RISE Feedback with NN Feedforward Control of a Servo-Positioning System for Track Following in HDD

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Abstract: This paper addresses design challenges associated with a servo system of a Hard Disc Drive (HDD). The recently developed Robust Integral of Sign Error (RISE) approach is proposed to control the Read/Write (R/W) head tip of the HDD. Such a technique, combined with a feedforward Neural Network (NN) control term, is not only able to meet the different imposed constraints on the system, but also guaranty the asymptotic stability of the overall closed-loop system. To the best knowledge of the authors, the proposed controller, applied at the low frequency region of a HDD, has never been conducted before on such a system. A comparative study between the RISE-NN controller and the classical Proportional Integral Derivative (PID) is performed under various operating conditions ranging from nominal case without external disturbances to more complex cases with disturbances and parametric uncertainties. The main objective of this study is to highlight the effectiveness of RISE-NN control approach in solving the track following problem in HDD.

Keywords: RISE feedback control, nonlinear systems, hard-disc-drives, asymptotic stability, robust control, neural networks.

1 Introduction

Since its appearance in 1956, the Hard-Disc-Drive (HDD) technology has continued to progress over the years. This accelerated evolution has primarily affected the storage capacity growing from few Megabytes to several Terabytes. In addition, many other characteristics have undergone perceptible changes [1]. These include the size factor which has been reduced from 24-inch diameter in a 50 disks prototype to one disk of 3.5-inch diameter, the spindle speed which has steadily increased to reach 15000 rpm in the latest versions of HDDs,etc. The main objective of such a development is to improve the system operating performance in terms of access speed, precision of the positioning, data access, and reliability.

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From a technical standpoint, it can clearly be seen that a HDD is a mechatronic system. Indeed, the system is constructed through the synergistic integration of mechanical engineering, electronics, control engineering, and computer technology. Figure 1 shows a view of the main components of a typical HDD servo-system.

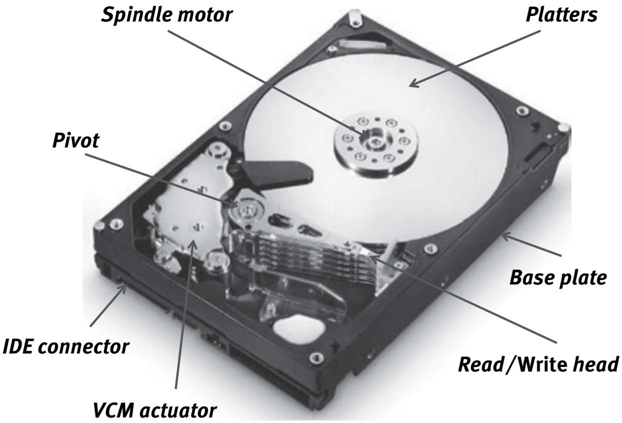

Fig. 1. View of the main components of a typical HDD.

A HDD is composed of a spindle motor devoted to drive the rotating platters, where digital data are stored in concentric tracks. In order to treat these data, whether to read from or write on the disc, the system is equipped with several magnetic Read/Write (R/W) heads. These heads are connected to a second motor, called Voice-Coil-Motor (VCM), which is designed to manage their movement on the disk surface and achieve access to the desired track.

A good HDD is evaluated according to its ability to move the R/W head tip rapidly from its current position to a desired target track and to maintain it as close as possible to its center while treating data. Therefore, the Position Error Signal (PES), defined as the deviation of the R/W head from the desired track center, should be as minimal as possible in order to guarantee a reliable data reading or writing. Such a regulation is tighter with the modern HDD servo-systems becoming more and more small in size. In addition to the reduced size factor, many sources of errors can be noticed in the system. These factors contribute significantly to the degradation of the overall system's performance in terms of precision and access to the information. They mainly include nonlinear frictions caused by the pivot bearing and the flex cable and inaccuracies caused by the movement of the head form one track to another. Generally, a HDD is often subject to various disturbances which can be classified into three categories: The input disturbances caused by mechanical perturbations such as resonances, friction and vibrations The output disturbances which are due to the rotation of the spindle motor rotation and its effects. The measurement noise caused by the position-measurement techniques and/or sensors.

All the above-listed errors' sources threaten the performances of the HDD servo-system and may degrade the system reliability. Consequently, it would be necessary to deal with them rigorously and compensate their effects as much as possible.

To do that, several research efforts have been devoted to design efficient robust controllers. Their common objective was not only to overcome the different HDD problems cited above, but also to ensure a tighter PES while positioning the R/W head even in the presence of eventual disturbances, nonlinearities, and inaccuracies on the system's dynamics.

Among these control solutions, we can distinguish classical approaches such as PID controllers [2], lead-lag compensator [3] and classical filters [4] which can no longer meet the demand for HDDs higher performances. Accordingly, to deal with these difficulties, several control attempts have been recently developed including (i) advanced control approaches such as optimal controllers [5, 6], Composite Nonlinear Feedback technique (CNF) [7] and Robust Perfect Tracking (RPT) [8] and (ii) several robust control solutions such as adaptive control [9, 10], sliding mode control [11, 12], robust control [13, 14] and lately predictive control approaches [15, 16]. Some of these methods have been experimentally tested to show their strengths and weaknesses on a real system.

This paper is dedicated to the application of the recently developed control method based on Robust Integral Sign of the Error (RISE) [17] to the case of HDDs. This control technique is chosen based on its advantages in addressing the problem of trajectory tracking of a class of uncertain and high order nonlinear systems [17, 18]. Since RISE is a high gain feedback method, the idea proposed in [19] was to develop an improved version of this technique which involves the combination of a Neural Network based feedforward control term with the feedback controller. In this paper, this control solution is proposed to address the track following problem in a HDD servo-system and to ensure both robust performance and asymptotic stability of the overall closed-loop servo-system.

The reminder of this paper is organized as follows. In section 2, the HDD low-frequencies dynamic modeling is introduced. Then, in section 3, the HDD servo-positioning control problem is formulated. In section 4, the RISE feedback based NN controller is developed. Section 5 is devoted to a comparative study between the proposed RISE-NN and a classical PID controllers, where numerical simulations in different operating conditions are presented and discussed. Finally, in section 6, some concluding remarks are drawn.

2 HDD Low Frequencies Dynamic Modeling

In a HDD servo-system, one of the important limitations for high track density is the nonlinear effects arising from frictions. Such nonlinear frictions are mainly induced by the pivot bearing and data flex cable in the VCM actuator (see Fig. 1). Their presence leads to the generation of large residual errors and oscillations which degrade the overall system performances and reduce its reliability.

Certainly, a deeply understanding of the nonlinear friction behavior would be helpful to find an efficient control solution that mitigate their degrading effects. Therefore, for the aim of developing a representative friction model in a HDD servo-system, many researchers have provide considerable efforts in the literature [20, 21]. The best representation that encompasses all static and dynamic features turned out to be that of LuGre friction model [22]. For a complete review of the friction modeling, the reader is referred to [23].

In order to enhance the track following performances in a HDD servo-positioning system, it would be necessary to compensate the overall nonlinear frictions. A survey of the literature showed that many control approaches dealing with the above compensation have been proposed. Some of them include an accurate modeling of the friction behavior [24, 25] and others are non-model-based friction estimation [26, 27]. In spite of all the proposed solutions, the study of the nonlinear friction behavior and the search for a good compensation control solution are still open problems in HDD technology.

Based on recent works of [28], the low-frequency mathematical model of the VCM actuator can be expressed as follows:

$$M(q)\ddot{q} + F(q,\dot{q}) = u \qquad (1)$$
$$y = q + w_{out}$$

where $M(q)$ denotes the system inertia verifying $M(q) > 0$. q, $\dot{q}$ and $\ddot{q}$ denote the actual position, velocity and acceleration of the VCM-actuator head tip respectively. u represents the control input, y is the measured position of the VCM-actuator in presence of the eventual output disturbance w_{out} representing external vibrations and chocks caused by the flexibility of the material. $F(q,\dot{q})$ is a nonlinear function representing the pivot bearing hysteresis friction whose behavior can be described by the LuGre friction model [22]. This last one is expressed as follows:

$$F(q,\dot{q}) = \sigma_0 z + \sigma_1 \dot{z} + \sigma_2 \dot{q} \qquad (2)$$

$$\dot{z} = \dot{q} - \alpha(\dot{q}) \mid \dot{q} \mid z \qquad (3)$$

$$\alpha(\dot{q}) = \frac{\sigma_0}{f_c + (f_s - f_c)\,\exp\left(-\left[\frac{\dot{q}}{\dot{q}_s}\right]\right)^2} \qquad (4)$$

where z is an internal state of the friction model assumed to be immeasurable. σ_0, σ_1, and σ_2 are the model parameters reflecting the small displacements which are the stiffness, the micro damping, and viscous coefficient respectively. f_s corresponds to the stiction force, f_c is the Coulomb friction force, and the parameter q_s is the Stribeck velocity [29].

3 Control Problem Formulation

The main goal of a HDD servo-system control is to read/write data from/on concentric track circumscribed onto the disc surface. Therefore, by controlling the current in the VCM, the head is able to move in both directions to follow the desired target track. Consequently, in order to reach its target, two main functioning modes can be distinguished [1]: The first one, being the *track seeking* mode, deals with moving the R/W head from one desired track to another, at a distance of about a micro-inch between two adjacent tracks. The displacement of the head is required to be as quick as possible with a limited control effort. The second mode, being the *track following* mode, consists of maintaining the head as close as possible to the center of the desired data track to guarantee an accurate positioning, crucial for reading/writing digital data. Therefore, the drive initiates its functioning by a track seeking control with a saturated control law. Then, when the head is positioned onto the target track, the drive switches into the track following mode. A schematic illustration of the above mode functions is shown in Fig. 2.

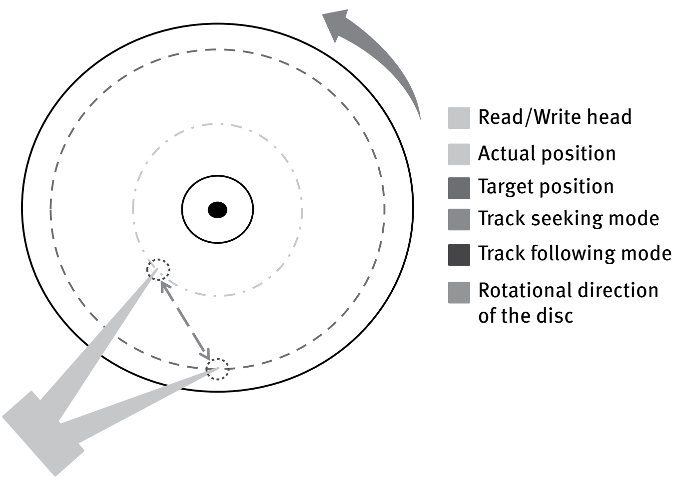

Fig. 2. Illustration of the main operating functions of a HDD servo-system.

Let q_d be the desired track position. In order to evaluate the tracking performance, the position error e_1 is introduced. It is defined as the deviation of the HDD head tip from the center of the desired position:

$$e_1 = q_d - q \tag{5}$$

The main control objective consists of moving the head onto the surface of the disc so that it follows a predefined target track. Then, the head is required to be as close as possible to this desired position while reading/writing data, in order to ensure superior HDD performances. The setting equation of the control objective can be reformulated as follows:

$$\lim_{t\to\infty} |e_1(t)| = \lim_{t\to\infty} |q_d(t) - q(t)| = 0 \tag{6}$$

In the present paper we aim to design an efficient control solution for the track-following mode.

4 Proposed Control Solution

The recent developed feedback control strategy RISE [17] is proposed in this paper to deal with the track following problem of the HDD servo-system. Such a control technique, blend with a NN-based feedforward, is able to deal with the non-explicit knowledge of the friction model $F(q, \dot{q})$ introduced in the dynamic model (1)-(4). Before going further, to give an overview of the control strategy, an illustrative block diagram of such controller is shown in Fig. 3.

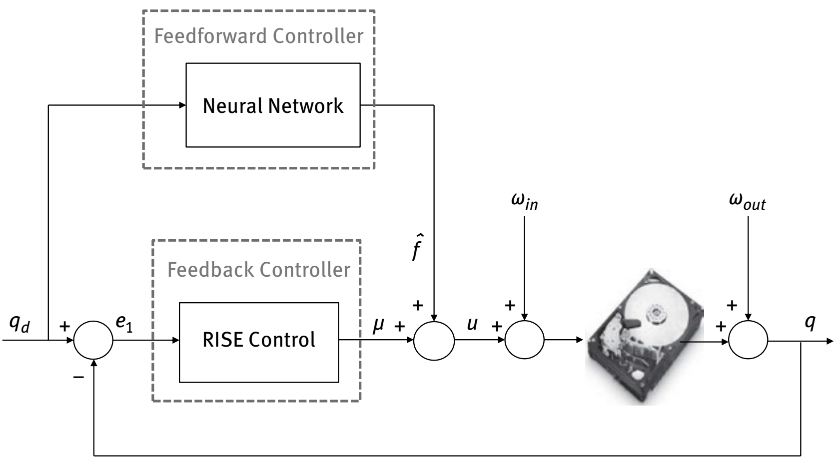

Fig. 3. Overview of the control scheme including a RISE feedback with a NN feedforward.

Starting from a desired target track q_d, the global control input u, which is the sum of a feedforward NN control term $\hat{f}$ and a RISE feedback term μ, is calculated at each sample time to move the head tip to the desired position. In the following section, a background on NN-based Feedforward then RISE Feedback controllers are introduced illustrating how they can be combined together to achieve an asymptotic stability of the overall closed-loop system.

4.1 Background on NN Feedforward Control

Dynamic neural networks present an effective tool for estimation and control of nonlinear and complex systems [30]. The universal approximation remains the key feature of the NN-based controllers [31]. Consider $\mathbb{S}$, a compact set and $f(x)$ a smooth function defined as $f : \mathbb{S} \to \mathbb{R}^n$. There exists always three-layer NN able to represent $f(x)$ [19] such that $f(x) = W^\top \sigma(V^\top x) + \varepsilon(x)$ for given inputs $x(t) \in \mathbb{R}^{a+1}$. $V \in \mathbb{R}^{(a+1)\times L}$ is a bounded constant weight matrix for the first-to-second layer and $W \in \mathbb{R}^{(L+1)\times 1}$ is the ideal weight matrix for the second-to-third layer. a is the number of inputs and L is the number of neurons in the hidden layer. $\sigma(.) \in \mathbb{R}^{L+1}$ is the activation function and $\varepsilon(x) \in \mathbb{R}^n$ is the functional error approximation, satisfying $\| \varepsilon(x) \| \leq \varepsilon_N$, with ε_N is a known constant bound. Figure 4 shows an illustrative description of a three-layer NN principle.

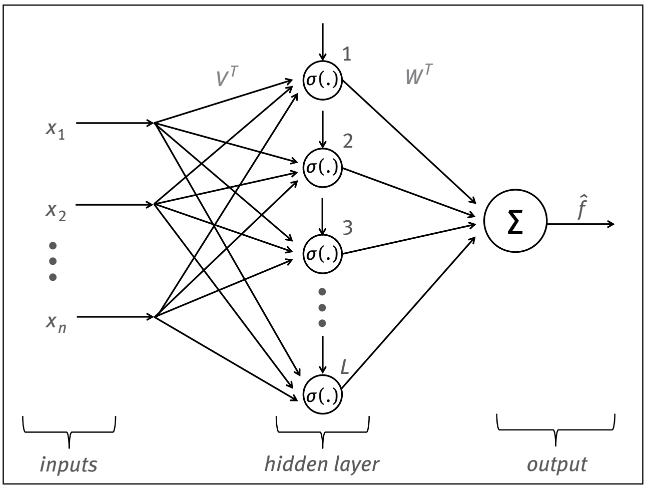

Fig. 4. Schematic view of a three-layer NN.

Remark 1: The activation function $\sigma(.)$ can take different forms such as sigmoid, hyperbolic tangent or a radial basis function. In this paper, the considered $\sigma(.)$ is a radial basis function described by the following equation:

$$\sigma(x_i) = \exp\left(-\frac{\|x_i - c_i\|^2}{\sigma_i^2}\right) \quad , \quad \forall i \in \mathbb{N}$$

where c_i is the center of the basis function and σ_i is its width; they are chosen a priori and kept fixed throughout this work for reason of simplicity.

For subsequent developed calculations of the control input, some assumptions and properties have to be exploited which are the following:

Assumption The desired position q_d, as well as its first and second time derivatives exist and are all bounded, i. e., q_d, $\dot{q}_d$, and $\ddot{q}_d \in \mathcal{L}_\infty$.

Property The NN quantities are bounded such as $\| W \| \leq W_m$, $\| \sigma \| \leq \sigma_m$, where W_m and σ_m are known positive constants [32].

4.2 Background on RISE Feedback Control

In this work, the main control objective is to maintain the R/W head as close as possible to a predefined desired position in order to perform an accurate track following task. Therefore, a RISE feedback control approach with NN feedforward estimation is therefore proposed as a control solution (i) to deal with the unknown nonlinear dynamics and (ii) to guarantee the asymptotic stability of the controlled HDD model (1)-(4). The control strategy is detailed in this section, introducing the open-loop and closed-loop tracking errors. Based on assumption 1, the position tracking error $e_1(t)$, the filtered tracking errors denoted by $e_2(t)$ and $r(t)$, are defined as follow

$$e_1 = q_d - q \tag{7}$$

$$e_2 = \dot{e}_1 + \alpha_1 e_1 \tag{8}$$

$$r = \dot{e}_2 + \alpha_2 e_2 \tag{9}$$

where α_1 and α_2 are positive tuning gains.

Remark 2: The filtered tracking error $r(t)$ is an immeasurable quantity since it depends on $\ddot{q}(t)$ which is not measurable in a HDD.

4.2.1 Open-loop tracking error system

To develop the open-loop tracking error system, a multiplication of (9) by $M(q)$ is made. Then, based on the expressions (1), (7), and (8), the resulting system can be expressed as follow:

$$M(q)r = F_d + S - u \tag{10}$$

where F_d is an auxiliary function defined by:

$$F_d = M(q)\ddot{q}_d + F(q_d, \dot{q}_d) \tag{11}$$

and S is a second auxiliary function defined by:

$$S = M(q)(\alpha_1 \dot{e}_1 + \alpha_2 \dot{e}_2) + F(q, \dot{q}) - F(q_d, \dot{q}_d) \tag{12}$$

Based on the NN approximation, F_d can be expressed as follows:

$$\dot{F}_d = W^\top \sigma(V^\top x_d) + \varepsilon(x_d) \tag{13}$$

where $x_d = \begin{bmatrix} 1 & q_d & \dot{q}_d & \ddot{q}_d \end{bmatrix}^\top$ and $\varepsilon(x_d)$ is the bounded NN approximation error. According to assumption 1, the following inequalities hold:

$$\| \varepsilon(x_d) \| \le \varepsilon_N \tag{14}$$

$$\| \dot{\varepsilon}(x_d, \dot{x}_d) \| \le \varepsilon'_N \tag{15}$$

where ε_N and ε'_N are known positive bounded constants.

4.2.2 Closed-loop tracking error system

Using the previous open-loop tracking error system (10), the control input can be expressed as the sum of the feedforward NN estimation term and the RISE feedback term. As detailed in [33], the RISE control term $\mu(t)$ is given by:

$$\mu(t) = (k_s + 1)e_2(t) - (k_s + 1)e_2(0) + \int_0^t \{(k_s + 1)\alpha_2 e_2(s) + \beta_1 \operatorname{sign}[e_2(s)]\} ds \tag{16}$$

where $k_s, \beta_1 \in \mathbb{R}^+$ are positive feedback gains. The time derivative of (16) leads to:

$$\dot{\mu}(t) = (k_s + 1)r(t) + \beta_1 \operatorname{sign}[e_2(t)] \tag{17}$$

Since the nonlinearities in the system's dynamics are supposed to be unknown, a new control term, denoted $\hat{F}_d$, and generated by the NN feedforward estimation is added cancel out the effects of the uncertainties. $\hat{F}_d$ is then expressed by:

$$\dot{\hat{F}}_d = \hat{W}^\top \sigma(V^\top x_d) \tag{18}$$

where $V \in \mathbb{R}^{(a+1)\times L}$ is a bounded constant weight matrix, and $\hat{W} \in \mathbb{R}^{(L+1)\times 1}$, is the matrix of the estimates of the NN weights, generated on-line by:

$$\dot{\hat{W}} = K[\sigma(V^\top x_d)e_2^\top - \kappa \hat{W}] \tag{19}$$

where κ is a positive design constant parameter. $K = K^\top > 0$ is a constant positive definit control gain matrix. According to property 1, the upper bound of $\dot{\hat{W}}$ can be formulated as follows:

$$\| \dot{\hat{W}} \| \leq F_N \sigma_m \| e_2 \| \tag{20}$$

where F_N is a known bound constant. The overall control input is then given by:

$$u = \hat{F}_d + \mu \tag{21}$$

By evaluating the time derivative of (21) and substituting the expressions of $\dot{\mu}$ and $\dot{\hat{F}}_d$ given by (18) and (17) respectively, we get:

$$\dot{u} = \dot{\hat{F}}_d + \dot{\mu} \; = \; \hat{W}^\top \sigma(V^\top x_d) + (k_s+1)r(t) + \beta_1 \operatorname{sign}[e_2(t)] \tag{22}$$

Thereby, the closed-loop tracking error system dynamics are formulated by considering the first time derivative of (10)

$$\begin{aligned} M(q)\dot{r} &= -\dot{M}(q)r + \dot{F}_d + \dot{S} - \dot{u} \\ &= -\dot{M}(q)r + \dot{F}_d + \dot{S} - \hat{W}^\top \sigma(V^\top x_d) - (k_s+1)r(t) \\ &\quad -\beta_1 \operatorname{sign}[e_2(t)] \\ &= -\frac{1}{2}\dot{M}(q)r + \tilde{W}^\top \sigma(V^\top x_d) + \varepsilon(x_d) - (k_s+1)r(t) \\ &\quad +(-\frac{1}{2}\dot{M}(q)r + \dot{S} + e_2) - \beta_1 \operatorname{sign}[e_2(t)] - e_2 \end{aligned} \tag{23}$$

where $\tilde{W}^\top = W^\top - \hat{W}^\top$ is the estimation error. Equation (23) can then be rewritten as follows:

$$M(q)\dot{r} = -\frac{1}{2}\dot{M}(q)r + \tilde{N} + N_{B_1} + N_{B_2} - e_2 - (k_s+1)r(t) - \beta_1 \operatorname{sign}[e_2(t)] \tag{24}$$

with

$$\tilde{N} = -\frac{1}{2}\dot{M}(q)r + \dot{S} + e_2 \tag{25}$$

$$N_{B_1} = \varepsilon(x_d) \tag{26}$$

$$N_{B_2} = \tilde{W}^\top \sigma(V^\top x_d) \tag{27}$$

As detailed in [33], thanks to the Mean Value Theorem, $\tilde{N}$ is upper bounded as follows:

$$\| \tilde{N} \| = \| -\frac{1}{2}\dot{M}(q)r + \dot{S} + e_2 \| \leq \rho(\| z_1 \|) \| z_1 \| \tag{28}$$

where $z_1(t) \in \mathbb{R}^3$ is given by:

$$z_1(t) = \begin{bmatrix} e_1^\top & e_2^\top & r^\top \end{bmatrix}^\top \tag{29}$$

and $\rho(\| z_1 \|)$ is a positive non decreasing bounding function. In order to facilitate the stability analysis, some important inequalities are considered according to the following lemma.

Lemma 1
Consider N_{B_1} and N_{B_2} as expressed respectively by (26) and (27). The following inequalities hold.

$$\| N_{B_1} \| \leq \varepsilon_N \tag{30}$$
$$\| \dot{N}_{B_1} \| \leq \varepsilon'_N \tag{31}$$
$$\| N_{B_2} \| \leq (\tilde{W}_m^\top + F_N \sigma_m \| e_2 \|)\sigma_m \equiv \xi_{B_2} \tag{32}$$
$$\| \dot{N}_{B_2} \| \leq \xi_1 \| e_2 \| + \xi_2 \tag{33}$$

where ξ_{B_2}, ξ_1, and ξ_2 are positive known constants.

Proof:
Inequalities (30) and (31) can be directly determined according to equations (14), (15), and (26). Based on Property 1 and equation (20) dealing with the upper bound of the NN weights, the inequality (32) can be easily justified. Then, by considering the derivative relation $\dot{\sigma}_m = \sigma_m(1 - \sigma_m)$ together with the time derivative of N_{B_2} expressed as $\dot{N}_{B_2} = \dot{\tilde{W}}\sigma_m + \tilde{W}\dot{\sigma}_m$, inequality (33) is concluded.

For a complete review of the stability analysis of the RISE-NN control approach, the reader is referred to [19].

5 Numerical Simulations

In this section, numerical simulations are conducted in the framework of Matlab/Simulink software. The 3.5” HDD (Seagate Barracuda 7200.10) dynamic model [34] is chosen as a demonstrator in simulation to test the effectiveness of the proposed control schemes. The full mathematical description of this prototype is given by equations (1)-(4) with a sample time fixed to $T_e = 0.05ms$. The normalized dynamic model parameters are given by: $M(q) = 1$, $\sigma_0 = 10^5$, $\sigma_1 = \sqrt{10^5}$, $\sigma_2 = 0.4$, $f_s = 1.5$,

$f_c = 1$, and $\dot{q}_s = 10^{-3}$. The NN weights are manually tuned off-line for the best possible controller performance. A physical restriction is imposed on the VCM actuator leading to the saturation of the control input u, that is $|u| \leq 3v$ corresponding to a practical range in real HDD servo-systems. All initial conditions are chosen to be at the origin. Three different simulation scenarios have been considered.

The first scenario deals with tracking of both sinusoidal and step desired trajectory q_d without external disturbances [34]. The sinusoidal reference is chosen as $q_d = A\sin(\pi f t)$ where $A = 2\mu m$ and $f = 200Hz$, whereas the constant desired trajectory is chosen to be a unit step $q_d = 1\mu m$ and a zero mean value Gaussian white noise w_{noise} with a variance $\sigma^2 = 9 \times 10^{-9}(m)^2$ has been considered for this scenario as well as for the other scenarios.

In the second scenario, only the step response is investigated for a robustness test of the proposed controller towards external perturbations. Both input w_{in} and output w_{out} disturbances have been considered in this scenario, as schematically illustrated in Fig. 3. w_{out} is assumed to be an impulse disturbance with an amplitude of $0.3\mu m$ applied to the system at the time instance $t = 4ms$, while w_{in} is an unknown persistent bounded disturbance such that $w_{in} = -3mv$. In the third and last scenario, uncertainties on the system's inertia mass $M(q)$ are considered which can be caused by the movement of the R/W head tip onto the disc surface. Therefore, an efficient controller is required to ensure the convergence of the head to the target position, and to be robust enough against parametric uncertainties.

For all the proposed simulations scenarios described above, and in order to highlight the performance of the proposed control solution, the RISE-NN closed-loop responses are compared to those of a classical Proportional Derivative controller (PD). The PD control gains are manually tuned to get the best performance. However, automatic optimization tools can also be used to determine these parameters based on a suitable objective function.

For the purpose of performance comparison, an energy function E is introduced, it is expressed by:

$$E = \sum_{i=1}^{N_{sim}} |u_i|, \tag{34}$$

where N_{sim} is the sample number for the whole simulation duration.

Table 1 summarizes the parameters of the proposed controllers, while Tab. 2 gives a summary of the overall closed-loop system's performance with the different control solutions.

Tab. 1. Summary of the controllers' parameters.

Reference (μm)	RISE-NN				PD	
q_d	α_1	α_2	K_s	β_1	K_p	K_d
$2\sin(200\pi\, t)$	3000	2900	1850	1	2×10^7	10^3
1	1500	1500	1850	1	2×10^7	10^3

Tab. 2. Controllers performances comparison.

Without disturbances (Sinusoidal Reference)		
	PD	**RISE-NN**
Settling time	2.85 ms	1.62 ms
Maximum overshoot	40%	25%
Control input $\mid u \mid$	3 v	3 v
Energy function (E)	3.11×10^2v	5.38×10^2v
Without disturbances (Step response)		
	PD	**RISE-NN**
Settling time	5.55ms	2.33 ms
Maximum overshoot	50%	1.5%
Control input $\mid u \mid$	3 v	1.07 v
Energy function (E)	3.03×10^2v	43.44v
Disturbances Rejection		
	PD	**RISE-NN**
Recovery time	3.2 ms	2.7 ms
Maximum overshoot	9.5%	15%
Control input $\mid u \mid$	3v	1.5v
Energy function (E)	3.84×10^2v	$1.2\times10^2 v$
Parameters uncertainties (80% of error)		
	PD	**RISE-NN**
Settling time	9.8 ms	5.6 ms
Maximum overshoot	62%	15%
Control input $\mid u \mid$	3 v	1.5 v
Energy function (E)	4.83×10^2 v	77.66 v

5.1 Scenario 1: Tracking Problem in Nominal Case

Comparison between the performance of RISE-NN and PD controllers is illustrated in Figs. 5–9.

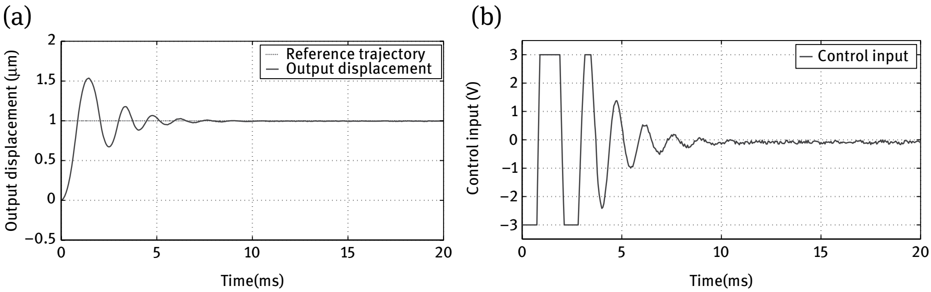

Fig. 5. Step response in non disturbed case with PD controller: (a) Output displacement and (b) Control input.

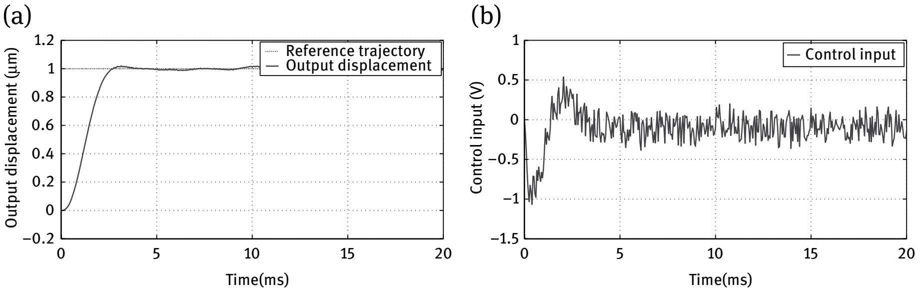

Fig. 6. Step response in non disturbed case with RISE-NN controller: (a) Output displacement and (b) Control input.

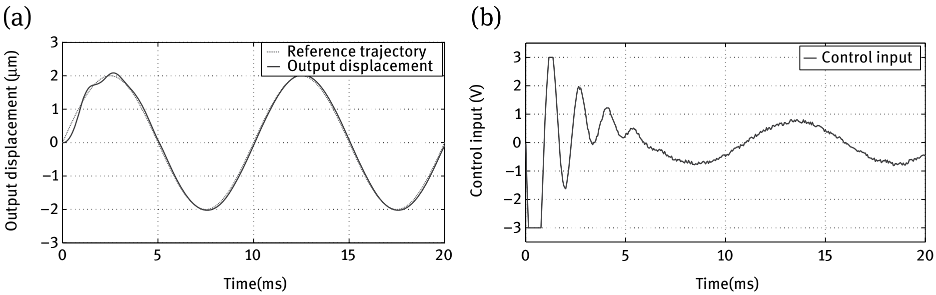

Fig. 7. Tracking of a sinusoidal reference trajectory in non disturbed case with PD controller: (a) Output displacement and (b) Control input.

First, in the case of the time varying reference signal (cf. Figs. 7–8), it can be observed that the proposed control solution RISE-NN achieves a better track following performance. Indeed, the head tip converges faster to the target position such that the tracking error is reduced around zero and little overshoots are generated.

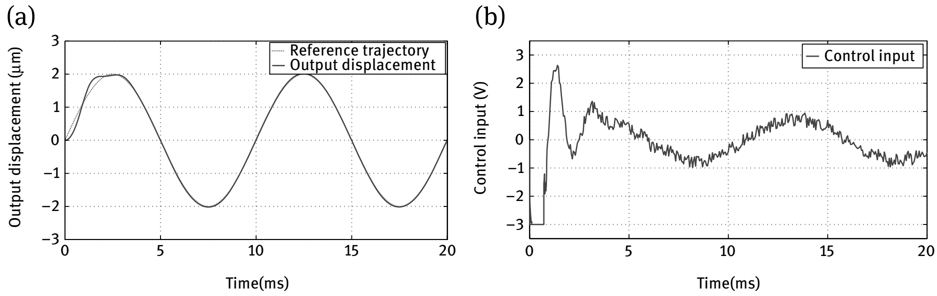

Fig. 8. Tracking of a sinusoidal reference trajectory in non disturbed case with RISE-NN controller: (a) Output displacement and (b) Control input.

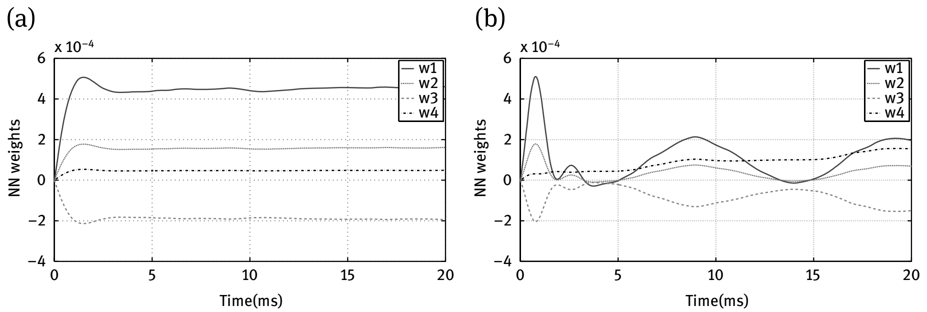

Fig. 9. Time history of the neural network weights in nominal case: (a) step response and (b) sinusoidal reference.

Second, the investigated step response (cf. Figs. 5–6) shows that RISE-NN tracking performances are much better than the PD controller. This is perceptible through the decreased overshoots which are negligible compared to those of the PD controller. In term of speed and precision, the RISE-NN settling time is substantially reduced, i.e. the R/W head tip reached the target and remains around such that the positioning accuracy is ensured.

In addition, the RISE-NN control energy consumption is very low in the case of step response, that is the control input is kept within the admissible limits.

The time history of the NN weights is displayed in Fig. 9 and shows that in both cases, sinusoidal and constant reference trajectories, the boundedness of the NN weight is ensured.

5.2 Scenario 2: External Disturbances Rejection

The main objective of this scenario is to test the effect of external disturbances on the closed-loop system and how the proposed control solutions deal with. The resulting disturbance rejection simulations with both PD and RISE-NN controllers are illustrated in Figs. 10, 11 respectively.

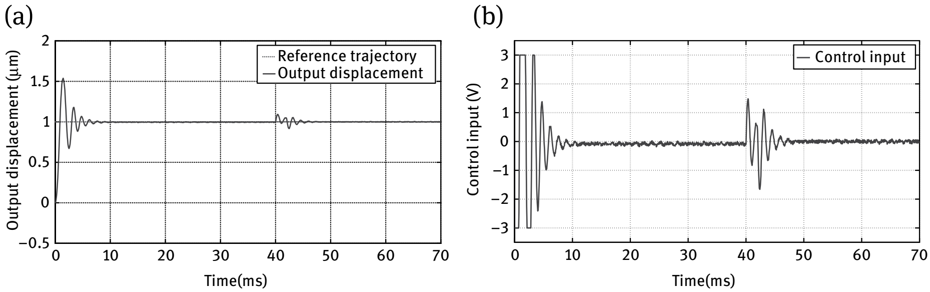

Fig. 10. Tracking under external disturbances with PD controller: (a) Output displacement and (b) Control input.

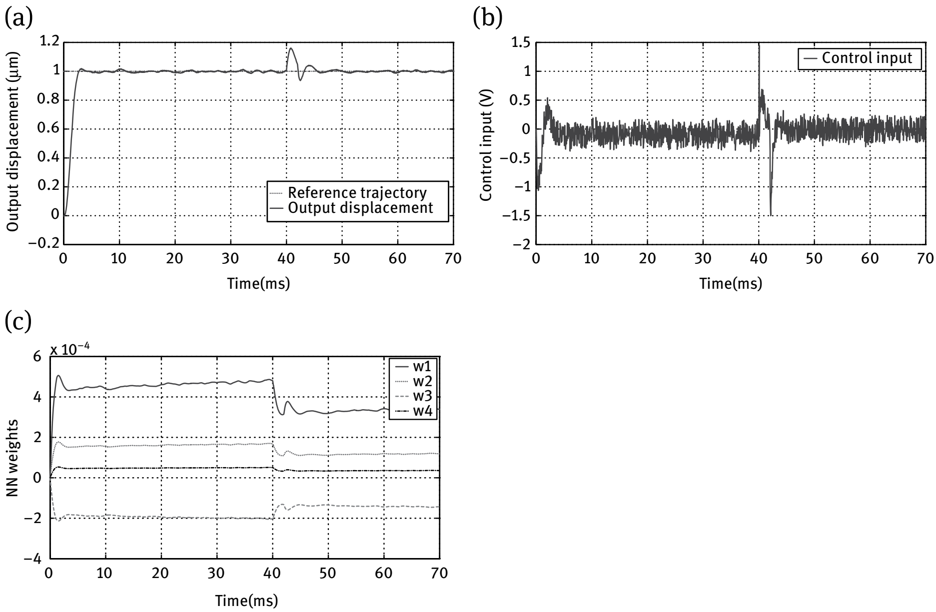

Fig. 11. Tracking under external disturbances with RISE-NN controller: (a) Output displacement, (b) Control input, and (c) Time history of the neural network weights.

For a persistent external disturbance ω_{in} and a punctual output disturbance ω_{out} applied at the time instant $t = 40ms$, both controllers successfully performed the rejection and the head tip is returned to its target track. However, with RISE-NN, the displacement of the head, as shown in Fig. 11(a), is faster with a reduced 5% settling time which results in a quick return of the position error signal to around zero, but the overshoot remains relatively significant.

Moreover, the RISE-NN control input evaluation satisfies the physical constraints and is kept within the interval $[-3v, 3v]$ without reaching the saturation limits. This results in a reduced control effort reflected by the energy function E. It is worth noting that the norm of the NN weights can be easily upper bounded by a constant as depicted in Fig. 11(c).

5.3 Scenario 3: Robustness Towards Parametric Uncertainties

For a complete comparative study between both proposed controllers, let us consider uncertainties on the system inertia of the HDD servo-system. The obtained simulation results for this case are shown in Figs. 12 and 13.

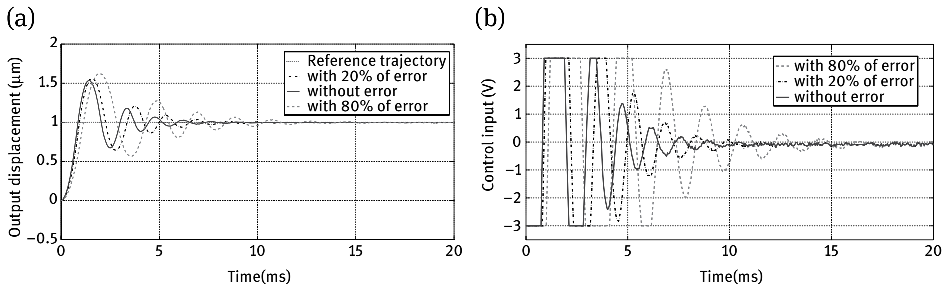

Fig. 12. Robustness towards parameters' uncertainties with PD controller: (a) Output displacement and (b) Control input.

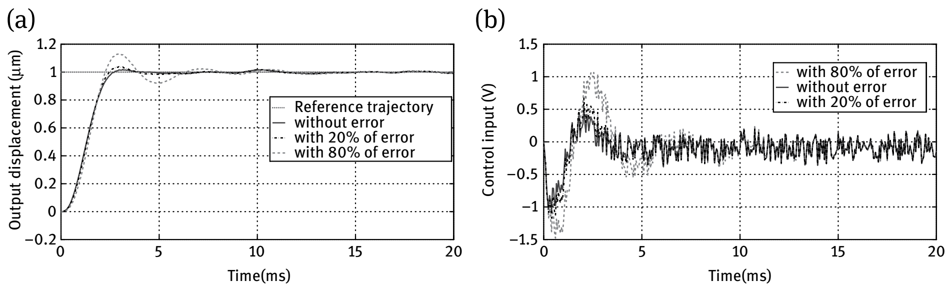

Fig. 13. Robustness towards parameters' uncertainties with RISE-NN controller: (a) Output displacement and (b) Control input.

For an uncertainty amount up to 80%, with respect to the nominal value, the closed-loop system behavior with a PD controller is so degraded. Therefore, as illustrated in Fig. 12, significant overshoots can be observed and the 5% settling time is too long.

However, with a RISE-NN controller, the system shows a good robustness against these uncertainties and the head tip achieves a quick convergence to the target position with a relatively smaller overshoots.

Consequently, according to these results, it can be concluded that against parametric uncertainties, the RISE-NN control solution is able to ensure better tracking performances.

6 Conclusion and Future Work

In this paper, a RISE based NN controller was proposed as a solution to solve a Hard-Disc-Drive head track following problem. The main objective was to guarantee that the tracking error is minimized as much as possible and converges to a neighborhood of zero.

Numerical simulations for different operating conditions are provided to show the effectiveness of the proposed controller. Thereby, through a comparative study with a PD controller, it was clearly shown that, with the RISE-NN approach, the convergence of the head tip to the target track can be ensured with superior performance in terms of speed, accuracy and robustness against external disturbances and parametric uncertainties.

Our future work will be focused on the optimization tools for an extended version of the RISE-NN controller as well as real-time experiments.

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