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PERFORMANCE ANALYSIS IN TIME DOMAIN OF CONTROL SYSTEM DESIGN

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Abstract In this paper, we discuss the time domain performance analysis of the model of a Disk Drive Read (DDR) System. We presented the model a DDR system and compared the system responses with the introduction of Amplifier Gain in Proportional Derivative (PD) and Proportional Integral Derivative (PID) controllers. The closed loop model of DDR system was modeled using typical parameters for DDR which include Inertia of the read/write head of DDR, Friction, Amplifier Gain, Armature Resistance, Motor Constant and Armature Inductance. The time domain response of the system was analysed using amplifier gain in PD and PID control algorithms. The results of the analysis and simulation of the DDR model using MATLAB Simulink show a noticeable improvement in the system response with PID controller over the same system with amplifier gain and PD controller. Percentage overshoot of the system when operated with PD controller was 67.9% and never settles on the reference value. While the introduction of PID gave percentage overshoot of 10.4%, settling time of 55ms against the desired value of 200ms. These results imply that, PID controller maintains the stability of the system performance and consequently improves the tracking performance while retaining parameter uncertainties.

Keywords: Control System, Time Domain, Proportional Integral Derivative (PID), Disk Drive Read (DDR)

1 Introduction

Control systems are inherently time-domain system and as such the design and its performance specifications analysis such as the transient time or time performance design are paramount. Feedback control system has numerous applications in many automated industrial processes using control algorithms and we anticipate that feedback-controlled processes should perform better than non-feedback-controlled processes, although with complexities in control structure. Performance analysis of control system gives insight in predicting the performance of the feedback to ensure that the objectives of the control system which includes safety, product quality and profitability, reduced cost, optimum design are met.

Generally, control systems are mainly dynamic systems and their performances are specified in transient response and steady-state response (Dorf and Bishop, 2011). The objectives of any control system include shaping the response of the system to a given reference input, achieving a stable closed-loop system with desired performances, minimizing the effects of disturbances and measurement noises, avoiding actuators saturation, and adapting to modeling uncertainties and parameter changes (Simon, 2009). The transient response is the response that goes to zero as the time becomes very large.
That is,

$$\lim_{t\to\infty} c_t(t) = 0 \quad (\mathbf{1})$$

While the steady-state response is the response that exists for a long time after the complete

transient response vanishes away from the output following the injection of an input signal into the system.
That is,

$$\lim_{t \to \infty} c_t(t) = c_{ss}(t) \quad \mathbf{(2)}$$

Where $c_t(t)$ – Transient response
$c_{ss}(t)$ – Steady state response
$c(t)$ – Time Response

The transient and steady states responses of a control system are used to determine the stability of the system. When the transient response of a system does not decay with the progression of time, the system is unstable and vice versa.

The performances of a control system design based on the transient and steady state responses in time domain are characterized by Standard Test Input Signals. The common Standard Test Input Signals are Step Input, Ramp Input, Parabolic Input, and Impulse input signals (Nise, 2004). In system design, the design specifications are usually characterized by the system response to any of the test input signals assuming the control system is stable and has a unity feedback. The output is expected to be the transient response characterized by the rise time, the settling time, the percentage overshoot and the steady state error. Some constraints which are most often encountered in design are disturbance rejection, sensor noise, actuation saturation, transient profile, and plant dynamics. In the pursuit for explicit design engineering goals in control system design such as complexity, reliability, and economic design, different solutions may be apparent. In any case, a good controller has to be designed such that the desired performance specifications or metrics are achieved.

In this paper, the control system presented is the Disk Drive Read (DDR) system which is used for data read/write operation on magnetic disk storage device of digital systems. DDR system is a typical example of a precision control of a mechatronics control system. The fundamental goal of the DDR system is to move accurately, and precisely position the reader head on the data track on the disk. According to (Aysha et al, 2016), the most sought after characteristics for a hard disk drive are high data transfer rates, reliability as well as lower latency and access time. The rotating disk inside the compartment of the DDR system is coasted with a thin magnetic layer (see figure 1). The data written on the disk are arranged in spherical tracks from which a horseshoe-shaped electromagnetic read/write head reads or write data (Chen et al, 2002). It was noted in Atsumi(2009), that higher area density, reduction of cost and more precise positioning are essential to meet the increasing demand for more robust hard disk unit, and this trend has led to the need for improved performance of the head-positioning system which aims at accurately and priciesely maintaining seeking and tracking performance of DDR system. The objective of this work is to compare the DDR system responses when PD and PID controller are used in controlling the read/write head of the DDR system.

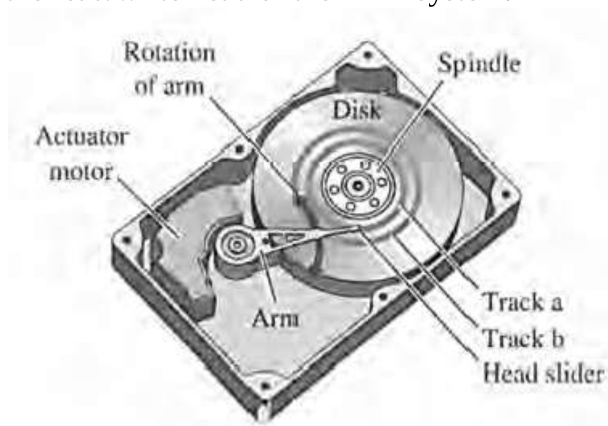

Figure 1: Internal layout of a DDR system. (Dorf and Bishop, 2011).

2 Materials and Methods

The performance analysis of the DDR system done in this work followed six stages:

1) Identification of the design goals.
2) Identification of the variables to be controlled and the specifications of the Controlled Plant (DDR system).
3) Establishment of the configuration of the system.
4) Development of a model of the DDR.
5) Development of a model of the controller and identify the parameters to be adjusted.

6) Optimizing the parameters if need be and analyze the performance of the DDR system under the influence of the controller while varying the parameters.

Design Goals:

The design goals for the DDR system are; (1) to control the movement of the Direct Current (DC) Motor in order to accurately position the read/write head on the desired rack, (2) to achieve possible minimum track-to-track movement of the head, (3) to compare the performance responses of the DDR model with the introduction of Amplifier Gain in Proportional Derivative (PD) and Proportional Integral Derivative (PID) controllers.

Control Variables and System Specification:

The variable to be controlled in the design is the Amplifier Gain (K) in PD and PID controllers. The specifications for the DDR system in transient response as in Aysha et al (2016), are (1) faster response to step input, with overshoot of less than 4% and Settling Time of the oscillation of the output response of less than 200ms, and (3) Steady State Error less than 1%.

System Configuration:

DDR system uses permanent magnet DC motor that converts DC current into rotational mechanical energy, which is called the voice call motor, to move read/write head over the tracks on the surface of the disk. The read/write head is mounted on a slider as shown in figure 1, and a flexible metal spring suspends the head directly over the disk so as sense the magnetic flux and provides an electrical signal the amplifier.

The DDR system considered in this work has one single disk and its closed-loop feedback control block is given in figure 2.

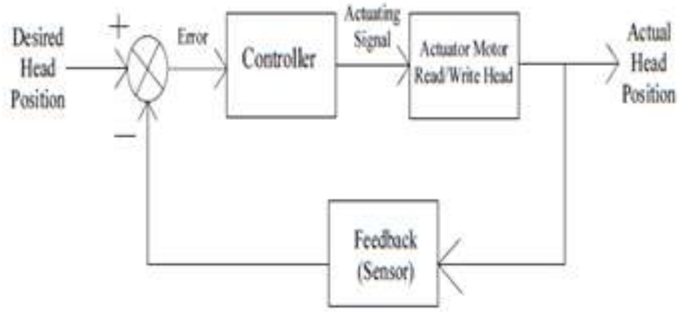

Figure 2: DDR Closed-Loop Feedback control structure.

In Ahmed (2012), Malviyan and Dubey (2015) and Tripathi, Singh,and Yadav (2015) the typical parameters for the model of a DC motor that delivers energy to a load is as shown in table 1.

Table 1: Typical Parameters for DDR system

Parameters	Symbols	Typical Value
Inertia of arm and the read/write head	J	$1\ N\ ms^2/rad$
Friction	b	$20\ Nm\ s/rad$
Amplifier Gain	k_a	$10 - 1000$
Armature Resistance	R	$1\ \Omega$
Motor Constant	k_m	$5\ N\ m/A$
Armature Inductance	L	$1\ mH$

Using the typical parameters of a DDR system and the model of the armature controlled DC motor shown in figure 3 which is a close approximation to the voice call motor in DDR system. The block diagram model of the DC motor in shown in figure 4

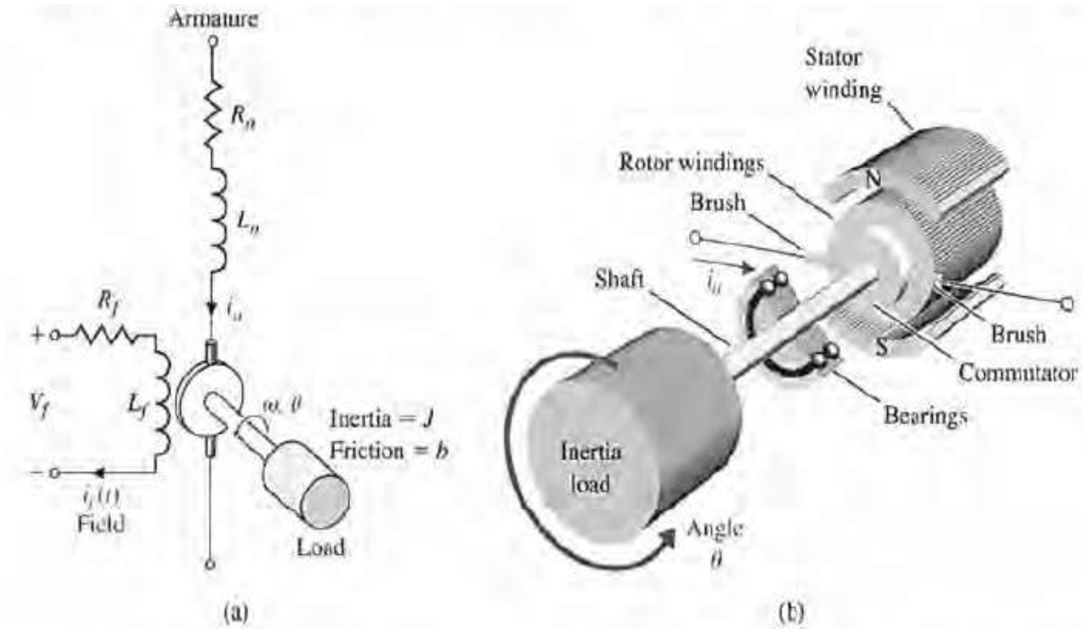

Figure 3: Descriptions of A DC Motor (a) Equivalent electrical circuit diagram of a DC motor (b) Internal structure of a DC motor. (Dorf and Bishop, 2011)

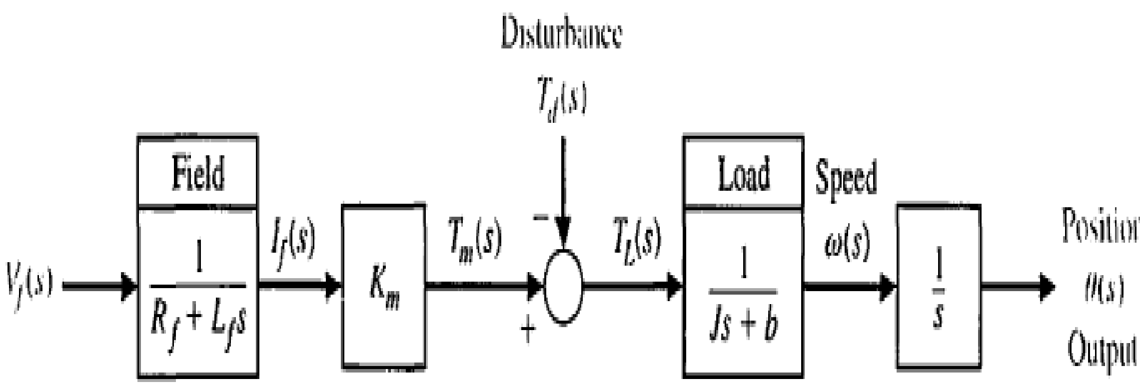

Figure 4: Block diagram representation of DC motor

The Transfer Function of the linear approximation of a DC motor, neglecting hysteresis and voltage drop across brushes, having air gap flux ϕ of the motor proportional to unsaturated field current, and input voltage applied to the armature terminal, is given as follows (Dorf and Bishop 2011):
Let the transfer function of thr linear approximation of a DC motor of the be denoted by $G_{DC}(s)$, so that,

$$G_{DC}(s) = \frac{\theta(s)}{V_f(s)} = \frac{K_m}{s(Js + b)(L_f s + R_f)} \quad \textbf{(3)}$$

$$G_{DC}(s) = \frac{\theta(s)}{V_f(s)}$$

$$= \frac{K_m}{s\left(s + {}^{b}\!/_{J}\right).J \times (s + {}^{R_f}\!/_{L_f})L_f} \quad \textbf{(4)}$$

$$G_{DC}(s) = \frac{\theta(s)}{V_f(s)}$$

$$= \frac{{}^{K_m}\!/_{(JL_f)}}{s\left(s + {}^{b}\!/_{J}\right)(s + {}^{R_f}\!/_{L_f})} \quad \textbf{(5)}$$

Where the time constants of the motor $\tau_L = \frac{J}{b}$, $\tau_f = \frac{L_f}{R_f}$, Eq. 5 can alternatively be written in terms of the time constants as

$$G_{DC}(s) = \frac{\theta(s)}{V_f(s)} = \frac{{K_m}/{(\tau_L b.\tau_f R_f)}}{s\left(s + {1}/{\tau_L}\right)\left(s + {1}/{\tau_f}\right)} \quad \textbf{(6)}$$

Multiply the numerator and the denominator of Eq. 6 by $\tau_L.\tau_f$, to get

$$G_{DC}(s) = \frac{\theta(s)}{V_f(s)} = \frac{K_m/(bR_f)}{s(\tau_f s + 1)(\tau_L s + 1)} \quad (7)$$

Where

$G_{DC}(s)$ is the closed loop transfer function of the DC motor

$V_f(s)$ is the input signal (Electrical signal)

$\theta(s)$ is the system position output

K_m is the motor constant

J is the inertia of the arm and the read/write head

b in the friction

L is the armature inductance

R is the armature resistance

The Controlled Plant

Assume an ideal read/write head, so that the feedback sensor Transfer Function H(s) = 1 as shown in figure 5. The control input U is an electrical signal "Voltage" that passes through a control device current amplifier. The output Y is the measured head position in the disk track. Using the typical DDR parameters on table 1, the block diagram of figure 5, and assume the entire structure is completely rigid, we have the transfer function of the controlled plant to be;

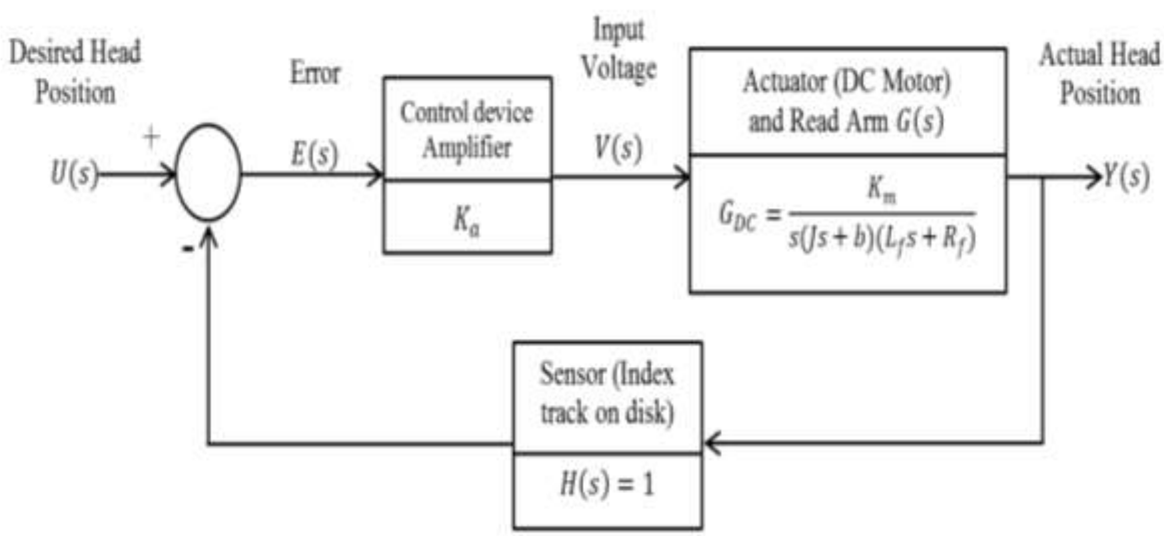

Figure 5: Block diagram model of DDR system.

$$G_{DC} = \frac{Y(s)}{U(s)} = \frac{K_m}{s(Js+b)(L_f s+R_f)} = \frac{K_m/(bR_f)}{s(\tau_f s+1)(\tau_L s+1)}$$
(8)

Substituting the typical DDR Parameters;

$$G_{DC} = \frac{5\times 10^3 N/A}{s(s+20)(s+1000)} \quad (9)$$

Since $\tau_f \ll \tau_L$,

$$G_{DC} \approx \frac{K_m/(bR_f)}{(\tau_L s+1)} = \frac{0.25}{s(0.05s+1)} = \frac{5}{s(s+20)} \quad (10)$$

Using the analogy of the transfer function of a basic closed-loop with unity feedback, where $K_a = 40$we have the closed-loop transfer function of the DDR block diagram model in figure 5 is;

$$G(s) = \frac{Y(s)}{U(s)} = \frac{K_a G_{DC}}{1+K_a G_{DC}} = \frac{5K_a}{s^2+20s+5K_a} \quad (11)$$

$$Y(s) = \frac{200}{s^2+20s+200} \cdot U(s) \quad (12)$$

The Controller Design

The PID controller was chosen for the control of the model of DDR system due its robustness and better tracking performance. PID is a three-action controller which combines the Proportional, Integral, and Derivative actions performing concurrently (Sungh et al, 2013). Many industrial processes employ PID because of its good performance, wide range of operating conditions, and simplicity (Reddy & Nigam, 2007). The beauty of PID controller is seen in time domain characterization of closed loop dynamic plants. During the control action of the PID, the change in the error value from the summation of actual value and the desired reference value is repeated by the proportional action. The derivative action sums up the increment of the output and acts according to the rate off error changing (Kumar et al, 2014). The PID controller was fixed in the forward path of the DDR block model to make the output voltage signal become the input to the motor's armature and the error signal is the input to the PID controller as shown in figure 6. Optimum performance of the PID controller is achieved by the appropriate adjustment of proportional gain (K_p), integral gain (K_i), and differential gain (K_d), in so doing the control system design specification is met. The mathematical expression of PID controller is written as (Nise, 2004),

$$u(t) = K_p e(t) + K_i \int_0^t e(t)\, dt + K_d \frac{de(t)}{dt} \quad (13)$$

The s-domain of the PID controller is obtained using Laplace Transformation while assuming zero initial conditions as;

$$U(s) = K_P E_R(s) + \frac{K_I}{s} E_R(s) + sK_D E_R(S) \quad (14)$$

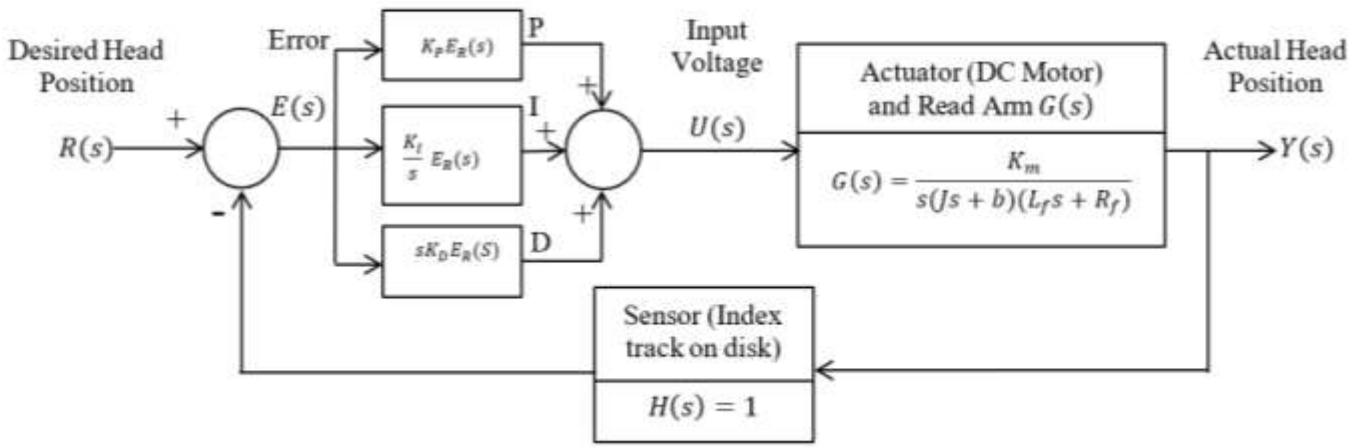

Figure 6: Disk Drive Head Control System with a PID Controller.

The transfer function of the control system with a PD and PID controller are given in Eq. 15 and Eq. 16 respectively.

$$\frac{C(s)}{E(s)} = \left(K_P E_R(s) + \frac{K_I}{s} E_R(s) + sK_D E_R(S)\right) . \frac{200}{s^2 + 20s + 200} \quad (15)$$

$$\frac{C(s)}{E(s)} = \left(K_P E_R(s) + sK_D E_R(S)\right) . \frac{200}{s^2 + 20s + 200} \quad (16)$$

Controller Tuning

Controller tuning is the selection of control parameters such as the gains of the controller to their optimum values in order to get desired stable control response. Different systems have varying behaviors thus leading to different sets of controller parameters values. However, if wrong control parameters are chosen, the system will most times be unstable while having the output oscillating indefinitely until it reaches a saturation point or system collapse. The sole aim of using a controller in a system is to make the system operate properly such that the output will be stable, and the process should not oscillate even to the minimal disturbance or varying set point.

Among different tuning methods for PID controllers, the most common methods are, Manual Tuning Method, Ziegler-Nichols Tuning Method, Cohen-Coon Tuning Method, PID Tuning Software Methods (In MATLAB) (Temel et al, 2013). In this work, the PID parameters are manually tuned using the MATLAB PID tuner for best possible faster response time and robust transient behavior. The K_i and K_d are set to zero and only K_p value was increased until it creates an oscillation at the output response. After that the K_i and K_d were varied accordingly to obtain a faster settling time and lower overshoot.

3 Result and Discussion

The transfer function of the DDR has been formulated and is given by Eq. 11. Step responses for different values of K_a are shown in Fig. 7 and table 2. It was shown in table 2 that a gain of $K_a = 100$ gave minimum overshoot of 16.3% which is selected for the DDR system under PI and PID controller design.

Table 2 Response of the equation 3 for a step input

Ka	80	1000	8000
Percent Overshoot (%)	16.3	68.3	85.4
Settling Time (ms)	0.404	0.37	0.38
Steady State Error (%)	1	1	1

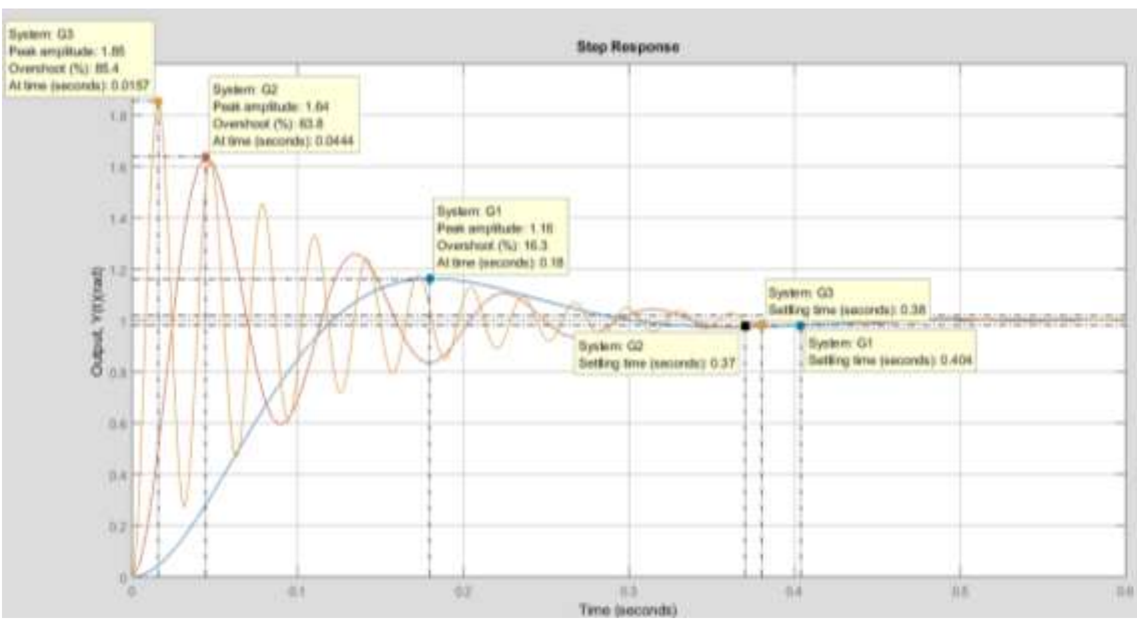

Figure 7: Step responses to Eq. 11 with different K_d values

The closed-loop system under PID controller is shown in Figure 6. After modeling the Plant with the PD and PID controllers, the overall system model was simulated in MATLAB Application using the instructions. The initial baseline tuning was done by choosing $K_p = 1$, $k_i = 0, K_d = 0$ which give the combined system response of figure 8, showing that the DDR model settling time was *0.422sec* when the PI and PID controllers were not tuned.

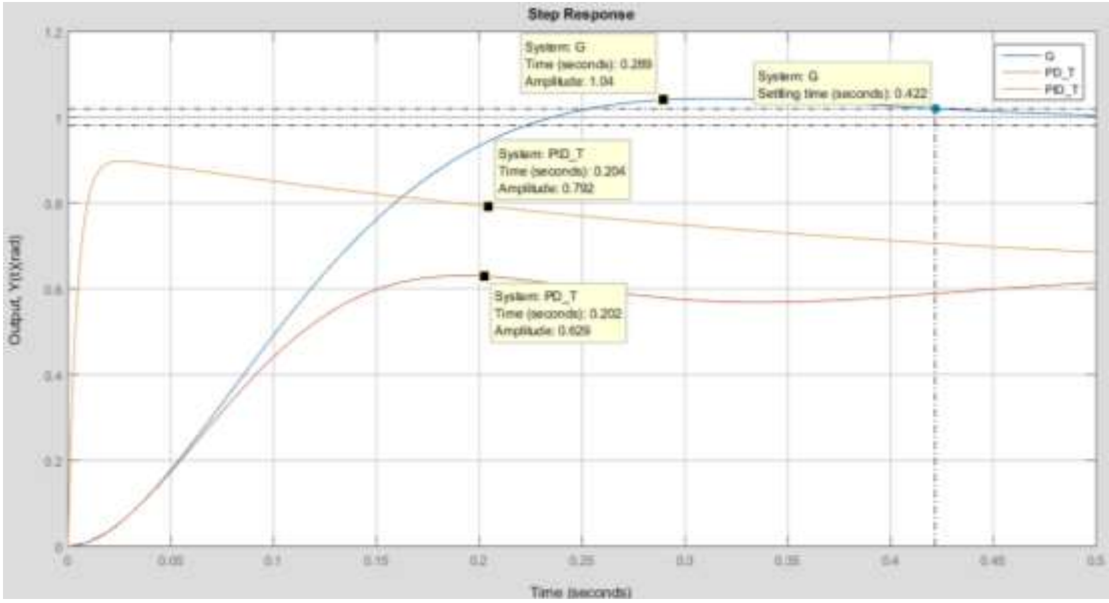

Figure 8: Systems response of the plant when the controller parameters were not tuned

Appraisal for the actions of the PD and PID controllers on the DDR plant

In order to study the performance of the PD controller against PID controller on the model of a DDR system, the controller parameters of the tuned PD and PID were chosen as PD_K_p= 44, PD_K_d = 0.8 and PID_K_p = 49, PID_K_i = 687, PID_K_d = 0.9 respectively. The step responses for the PD and PID controllers were shown in figure 9 and figure 10 respectively. The system under PD controller never settles down, thus it is not desirable. Figure 11 shows the combined plot of the output responses for the PD and PID Controllers on the DDR system.

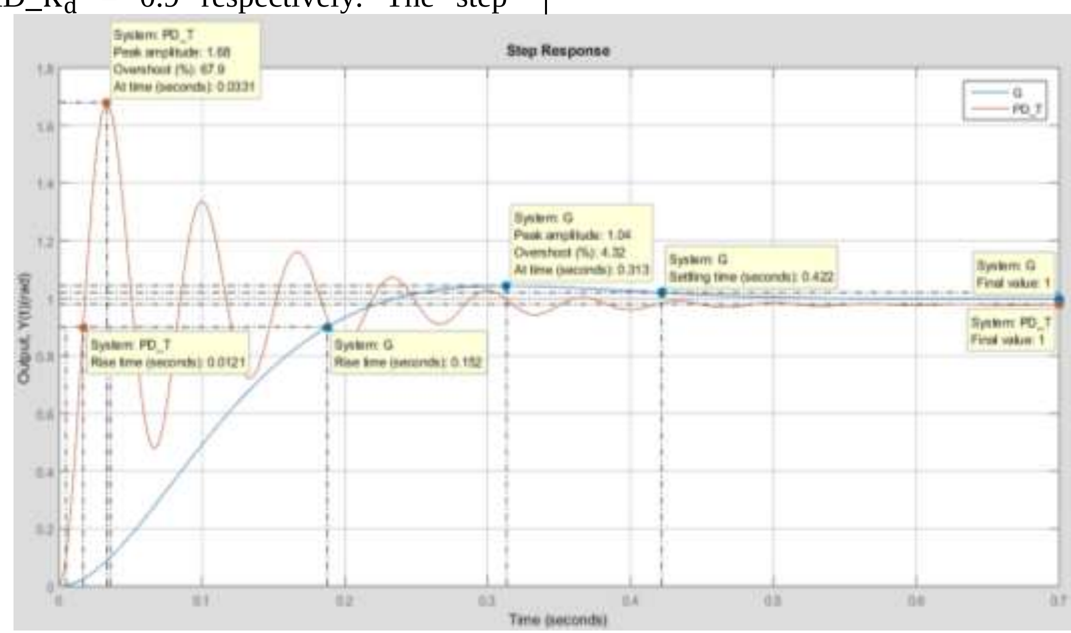

Figure 9: Plant response with PD controller.

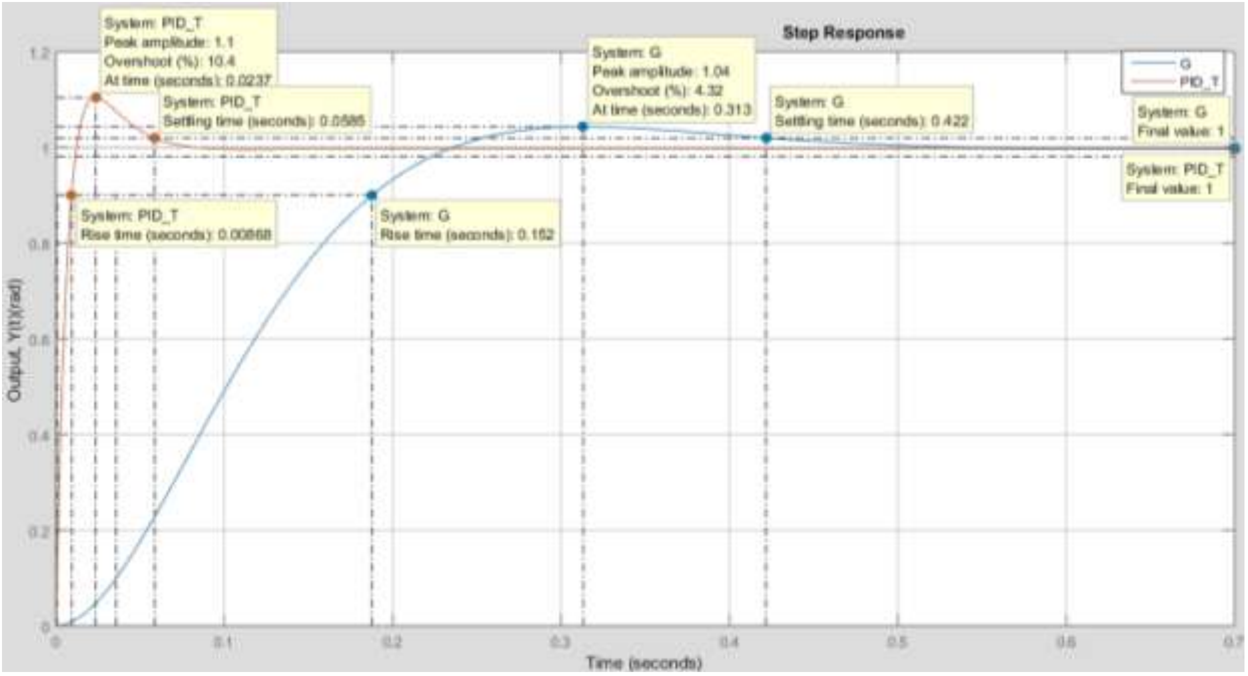

Figure 10: Plant response with PID controller.

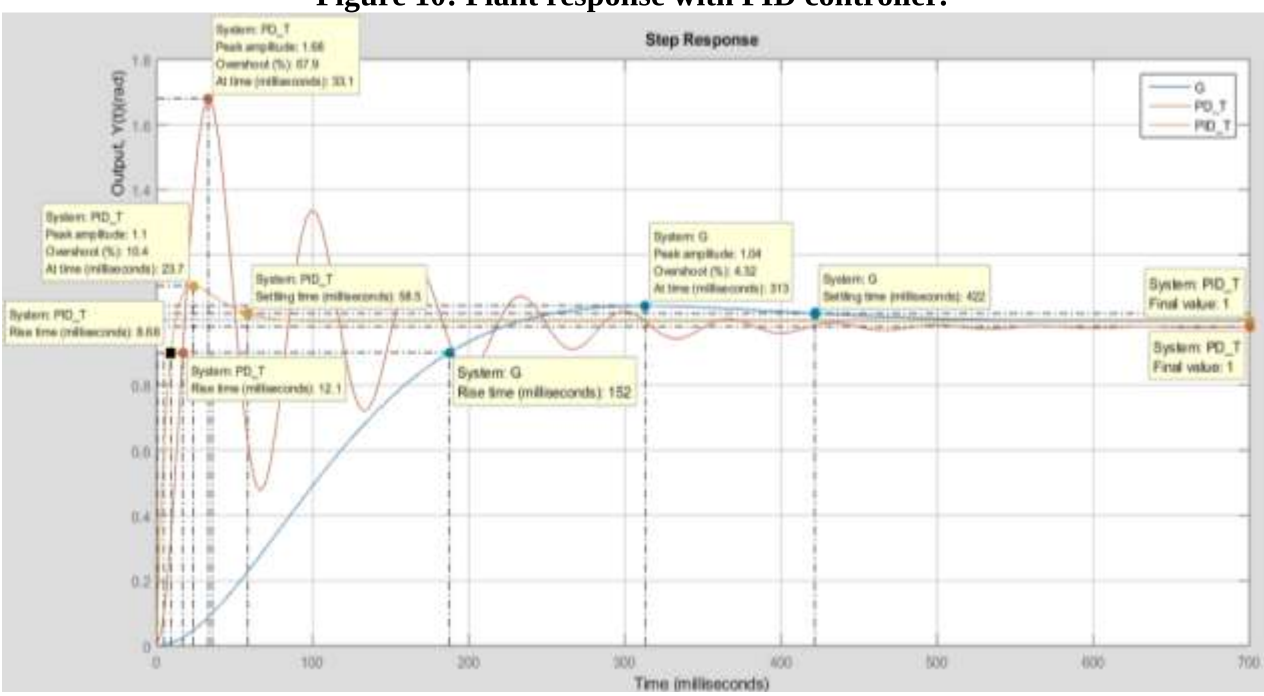

Figure 11: Combined responses of the plant with the PI and PID controller with tuned parameters.

The performance and robustness of the system in time domain under PD and PID controllers are shown in Table 3. It was shown that the model of the DDR system with PID was observed to be stable as against the DDR system alone and with PD controller alone. The PID gave a faster response, but at a peak overshoot of 10.4% against the actual value of 4% achieved by the DDR system without a controller. The PID controller achieved a settling time and rise time of 58.5 and 8.68 respectively, while PD controller never settles on the reference value, showing that the system response was faster on PID scheme.

Table 3: Step response for the DDR model, PD, and PID controllers against the design specifications

Parameters	System Specification (Expected Result)	DDR System	PD	PID (Actual Result)
Rise Time (ms)	*200*	*152*	*12.1*	*8.68*
Peak Amplitude	*1.50*	*1.04*	*1.43*	*1.10*
Percentage Overshoot (%)	*4.00*	*4.32*	*67.9*	*10.4*
Settling Time (*ms*)	*200*	*422*	∞	*58.5*
Steady State error (%)	*1*	*1*	*1*	*1*

4 Conclusion

This paper presented the results obtained from implementation of PD and PID control schemes on a positioning of the DDR system of a magnetic storage disk. The controller gains were tuned to obtain the possible faster and robust transient and steady state responses. The performance analysis of the PD and PID control schemes for the DDR system was done. The actual settling time has been reduced to 58.5ms with PID controller which is less than the expected value of 200ms; however, the actual overshoot obtained with PID control was higher than the expected overshoot. Thus, it was shown by comparing the different responses that the performance of DDR control system under the PID control scheme performed within the stated specifications. The system simulation was done using standard functions found in MATLAB. The results from this work showed that the head positioning of a DDR system can follow the concentric data tracks on the disk more precisely and accurately when implemented with PID controller than when it is implemented with PD controller.

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