$$

In the above equation, E[.] represents expectation with respect to v, a weakly stationary random process. Two terms in the quadratic criterion are frequency weighted by filters L_y and L_u, respectively. In IFT, the abovementioned quadratic criterion is minimized with respect to ρ for a controller of pre-specified structure. This is equivalent to finding a solution to the equation

$$0=\frac{\partial J}{\partial \rho}=\frac{1}{N}E\left[\sum_{k=1}^{N}\tilde{y}_k(\rho)\frac{\partial \tilde{y}_k}{\partial \rho}+\lambda\sum_{k=1}^{N}u_k(\rho)\frac{\partial u_k}{\partial \rho}\right]. \tag{3}$$

If the gradient $\partial J/\partial \rho$ can be computed then one can find the solution using the iterative algorithm

$$\rho_{i+1}=\rho_i-\gamma_i R_i^{-1}\frac{\partial J}{\partial \rho}(\rho_i). \tag{4}$$

In each iteration i, R_i is an appropriate positive definite matrix; typically a Gauss-Newton approximation of the Hessian of J is used. The positive real scalar γ_i determines the step size. This problem involving unknown expectations can be solved by using stochastic approximation algorithm. In order to solve this problem, one needs to generate the following quantities –

1. the signals $\tilde{y}(\rho_i)$ and $u(\rho_i)$;
2. the gradients $\partial\tilde{y}/\partial\rho$ and $\partial u/\partial\rho$ at each iteration i;
3. unbiased estimates of the products $\tilde{y}(\partial\tilde{y}/\partial\rho)$ and $u(\partial u/\partial\rho)$ at each iteration i.

These quantities can be obtained by performing experiments on the closed loop formed by the actual system with controllers $C_r(\rho)$ and $C_y(\rho)$. Since HDD servomechanism uses one degree-of-freedom (1DOF) controller, we elaborate the IFT design for 1DOF case.

C. IFT for 1DOF Controller

Block diagram of the HDD servomechanism with 1DOF controller is shown in Fig. 2. Input disturbance d_k is usually constant bias force contributed by the flex cable carrying electrical signals between read-write heads and drive's PCB mounted outside the drive enclosure [2]. A PID controller in series with notch filter is commonly used for track following mode of operation whereby the servo loop controls the position of the read sensor on the center of the data-track being accessed. The same PID controller is also used for short seek mode when the head is positioned from one data-track to another data-track not very far from the initial track. However, performance of linear controller with bounded control authority deteriorates when it has to move the head from one data-track to another far away track and time-optimal control or its variants are used for such long seek. Variety of methods has been proposed for smooth transition between seek mode and track-following mode; interested readers may refer to [2] and [21]. In this paper, we consider a PID controller and, therefore, issues critical to long seek mode are not addressed.

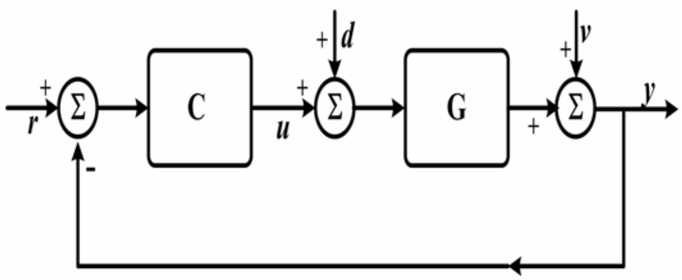


Fig. 2: 1DOF controller for HDD servomechanism

A deterministic case is considered for explaining IFT algorithm. The control objective is to minimize the quadratic criterion,

$$J(\rho)=\frac{1}{2N}\sum_{k=1}^{N}\left(\tilde{y}_k^2(\rho)+\lambda u_k^2(\rho)\right) \tag{5}$$

where $\tilde{y}_k=\left(y_k-y^d\right)$ is the deviation of the actual output y_k from the desired output y^d, k is the discrete time instant and N is the number of samples. The scalar λ is used to provide relative weight of control effort with respect to the error $\tilde{y}$. We have taken the filters L_y=1 and L_u = 1 in equation (2). The goal is to find the optimal parameter vector,

$$\rho^* = \arg\min_{\rho} J(\rho). \tag{6}$$

Minimization of the quadratic criterion requires an expression for the gradient of the cost function $J(\rho)$ with respect to ρ. In IFT, this gradient is determined using the data collected from the actual closed loop system. Differentiating $J(\rho)$ of equation (5) with respect to ρ gives

$$J'(\rho)=\frac{1}{N}\sum_{k=1}^{N}\left(\tilde{y}_k(\rho)y_k'(\rho)+\lambda u_k(\rho)u_k'(\rho)\right). \tag{7}$$

Following the expression in equation (1), differentiation of $\tilde{y}$ yields

$$\tilde{y}'(\rho)=y'(\rho)=\frac{C'}{C}T(r-Tr) \tag{8}$$

where, $T=\frac{CG}{1+CG}$ is the complementary transfer function of the closed loop, and C' is derivative of C with respect to parameter vector ρ. Similarly, differentiating the control signal $u(\rho)=C(\rho)(r-y)$ yields

$$u'(\rho)=\frac{C'}{C}\frac{C}{1+CG}(r-Tr). \tag{9}$$

These expressions for derivatives of error and control input lead to a procedure involving the following two experiments for obtaining these derivatives, which is the key idea in IFT.

Experiment 1: *A known deterministic reference input r_k is applied n the i^{th} iteration of IFT; let this signal be designated as* $r_1^i = \{r_k\}$. *Signals from the closed loop are acquired during this experiment which are designated as* $u_1^i = \{u_k\}$ *and* $y_1^i = \{y_k\}$.

Experiment 2: *A new reference input* $r_2^i = r_1^i - y_1^i$ *is constructed and applied to the closed loop; samples of the output signal and control signal are collected. Let these be designated as* y_2^i *and* u_2^i*, respectively.*

Reference input in the second experiment is *r-Tr* from the first experiment and therefore, $y_2^i = T(r_1^i - Tr_1^i)$. Thus the derivative of $\tilde{y}$ (equation 8) with respect to ρ can be approximated by filtering experimentally acquired signal y_2^i through $\frac{C'}{C}$. Since the structure of the controller is fixed, C' can be obtained analytically by differentiating C with respect to ρ. Applying similar argument and using equation (9), we can conclude that derivative of u with respect to ρ can similarly be obtained by filtering u_2^i through $\frac{C'}{C}$.

Let the estimated derivatives of y and u obtained from the two experiments mentioned above be denoted as $\hat{y}'(\rho)$ and $\hat{u}'(\rho)$, respectively. Then the approximate gradient of the cost criterion is

$$\hat{J}'(\rho) = \frac{1}{N}\sum_{k=1}^{N}\left(\tilde{y}_k(\rho)\hat{y}'_k(\rho) + \lambda u_k(\rho)\hat{u}'_k(\rho)\right). \qquad (10)$$

Once the gradient is estimated, it is possible to update controller parameters according to the algorithm $\rho_{i+1} = \rho_i - \gamma_i R_i^{-1}\hat{J}'(\rho_i)$ where the matrix R_i is used to modify search direction and γ is used to adjust step size. Typically an estimate of the Hessian of J is used as the positive definite matrix R. A good estimate of the Hessian is obtained using

$$\hat{R}_i = \frac{1}{N}\sum\left(\hat{y}'_k(\rho_i)\right)^2 . \qquad (11)$$

However, this produces a biased estimate of the Hessian. Alternative approaches have been suggested by researchers but those usually require more computation. In HDD servomechanism, computational resources are expensive and it is generally desired to have calculations less complex. In this paper, we emphasize more on the cost of computation and use equation (11) to estimate the Hessian of J.

III. Controller Design

Tuning of controller becomes necessary for mass produced systems when mismatch exists between the model used to design controller and the actual plant controlled. However, the results presented in this paper are obtained using only one actuator and these results are used to verify the suitability of using IFT for tuning of HDD servo controller. A nominal controller is first designed using the model without paying enough attention to the selection of controller parameters. The controller is rather deliberately designed poorly so that the performance of the nominal stabilizing controller is far from being optimal. This, in a way, mimics the mismatch between actual plant and the model used at the time of designing controller. Then IFT algorithm is applied to tune controller gains. We present in the following sub-sections (i) model of the actuator, (ii) design of PID (not optimally tuned) controller and (iii) tuning of PID gains.

A. Nominal Model of the Actuator

A model of the actuator is obtained from the frequency response of the VCM actuator. In case of an actual disk drive, position feedback is obtained by reading and decoding specially written spatial patterns on the data tracks [2]. Position error signal (PES) is generated using built-in electronic circuits of the HDD which are proprietary and available only in the laboratories associated with the HDD industry. It is not easy to replicate such process in our laboratory setup. Therefore, instead of decoding the position signal from the readback waveform, we use a Laser Doppler Vibrometer (LDV) to measure the in-plane displacement of the head slider attached to the tip of actuator-suspension assembly. This approach is widely used by researchers around the globe working on HDD servomechanism [20]-[23]. The experimental setup for the measurement of frequency response is shown in Fig. 3. This same setup is also used to implement the controller.

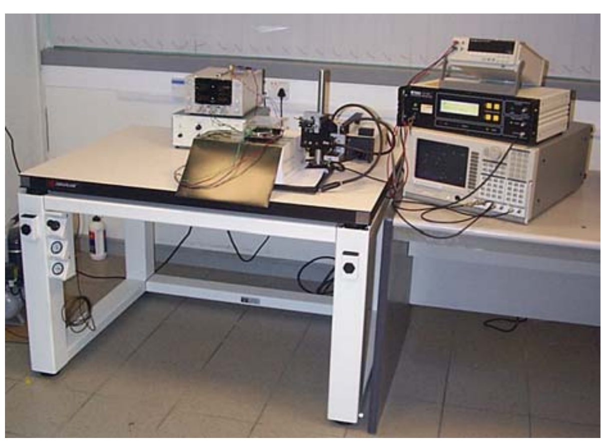


Fig. 3: Experimental setup used for model identification and controller implementation

Frequency response is measured using swept-sine signal using sinusoidal frequencies from 200 Hz to 10 kHz, generated by the frequency response analyzer. The swept-sine signal plus a DC-bias is applied to the VCM coil. The DC-bias ensures that the slider is held somewhere in the mid-range of the actuator's movement. The amplitude of the sinusoidal excitation is set to 180 mV for low frequency. If the amplitude of input excitation is kept constant then at high frequencies displacement of the slider becomes very small because the gain of the actuator decreases with increasing frequency. Measurement of such small displacement is often corrupted by noise and the signal-to-noise ratio becomes very low. The auto adjustment feature of the analyzer is used to adjust the amplitude of input excitation according to the strength of the feedback signal measured from the LDV. Resolution of the displacement measurement is set to 8 μm/V. Frequency response is shown in the figure below.

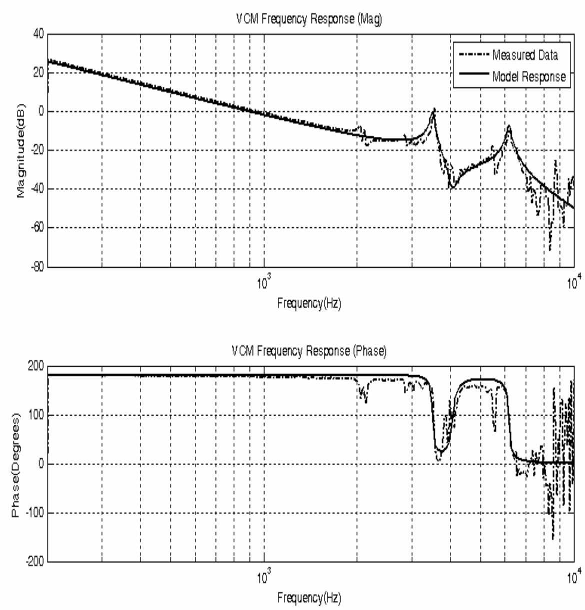


Fig. 4: Frequency response of the actuator and its model

Resemblance between the frequency response of the model and that of a double integrator (K/s^2) is clearly visible in the plot. High frequency response manifests lightly damped resonant poles and zeros. So we model the actuator as a double integrator in cascade with several lightly damped poles and zeros,

$$G(s) = \frac{K}{s^2} H_{d1}(s) H_{d2}(s) H_{d3}(s), \tag{12}$$

where,

$$H_{d1}(s)=\frac{\omega_{p1}^2}{s^2+2\xi_{p1}\omega_{p1}s+\omega_{p1}^2}, \tag{13-a}$$

$$H_{d2}(s)=\frac{s^2+2\xi_{z1}\omega_{z1}s+\omega_{z1}^2}{\omega_{z1}^2}, \tag{13-b}$$

$$H_{d3}(s)=\frac{\omega_{p2}^2}{s^2+2\xi_{p2}\omega_{p2}s+\omega_{p2}^2}. \tag{13-c}$$

Parameters of the proposed model are obtained using non-linear least square estimator function of MATLAB; these parameters are shown in TABLE 1. The frequency response of the identified model is superimposed on the experimental data in Fig. 4.

TABLE 1: PARAMETERS OF THE IDENTIFIED MODEL OF HDD ACTUATOR

Symbol	Parameter	Value
K	Acceleration constant	3.0×10^7 Hz^{-2}
ω_{p1}	First pole frequency	22,000 rad/s
ω_{p2}	Second pole frequency	38,840 rad/s
ω_{z1}	First zero frequency	25,540 rad/s
ξ_{p1}	First pole damping	0.0125
ξ_{p2}	Second pole damping	0.0137
ξ_{z1}	First zero damping	0.0235

B. *Nominal PID Controller*

We use a PID controller with a common gain, defined in equation 14 below, as the nominal controller.

$$U(s)=K_k\left[K_p+\frac{K_i}{s}+K_d s\right]E(s). \tag{14}$$

The controller is mapped onto the discrete domain using Euler's method to produce,

$$\begin{gathered}u(k)=K_k u(k)+\\ K_k K_p\left(e(k)-e(k-1)+K_i T_s e(k)+\frac{K_d}{T_s}\left(e(k)-2e(k-1)+e(k-2)\right)\right)\end{gathered} \tag{15}$$

Two dominant resonant peaks seen in the frequency response are nullified by a series of notch filters put at the input of the plant. Center frequencies of the notch filters match the resonant frequencies identified from the frequency response.

The controller and eventually the auto-tuning algorithm are implemented using the dSPACE

DS1103 PPC controller board. The DS1103 is a powerful controller board for rapid control prototyping. It is possible to generate the control codes automatically from block diagrams in SIMULINK using Real-Time Interface (RTI) which can then be downloaded into DS1103. However, the implementation of IFT algorithm requires complex computations and is not easily realizable using SIMULINK block diagrams. We use S-function of MATLAB to implement IFT algorithm and the nominal controller which is then coded in C programming language and cross-compiled to download into the DS1103.

Parameters of the notch filters are chosen carefully such that the resonant peaks are cancelled. However, same level of care is not used while choosing the gains of PID controllers. This simulates a condition of mismatch between the plant and the model. The PID parameters are chosen by observing the transient response when a square wave of 20 Hz is set as the reference signal for the system. The gains obtained for K_k, K_p, K_i and K_d are 1.314, 0.052, 1.5 and 6×10^{-5}, respectively. Simulated step response is shown in Fig. 5. It may be noted that the measurement gain of LDV is 8 μm/V and step input of 1 V corresponds to 8 μm displacement of the slider. Rise time, settling time and overshoot are 0.73 ms, 3.23 ms and 20.8%, respectively.

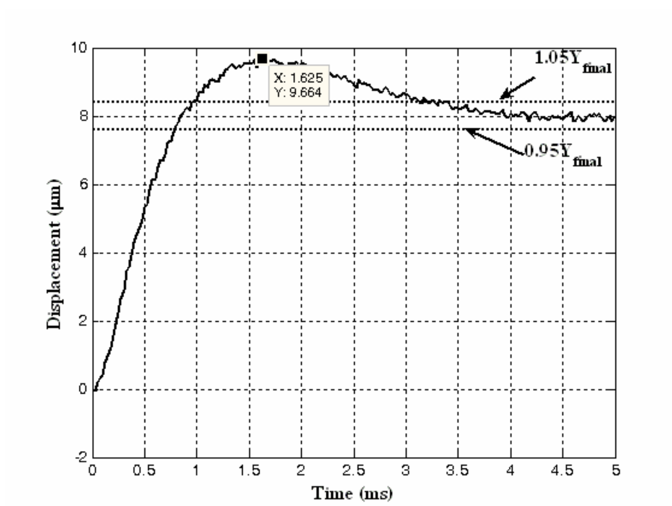


Fig. 5: Simulation with nominal PID controller

C. *Tuning of PID Gains using IFT*

We simulate the IFT algorithm using MATLAB and step responses for 3 iterations are shown in Fig. 6 along with the response when nominal controller is used. Tuning parameters used for IFT algorithms are $\lambda = 0.2$ and $\gamma = 0.8$. It is evident from simulation results that IFT algorithm is capable of finding control gains that improve closed loop performance from iteration to iteration. Improvement in closed loop performance is summarized in TABLE 2. In the comparison shown in this table, t_r is the time required for actuator to reach 90% of the final value and t_s is the time when the displacement settles between 95% and 105% of the final value. These results clearly show that the gains of PID controller move towards their optimum values with each step of IFT.

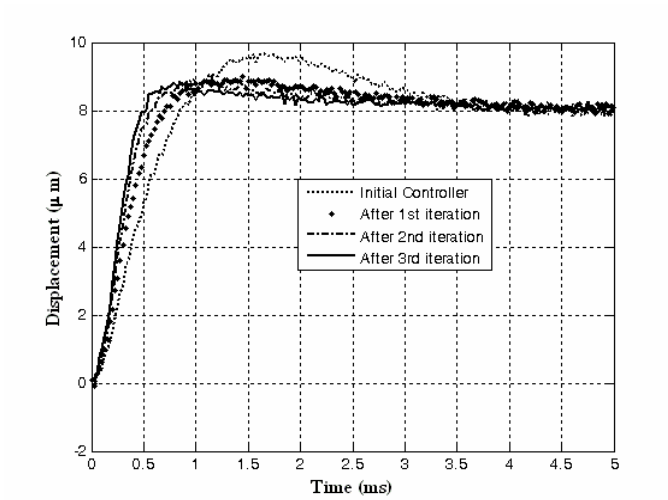


Fig. 6: Tuning of PID controller using IFT (Simulation)

TABLE 2

IMPROVEMENT OF PERFORMANCE DUE TO TUNING OF PID GAINS

	t_r (ms)	t_s (ms)	Overshoot
Initial design	0.73	3.23	20.80%
After iteration 1	0.58	2.85	12.66%
After iteration 2	0.45	2.50	12.61%
After iteration 3	0.43	2.22	10.78%

IV. EXPERIMENTAL RESULTS

The nominal PID controller is implemented using the setup shown in Fig. **3** to control the position of the read-write head. Step response with initial control gains is shown in FIG. 7. Rise time (t_r), settling time (t_s) and overshoot are approximately 1 ms, 4 ms and 15%, respectively. The IFT algorithm is then implemented to tune the control gains. Improvement in performance is shown in TABLE 3 using the step response measurements after different iterations. It is clearly evident that IFT tunes the gains of PID controller such that performance is improved successively.

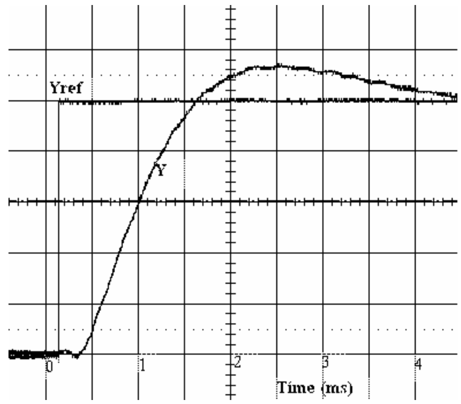
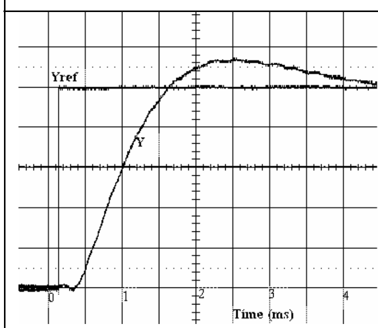
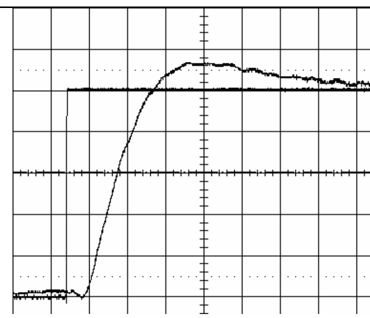
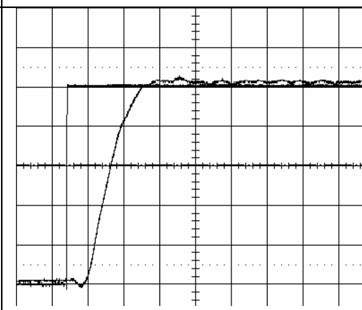


Fig. 7: Experimental step response with initial design of PID controller (Vertical: 0.2 V/div or 1.6 μm/div; Horizontal: 0.5 ms/div)

TABLE 3

STEP RESPONSES AT DIFFERENT STAGES OF TUNING

(Vertical: 0.2 V/div or 1.6 μm/div; horizontal: 0.5 ms/div)

Initial design	After 1 iteration	After 2 iterations
		

V. CONCLUSION

This paper presents the results of our investigation in application of iterative feedback tuning to find optimal gains of stabilizing PID controller in the head positioning servomechanism of hard disk drive. Design steps are explained and results are verified using both simulation and experiment. It is established that IFT can be used for a mass-produced system like HDD to find controller gains without paying much attention to the model of the plant. Tuning can also be used from time to time so that performance of the controller remains always within the acceptable specifications even if the dynamic properties of actuator are changed due to wear and tear or due to changes in operating conditions.

We have used in our simulation and experiment fixed notch filters for compensation of resonant modes of the actuator. The fact, however, is that frequencies and damping factors of resonant modes vary within some statistical tolerances from actuator to actuator produced in the same batch. Resonant properties may also vary with the usage of actuators and with changes in operating conditions, e.g., temperature. Keeping performance at the optimal level in spite of such variation requires adaptive notch filter whose center frequency can be altered. Achieving such adaptation using IFT is an interesting problem to explore and we are currently working on it.

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