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► **To cite this version:**

Manel Taktak-Meziou, Ahmed Chemori, Jawhar Ghommam, Nabil Derbel. Mechatronics of Hard Disk Drives: RISE Feedback Track Following Control of a R/W Head. Mechatronics: Principles, Technologies and Applications, Nova Science Publishers, Inc., 2015, 978-1-63482-854-3. lirmm-01893919

**HAL Id: lirmm-01893919**

**<https://hal-lirmm.ccsd.cnrs.fr/lirmm-01893919v1>**

Submitted on 11 Oct 2018

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*Chapter 1*

## MECHATRONICS OF HARD DISK DRIVES: RISE FEEDBACK TRACK FOLLOWING CONTROL OF A R/W HEAD

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### Abstract

This chapter addresses design challenges associated with a servo system of a Hard Disc Drive (HDD). A P-RISE-NN control approach is proposed. The main objective of this novel controller is to enhance the track following in a Hard Disc Drive. Indeed, P-RISE-NN approach involves an optimal gain selection, in a RISE-NN controller. Taking advantage of the prediction feature, the controller is able to anticipate the future behavior of the system. Consequently, it can easily handle various constraints that may be imposed on its variables. Furthermore, the boundedness of the closed-loop signals as well as the convergence of the tracking error to zero are ensured. Comprehensive comparison between the classical RISE-NN and P-RISE-NN are provided through numerical simulations in different operating conditions. It is shown that P-RISE-NN can maintain a good control performance in nominal case and in the presence of external disturbances. Besides, the controller is also robust towards uncertainties on the system parameters.

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**Key Words:** Hard-Disc-Drives servo-systems, Predictive Control, RISE feedback, Neural Networks, Nonlinear systems, Control Design and Asymptotic Stability.

## 1 INTRODUCTION

One of the most important parts of a computer is the hard drive (HDD). All of the information displayed on the screen of a computer are stored on the hard drive. For this reason, higher capacities HDD are always required and new generations of computers are expected to contain larger storage capacities with a rapid access to the stored data.

Consequently, the HDD industry has undergone a tremendous growth. This big change is noticeable both in the physical size and the performance characteristics. The first generation of this devise, known as RAMAC 305, has been introduced in 1956 by IBM. It was a huge material with fifty 24" disks able to store about 5 Megabytes of digital data at a bit density of  $2K \text{ bits}/in^2$ . The data throughput was about  $8.8K \text{ bits}/s$ . Today's used HDD are very advanced with a storage capacity close to 5 Terabytes of data on one disk surface whose the factor form ranges from 2.5" to 3.5" drive.

Along with this trend toward smaller HDD, the task of the head positioning servo-system is the most objective to be accomplished with the highest possible performances. In a HDD, the Read/Write (R/W) head is moved from its actual position to the desired destination track to record or to retrieve data onto the disc. For a reliable data treatment, the position error defined as the distance between the head tip and the target track center, has to be as minimal as possible. Besides, the transition from one position to another is required to be achieved in minimum time using a bounded control effort.

Unfortunately, the HDD servo-positioning system is often subject to several errors' sources leading to the degradation of the overall closed-loop system performances. These sources may include: (i) mechanical resonance modes caused by the flexibility of the materiel and vibrations induced by the high-speed air flowing around the suspension arm and head assembly, (ii) nonlinearities in the dynamics and uncertainties on the parameters of the whole system, (iii) presence of measurement noise, (iv) run-outs due to the spindle motor bearings and (v) track miss-registration caused by the nonlinear hysteresis behavior of the pivot bearing.

All these factors have been neglected in the earliest drive versions. However, in small drives, they require a rigorous analysis and become one of the challenges in the head positioning servo systems control design. Therefore, several efforts have been put into the HDD research. Their main objective is to find an effective control solution able to treat these factors and compensate as much as possible their degrading; Subsequently, this enables the system to meet the increasing demands for a high track density, accurate and rapid functionality of the HDD servo-positioning system.

A survey of the different control approaches developed to design servo controllers for HDDs allows to classify them into different categories. These latter range from classical approaches such as PID controllers (Isayed & Hawwa, 2007), lead-lag compensator (Ishikawa & Tomizuka, 1998) and different filters (Atsumi, et al., 2007), to more advanced control

solutions including adaptive control (Horowitz & Li, 1995)(Kobayashi, et al., 2004), sliding mode control (Yamaguchi, et al., 1997)(Yamaguchi & Hirai, 1998)(Venkataramanan, et al., 2002), robust control (Nie, et al., 2011)(Graham & De Callafon, 2006)(Hirata, et al., 2003), Robust and Perfect Tracking (RPT) (Goh, et al., 2001), Composite Nonlinear Feedback (CNF) control (Chen, et al., 2003) and more recently predictive control (Taktak, et al., 2013)(Taktak, et al., 2012) and prediction based state feedback control (Lee & Suh, 2011). Despite the diversity of the control techniques, more researches need to be conducted to carry out the functioning of the HDD and achieve higher performances.

This chapter focuses on the positioning control problem of a HDD servo system's track following. The main contribution of this paper consists of combining MPC with a classical RISE based Neural Network control method (Patre, et al., 2008b)(Makkar, et al., 2007). The key benefit of the proposed method is its ability to control the sensitivity of the gain feedback term of RISE to variation which impact the overall closed-loop system under the imposed restrictions. The fundamental idea is inspired from the Nonlinear Model Predictive Control (NMPC) (Camacho & Bordons, 2004). Indeed, instead of calculating an optimal control sequence, the proposed method determines the optimal value of the feedback gain based on the predicted behavior of the system. The controller, called P-RISE-NN, is able to predict the evolution of the system in the future over a prediction horizon. Besides, it can deal with any external disturbances affecting the controlled system and any change in the dynamic parameters.

The proposed P-RISE-NN scheme will be studied for its effectiveness not only to the mitigate inappropriate responses, but also to ameliorate the tracking performances in terms of speed, robustness and accuracy in various HDD operating conditions.

## 2 HARD DISC DRIVE: MECHATRONIC SYSTEM

### 2.1 Components of a HDD

According to the general definition of the Mechatronic Forum (Mahalik, 2003), *Mechatronics is the synergistic integration of mechanical engineering with electronics and control in the design and manufacturing of product process*. Therefore, the HDD is obviously an amazing mechatronic device. Its components can be classified into four essential categories including: Electronic part, mechanical components, automatic and real-time computing. The main components of a typical HDD are illustrated in Figure 1.

#### 2.1.1 Electronic part

The electronic part of an HDD includes the necessary components to perform the following various functions: reading/ writing data, spinning the discs, positioning the R/W head onto the platter surface, controlling the various operation of the disc (reading/ writing/ transfer data), interface with the host system, RAM-ROM, etc. A brief description of these

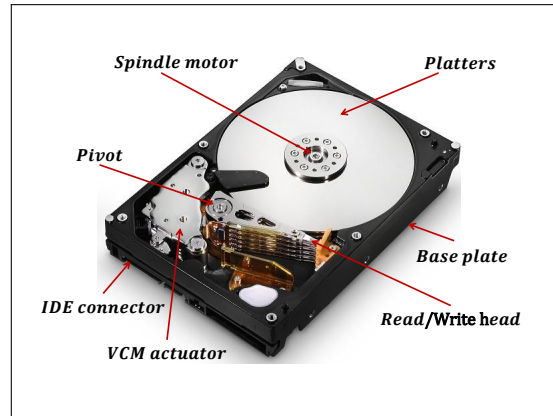


Figure 1: Schematic diagram of a typical HDD

components is elaborated in the following.

**Disk platters:** In a HDD, digital data are recorded on magnetic continuously rotating disk in the form of circular patterns called tracks. A disk has two surfaces called platters which are coated with thin layers of magnetic material (cf. Figure 2). These platters are placed around a rotating axis driven by an electric motor (spindle motor). The speed varies according to both the mark and the model of hard drive. It is usually between 5400 rpm and 15000 rpm. The manufacture of the platters surfaces requires an accurate treatment that remove any impurity and guarantee a smooth-lightweight material for the best data storage performances.



Figure 2: Multiple platters of a HDD

**Spindle-motor assembly:** It is the primarily responsible of spinning the disk platters of the HDD with constant, stable and reliable speed for thousands of hours (cf. Figure 3). The spindle motor assembly is mainly composed of a servo-controlled brushless DC motor directly connected to the HDD platters. The fluid dynamic or aerodynamic bearing spindles are normally used in high performance HDDs in which the spindle speed exceeds 10000 rpm. However, several HDD models devoted for desktop use and mobile environment are still using a lower spindle speed varying between 5400 rpm and 6000 rpm. Recently, designed HDDs are using higher spinning rates of up to 15000 rpm for superior operating performance.

Setting spindle motor bearings at the extremity of each spindle shaft in one of the most critical component in HDD's spindle motor. Indeed, with the increasingly demand for higher

areal density and faster spindle speed, the fluid dynamic bearing (FDB) spindle motor are more adopted in HDDs. It turned out that in ball bearing motors, the mechanical contact between the ball and race of the bearings contributes to the degradation of the system working performances. Moreover, it is worth noting that the variation of spindle speed is a key source of disturbance generation in the tracking task of the HDD; hence the need for an accurate control of the motors' speed.

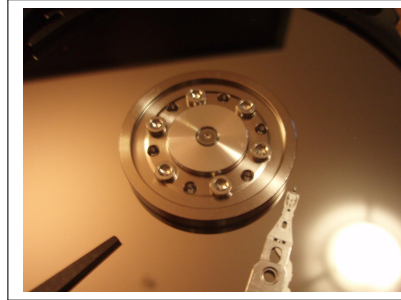


Figure 3: Spindle motor assembly of the HDD

**Actuator assembly:** In a HDD, the actuator assembly is dedicated to ensure the displacement and the positioning of the R/W head over the disk surface. It consists of a Voice Coil Motor (VCM), a pivot bearing, data flex cable or printed circuit cable carrying signal to/from the R/W heads and VCM, and actuator arms.

The actuator is located at the end attached to the actuator arm. This latter is somewhat long and triangular-shaped with the base being attached to the actuator itself. Earlier actuators tended to be solid metal pieces but increasingly today they are largely hollow, more like a triangular frame. The actuator is connected to a Voice Coil Motor (VCM) (cf. Figure 4). Through the operation of the VCM, it moves the actuator arm back and forth over the disk surface in an arc. This allows the actuator arm to be moved into position above every data track and sector on the disk. The actuator/VCM assembly lifts the actuator arm up and moves it over the track where the data sought is located. The actuator assembly is able to displace the actuator arm and its head at a feverish pace with a high rotating speed of the disks.

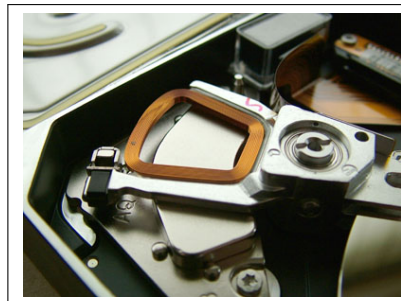


Figure 4: VCM actuator of a HDD

**Head positioning actuator assembly:** The R/W heads are used to treat data on the disk. They are small mobile components able to move in both directions over the disc. Older

HDDs used the electromagnetic induction principle with ferrite, metal-in-gap and thin-film single head. However, modern HDD use separate heads for reading (giant-magneto-resistive heads) and other for writing (thin-film inductive heads).

Each disk surface is accessed by a typical head slider mounted at the suspension arm. The movement of the slider between any two tracks of the disc is driven by the VCM actuator. It is worth knowing that the heads are positioned only micro-inches above the recording medium on an air-bearing surface. A gimbal attaches the slider to a stainless steel suspension to allow for pitch and roll, and the suspension is attached to the arm of the actuator by a ball swagging (cf. Figure 5).

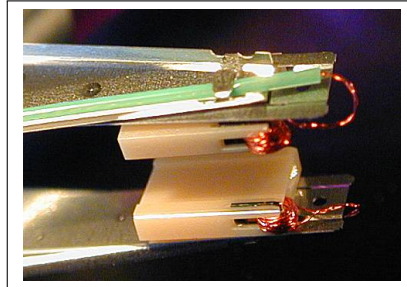


Figure 5: Head positioning actuator assembly

**Electronic card:** This component is responsible for making the relationship between the host personal computer and the hard disk. There are different types of electronic cards. They include: (i) the Parallel Advanced Technology Attachment (PATA) used for a long time and can link up to two hard drives or CD / DVD on a ribbon cable. An element must be configured as master and the other slave using jumpers, (ii) the Serial Advanced Technology Attachment (SATA) available since 2003; this technology uses different connectors and requires no special configuration. It is even possible to connect / disconnect a turned on SATA element and (iii) the Small Computer Systems Interface (SCSI) which is highly efficient; they are also very expensive and require an additional controller card. SCSI technology is reserved for the professional field.

All these integrated circuits have a power driver for the spindle motor, VCM, R/W electronics, servo demodulator, controller chip for timing control and control of interface, micro-controller/digital signal processor (DSP) for servo control, and ROM and RAM for microcode and data transfer.

### 2.1.2 Mechanical components

The most important component of the HDD is the device enclosure. It is responsible of the reliability of the prototype. It is sealed to protect the inner components from any danger that may damage it. It is essential that the enclosure is capable of isolating the drive of the dust, humidity, temperature and dirt that can enter inside the enclosure. This will keep components safe and reduce the risk of damaging them. Therefore, because the head is so close to the disc's surface, any particles could damage the disc resulting in data loss. So, the idea is to place a recirculating filter in the airflow. It removes small particles scraped off the platter. Thus, the mechanical hard drive is treated as a clean room to ensure the perfection

of the surfaces and the smooth operating of the drive.

### 2.1.3 Automatic

Control engineering is an important part of the design process of the HDD. The HDD, as a physical system, has a nonlinear behavior due to many factors, essentially due to disturbances and external shocks. The challenge is therefore to drastically improve the HDD performances despite the ever presence of these factors.

In order to safeguard the digital information in the disks, it is important to robustly controlling the HDD. An effective control have to regulate the head position throughout their working such as the position error is minimized. In fact, the imposed constraints on the controlled system, external disturbances and uncertainties in the system's model have to be compensated properly.

### 2.1.4 Real-time computing

Real-time control system is required when the HDD is involved in operations such as closed-loop tracking control problems for R/W head, state estimation and external disturbance compensation. At this point, it is obvious to verify the quality of the HDD model, to discover unexpected effects and consider ways to improve the control design. This can be achieved by implementing the controller using an embedded software/hardware which run periodically on the basis of a clock that can be derived from an I/O signal or a precise CPU timer.

## 2.2 Operating principle of HDD servo systems

A home computer is a powerful tool which must store data reliably for a more efficient functioning. To better manage its operation, it is essential to understand how its HDD works.

Principally, a HDD is devoted to store data in binary form, 1's and 0's. The actuator arm supports a head. It is an electromagnet that scans over the disc and either writes data by changing the magnetization of specific sections on the platter or it just reads the data by measuring the magnetic polarization. The key focus lies in being sure that the head can precisely, error free, read and write to the disc. The first order of business is to move it with great control.

To position the arm, engineers use a voice coil actuator (cf. Figure 4). The base of the arm sits between two powerful magnets. They're so strong, they're actually kind of hard to pull apart. The arm moves because of a Lorentz force. Passing a current through a wire that's in a magnetic field and then the wire experiences a force. Reverse the current and the force also reverses. As current flows in one direction in the coil, the force created by the permanent magnet makes the arm move in one direction. Reverse the current and it moves back. The force from the arm is directly proportional to current through the coil, which allows the arms position to be finely tuned. Unlike a mechanical system of linkages, there is minimal wear and it is not sensitive to temperature.



At the end of the arm lies the head. As it passes over the magnetized sections of the platter, it measures changes in the direction of the magnetic poles, the so-called Faraday's law, a change in magnetization produces a voltage in a nearby coil. So, as the head passes a section where the polarity has changed, it records a voltage spike. The spikes, both negative and positive represent a 1 and when there is no voltage spike, corresponds to a 0.

The head gets astonishingly close to the disc surface about 100 nanometers in older drives. However, today, under 10 nanometers in the newest ones. As the head gets closer to the disc, it's magnetic field covers less area, allowing for more sectors of information to be packed onto the discs surface.

To keep that critical height, the head floats over the disc: as the disc spins it forms a boundary layer of air that gets dragged past the stationary head at 80 mph at the outer edge. The head rides on a slider aerodynamically designed to float above the platter and the genius of this air-bearing technology, is it's self-induced adjustment. If any disturbance causes the slider to rise too high, it floats back to where it should be.

For a comprehensive reading on the HDD magnetic operating principle in specific, interested readers may refer to (Mee & Daniel, 1996).

### 3 SYSTEM MODELING

#### 3.1 High frequencies dynamics

At high frequencies, the flexibility of the pivot bearing, flex cable, arm, etc, are at the origin of several resonance modes in the Hard drive. It is imperative to take these factors into consideration while modeling the VCM actuator, then treat them carefully. Otherwise, they may degrade the system stability and generate steady state in tracking performances.

Based on the work of (chen, et al., 2006), a realistic model of a VCM actuator can be expressed by the following linear model:

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

where  $k_y$  is the position measurement gain,  $k_v = \frac{k_f}{m}$ , with  $k_f$  is the current-force conversion coefficient and  $m$  is the mass of the VCM actuator.  $u$  is the control input (in volts),  $y$  and  $v$  are respectively the position (in  $\mu m$ ) and the velocity of the R/W head (in  $\mu m/s$ ).  $N$  is the number of resonance modes and  $G_{r,i}(s)$  for  $i = 1, \dots, N$  are their transfer functions.

In order to ensure superior performances, the high-frequency resonance mode effects are often minimized by the use of a notch filter as a pre-compensator. Such a filter is able to suppress lightly damped poles and replace them by a pair of well-damped poles (Weaver & Ehrlich, 1995).

#### 3.2 Low frequencies dynamics

At low frequencies, the actuator rotary pivot bearing and data flex cable behaviors have to been rigorously analyzed. Indeed, while the R/W head moves from one track to

another, the data flex cable is subjected to expansions and contractions. These factors causes frictional forces and nonlinearities in HDD VCM actuators, especially those with reduced form. Such factors cause not only the generation of significant residual errors, but also make difficult to maintain the head as close as possible to the desire track center. Hence, a good comprehensive of all the aforementioned factors' behavior is essential to include a comprehensive modeling and compensation schemes of the degrading effect of nonlinearities and friction.

The resulting nonlinear VCM actuator dynamics is expressed as follows (San, et al., 2009):

$$\begin{aligned} M(q)\ddot{q} + F(q, \dot{q}) &= u \\ y &= q + w_{out} \end{aligned} \quad (2)$$

where  $M(q)$  denotes the system inertia verifying  $M(q) > 0$ .  $q$ ,  $\dot{q}$  and  $\ddot{q}$  denote the position, velocity and acceleration of the VCM-actuator head tip respectively.  $u$  is the control input,  $y$  is the actual position of the VCM-actuator in presence of the output disturbance  $w_{out}$ . Such a disturbance is mainly caused by spindle rotation run-outs.  $F(q, \dot{q})$  represents the nonlinear hysteresis friction induced by the pivot bearing. The behavior of  $F(q, \dot{q})$  in HDD applications has been investigated in (De Wit, et al., 1995). It has been shown that the LuGre friction model is able to capture all the static and dynamic characteristics of the hysteresis friction such that:

$$F(q, \dot{q}) = \sigma_0 z + \sigma_1 \dot{z} + \sigma_2 \dot{q} \quad (3)$$

$$\dot{z} = \dot{q} - \alpha(\dot{q}) | \dot{q} | z \quad (4)$$

$$\alpha(\dot{q}) = \frac{\sigma_0}{f_c + (f_s - f_c) e^{-\left(\frac{\dot{q}}{q_s}\right)^2}} \quad (5)$$

where  $z$  is an internal state of the friction model assumed to be unmeasurable.  $\sigma_0$ ,  $\sigma_1$  and  $\sigma_2$  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 (Astrom & De Wit, 2008).

## 4 CONTROL PROBLEM FORMULATION

The displacement of the R/W head tip on the surface of the disc is one of the most important issues in a HDD servo-control system. The principle goal of such a system is to carry out two main functions: The first function is to ensure a quick transition of the head tip from one target track to another using bounded control effort (track seeking). This function is required to be achieved with the smallest possible the seek time, which is defined as the needed time duration to move the R/W head tip from its actual position to another. The second function is to maintain the head as close as possible to the desired track center while digital information is being read/written from/on the disc (track following). These two control problems can be represented graphically as shown in Figure 6.

Let  $q_d$  be the target track position. The tracking error can be expressed as follows:

$$e_1 = q_d - q \quad (6)$$

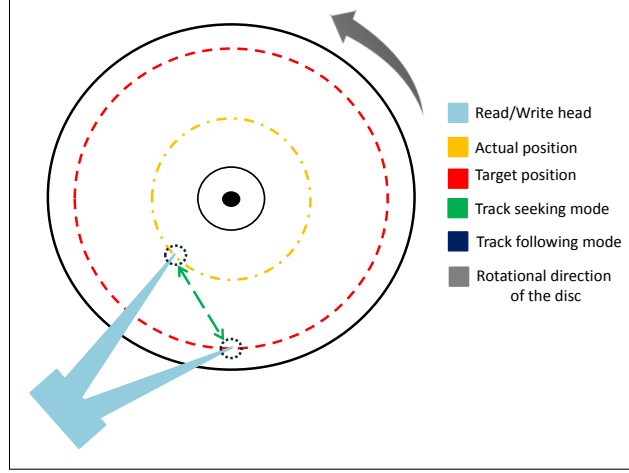


Figure 6: Main operating functions in a HDD servo-system

The control objective is then to ensure the convergence of the the R/W head to the desired destination. Then, the head must be maintained super near this target track center such that following objective is obtained:

$$\lim_{t \rightarrow \infty} |e_1(t)| = \lim_{t \rightarrow \infty} |q_d(t) - q(t)| = 0 \quad (7)$$

Unfortunately, as the track density increases and the track pitch decreases, several error sources are becoming more challenges due to the continuing decrease in the allowable Track Miss-registration (TMR) limits. The most relevant error sources include external vibration and shocks, nonlinearities and parametric uncertainties. These are caused by the head movement effect, non-repeatable and repeatable run-outs due to the spindle bearing and thermal effect respectively.

A good HDD servo-system controller is required not only to achieve the desired track seeking and following tasks, but also to ensure a reliable data treatment and superior tracking performances in terms of speed and accuracy.

In this work, our main objective is to design an effective robust controller based on the low-frequencies nonlinear VCM actuator model (2-5). The effectiveness of the proposed controller will be tested in various operating conditions ranging from nominal case without disturbances to cases with external disturbances and parametric uncertainties in the system dynamics.

To reach this aim, filtered tracking errors, denoted by  $e_2(t), r(t)$  are introduced to facilitate the ulterior key analysis. They are defined as:

$$e_2 = \dot{e}_1 + \alpha_1 e_1 \quad (8)$$

$$r = \dot{e}_2 + \alpha_2 e_2 \quad (9)$$

where  $\alpha_1, \alpha_2 \in \mathcal{R}$  are positive tuning gains.  $r(t)$  is an immeasurable quantity since its expression (9) depends on  $\dot{q}(t)$ .

## 5 RISE FEEDBACK BASED NEURAL NETWORK CONTROL

In this section, the classical RISE feedback based Neural Network controller (RISE-NN) is introduced. As its name indicates, this technique combines the universal approximation property of Neural Network control to approximate unknown uncertainties in the system dynamics, with the recently developed RISE feedback method originating in (Xian, et al., 2004) and nominated as RISE feedback in (Patre, et al., 2008a). This combination is advantageous in terms of asymptotic stability of the controlled system. It's a technique that can be used to develop a tracking controller for nonlinear systems even in the presence of additive disturbances and uncertainties on the dynamic system parameters. This is feasible under the assumption that the considered disturbances are  $\mathbb{C}^2$  with bounded time derivatives. First, we propose to introduce the NN feedforward controller. Then, the RISE feedback principle is detailed.

### 5.1 Feedforward NN estimation

Consider a three-layer NN as in (Lewis, 1999). Then, consider a compact set  $\mathbb{S}$  and a smooth continuous function  $f(x)$  expressed by:

$$f(x) = W^T \sigma(V^T x) + \varepsilon(x) \quad (10)$$

were  $x(t) \in \mathbb{R}^{a+1}$  is the inputs vector.  $V \in \mathbb{R}^{(a+1) \times L}$  and  $W \in \mathbb{R}^{(L+1) \times 1}$  are bounded constant weights for the first-to-second and the second-to-third layers of the network, respectively.  $a$  denotes the number of neurons in the input layer and  $L$  is the number of neurons in the hidden layer. Only one neuron describes the third layer. In (10), the activation function is denoted by  $\sigma(\cdot) : \mathbb{R}^{a+1} \rightarrow \mathbb{R}^{L+1}$ . However, the functional error approximation is denoted by  $\varepsilon(x) : \mathbb{R}^{a+1} \rightarrow \mathbb{R}$ . The basic Neural Network principal is as shown in Figure 7.

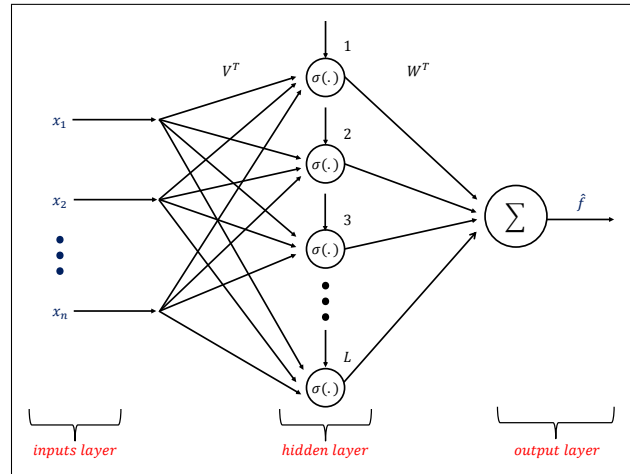


Figure 7: Illustration of a three-layer Neural network

Different activation functions could be exploited for the control development. They include for example sigmoid, hyperbolic tangent or radial basis functions. In this paper, we propose the use of radial basis functions expressed as follows:

$$\sigma(x_i) = \exp\left(-\frac{\|x_i - c_i\|^2}{\sigma_i^2}\right) \quad \forall i \in \mathbb{R} \quad (11)$$

where  $c_i$  and  $\sigma_i$  are respectively center and the width of the basis functions. These parameters are *a priori* chosen and kept fixed in simulations. Taking advantage of the universal NNs estimation property, the function  $f(x)$  given in (10) can be approximated (Lewis, 1999):

$$\hat{f}(x) = \hat{W}^\top \sigma(V^\top x) \quad (12)$$

where  $\hat{W} \in \mathbb{R}^{(L+1) \times 1}$  is the approximated ideal weights of the network.

**Assumption 2** There exist bounds on the ideal weights and the activation function such that  $\|W\| \leq W_m$ ,  $\|\sigma\| \leq \sigma_m$ , where  $W_m$  and  $\sigma_m$  are known positive constants.

## 5.2 Background on RISE Feedback control

In the sequel, the control input  $u(t)$  is developed based on RISE feedback approach. First, the filtered error (9) is pre-multiplied by  $M(q)$  and the system dynamic model (2)-(5) is used such that we get:

$$M(q)r = F_d + S - u \quad (13)$$

where  $F_d$  and  $S$  are auxiliary functions defined by:

$$F_d = M(q)\ddot{q}_d + F(q_d, \dot{q}_d) \quad (14)$$

$$S = M(q)(\alpha_1 \dot{e}_1 + \alpha_2 \dot{e}_2) + F(q, \dot{q}) - F(q_d, \dot{q}_d) \quad (15)$$

The expression of  $F_d$  in (14) can be approximated using a three-layer NN as given by equation (12), that is:

$$F_d = W^\top \sigma(V^\top x_d) + \varepsilon(x_d) \quad (16)$$

In (16), the input vector  $x_d(t) \in \mathbb{R}^{(3a+1)}$  is defined as  $x_d = [1 \quad q_d \quad \dot{q}_d \quad \ddot{q}_d]^\top$ . Since the desired trajectory is bounded as stated in assumption 1,  $\varepsilon(x_d)$  satisfies the following inequalities:

$$\|\varepsilon(x_d)\| \leq \varepsilon_N, \quad \|\dot{\varepsilon}(x_d)\| \leq \varepsilon'_N \quad (17)$$

where  $\varepsilon_N$  and  $\varepsilon'_N$  are known positive constants.

The control input  $u(t)$  of the system (2)-(5) is composed of the three-layer NN feedforward control term  $\hat{F}_d(t)$  plus the RISE feedback control term  $\mu(t)$  such that:

$$u = \hat{F}_d + \mu \quad (18)$$

The RISE feedback term  $\mu(t) \in \mathbb{R}^{(a)}$  is defined as (Xian et al., 2004):

$$\begin{aligned} \mu(t) &= (k_s + 1)e_2(t) - (k_s + 1)e_2(0) \\ &+ \int_0^t [(k_s + 1)\alpha_2 e_2(s) + \beta_1 \text{sgn}(e_2(s))] ds \end{aligned} \quad (19)$$

where  $k_s, \beta_1 \in \mathbb{R}^+$  are positive constant feedback gains. In this paper, the optimal tuning of the feedback gain  $k_s$  is the main objective. To the author's best knowledge, this technique is a new contribution in the field of nonlinear system's control. We propose to generate an optimal variable tuned parameter  $k_s^{opt}$  capable of ensuring an effective path tracking of the HDD servo system with much better performance than a fixed gain. A detailed description of the proposed approach will be developed in the next section.

The feedforward NN component  $\hat{F}$  in (18) is defined by equation (12). The estimates of the NN weights  $\hat{W}^\top$  are generated online and take the following forms:

$$\dot{\hat{W}} = K[\sigma(V^\top x_d)e_2^\top - \kappa \hat{W}] \quad (20)$$

where  $\kappa$  is a positive design constant parameter.  $K$  is a symmetric constant positive definite control gain matrix  $K = K^\top > 0$ . The boundedness of  $\dot{\hat{W}}$  is easy to prove based on assumption 2. Time derivative of (19) is given as:

$$\dot{\mu}(t) = (k_s + 1)r(t) + \beta_1 \text{sgn}(e_2(t)) \quad (21)$$

Using (12) and (21), the time derivative of the overall control input of the system can be expressed as:

$$\dot{u} = \hat{W}^\top \sigma(V^\top x_d) + (k_s + 1)r(t) + \beta_1 \text{sgn}(e_2(t)) \quad (22)$$

In order to formulate the closed-loop system dynamics, equations (22) and (16) are combined such that we get:

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

where  $\tilde{W}^\top = W^\top - \hat{W}^\top$  is the weight estimation error.

Equation (23) can be further formulated as follows:

$$\begin{aligned} M(q)\dot{r} &= -\frac{1}{2}\dot{M}(q)r + \tilde{N} + N_{B_1} + N_{B_2} - e_2 \\ &\quad - (k_s + 1)r(t) - \beta_1 \text{sgn}(e_2(t)) \end{aligned} \quad (24)$$

where

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

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

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

Based on the Mean Value Theorem and following the same procedure detailed in (Xian et al., 2004), one concludes that  $\tilde{N}$  is upper bounded as follow:

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

where  $z(t) = [e_1^\top \ e_2^\top \ r^\top]^\top \in \mathbb{R}^3$  and  $\rho(\|z\|)$  is a positive non decreasing bounding function.

## 6 EXTENDED VERSION OF RISE CONTROL: P-RISE-NN

In this section, a new enhanced version of the classical RISE-NN controller will be presented. The proposed controller is capable of achieving better track following of the R/W head position in the servo system. Based on the control parameter setting in the RISE-NN technique, it turned out that a little variation of the parameter  $k_s$  can affect the working of the HDD and degrade or improve the tracking performance. In order to deal with this issue, we propose to add a prediction based optimization to the classical RISE-NN which allows the determination, at each sampling time, of the optimal value of  $k_s$ . Such a solution will be able to improve the overall system behavior in terms of speed of convergence and robustness against unexpected external disturbances and dynamic changes on the system parameters.

The proposed prediction based optimal gain tuning solution, called P-RISE-NN, is inspired from the Model Predictive Control (MPC) approach (Camacho & Bordons, 2004). Several works have been developed in the literature to show the effectiveness of the predictive approaches and illustrate their importance in trajectory tracking system control. The principle is mainly based on an online optimization dedicated to predict the future outputs of the plant and calculate an optimal control parameter  $k_s^{opt|k}$  instead of an optimal control sequence as in the classical MPC method.  $k_s^{opt|k}$  is derived from the minimization of a cost function  $J$  often subject to different constraints. The basic idea of the P-RISE-NN control algorithm is illustrated in Figure 8.

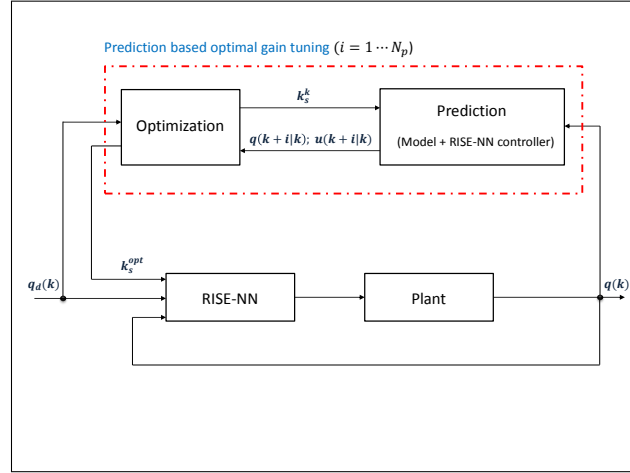


Figure 8: Block Diagram of the proposed P-RISE-NN controller

At each time instant  $kT_e$ , where  $k$  is a positive constant integer and  $T_e$  is the sampling time, the prediction of the future behavior of the controlled system is performed. Vectors of future outputs and control inputs denoted respectively by  $\hat{q}(k+i|k)$  and  $\hat{u}(k+i|k)$ , for  $i = 1, \dots, N_p$ , are generated over a predefined prediction horizon  $N_p$ . Their calculation shall use the nonlinear model of the system described by (2)-(5) according to the basic principle of RISE-NN procedure detailed in section 5. Through the minimization of a performance

index, the optimal control gain  $k_s^{opt|k}$  is determined at each time instant  $k$ . The objective function denoted  $J$  can be stated as a quadratic function including the future control inputs and tracking errors as follows:

$$e(k+i|k) = q_d(k+i|k) - \hat{q}(k+i|k) \quad (29)$$

where  $q_d(k+i|k)$  is the desired track trajectory to follow assumed to be known *a priori* and  $\hat{q}_d(k+i|k)$  is the future predicted outputs. The objective function  $J$  can be expressed as follows:

$$J = \sum_{i=1}^{N_p} \|e(k+i|k)\|_Q^2 + \|u(k+i|k)\|_R^2 \quad (30)$$

where  $\|\mathbf{x}\|_M^2 = \mathbf{x}^T \mathbf{M} \mathbf{x}$ .  $Q$  and  $R$  are the symmetric positive definite weighting matrices,  $Q \geq 0$  and  $R > 0$ . In addition to the calculation of the optimal control gain parameter  $k_s^{opt|k}$ , the proposed prediction based optimal control aims to maintain the output as close as possible to the reference trajectory.

$$k_s^{opt|k} \equiv \arg \min_{k_s} J \quad (31)$$

Since the HDD has a nonlinear dynamic model, the optimization is in general a non-convex problem. Therefore, an online nonlinear programming algorithm should be used to find the optimal solution  $k_s^{opt|k}$ . Once  $k_s^{opt|k}$  is obtained, it will be applied to the controlled system over the next sample period  $[k, k+1]$ . Then, the prediction horizon is shifted, the state of the system is measured and all the above procedure is repeated at the next sampling time. The time history of the proposed extended version P-RISE-NN parameters is illustrated in Figure 9.

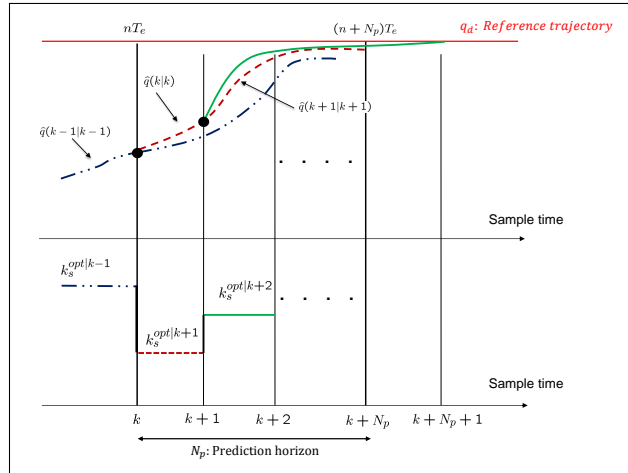


Figure 9: Prediction-based optimal tuning

## 7 SIMULATION RESULTS: A COMPARATIVE STUDY

In this section, we present different simulation results obtained with the proposed P-RISE controller and their comparison with those of the classical RISE-NN controller. The simu-



lation studies have been performed using Matlab 7.9 software of MATHWORKS. The NN parameters are manually tuned to obtain the best possible performances of the controllers. Since the predictive algorithm is based on a nonlinear optimization problem, this makes it extremely difficult to find an analytical solution of the optimal gain  $k_s^{opt|k}$ . Consequently, the optimization problem in the P-RISE-NN approach has to be solved online using the MATLAB routine *fmincon* including the control constraints. The parameters of the applied controllers are summarized in Table 1.

Table 1: Parameters of the RISE-NN and P-RISE-NN controllers

Reference trajectory	$q_d$	$1\mu m$
Minimum control effort	$u_{min}$	-3v
Maximum control effort	$u_{max}$	3v
Prediction horizon	$N_p$	25
Weighting matrix	$Q, R$	$100I, 100I$
Sampling time	$T_e$	0.05ms
Simulation duration	$N_{sim}$	400
Control gain parameters	$\alpha_1, \alpha_2, \beta_1$	1500, 1500, 1
Inertia matrix	$m$	1

All the initial conditions are chosen to be at the origin. Three different tests are considered. In the first scenario, the track following task is performed in nominal case without any external disturbance. The second scenario includes external disturbances, which are challenging for controllers and must be compensated as much as possible. Finally, the third scenario deals with uncertainties on the system parameters. For this, uncertainties of 20%, 40% and 80% of the nominal value of the system inertia are considered to check the robustness of the controllers against these changes. To facilitate the comparative study, an energy function  $E$  is introduced, it is defined as follows:

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

where  $N_{sim}$  is the simulation duration,  $u_i$  is the control input value at time instant  $i$ .

### 7.1 Scenario 1: Track following in nominal case

The objective behind this scenario is to control the position of the R/W head tip of the HDD servo system without any external disturbances. The nominal value of the control gain parameter is chosen  $k_s = 1850$  for RISE-NN controller. Figure 10 displays the evolution of the measured output, the tracking error and the control input. As shown in the figure, both RISE-NN and P-RISE-NN are able to steer the R/W head to the desired target track and to maintain it on this target location. However, the convergence with P-RISE-NN controller is much faster and has very little overshoots. Moreover, with P-RISE-NN, less control energy is consumed. The resulting 5% settling time and energy function  $E$  (defined above) are summarized in Table 2.

Table 2: Track following performance of both controllers in nominal case without disturbances: scenario 1

	RISE-NN	P-RISE-NN
Settling time (ms)	4.13	1.55
Energy (v)	62.783	25.60

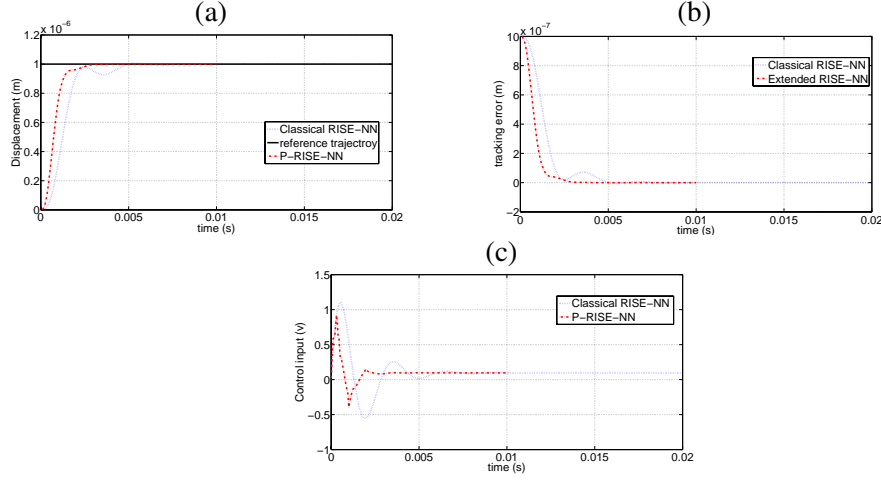


Figure 10: Simulation results without external disturbances (Plots with RISE-NN and P-RISE-NN controllers): (a) Evolution of the measured outputs, (b) Evolution of the tracking error and (c) Evolution of the control input

## 7.2 Scenario 2: Track following with external disturbances

This second scenario was performed while considering external disturbances  $w_{out}$  (on output) and  $w_{in}$  (on input). Therefore, the main objective is to check the robustness of both controllers towards perturbations and their ability to compensate them. The unexpected impulse output disturbance  $w_{out} = 0.3 \mu m$  is assumed to affect the controlled closed-loop system at the time instant  $t = 10 ms$ . However, the input disturbance  $w_{in}$  is often an unknown perturbation satisfying  $|w_{in}| \leq 3 mV$  (chen et al., 2006). Consider the case of a persistent perturbation  $w_{in} = -3 mV$  representing an offset of the control input in this scenario. The obtained simulation results are depicted in Figure 11. For comparison purpose, the recovery time  $t_{rec}$  performance index is introduced. It is defined as the time needed by the system to reach the 2% of the desired final value after the application of the output disturbance. Figure 11-(a) shows the evolution of output. With the RISE-NN controller, the positioning of the R/W head tip is much more affected by the disturbance and has a longer recovery time compared with that with P-RISE-NN controller. Furthermore, in Figure 11-(c), it can be clearly seen that a higher control energy is consumed and several overshoots are generated with RISE-NN. However, P-RISE-NN control provides a better performance in the case of disturbance rejection. This can be explained by the prediction aspect of the latter approach

which uses the system's model in the optimization procedure. This allows it to predict the behavior of the closed-loop system over the prediction horizon  $N_p$  and to choose the best feedback gain  $k_s$ . Table 3 summarizes the performances of the two applied controllers.

Table 3: Performances of the track following controller in case with disturbances: scenario 2

	RISE-NN	P-RISE-NN
Recovery time (ms)	13.8	11.5
Energy (v)	61.63	42.84

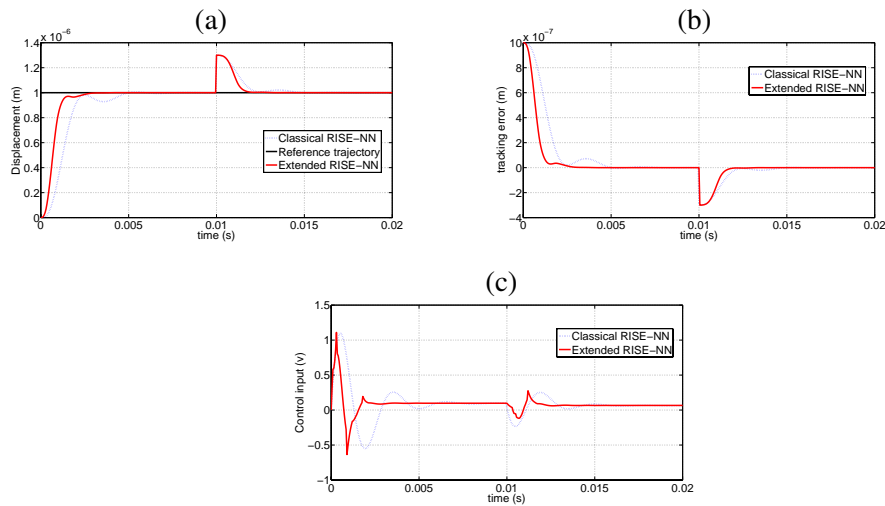


Figure 11: Simulation results with external disturbances (Plots with RISE-NN and P-RISE-NN controllers): (a) Evolution of the measured outputs, (b) Evolution of the tracking error and (c) Evolution of the control input

### 7.3 Scenario 3: Track following with parameter uncertainties

In this scenario, the model of the controlled system is considered to be affected by parametric uncertainty on the mass inertia of the system  $m$ . Such dynamic parameter is expected to undergo some changes during the movement of the R/W head from one track to another. The objective is to see whether the proposed controllers are robust enough to deal with this uncertainty and ensure a good performance of the overall closed-loop system in terms of precision and speed. Errors of 20% and 80% on the mass inertia are considered. The obtained simulation results for this scenario are as depicted in Figures 12 and 13.

The system's response with RISE-NN is hardly affected by the considered uncertainties, whereas with P-RISE-NN, the behavior of the system is much better. In fact, up to 80% of uncertainty, P-RISE-NN is able to converge faster to the desired position with small

tracking errors and negligible oscillations. These results clearly show the effectiveness of the P-RISE-NN over the classical RISE-NN controller. Thereby, the importance of its predictive aspect is illustrated though the robustness against even strong model parameter uncertainties.

## 8 CONCLUSION

In this chapter, the mechatronics of a Hard Disc Drive has been presented. Then, a P-RISE-NN control scheme have been proposed for a path tracking problem. Compared with a classical RISE-NN approach. The P-RISE-NN shows much better performance in terms of accuracy and speed compared with a classical RISE-NN approach. Moreover, the P-RISE-NN controller has a significant robustness towards unexpected disturbances and parameters' uncertainties. Small overshoots were noticed and the controller was able to converge faster. Thanks to the predictive aspect, P-RISE-NN is able to anticipate the future behavior of the controlled system. Such a feature would have a great consideration when controlling the HDD and especially in meeting the increased demands on the servo performance. The real-time implementation of this proposed control solution on a HDD will be the subject of our future work.

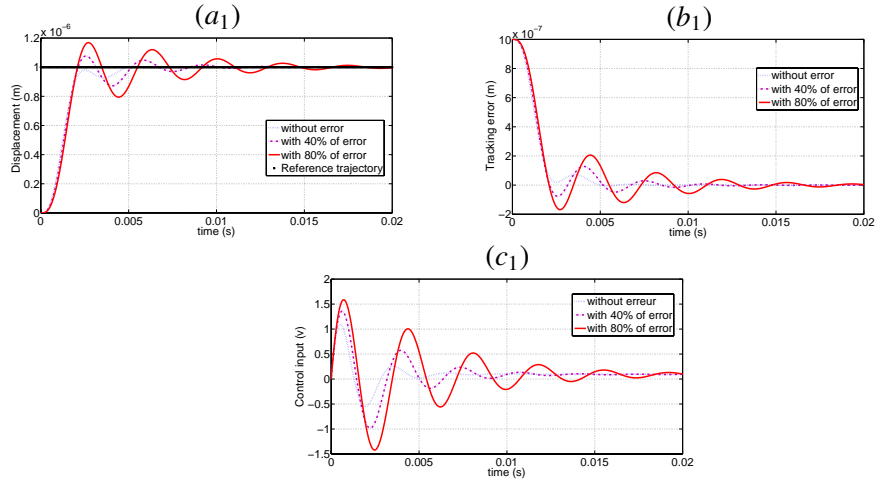


Figure 12: Robustness towards parameter' uncertainties (Plots with RISE-NN controller): (a<sub>1</sub>) Evolution of the measured outputs, (b<sub>1</sub>) Evolution of the tracking error and (c<sub>1</sub>) Evolution of the control input

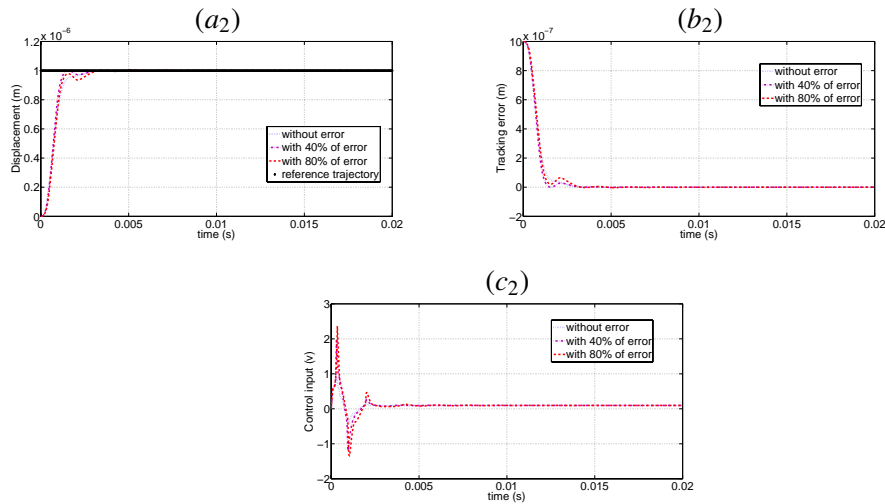


Figure 13: Robustness towards parameters' uncertainties (Plots with P-RISE-NN controller): (a<sub>2</sub>) Evolution of the measured outputs, (b<sub>2</sub>) Evolution of the tracking error and (c<sub>2</sub>) Evolution of the control input

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## ACRONYMS

**RISE** : Robust Integral of the Sign Error

**NN** : Neural Networks

**P-RISE-NN** : Predictive in Robust Integral of the Sign Error based Neural Networks

**R/W** : Read/Write

**HDD** : Hard Disc Drive

**PID** : Proportional Integral Derivative

**MPC** : Model Predictive Control

**NMPC** : Nonlinear Model Predictive Control

**VCM** : Voice Coil Motor

**rpm** : round per minute

**I/O** : Input/Output

**TMR** : Time Miss-Registration