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Adaptive Robust Controller Synthesis for Hard Disk Servo Systems

H. D. Taghirad[1] and **E. Jamei**[2]
Advanced **R**obotics and **A**utomated **S**ystems (ARAS),
Department of Electrical Engineering,
K.N.Toosi University of Technology,
P.O.Box 16315-1355, Tehran, Iran.
[1]Taghirad@kntu.ac.ir, [2]E.Jamei@eetd.kntu.ac.ir

Abstract— **Adaptive robust controller is proposed for read/write head systems for hard disk drives (HDD). This structure can be applied to both track seeking and track following modes, and it makes the mode switching control algorithms proposed in conventional HDD servo system unnecessary. This controller theoretically guarantees a prescribed transient performance and tracking in presence of parametric uncertainties. An Improved Desired Compensation ARC (IDCARC) scheme is then proposed, which has powered by a dynamic adaptive term compared to DCARC. The regressor is calculated using reference trajectory information. This has been done by structural vibration minimized acceleration trajectory control method. Simulation result show that the dynamic adaptation mechanism in IDCARC provide better performance compared to that of ARC, DCARC and the conventional servo system with mode switches control law.**

Keywords- Hard disk drive, adaptive robust control, structural vibration minimized acceleration

I. INTRODUCTION

Hard disk servo systems play a vital role for meeting the demand of increasingly high density and high performance hard disk drives. The servo system must achieve precise positioning of the read/write head on a desired track, called track following, and fast transition from one track to another target track called track seeking. The transition time, or seek time, should be minimized for faster data transfer rates. Because of the different objectives, the control algorithm of seeking is different from that of following, many drives use mode switching control (MSC) for this respect. In MSC nonlinear controller such as proximate time optimal servo (PTOS) are popular choices for track seeking [1]. For track following adaptive control [2,3], repetitive control, and many other approaches have been proposed. Switching of control mode from track seeking to track following should be so smooth that residual vibration of the system is minimal [4]. There have been several attempts to develop unifying control algorithms, which work for track seeking and following. Such control algorithms utilize the two-degree-of-freedom (2-DOF) control structure [4,5,6]. Tomizuka and Yi [6] proposed 2-DOF with adaptive robust control for HDD, track seeking is accomplished by using the feed-forward controller which is based on off-line identification; it may be very sensitive and costly. In [2] Yao proposed another ARC method for cancellation of the pivot nonlinearity and hysteresis effect in following mode. Yao and Xu proposed Desired Compensation ARC (DCARC) for linear motors [7] in which the regressor is calculated using trajectory information based on Sadegh and Horowitz previous results [8].

This Paper focuses on the design of a unifying controller structure base on Improved Desired Compensation ARC (IDCARC). IDCARC incorporate DCARC advantages [7], and in order to achieve fast disturbance attenuation, uses dynamical adaptation for control signal [6]. The algorithm is implemented as a unified controller on seeking and following modes. Reference trajectory generated based on structural vibration minimized acceleration, minimizes the residual vibration of the suspension [4]. Therefore, reference trajectory and its second order derivation which are necessary in the ARC method, are generated on-line, and differentiation from reference input becomes unnecessary. The proposed new ARC controller has some advantages such as: separation of robust control design from parameter adaptation process [9], reduction of the effect of measurement noise, faster adaptation process and no need for feed forward control in seeking time. Moreover, the controller takes into account the delay in seeking time and the effect of model uncertainties and pivot friction.

In this paper, plant modeling is introduced briefly in order to fulfill high performance requirement, the model includes most significant nonlinear dynamics of the system, namely the friction. The objective is to synthesize a controller for a tracking performance despite the model uncertainties. Next in this paper adaptive robust algorithm including on-line-signal generation method has been introduced and its benefits and stability conditions are analyzed.

The presentation of the paper is as following: plant modeling and problem formulation is introduced in section 2, and adaptive robust algorithm incorporating the on-line-signal generation method has been introduced in section 3. In section 4 and 5, DCARC and IDCARC are sequentially introduced, and finally, the comparative studies are elaborated in section 6.

II. PROBLEM FORMULATION AND DYNAMIC MODEL

The mathematical model of the system is assumed to have the following form:

$$\begin{cases} \dot{x}_1 = x_2 \\ J\dot{x}_2 = u - Bx_2 - A_f Sign(\dot{y}) - F_{hys} + F_d \end{cases} \quad (1)$$
$$y = x_1$$

in which, $x = [x_1, x_2]^T$ represent the state vector of the position and velocity, where the output y is position, J is the moment of inertia, u is control input, B and A_f are sequentially coefficient of viscous and coulomb friction, F_{hys} represent the effect of hysteresis loop and F_d is the external disturbance.

Let y_r be the reference motion trajectory. The objective is to synthesize a control input u such the output y tracks $y_r(t)$ as closely as possible in spite of various model uncertainties.

III. ADAPTIVE ROBUST CONTROL

The state space can be linearly parameterized as:

$$\dot{x}_1 = x_2 \quad (2)$$

$$\theta_1 \dot{x}_2 = u - \theta_2 x_2 - \theta_3 Sign(x_2) + \theta_4 + \tilde{d} \quad (3)$$

In which $\theta = [\theta_1, \theta_2, \theta_3, \theta_4]^T$ as $\theta_1 = J$, $\theta_2 = B$, $\theta_3 = A_f$, and $\theta_4 = d_n$, d_n is nominal value of lumped disturbance d. It is assumed the every effect of hysteresis absorbed in to term d, $\tilde{d} = \overbrace{-F_{hys} + F_d}^{d} - d_n$. The following practical assumption is made.

Assumption 1: The following uncertainties and uncertain nonlinearities are known.

$$\theta \in \Omega_\theta \equiv \{\theta : \theta_{\min} < \theta < \theta_{\max}\} \quad (4)$$

$$\tilde{d} \in \Omega_d \equiv \{\tilde{d} : |\tilde{d}| < \delta_d\} \quad (5)$$

where, $\theta_{\min} = [\theta_{1\min}, ..., \theta_{4\min}]^T$, $\theta_{\max} = [\theta_{1\max}, ..., \theta_{4\max}]^T$ and δ_d are known. In (4), the operation $<$ for two vectors is performed in term of corresponding elements of the vectors.

Let $\hat{\theta}$ denotes the estimate of θ and $\tilde{\theta}$ the estimation error (i.e. $\tilde{\theta} = \hat{\theta} - \theta$). In view of (4) the following adaptation law with discontinuous projection modification can be used:

$$\dot{\hat{\theta}} = \mathrm{Proj}(\Gamma\tau) \quad (6)$$

where, $\Gamma > 0$ is a diagonal matrix, τ is adaptation function to be synthesized later. The projection mapping $\mathrm{Proj}_{\hat{\theta}}(\bullet) = [\mathrm{Proj}_{\hat{\theta}_1}(\bullet_1), ..., \mathrm{Proj}_{\hat{\theta}_p}(\bullet_p)]^T$ is defined as:

$$\mathrm{Proj}_{\hat{\theta}_i}(\bullet_i) = \begin{cases} 0, & (if\ \hat{\theta}_i = \theta_{i\max}\ \&\ \bullet_i > 0) or (if\ \hat{\theta}_i = \theta_{i\min}\ \&\ \bullet_i < 0) \\ \bullet_i & Otherwise \end{cases} \quad (7)$$

It can be shown [10] that for any adaptation function τ, the projection mapping used in (7) guarantees:

$$\begin{array}{ll} P1 & \hat{\theta} \in \Omega_\theta \equiv \{\hat{\theta} : \theta_{\min} \le \hat{\theta} \le \theta_{\max}\} \\ P2 & \tilde{\theta}^T (\Gamma^{-1}\mathrm{Proj}(\Gamma\tau) - \tau) \le 0 \quad \forall \tau \end{array} \quad (8)$$

• ARC Controller Design

Define a switching-function quantity as $p = \dot{e} + k_1 e = x_2 - x_{2eq}$, where $x_{2eq} \equiv \dot{y}_d - k_1 e$ and $e = y - y_d(t)$ is the output tracking error, $y_d(t)$ is the desired trajectory to be tracked by y, and k_1 is any positive feedback gain. With respect to (3) can obtain:

$$J\dot{p} = u - \theta_1 \dot{x}_{2eq} - \theta_2 x_2 - \theta_3 Sign(x_2) + \theta_4 + \tilde{d} = u + \varphi^T \theta + \tilde{d} \quad (9)$$

If p is small or converges to zero exponentially, then the output tracking error e will be small or converges to zero exponentially, since $G_p(s) = e(s)/p(s) = 1/(s + k_1)$ is stable transfer function. So the rest of design is to make p as small as possible. Where $\varphi^T = [-\dot{x}_{2eq}, -x_2, -Sign(x_2), 1]$ and $\dot{x}_{2eq} = \ddot{y}_d - k_1 \dot{e}$. The control law consists of two parts:

$$\begin{array}{ll} u = u_a + u_s & u_a = -\varphi^T \hat{\theta} \\ u_s = u_{s1} + u_{s2} & u_{s1} = -k_2 p \end{array} \quad (10)$$

where u_a is the adjustable model compensation needed for achieving perfect tracking, and u_s is robust control law consist of two parts: u_{s1} is used to stabilize the nominal system which is a proportional feedback in this case, and u_{s2} is a robust feedback term to attenuate the effect of model uncertainties, which will be synthesize later. Substituting (10) in to (9), and simplifying can obtain:

$$J\dot{p} = u_s - \varphi^T \tilde{\theta} + \tilde{d} \quad (11)$$

Nothing Assumption 1 and P1 of (8), there exist a u_{s2} such that the following two conditions are satisfied:

$$\begin{array}{ll} i) & p\{u_{s2} - \varphi^T \tilde{\theta} + \tilde{d}\} \le \varepsilon \\ ii) & p u_{s2} \le 0 \end{array} \quad (12)$$

where, ε is a design parameter which can be chosen arbitrarily small. From condition (i) u_{s2} is synthesized to dominate the model uncertainties coming from both parametric uncertainties $\tilde{\theta}$ and uncertain nonlinearities $\tilde{d}$, and condition (ii) makes sure that u_{s2} is dissipating in nature so that it does not interfere with the functionality of the adaptive control part u_a.

Theorem 1: If the adaptation function in (6) is chosen as $\tau = \varphi.p$ then the ARC control law in (10) guarantees the following:

In general, all signals are bounded. Furthermore, the positive definite function $V_s = \frac{1}{2} J p^2$ is bounded by:

$$V_s \le \exp(-\lambda t)V_s(0) + \frac{\varepsilon}{\lambda}[1 - \exp(-\lambda t)] \quad (13)$$

where, $\lambda = 2k_2/\theta_{1\ \max}$.

B) If after finite time t_0, there exist only parametric uncertainties i.e., ($\tilde{d} = 0, \forall t \ge t_0$).then in addition to result in A) zero final tracking is achieved, $e \to 0$ and $p \to 0$ as $t \to \infty$. *Proof: in* [9].

IV. Desired Compensation ARC (DCARC)

In the ARC design presented in section 3, the regressor φ in the model compensation u_a (10) and adaptation function $\tau = \varphi.p$ depends on the actual measurement of the velocity x_2. Thus the effect of measurement noise may be severe. Second, despite of condition i of (12), practically there still exists certain interaction between the model compensation u_a and the robust control u_s. This may complicate controller gain tuning process in an experimental implementation. Sadegh and Horowitz [8] proposed a desired compensation adaptation law, in which the regressor is only calculated by desired trajectory information. The idea is then incorporated in the ARC design in some other works. In this paper, ARC (DCARC) [7] has been applied on the hard disk servo systems.

The proposed DCARC law and the adaptation function have the same from as (10) and $\tau = \varphi.p$, respectively, but with regressor φ substituted by the desired regressor φ_d:

$$u = u_a + u_s \qquad u_a = -\varphi_d^T \hat{\theta} \qquad \tau = \varphi_d p \quad (14)$$

where $\varphi_d^T = [-\ddot{y}_d, -\dot{y}_d, -Sign(\dot{y}_d), 1]$. Substituting (14) into (11), and nothing that $x_2 = \dot{y}_d + \dot{e}$, (15) is obtained:

$$J\dot{p} = u_s - \varphi_d^T \tilde{\theta} + \underline{(\theta_1 k_1 - \theta_2)\dot{e} + \theta_3[Sign(\dot{y}_d) - Sign(x_2)]} + \tilde{d} \quad (15)$$

Note that since only the desired trajectory information $y_d(t)$ is needed, the effort of noise is reduced significantly. Comparing (15) with (11), it can be seen that two additional terms (under lined) has been appeared, which may demand a strengthened robust control function u_s for a robust performance. Applying mean value theorem, we have; $Sign(x_2) - Sign(\dot{y}_d) = g(x_2, t)\dot{e}$, where $g(x_2, t)$ is a nonlinear function. The strengthened robust control function u_s has the same form as (10):

$$u_s = u_{s1} + u_{s2} \qquad u_{s1} = -k_{s1} p \quad (16)$$

but with k_{s1} being a nonlinear function must be $k_{s1} \ge k_2 + \theta_1 k_1 - \theta_2 - \theta_3 g + (\theta_2 + \theta_3 g)^2 / 2\theta_1 k_1$ such that the matrix A defined below gets positive definite.

$$A = \begin{bmatrix} k_{s1} - k_2 - \theta_1 k_1 + \theta_2 + \theta_3 g & -\frac{1}{2}k_1(\theta_2 + \theta_3 g) \\ -\frac{1}{2}k_1(\theta_2 + \theta_3 g) & \frac{1}{2}Jk_1^3 \end{bmatrix} \quad (17)$$

u_{s2} required to satisfy following constrains similar to (12).

$$\begin{aligned} &i) \quad p\{u_{s2} - \varphi_d^T \tilde{\theta} + \tilde{d}\} \le \varepsilon \\ &ii) \quad p u_{s2} \le 0 \end{aligned} \quad (18)$$

Theorem 2: If the DCARC law (15) is applied, then

A) In General, all signals are bounded. Furthermore, the positive definite function $V_s = 1/2Jp^2 + 1/2Jk_1^2 e^2$ is bounded by:

$$V_s \le \exp(-\lambda t)V_s(0) + \frac{\varepsilon}{\lambda}[1 - \exp(-\lambda t)] \quad (19)$$

where $\lambda = \min\{2k_2/\theta_{1\ \max}, k_1\}$.

If after finite time t_0, there exist parametric uncertainties only (i.e., $\tilde{d} = 0, \forall t \ge t$) then, in addition to result in A), zero final tracking error is also achieved, i.e., $e \to 0$ *and* $p \to 0$ *as* $t \to \infty$.

Proof: in [9]

Remark 1: Let h be any smooth function satisfying: $h \ge \|\theta_M\| \ \|\varphi\| + \delta_d$ where $\theta_M = \theta_{\max} - \theta_{\min}$.Then, one smooth example of u_{s2} satisfying (12) is given by: $u_{s2} = -\frac{1}{4\varepsilon}h^2 p$, also for (18):

$$h' \ge \|\theta_M\| \ \|\varphi_d\| + \delta_d, \ u_{s2} = -\frac{1}{4\varepsilon}h'^2 p.$$

Remark 2: To generate reference trajectory benefits jerk minimization based on structural vibration minimized acceleration (SMART), because of the use of SMART strategy, solving an optimal control problem for a double integrator plant with the following performance index is considered [4].

$$J = \int_{t_0}^{t_f} [\frac{du_{smart}(t)}{dt}]^2 dt \quad (20)$$

where t_f is the access time and access distance is y_f, the initial and terminating conditions are:

$$\begin{aligned} &y_{smart}(0) = 0 \quad v_{smart}(0) = 0 \quad i_{smart}(0) = 0 \\ &y_{smart}(t_f) = y_f \quad v_{smart}(t_f) = 0 \quad i_{smart}(t_f) = 0 \end{aligned}$$

Values of SMART output, voltage and current are given by the following:

$$\begin{aligned} y_{smart}(k) &= [6(k/k_f)^5 - 15(k/k_f)^4 + 10(k/k_f)^3] y_f \\ v_{smart}(k) &= [30(k/k_f)^4 - 60(k/k_f)^3 + 30(k/k_f)^2] \frac{y_f}{k_f} \\ i_{smart}(k) &= \frac{Jk_y}{k_T T_s^2}[120(k/k_f)^3 - 180(k/k_f)^2 + 60(k/k_f)] \frac{y_f}{k_f^2} \end{aligned} \quad (21)$$

Where k is discrete time index, k_f is final sample number, k_y is one track pitch angle (rad/track), k_T is torque constant, T_s is sampling time(sec),

We benefit (21) to generate reference trajectory and to generate φ_d in (14).

V. Improved Desired Compensation ARC

The DCARC design presented in section 4, is not able to attenuate disturbance fast enough to accommodate hard disk drives requirements. The idea of made dynamic in signal control u_a [6], is improved and implemented on hard disk drives. In this paper the main idea is to change the I (integrator) estimator to a PI (Proportional Integration) in estimation mechanism of θ. Consider the model of hard disk servo system in identification procedure.

$$\textit{Real system: } u + d = J\ddot{y} + B\dot{y} + A_f Sign(\dot{y}_d) \qquad (22)$$

It is suggested to reach to the

$$\textit{Ideal system: } p = J\ddot{y}_d + B\dot{y}_d \qquad (23)$$

Lemma 1: suppose; $y(t+t_d) = y_d(t)$ in which, t_d is the system delay. Hence, for the generated signal: $y(t+t_d) \geq y(t)$, and therefore:

$$y(t) = \alpha_1 y_d(t) \;\&\; \dot{y}(t) = \alpha_2 \dot{y}_d(t) \;\&\; \ddot{y}(t) = \alpha_3 \ddot{y}_d(t) \qquad (24)$$

where α_1, α_2 and α_3 are constant coefficient depending on time. Without loss of generality assume $u_{s2} = 0$; hence, $u = u_a + p$ by substitution of (14) into (22) with respect to (24) and some simplifications:

$$p + \underline{(\hat{J} - J\alpha_3)\ddot{y}_d + (\hat{B} - B\alpha_2)\dot{y}_d + (\hat{A}_f\, Sign(\dot{y}_d)} \\ \underline{- A_f Sign(\alpha_2 \dot{y}_d)) + (d - \hat{d})} = 0 \qquad (25)$$

From theorem 2 it can be seen that as $p \to 0$ or $p \to \varepsilon$, the underlined term of (25) will converge to zero or to a small number. Now we propose adding dynamic term to u_a to introduce the following dynamics to it.

$$p + (\dot{\hat{J}}\ddot{y}_d + k\,\hat{J}\ddot{y}_d - J\alpha_3\ddot{y}_d) + (\dot{\hat{B}}\dot{y}_d + k\,\hat{B}\dot{y}_d - B\alpha_2\dot{y}_d) + \\ (\dot{\hat{A}}_f\, Sign(\dot{y}_d) + k\,\hat{A}_f\, Sign(\dot{y}_d) - A_f Sign(\alpha_2 \dot{y}_d)) \\ + (d - \dot{\hat{d}} - k\,\hat{d}) = 0 \qquad (26)$$

Furthermore each term inside the brackets consist of a first order differential equation, i.e., by this means a suitable dynamics is introduced for the compensation signal. This structure will improve the effect of delay in seeking mode. Since, by the introduced dynamics (22) approaches dynamically to (23), and hence, better disturbance and friction compensation is obtained. Thus, the adaptation law can be interpreted as adding PI term to u_a.

The proposed improved IDCARC law and the adaptation function have the same form as (14), respectively, but with the difference that $\tau = \varphi_d p$ subjected to the introduced dynamics of τ_d.

$$u = u_a + u_s \qquad u_a = -\varphi_d^T \hat{\theta} \qquad \tau_d = \varphi_d(\dot{p} + kp) \qquad (27)$$

Equations (14) to (18) and theorem 2 for DCARC can be applied with this improvement to IDCARC.

VI. Comparative Studies

Simulations studies have been performed for ARC, DCARC and IDCARC using Fujitsu hard disk drive model [4]. The HDD components are shown in Fig.1. The parameters of Fujitsu M2954 are summarized in Table1.

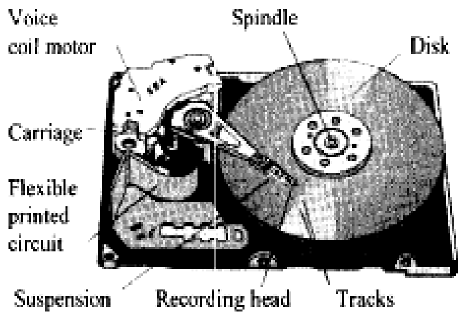

Fig. 1. Hard disk drive components

Table 1. Parameter of Hard Disk Drive Components

Spindle speed		7200 rpm
Track pitch	L_{track}	3.945μm
Sampling period	T_s	67.2μs
Maximum speed	v_{max}	42.3rad/s
Coil resistance and Current sensing resistance	R	8.516 Ω
Coil inductance	L	1.24mH
Back e.m.f constant	K_e	0.08976 $V*s/rad$
Torque constant	K_T	0.08976 $N*m/A$
Moment of inertia	I_b	$5.957\times10^{-6} kg*m^2$
High order vibration mode		3.4 kHz

For compensation of simulation results for different controllers as in [4, 6, 7], the following performance index are used:

I1) $L_2[e] = \sqrt{\frac{1}{T_f}\int_0^{T_f} |e|^2 dt}$, an average tracking performance index, for the entire error curve $e(t)$. T_f represents the total running time in here. I2) $e_M = \max_t\{|e(t)|\}$, the maximum absolute value of the tracking error. I3) $e_F = \max_{T_{f-1}\leq t\leq T_f}\{|e(t)|\}$, the maximum absolute value of the tracking error during the last one millisecond. I4) $L_2[u] = \sqrt{\frac{1}{T_f}\int_0^{T_f} |u|^2 dt}$, the averages control input. I5) $c_u = L_2[\Delta u]/L_2[u]$, the control input chattering, where is $L_2[\Delta u] = \sqrt{\frac{1}{N}\sum_{j=1}^{N}|u(j\Delta T) - u((j-1)\Delta T)|^2}$ the normalized control variations.

• Mode Switching Control During the seeking mode of MSC, the servo controller drives the read/write head to follow the desired velocity profile, which is calculated base on a rigid body plant model. Defining the velocity profile as $v(p) = -\mathrm{sgn}(p)\sqrt{2a|p|} - r_t$ if $|p| > 2r_t^2/a$ or $v(p) = -(a/2r_t).p$ if $|p| < 2r_t^2/a$ a proximate time optimal system (PTOS) can be generated [1]. In which, $p, a,$ and r_t are the remaining distance to the target track, the maximum acceleration, and the velocity offset, respectively. In PTOS approach, the back electromotive force, which physically behaves like linear friction, and the actuator bandwidth are not taken into consideration, and as a result, the velocity profile in PTOS method can only be approximately followed.

• **ARC:** The ARC law proposed in section 3. is applied onthe system. With $u_s = -k_s p$, $k_s \geq k_2 + h^2/4\varepsilon$ the control gains are chosen as: $k_1 = 644$ and $k_s = 1.34$. The adaptation rates are set as $\Gamma = diag\{10,0,1,10000\}$ The initial parameters are chosen as follows, $\theta(0) = [1e-6, ,12.5e-6,0,0]^T$ $\theta_{Max} = [1.1e-6,13.9e-6,1e-5,1]^T$.

• **DCARC:** The Desired Compensation ARC law proposed in section 4 with $u_s = -k_s{}' p$ is applied on the system. The control gains are chosen as $k'_s \geq k_2 + h'^2/4\varepsilon$ $k_1 = 644$ and $k_s{}' = 1.34$. The adaptation rates are set as $\Gamma = diag\{10,0,1,10000\}$.

• **IDCARC:** The Improved DCARC law proposed in section 5 is applied on the system. All coefficients are the same as DCARC coefficient and integrator gain in adaptive part is set to $k = 10000$.

Set1: To test tracking performance of the controllers in present of friction with $A_f = 1e-5$ from [3].

Set2: To test the performance with a step disturbance in $t = 7_{ms}$ with amplitude about 0.2v.

Set3: To test the performance with %10 variation in system gain.

Table 2. Performance Index for Desired trajectory

	Set1			Set2			Set3		
Controller	ARC	DCARC	IDCARC	ARC	DCARC	IDCARC	ARC	DCARC	IDCARC
$e_M \times 10^{-6}$	5.22	5.37	6.39e-3	5.22	5.37	6.39e-3	6.75	6.72	7.93e-3
$e_F \times 10^{-6}$	1.8e-1	2.6	2.85e-5	2.82	2.98	2.16e-4	1.77	4.30	3.27e-5
$L_2[e] \times 10^{-4}$	3.14	1.40	9.49e-4	3.31	1.42	8.51e-4	3.89	1.76	1.17e-3
$L_2[u]$	31.7	16.6	9.07	31.7	16.6	9.07	38.2	20.8	11.3
$L_2[\Delta u] \times 10^{-3}$	7.90e-1	1.87	56.3	2.18	6.03	57.4	1.66	2.34	60.2
c_u	2.48e-5	1.3e-4	6.21e-3	6.87e-5	3.63e-4	6.23e-3	4.35e-5	1.12e-4	5.33e-3

As quantitatively shown in Table 2, the simulation results in terms of performance indices e_M and e_F of ARC and DCARC are relatively poor for all sets compared to that of IDCARC. IDCARC has the best performance in terms of $L_2[u]$, $L_2[e]$, e_M and e_F for the abovementioned sets. The main reason for this significant improvement is due to the proposed dynamic term added in the estimation procedure. It can be seen in the Fig. 2 that the closed loop position results obtained through IDCARC method, has a suitable settling characteristics without any large overshoots and attenuate disturbances significantly compared to that of ARC and DCARC (Notice the power 10-3 in Fig. 2-c). In Fig. 3 smooth control effort signal confirm the advantages of jerk minimized reference input. The low values of obtained e_m in the IDCARC method shows the effectiveness of delay compensation. The rejection of the disturbance occurred in $t = 7_{ms}$ in IDCARC method shows superior characteristics in both following and seeking modes. The tracking error in Fig. 2 illustrates the superior performance of IDCARC compared to the other methods. The control inputs of three controllers are given in Fig.3. Because of the introduced dynamics in adaptation algorithm in IDCARC method, the proposed method is capable to pick up the actual value of disturbance more quickly. This can be seen from the comparison of the parameter estimation rates shown in Figs 4, 5 and 6.

The closed loop results with 10% variation in system parameters given in Set 3 of Table 2, confirms the robustness in the performance of IDCARC method compared to the other methods. Finally, as illustrated in Fig.7 the seeking time of IDCARC results are much faster than that in PTOS method. By this comparison study, the effectiveness of the proposed control algorithm is verified and illustrated compared to the other methods.

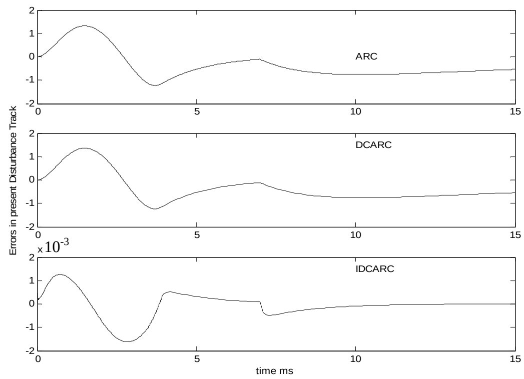

Fig 2. Tracking error

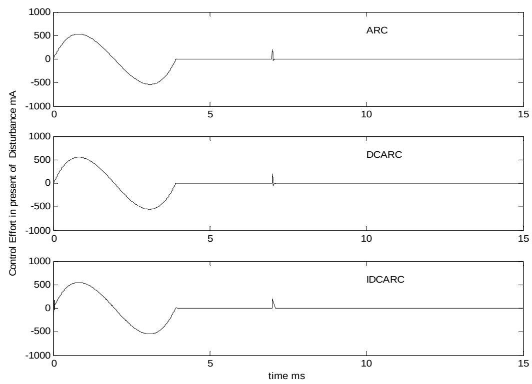

Fig .3. Control effort for smooth signal generated

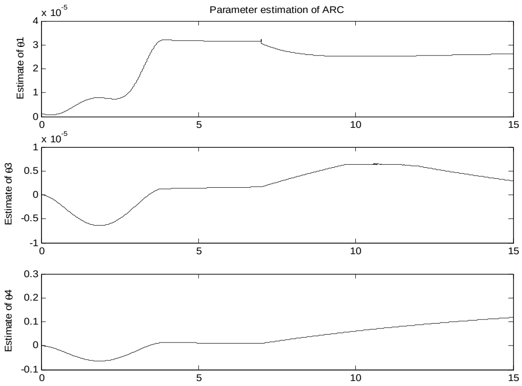

Fig 4. Parameter estimation of ARC

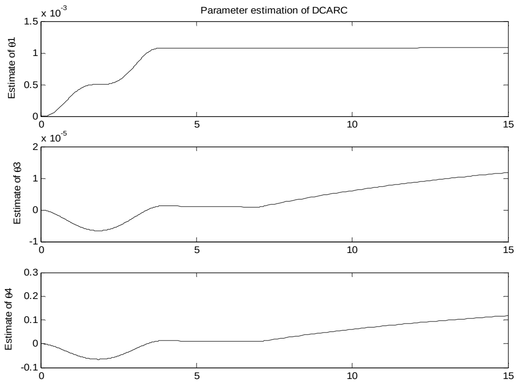

Fig 5. Parameter estimation of DCARC

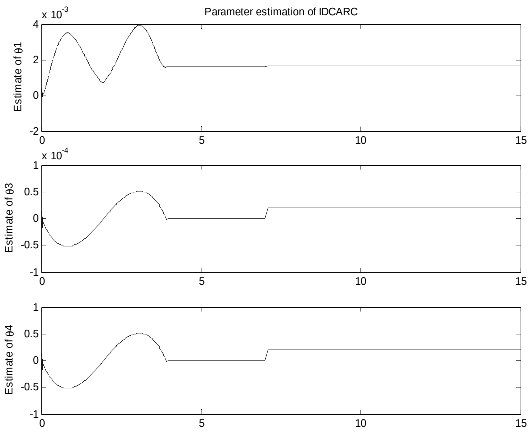

Fig 6. Parameter estimation of IDCARC

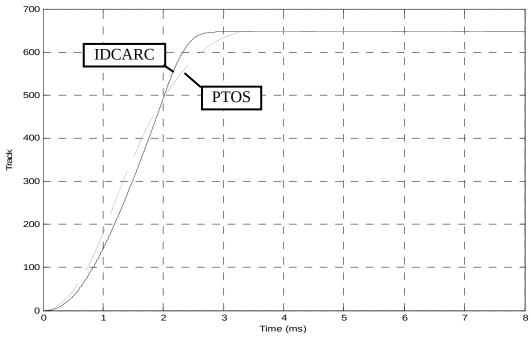

Fig 7. Seeking and following of 650 tracks

VII. Conclusions

In this paper, the adaptive robust controller is implemented for hard disk drives (HDD). This method with its unified structure can be applied to both seeking and following modes, without need of any mode switching control algorithm. A discontinuous projection based on adaptive robust controller (ARC) is considered first. This controller theoretically guarantees a prescribed transient performance and tracking in presence of parametric uncertainties. An IDCARC scheme is then presented, in which the regressor is calculated using reference trajectory information. This has been done by structural vibration minimized acceleration trajectory control method (SMART). The resulting controller has several implementation advantages such as on-line computation time reduction, vibration attenuation, reduction of noise measurement effect, separation of robust control design from parameter adaptation, and faster adaptation rate. The simulation and comparison results are presented to illustrate the effectiveness and the achievable control performance of the proposed controller algorithm. It is shown that the IDCARC method is capable of significantly improving the seeking and following performances, despite the variation in system parameters.

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