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Problem Title: Efficient Retrieval of Data from Hard Disk Drive Using Precise Controller

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Efficient Retrieval of Data from Hard Disk Drive Using Precise Controller

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ABSTRACT

Hard Disk Drive (HDD) is well known for data reading and writing. With the increment of the speed of this data transfer, the functionality of electronics becomes faster. This work is for finding out a precise controller for the control of armature head of a HDD so that the work of fast-reading becomes more efficient and accurate. At first, a physical block diagram is developed and then a mathematical one. Typical values of inertia, armature resistance, coil inductance, etc., are used in the system's transfer function. The Routh-Hurwitz stability criterion is used to show the stability of the system. MATLAB SIMULINK is used to analyse the system transfer function numerically. System response curve, rise time, settling time, peak time and overshoot are obtained. Root locus of the system is shown to obtain a visual representation of the effect of gain on the system poles and zeros. Ziegler-Nichols tuning method is used for initial guesses of different controller conditions. Through numerical iterations for different controller combinations, the PD controller is found to be the optimum choice for fast reading and writing at a value of K_P =18000 and K_D = 95. Further mathematical works have been carried out to do steady-state error analysis and determine the system's sensitivity against changing parameters.

Key Words: HDD, Controller, Sensitivity, Tuning.

1. INTRODUCTION

With the advancements of technology, a vast amount of data is being generated every second. Nibbles, bits, or bytes (also many and more of other units) of information are being generated every second at an unprecedented rate. A cumulative volume of approximately 65 zettabytes of data was generated at the end of the year 2021 [1]. This data volume can be extrapolated to a sheer magnitude of 180 zettabytes by 2025. At the same time, the demand for bulk data storage is also rising. There are different ways to store data. One of the most affordable and effective data storage techniques is hard disk drive (HDD). HDD offers a directly accessible, large chunk of non-volatile storage (whereby data can be stored without power) [2]. It also provides a much higher speed than other removable, non-volatile storage options. However, this technology has its limitation and also facing tremendous competition in the market. So, upgrading the current version has become a significant challenge for the engineers of the relevant industry.

The inception of magnetic data recording dates back to 1898 when Valdemar Poulsen presented the technique and filed a patent. On a commercial scale, IBM introduced HDD production in 1956 through RMAC, which had an areal density (number of bits recorded per unit area of the disk's surface) of 2kbits/in^2. In the year 1995, areal density rose to 1Gbits/in^2 [3] and in 2009, this density surpassed 0.25 Terabits/in^2 [4]. This value alone is enough to represent the astounding improvement of technology and engineering applications. Initially, the structure of HDD was a bit bulky and employed linear rotation of actuators. Engineers detected bottlenecks and rectified many of the gridlocks as the first 3-4 decades of the journey passed. The introduction of a rotary actuator, the shrinking of the disk dimension, and the ability to execute the same operations despite the size decrease are few such examples. The replacement of inductive pickup was a necessary step as it had poor operation capability and could not stand up with the demand. This next level was introduced with the commencement of magneto-resistive (MR) head. From the early studies of the MR effect [5]–[7] to the discovery of giant MR and tunnel MR [8]–[10] , it showed a great promise. MR head helped in the reduction of noise and allowed improvement of the timing of data retrieval. Due to the huge impact of the MR effect, Peter Grunberg and Albert Fert were nominated for the Nobel prize in 2007.

In 1975, Moore's law forecasted that the information density would be doubled every two years. However, at around 100 Gigabits/in^2 , further shrinkage of magnetic grains would make the magnetization unstable at room temperature and would cause subsequent data loss (Superparamagnetic effect) [11]. This problem was resolved around 2006 by a simple and yet extraordinary concept of perpendicular recording. The Magnetization axis would now be orthogonal to the disc plane rather than being horizontal [12]. This caused further shrinkage of grains and allowed an increased areal density of 1Terabits/in^2 in a high coercivity medium [13].

In the optimal performance of HDD, head positioning servomechanism plays a pivotal role. The disc runs at a high rpm with the help of a spindle motor, while the actuator arm, separated from the disc by an air-bearing surface (ABS), is placed on a particular track on the disc to read or write data. The motion of the actuator arm is controlled by a voice coil motor (VCM) [2]. Rapid transitioning from current track to target track is called track seeking. Accurately maintaining the read/write head on a desired track is called track following. Switching from seeking mode to the following mode is often the cause of some undesired transients at the beginning of the next mode. This ultimately induces error and lengthens the seek time. The continuous reduction of disc size and increased rpm intensifies an 'aeroelastic flutter' problem. The enormous rotational speed of a smaller disc also causes the wind to blow around it at high speed. This causes disc vibration termed as air flutter. Its ultimate effect is to cause track misregistration (TMR), leading to positioning error of actuator arm. In high-density systems this effect can virtually annihilate the capability of HDD to represent data faithfully. Efforts were made both computationally and experimentally to anticipate air movement around the disc and assess the effect of fluttering [14]. In the experiment of Takada *et al.* [15], an increase in disc flutter was obtained whenever the arm was travelling to the inner radius, regardless of whether its head is in following mode or in seeking mode. Flutter frequency also showed a rising behavior with the increase in the number of air-bearing surfaces. Similarly, there might be other disturbances like external shock, pivot friction, cogging torque, repeatable and non-repeatable runouts. These agitations have the combined effect of generating a position error signal (PES) and introducing noise into the signal [2]. When the disks are rotating at high speeds of around 12000 rpm, a slight error can be detrimental to the system's performance.

To fetch data accurately and adequately from the HDD, it is crucial to conduct smooth track seeking and track following. The introduction of the control system in the actuating mechanism tended to compensate for the disturbances and execute the functions of the actuator arm in the desired manner. Based on the two-degree-of-freedom (2DOF) control, Ishikawa *et al.* [16] proposed a high-speed track seeking technique. An initial value compensation (IVC) method had been used to settle the head at the target under a variety of disturbance conditions. Fujimoto *et al.* [17] presented a multi-rate sampling-based 2DOF controller. The use of feedforward controller for track-seeking and feedback controller for track-following mode gave a proper disturbance rejection model. 2DOF structure with adaptive robust control (ARC) showed a better performance than either conventional servo systems with mode switches or the 2DOF system with disturbance observer (DOB) [18]. Another alternative track-seeking controller had been proposed by Kobayashi and Horowitz [19]. The controller with a piezoelectric micro-actuator showed a considerable reduction of track-seeking time. The use of proportional, integral, and derivative (PID) controllers has always been getting significant attention. The reduction of model and simplified PID tuning to obtain, yet an optimal closed-loop behavior, had been provided by Skogestad [20]. In order to minimize the settling time, reduce percent overshoot and better steady-state correction, Isayed and Hawwa [21] proposed a novel non-linear PID control mechanism for the HDD servo system. The robustness of the system was verified using numerical analysis. Yadav *et al.* [22] showed a comparison among classical PID controllers, fuzzy logic with proportional-derivative (FL-PD) controller and self-tuning fuzzy logic with PID (STFL PID) controller. Each of them had the upper hand at different set criteria.

As a result, it's evident that a lot of work is being done to improve the control of the HDD's servo-mechanism. Better and more efficient control will always improve the entire computer environment's performance. To complement the ongoing effort to achieve the shortest possible seeking time and accurate track following, this paper proposes a comparative study of various classical P, PI, PID, and PD control systems in order to determine the best possible control scheme for achieving the goal of HDD speed enhancement.

2. METHODOLOGY

2.1. Physical Configuration

A HDD is a type of non-volatile, electro-mechanical data storage device that stores and retrieves digital data [2]. The major components of HDD are – circular disk (platter), spindle motor, read and write head (actuator arm), and actuator motor. A typical HDD diagram is shown in **Figure 1**.

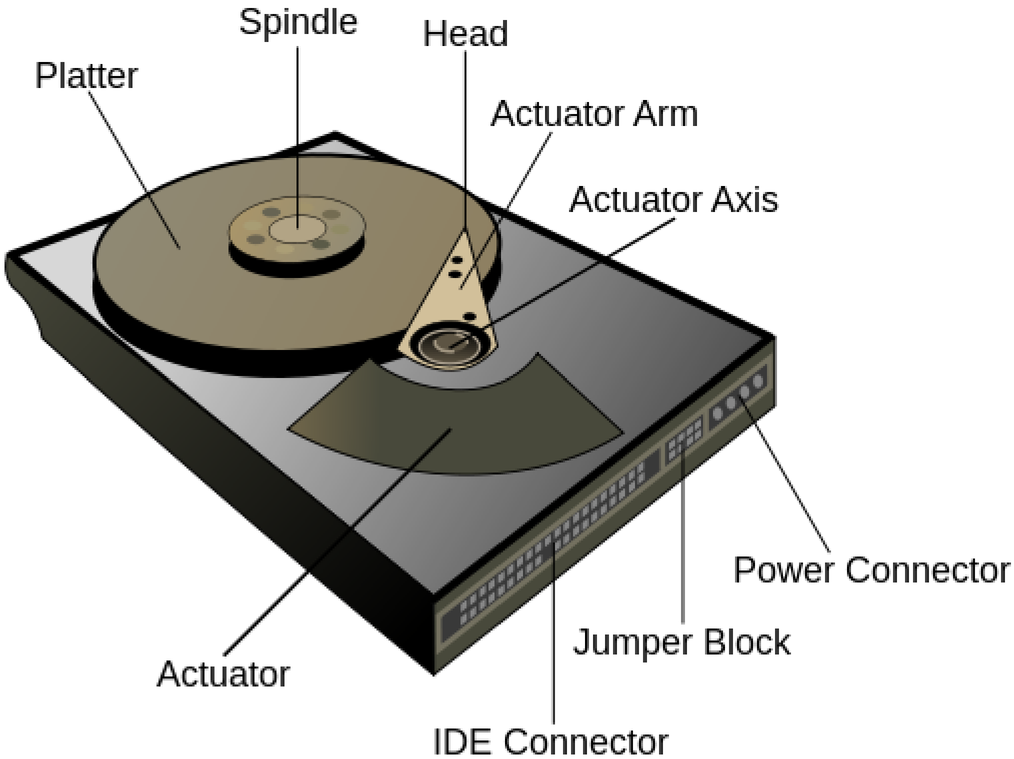


Figure 1: Schematic overview of an HDD with its essential parts [23].

The factors influencing the response time of an HDD are:

- The amount of time required to position the actuator arm on the platter
- The measure of time necessary to rotate the platter to the appropriate location
- The rate of data transfer

The faster the response time, the better the performance of HDD. By optimizing the operations of the parts of HDD such platter rotation, actuator arm movement, and data transfer rate, the response time can be shortened. This study focuses on decreasing the response time of HDD actuator arm movement by managing the performance of the motor that drives the actuator arm utilizing various controllers such as P, PI, PD, and PID controllers.

2.2. Physical Block Diagram

The actuator arm and actuator motor are the components of the system studied in this study. A closed loop control system with negative feedback is used. To improve the performance of the actuator arm, different controllers, and a head position sensor (potentiometer) are used in this system. Based on a user's read or write operation, the system gets input as required head position. The difference between the input and the current head position (output) as measured by the potentiometer sensor is the signal received by the controller. The actuator motor receives the controller output signal and turns the actuator arm. Until the necessary and present head locations match, the controller continues to send an output signal to the actuator motor. The system's function is depicted in the block diagram of **Figure 2**.

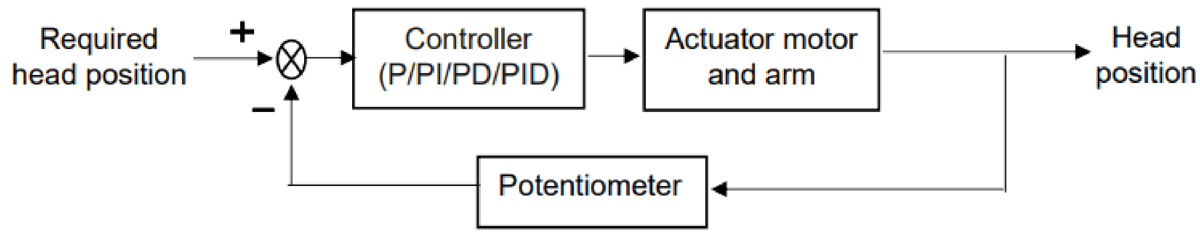


Figure 2: Physical block diagram of the control system of actuating arm.

2.3. Mathematical presentation of the system block diagram

To investigate the system's performance, the control system depicted in **Figure 3** is turned into a mathematical model, which is presented below.

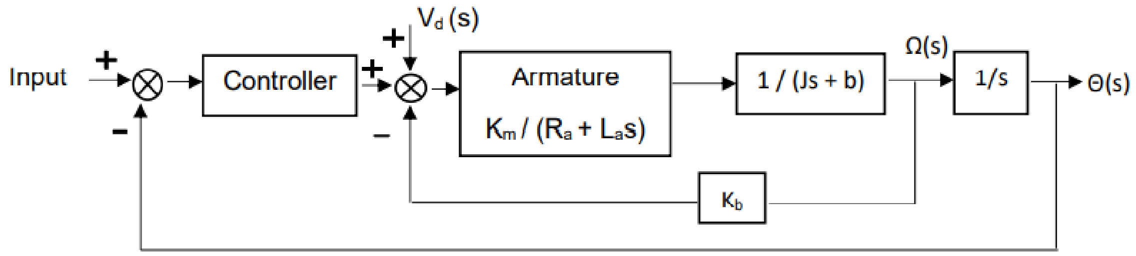


Figure 3: Mathematical block diagram of the control system.

The reduced form of the block diagram in **Figure 4** is described below:

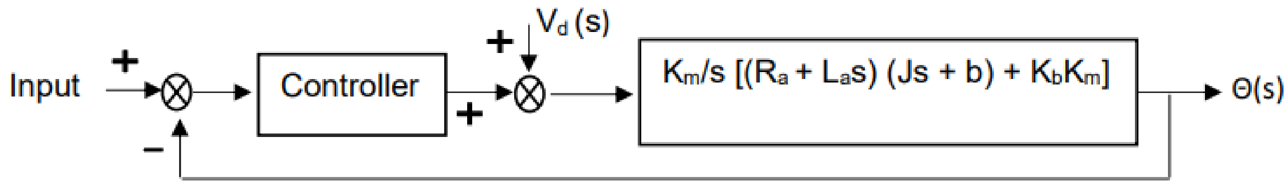


Figure 4: Reduced form of the block diagram of the mathematical model.

The plant transfer function becomes,

$$TF = \frac{K_m}{s[(R_a + L_a s)(Js + b) + K_b K_m]}, \tag{1}$$

The values of different parameters used in the plant transfer function of the system mathematical model are described below in **Table 1**.

Table 1 Typical parameters for armature arm and armature motor system [24]

Parameters	Typical Value
Inertia of actuator arm, J (N.m.s^2 /rad)	1
Armature resistance, R_a (Ω)	1
Motor constant, K_m (N.m/A)	5
Armature inductance, L_a (mH)	1
Damping coefficitent, b (N.s/m)	2

For zero back emf, $K_b = 0$.
After implementing the parameter values, the plant transfer function appears such as this:

$$TF = \frac{5}{0.001s^3 + 1.002s^2 + 2s}, \tag{2}$$

Error function of the system can be expressed as:

$$E(s) = \frac{1}{1 + G_1(s)G_2(s)} R(s) - \frac{G_2(s)}{1 + G_1(s)G_2(s)} D(s)\,, \tag{3}$$

where, $G_1(s)$ is controller transfer function and $G_2(s)$ is plant transfer function.
Steady state error of the system becomes:

$$e(\infty) = \lim_{s\to 0} sE(s) = \lim_{s\to 0} \frac{s}{1+G_1(s)G_2(s)} R(s) - \lim_{s\to 0} \frac{sG_2(s)}{1+G_1(s)G_2(s)} D(s) \\ = e_R(\infty) + e_D(s). \tag{4}$$

where, $e_R(\infty)$ is steady state error due to input and $e_R(\infty)$ is the steady state error due to disturbance.

3. NUMERICAL PROCEDURE

To find out system response for different cases, commercially available MATLAB SIMULINK has been used. As there is no hard and fast direct approach for identifying the appropriate controller gain values, a trial-and-error method have been adopted in this work to find the optimum controller gain values. In order to assume the initial values of the gains of various controllers, the second method of Ziegler-Nichols tuning rules is used.

4. RESULT & DISCUSSION

For efficient and accurate data retrieval, the motion of armature-controlled arm of hard disk drive (HDD) has been analysed in this study. Firstly, system response is observed using the derived unity feedback transfer function. According to the system response, Ziegler-Nichols tuning has been carried out to get the initial values of different controller combination. For each type of controller, the best values of controller constant are found iteratively. Then, all the results are considered together to get the most accurate controller which shows faster and efficient positioning of the controller arm.

4.1 System Response

The closed loop unity feedback transfer function, found from the system, is a type-1 transfer function. To confirm the stability of the system a Routh table is constructed as shown in **Figure 5**.

Characteristic equation: $0.001s^3 + 1.002s^2 + 2s = 0$

s^3	0.001	2
s^2	1.002	0
s^1	$\dfrac{\begin{vmatrix} 0.001 & 2 \\ 1.002 & 0 \end{vmatrix}}{1.002} = 2$	0
s^0	$\dfrac{\begin{vmatrix} 1.002 & 0 \\ 2 & 0 \end{vmatrix}}{2} = 0$	0

Figure 5: Routh table of the system without controller.

As there is no change in sign in the first column, it can be concluded that the system is stable. Then, system response is displayed in **Figure 6**, and it can be seen that, it is an under-damped response curve which shows zero steady state error. This zero steady state error is expected from any type-1 transfer function.

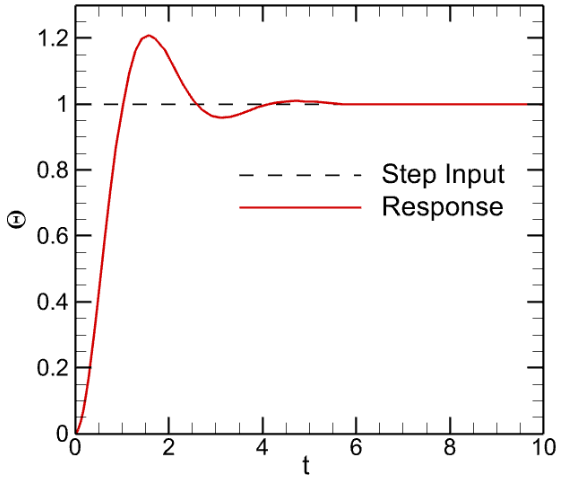


Figure 6: System response curve without any controller.

Also, some specifications of the response are showed in **Table 2**. Observing the specifications, several requirements can be noted as – lowering overshoot, decreasing rising and settling time and retaining zero steady state error.

Table 2 System specifications

Specifications	Value
% Overshoot	20.85
Rise time, T_r (s)	1.02
Settling time, T_s (s)	3.91
Peak time, T_p (s)	1.57

where, rise time, T_r is the time required to for the response to rise from 0% to 100% for underdamped system [25], settling time, T_s is the time required for the amplitude of sinusoid to decay to 2% of the steady state value and peak time, T_p is the time required for the response to reach it's first peak.

4.2 Root locus and Ziegler-Nichols Tuning

Afterwards, to track the change in roots with the change of a constant gain (K) root locus plot is constructed and illustrated in **Figure 7**. As there are three poles (K =0) and no zeros (K=∞) in the present system, all the poles approach to infinity upon the increment of system gain. Also, a clear insight is found from the root locus plot about the maximum possible value of K at which the system would remain stable.

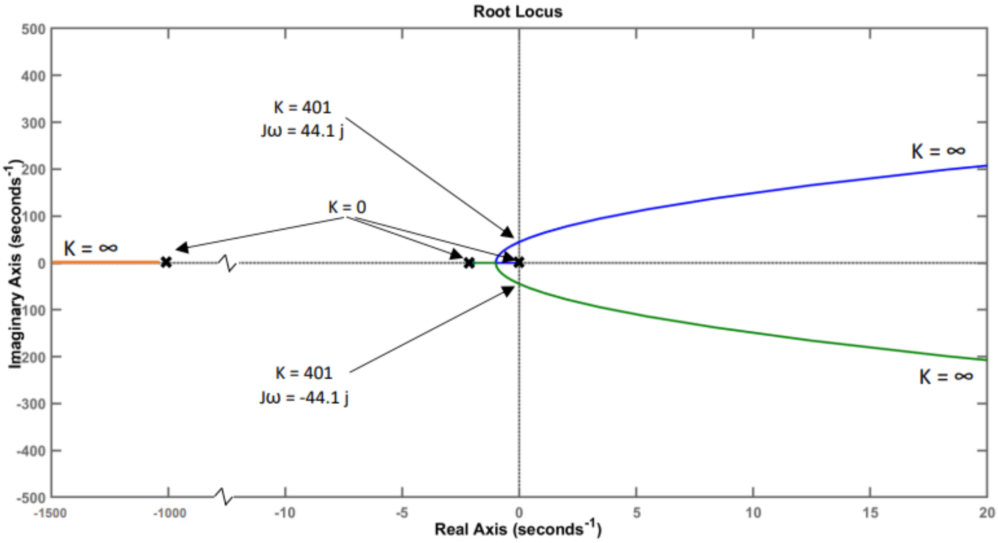


Figure 7: Root locus plot of the system transfer function.

Meanwhile, Ziegler-Nichols tuning method is used to get the initial values of controller gains which might be close to the required response. From this tuning method, critical value of gain at which system becomes marginally stable is, K_{cr} = 401. Then the critical gain is used to get the initial guess of proportional gain, integral time and derivative time. Summary of the tuning is expressed in **Table 3**.

Table 3 Ziegler-Nichols tuning summary.

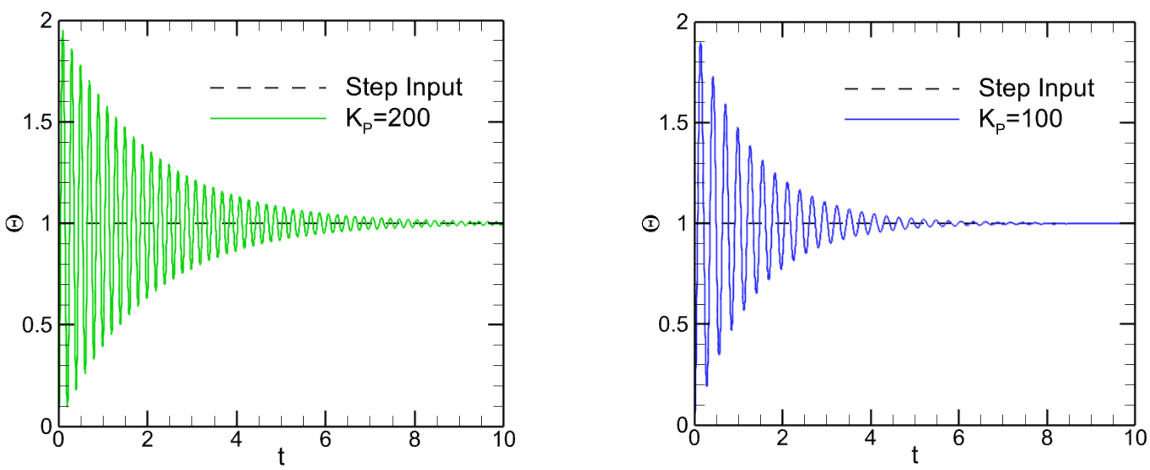
Types of controller	K_p	K_I	K_D
P	200	-	-
PI	180.5	1516.4	-
PID	240.6	3376.84	4.28

4.3 Controller Selection

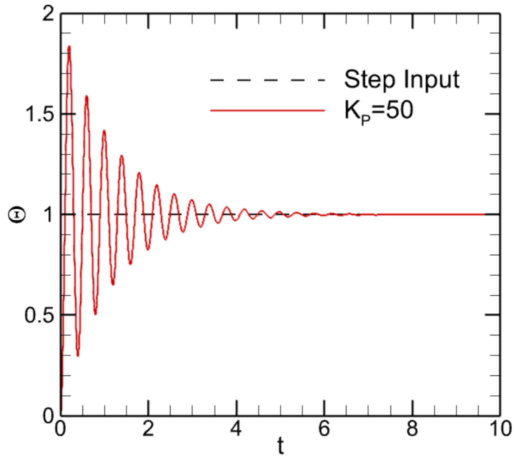
As, the initial values are found from the afore-mentioned tuning method, next task is to see the change in response with the controller. Separate controllers are coupled with the system individually and based on the change in response iterations are also conducted. The results of using different controllers are described below.

4.3.1 P controller

The effect of using P controller with the system is showed in **Figure 8**. Initial assumption of gain is taken from Ziegler-Nichols table. As K_P increases, stability of the system decreases and settling time increases. Increasing fluctuation indicates that no good choice of P controller is possible to make the system stable.



(a) (b)

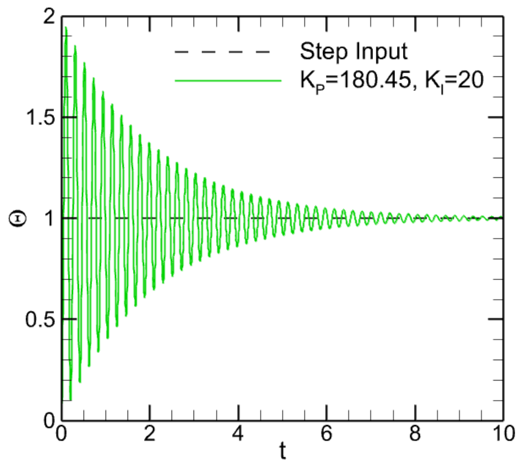


(c)

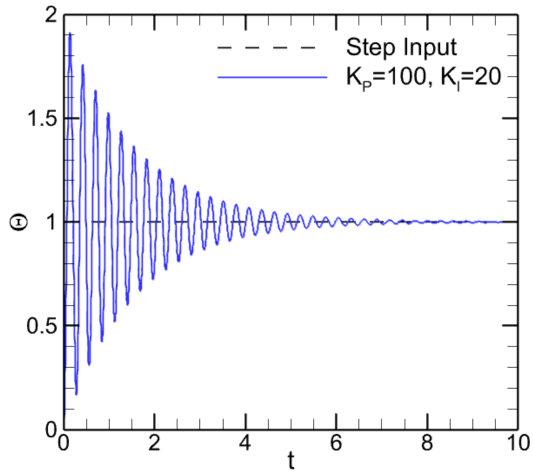
Figure 8: System response with P controller for (a) $K_P = 200$, (b) $K_P = 100$ (c) $K_P = 50$.

4.3.2 PI controller

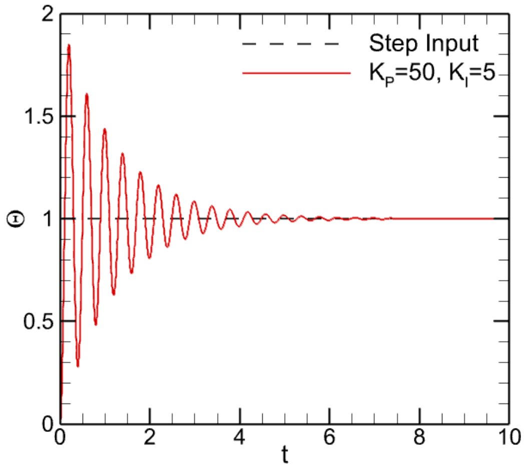
Firstly, output is obtained with the values found from Ziegler-Nichols tuning. Initial guess yields very poor result showed in **Figure 9(a)**. Then several iterations are conducted with other values of K_P and K_I and displayed in **Figure 9(b) - (c)**. The result is quite similar to the result found by using the P controller only. So, PI controller cannot be a good solution for this system.



(a)



(b)



(c)

Figure 9: System response with PI controller for (a) $K_P = 180.45$, $K_I = 20$, (b) $K_P = 100$, $K_I = 20$, (c), $K_P = 50$, $K_I = 5$.

4.3.3 PD controller

Among all the iterations, results of three sets of PD controller are illustrated in **Figure 10(a)-(c)**. With a moderate value (K_P = 1000 and K_D = 95), a good result can be obtained which drastically changes the settling time from around 3.91 seconds to 0.6 seconds. But as present study is dealing with a very sophisticated system, further iteration is carried out and conclude that proportionate increase in K_P and K_D enhance the performance to the best extent. Finally, the result found with K_P = 18000 and K_D = 95 is considered to be optimum for the present system which brings down the settling time to 11.64 milliseconds.

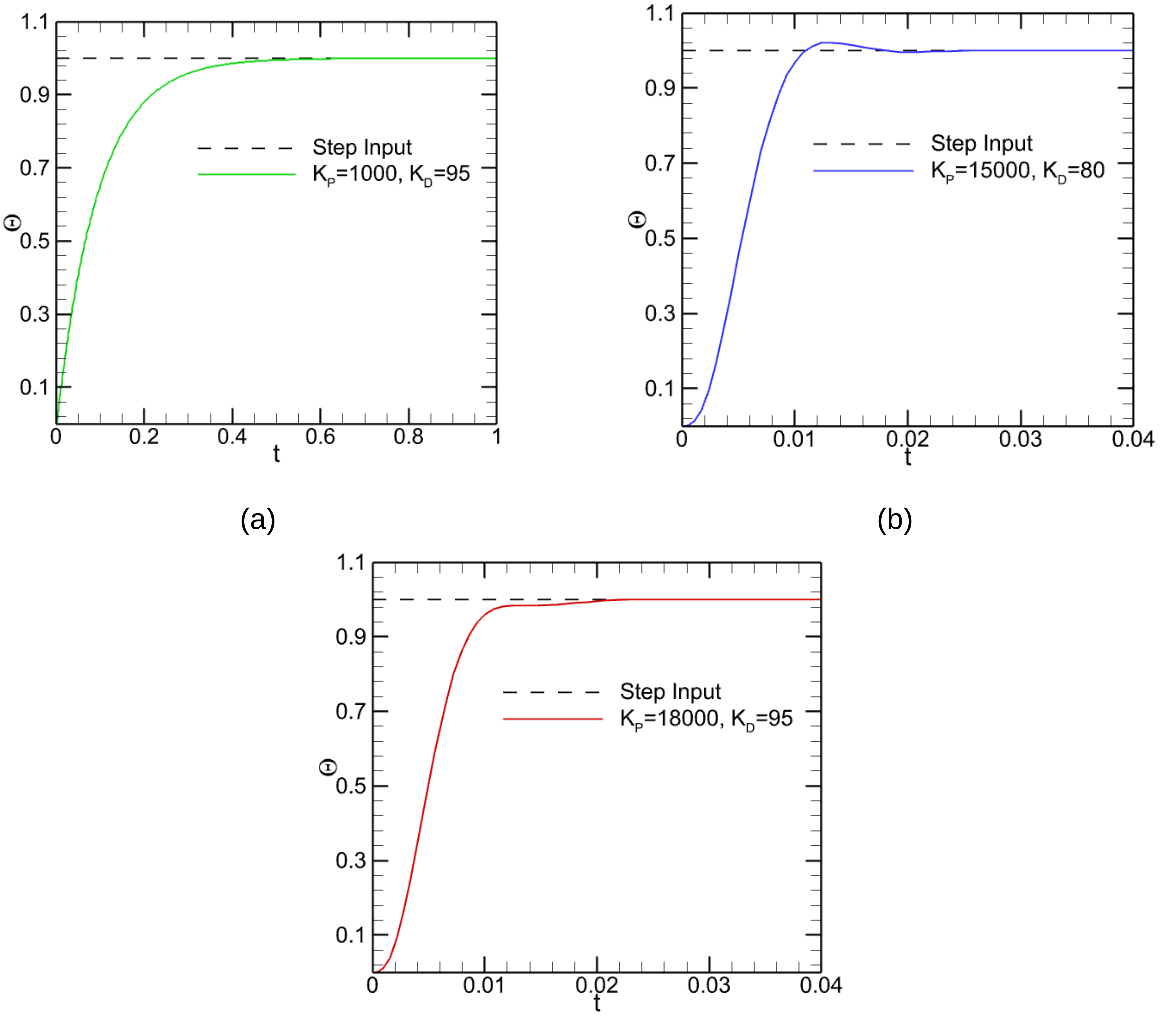


Figure 10: System response with PD controller for (a) K_P = 1000, K_D = 95 , (b) K_P = 15000, K_D = 80 , (c), K_P = 18000, K_D = 95.

4.3.4 PID controller

With the continuation of the present study, a PID controller is coupled with the system to observe all the way out. The Ziegler-Nichols tuning again gives a poor result as shown in **Figure 11(a)**. Then other values are tried out to find the best possible PID controller and results are presented in **Figure 11(b)-(c)**. Interestingly, the result shows that values of K_I have no effect in the performance. Settling time of the at **Figure 11(c)** is 11.64 milliseconds which is eventually same to the value obtained from PD controller. The reason is that, present study inheres a type-1 transfer function which does the job of the I controller. Finally, the optimum values are found for K_P and K_D and these are identical to those of PD controller.

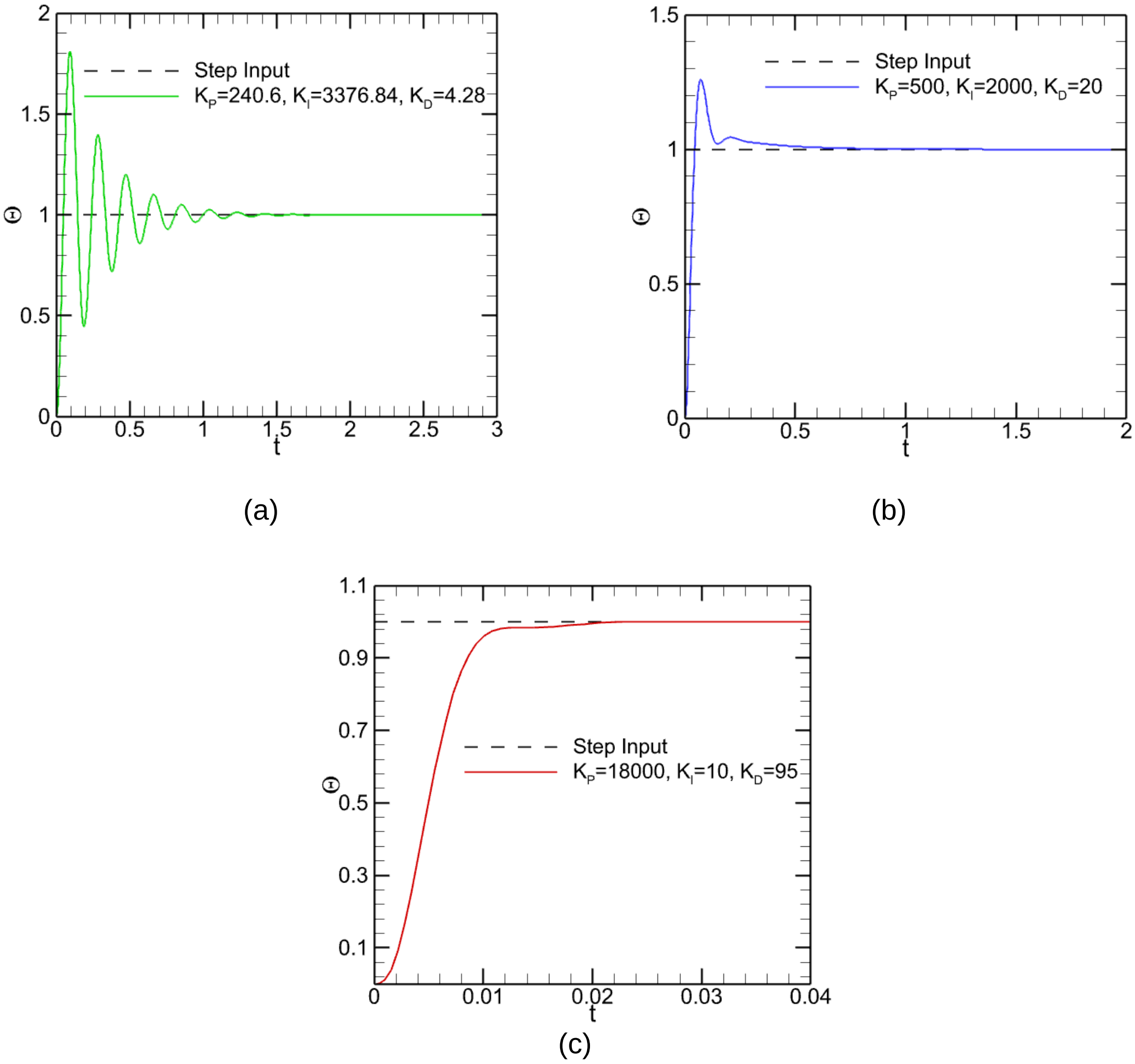


Figure 11: System response with PID controller for (a) $K_P = 240.6$, $K_I = 3376.84$ $K_D = 4.28$, (b) $K_P = 500$, $K_I = 2000$ $K_D = 20$, (c), $K_P = 18000$, $K_I = 10$, $K_D = 95$.

In the end, after going through all the possible combination of controller, it can be decided that PD controller of gain $K_P = 18000$ and $K_D = 95$ is the most optimized outcome. This controller can give as much as accurate and faster response (settling time, $T_s \approx 11.64$ milliseconds) to the armature-controlled head for efficient data reading from the hard disk.

4.4 Steady state error analysis

Analysis of steady state error is very significant in system design. Any control system should be adopted in order to minimize steady state error. After applying limit, steady state error for step input and disturbance is calculated separately as stated below:

$$e_R(\infty) = \lim_{s\to 0} \frac{s}{1+G_1(s)G_2(s)} R(s) = 0$$

$$e_D(s) = \lim_{s\to 0} \frac{sG_2(s)}{1+G_1(s)G_2(s)} D(s) = -\frac{1}{K_P}$$

As $K_P = 18000$, steady state error for any step disturbance is $e_R(\infty) = -5.55\times10^{-5}$ which indicates a good stability of the system for any unwanted perturbation.

4.5 Sensitivity Analysis

As step input gives zero error for any parametric change, sensitivity of the system is calculated in terms of disturbance. Steady state disturbance error is-

$$e_D(s) = -\frac{1}{K_P}$$

So, sensitivity of the system becomes:

$$S = \frac{K_P}{e} \cdot \frac{\partial e}{\partial K_P} = \frac{K_P}{-\frac{1}{K_p}} \cdot \frac{1}{K_P^2} = -1$$

This small value of sensitivity for step disturbance means that the system is less sensitive to any small change in K_P. On the other hand, zero error function for step input signifies the insensitivity of the output with the variation of K_P.

5. Conclusion

Hard disk drives (HDDs) are prominent computer storage devices in today's world. Improving HDD performance and response time is a top priority in the modern day. To contribute to this sector, this work focuses on decreasing actuator arm movement response time by controlling the actuator motor with various controllers and ensuring system stability. First, a mathematical model of the system is developed, and all numerical analyses are performed using MATLAB SIMULINK for various controllers. Second, the system's stability is determined by constructing a Routh table, and the system is found to be stable. The system has an overshoot of 20.85%, which indicates that the system is underdamped. A root locus plot is prepared to get the initial assumption of the trial-and-error method for analyzing the P controller. The Ziegler-Nichols Tuning rules are used to predict the beginning values of the trial-and-error method for selecting appropriate P, PI, PD, and PID controllers gain for the system. There is no gain value for P and PI controllers, which eliminates system overshoot.

Conversely, the PD and PID controllers have enhanced system performance by removing overshoot and decreasing response time. The system settling time of a PD controller is decreased from 3.91 seconds to 11.64 milliseconds when K_P = 18000 and K_D = 95 are used. However, a same drop in settling time is also obtained when K_P = 18000, K_I = 10, K_D = 95 are used. Hence, the performance of the PD controller is found to be comparable to that of the PID controller. Since PD has fewer separate controllers than PID, it will outperform all other controllers in this system.

The system considered here considers many simplifications. Some of these might affect the performance in practical scenario. Moreover, only the improvement of performance is focused in this study. However, the physical availability of the controllers and the improvement in the performance against the rising cost have not been considered. Whenever, a practical system is to be designed all of these factors are to be taken into consideration.

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