Bangladesh University of Engineering and Technology (BUET), Dhaka-1000

ME 461 - Control Engineering
Term Assignment

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

Group Number: 05

Submitted by:

Name	Student ID	Signature
Hm Toufik Ahmed Zisan	1610004	
Md Mehrab Hossen Siam	1610011	Mehr
Tahmidul Haque Ruvo	1610013	Tahmidul Haque Ruvo 1610013
Meraj Hossain	1610020	Meraj Hossain
Emran Hassan Bejoy	1610035	
Md. Nazmus Sakib	1610058	

Date of Submission: 25. 02. 2022

Efficient Retrieval of Data from Hard Disk Drive Using Precise Controller

Hm Toufik Ahmed Zisan[1], Md Mehrab Hossen Siam[2], Tahmidul Haque Ruvo[3], Meraj Hossain[4], Emran Hassan Bejoy[5] and Md. Nazmus Sakib[6]

Department of Mechanical Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka-1000

[1]1610004@me.buet.ac.bd, [2]1610011@me.buet.ac.bd, [3]1610013@me.buet.ac.bd, [4]1610020@me.buet.ac.bd, [5]1610035@me.buet.ac.bd, [6]1610058@me.buet.ac.bd

ABSTRACT

Hard Disk Drive (HDD) is well known for data reading and writing. With the increment of the speed of this data reading work, the functionality of electronics becomes faster. This work is for finding out a precise controller for the control of armature head of the 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. For getting the transfer function of the system, standard values of the parameters like inertia, armature resistance, coil inductance etc. are used. Routh-Hurwitz stability criterion is used to show the stability of system. MATLAB SIMULINK is used to numerically analyse the system transfer function. At first, system response curve, rise time, settling time, peak time and overshoot were obtained. Root locus of the system is shown to obtain 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, PD controller is found to be the optimum choice for the fast reading and writing at a value of K_P =18000 and K_D = 95. Further mathematical works have been carried out to do a steady state error analysis and to find out the sensitivity of the system against changing parameters.

Key Words: HDD, Controller, Sensitivity.

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 had been generated at the end of year 2021 [1]. This data volume can be extrapolated to a sheer magnitude of 180 zettabytes by the year 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 in comparison to other removable, non-volatile storage options. However, this technology has its own limitation and also facing tremendous competition in market. So, upgrading the current version has become a major 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. In 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. With the passing of first 3-4 decades of its journey, engineers identified the bottlenecks and also, fixed many of these gridlocks. Introduction of rotary actuator, shrinkage of disk dimension and capability of performing the functions at same level despite its reduction in size. 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 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 MR effect, Peter Grunberg and Albert Fert were nominated for 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. Magnetization axis would be now 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 air-bearing surface (ABS), is placed on a certain track on the disc to read or write data. 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 following mode is often the cause for upbringing some undesired transients at the beginning of following mode. This ultimately induces error and lengthens the seek time. The continuous reduction of disc size and increased rpm intensifies a problem called 'aeroelastic flutter'. Huge rotational speed of smaller disc also causes wind to blow around it at a 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 faithfully represent data. To predict the air movement around the disc and analyze the effect of fluttering, efforts were applied both numerically and experimentally [14]. In 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. Combined effect of these agitation are generation of position error signal (PES), noise introduction in signal [2]. When the disks are rotating at high speeds of around 12000 rpm, slight error can be detrimental to the performance of system.

In order to properly and accurately fetch data from the HDD, it is important to conduct smooth track seeking and track following. The introduction of control system in the actuating mechanism tended to compensate for the disturbances and to execute the functions of actuator arm in a 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 condition. Fujimoto *et al.* [17] presented a multirate sampling based 2DOF controller. 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 piezoelectric micro-actuator showed a considerable reduction of track seeking time. Use of proportional, integral and derivative (PID) controller had 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 servosystem. Robustness of the system was verified using numerical analysis. Yadav *et al.* [22] showed a comparison among classical PID controller, fuzzy logic with proportional-derivative (FL-PD) controller and self-tuning fuzzy logic with PID (STFL PID) controller. Each of them had upper hand at different set criterias.

Hence, it is clear that a lot of research has been ongoing to gain a better control of the servo-mechanism of HDD. A better and efficient control will always enhance the performance of the overall computing environment. In order to supplement the ongoing effort to attain smallest possible seeking time and accurate track following, this paper intends to propose a comparative study among different classical P, PI, PID, PD control systems and to sort out best possible control scheme to attain 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 below.

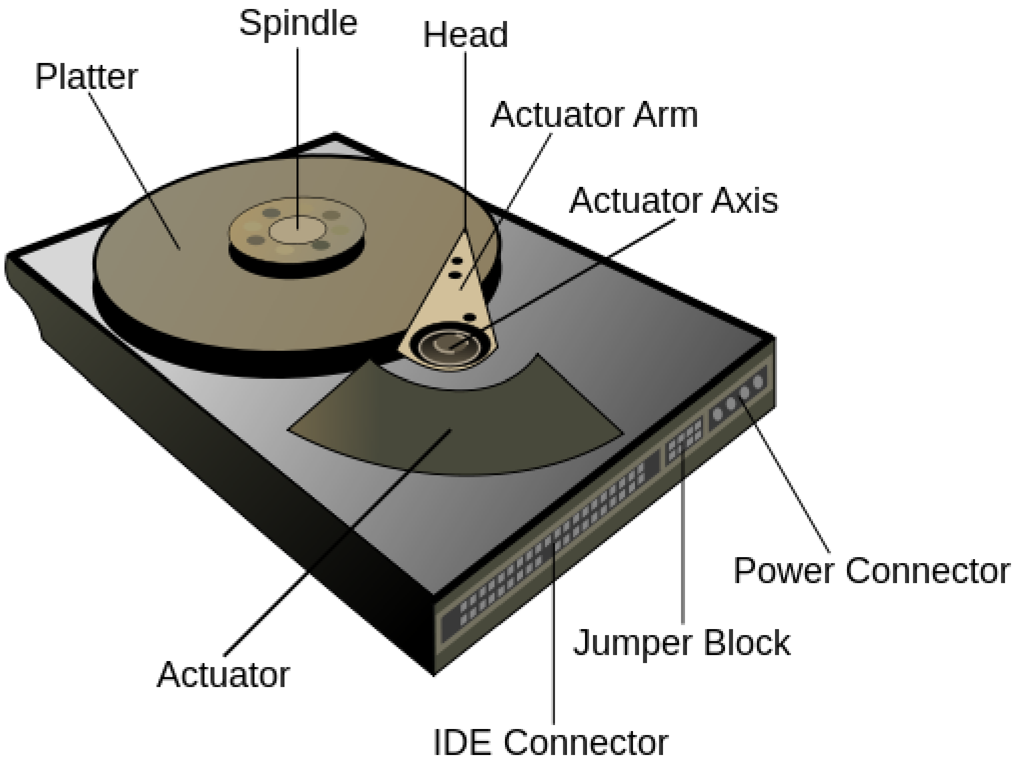


Figure 1: Schematic overview of an HDD with its essential parts [23].

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 system analyzed in this paper is made of actuator arm and actuator motor. A negative feedback closed loop control system is utilized. Different controllers, and head position sensor (potentiometer) are introduced in this system to optimize the performance of actuator arm. The system receives input as required head position based on read or write operation of a user of computer. The signal received by the controller is the difference between the input and the current head position (output) as measured by the potentiometer sensor. The controller output signal is then delivered to the actuator motor, which rotates the actuator arm. The controller continues to provide an output signal and transfers it to the actuator motor until the required and current head positions match. The function of the system is illustrated in the block diagram below.

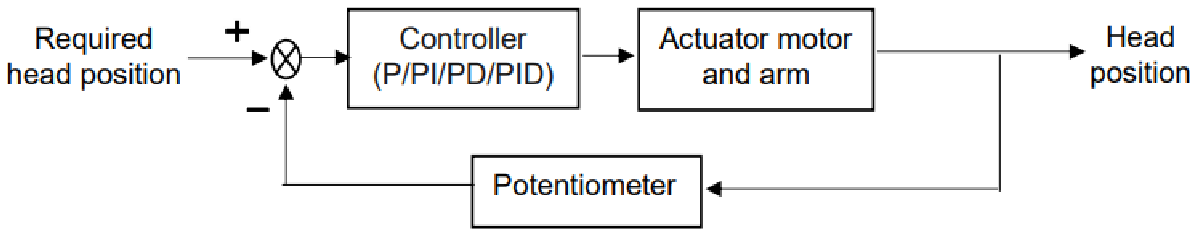


Figure 2: Physical block diagram of the control system of actuating arm.

2.3. Mathematical presentation of the system block diagram

To investigate the system's performance, the control system depicted in Figure 2 is turned into a mathematical model, which is presented below.

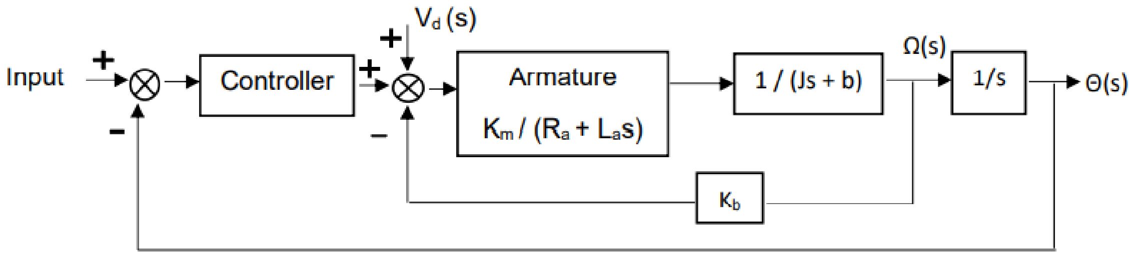


Figure 3: Mathematical block diagram of the control system.

The reduced form of the block diagram in figure 3 is described below:

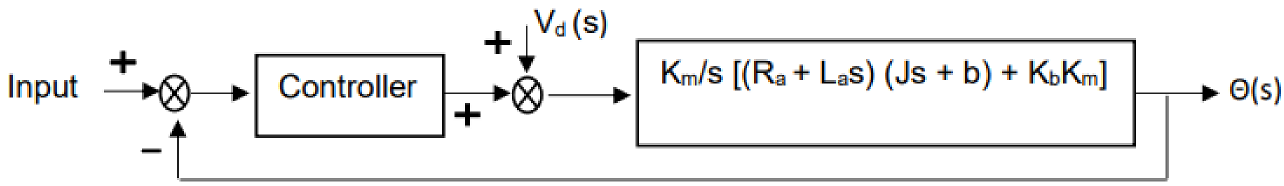


Figure 4: Reduced form of the block diagram of the mathematical model.

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.

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, G1(s) is controller transfer function and G2(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 analyzed 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 below:

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

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 Fig 1, 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.

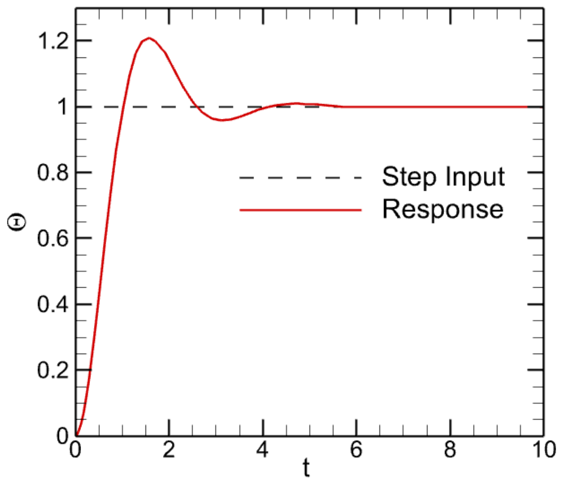


Figure 5: System response curve without any controller.

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

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 6**. 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.

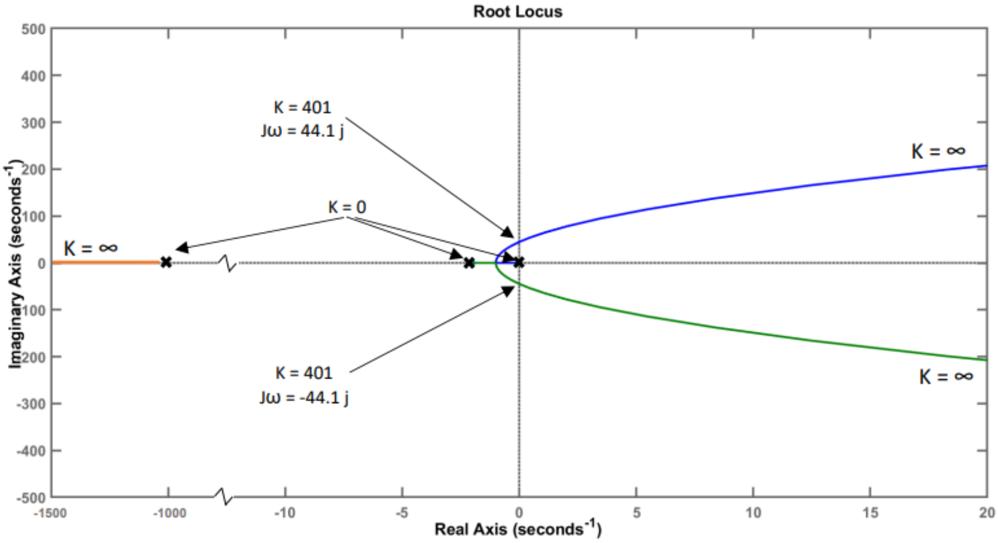


Figure 6: Root locus plot of the system transfer function

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 2**.

Table 2 Ziegler-Nichols tuning summary.

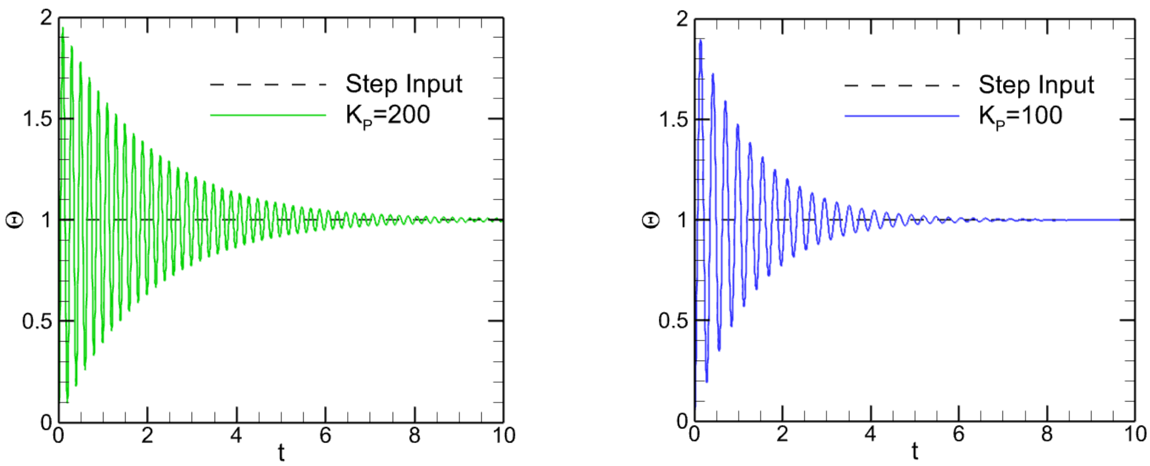
Types of controller	K_p	K_I	K_D
P	200	-	-
PI	180.5	1516.4	-
PID	240.6	3376.84	4.28

4.3 Controller Selection

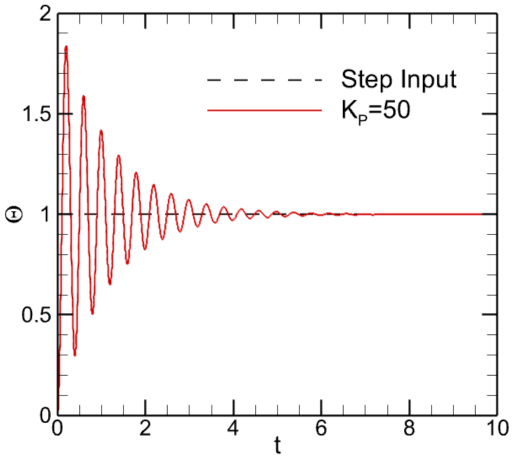
As, the initial values are found from the afore-mentioned tuning method, next task is to see the change in response with the controller. Separate controllers are coupled with the system individually and based on the change in response iterations are also conducted. The results of using different controllers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

4.3.1 P controller

The effect of using P controller with the system is showed in **Figure 7**. 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)

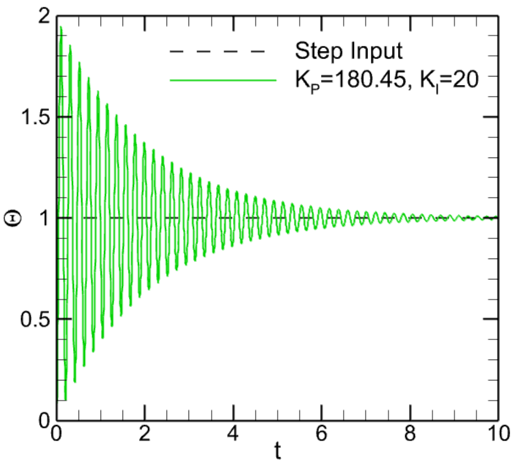


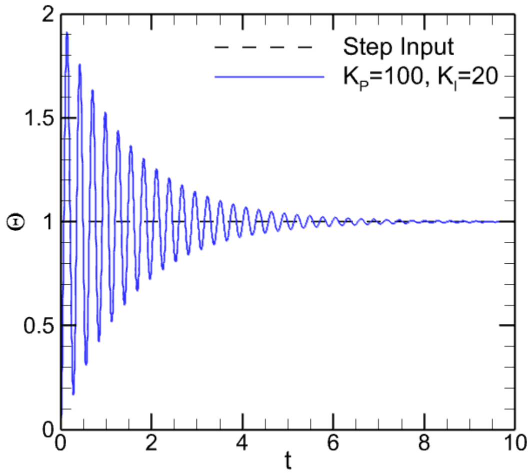
(c)

Figure 7: System response with P controller for (a) $K_P = 200$, (b) $K_P = 100$ (c) $K_P = 50$

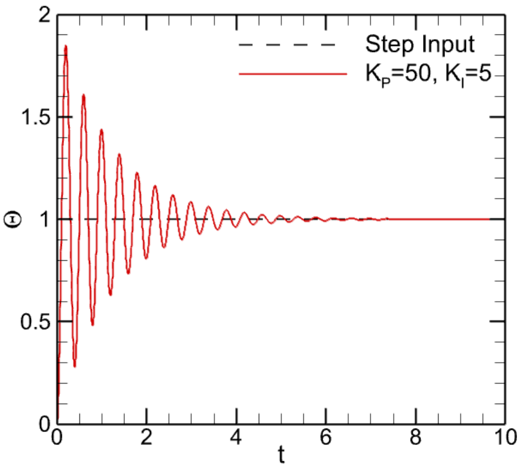
4.3.2 PI controller

Firstly, output is obtained with the values found from Ziegler-Nichols tuning. Initial guess yields very poor result showed in **Figure 8(a)**. Then several iterations are conducted with other values of K_P and K_I and displayed in **Figure 8(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)

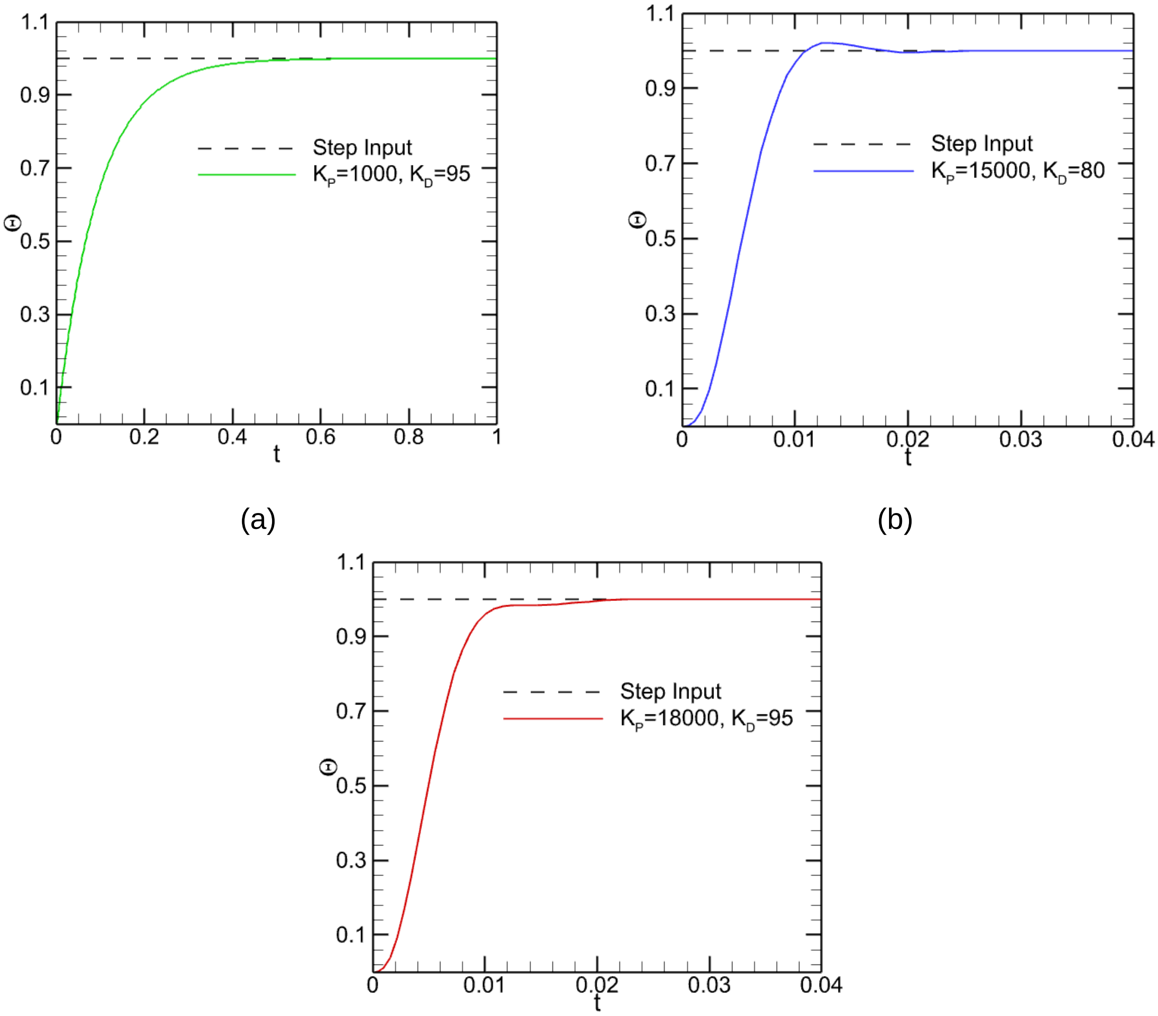


(c)

Figure 8: 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 9(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 6 seconds to 0.6 second. 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.

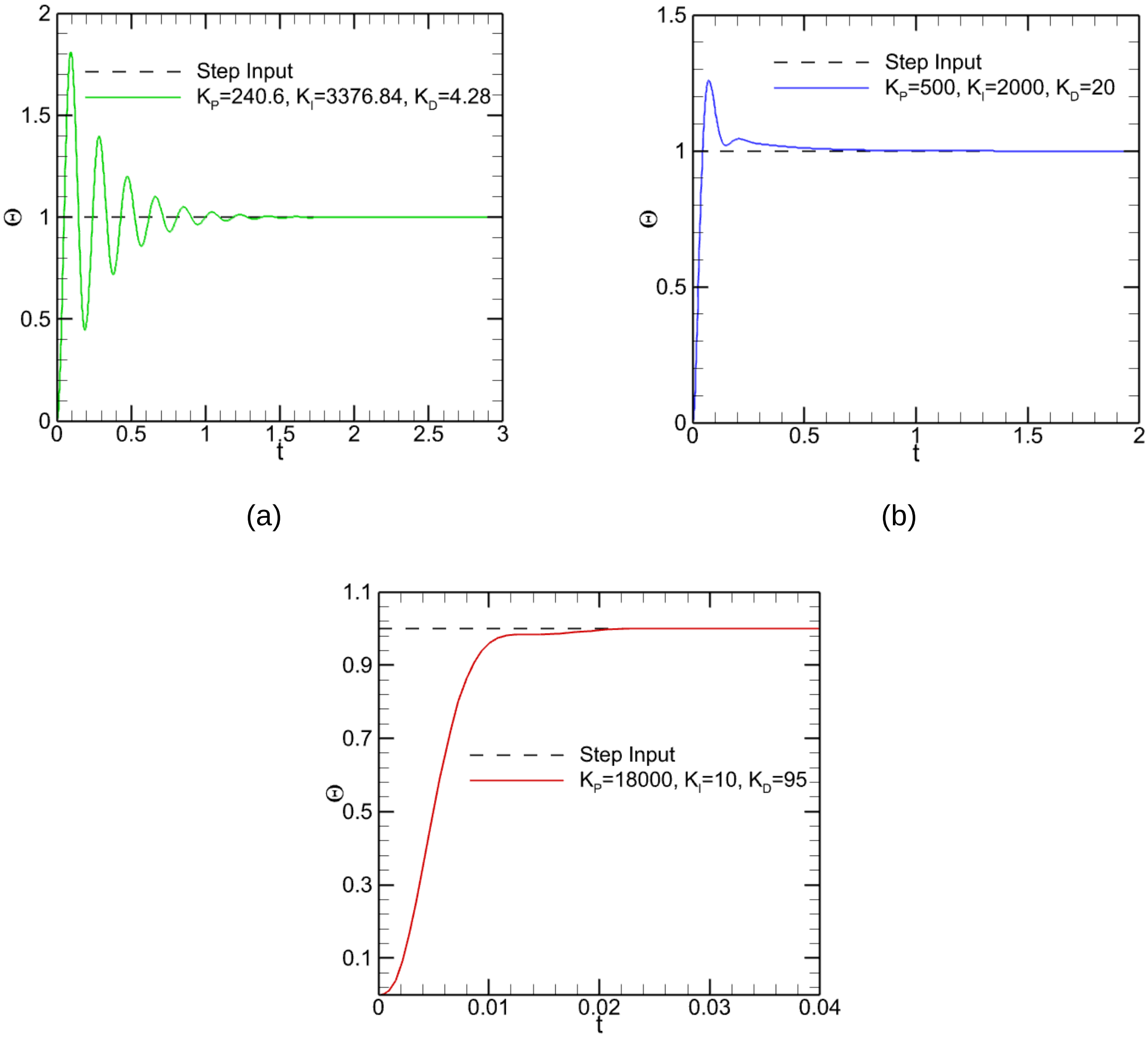


(c)

Figure 9: 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 10(a)**. Then other values are tried out to find the best possible PID controller and results are presented in **Figure 10(b)-(c)**. Interestingly, the result shows that values of K_I have no effect in the performance. The reason is 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.



(a) (b) (c)

Figure 10: 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, $T_s \approx 19$milisecond) 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

In today's world, hard disk drives (HDDs) are a popular type of computer storage device. It is a high priority in the present era to improve the performance and response time of HDDs. To contribute to this sector, this work focuses on decreasing the response time of actuator arm movement by controlling 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 trial and error method for analyzing 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, both 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 3.91s to 11.64ms when K_P = 18000 and K_D = 95 are used, but the settling time of a PID controller is reduced from 3.91s to 11.64 ms when K_P = 18000, K_I = 10, K_D = 95 are used. In this study, the performance of PD controller is found to be comparable to that of PID controller. Since PD has fewer separate controllers than PID, it will perform more effectively than any other controller for this system..

REFERENCES

[1] A. von See. (2021), Total data volume worldwide 2010-2025. https://www.statista.com/statistics/871513/worldwide-data-created/ (accessed Feb. 23, 2022).

[2] A. Al Mamun, G. Guo, and C. Bi. (2007), *Hard Disk Drive, 1st ed.*, . Taylor & Francis Group. doi: 10.1201/9781420004106

[3] E. Grochowski and R. F. Hoyt. (1996). Future trends in hard disk drives. *IEEE Trans. Magn. 32(3)*, pp. 1850–1854, doi: 10.1109/20.492876

[4] R. Wood. (2009). Future hard disk drive systems. *J. Magn. Magn. Mater. 321(6)*, pp. 555–561, doi: 10.1016/j.jmmm.2008.07.027

[5] K. E. Kuijk, W. J. van Gestel, and F. W. Gorter. (1975). The Barber Pole, a Linear Magnetoresistive Head. *IEEE Trans. Magn. 11(5)*, pp. 1215–1217, doi: https://doi.org/10.1109/TMAG.1975.1058886

[6] D. Hannon, M. Krounbi, and J. Christner. (1994). Allicat Magnetoresistive Head Design and Performance. *IEEE Trans. Magn. 30(2)*, pp. 298–302, doi: 10.1109/20.312276

[7] K. Ohashi *et al.* (2000). Low-resistance tunnel magnetoresistive head. *IEEE Trans. Magn. 36(5 I)*, pp. 2549–2553, doi: 10.1109/20.908506

[8] J. M. De Teresa, A. Barthélémy, A. Fert, J. P. Contour, F. Montaigne, and P. Seneor. (1999). Role of metal-oxide interface in determining the spin polarization of magnetic tunnel junctions. *Science (80-.). 286(5439)*, pp. 507–509, doi: 10.1126/science.286.5439.507

[9] M. Gajek *et al.* (2007). Tunnel junctions with multiferroic barriers. *Nat. Mater. 6(4)*, pp. 296–302, doi: 10.1038/nmat1860

[10] P. A. Grünberg. (2008). Nobel lecture: From spin waves to giant magnetoresistance and beyond. *Rev. Mod. Phys. 80(4)*, pp. 1531–1540, doi: 10.1103/RevModPhys.80.1531

[11] H. J. Richter. (2009). Density limits imposed by the microstructure of magnetic recording media. *J. Magn. Magn. Mater. 321(6)*, pp. 467–476, doi: 10.1016/j.jmmm.2008.04.161

[12] S. I. Iwasaki. (1980). Perpendicular magnetic recording. *IEEE Trans. Magn. 16(1)*, pp. 71–76, doi: 10.1109/TMAG.1980.1060546

[13] M. Mallary, A. Torabi, and M. Benakli. (2002). One terabit per square inch perpendicular recording conceptual design. *IEEE Trans. Magn. 38(4 I)*, pp. 1719–1724, doi: 10.1109/TMAG.2002.1017762

[14] B. C. Kim, A. Raman, and C. D. Mote. (2000). Prediction of aeroelastic flutter in a hard disk drive. *J. Sound Vib. 238(2)*, pp. 309–325, doi: 10.1006/jsvi.2000.3209

[15] S. Takada, T. Kusukawa, N. Tagawa, A. Mori, Y. Mizoh, and M. Nakakita. (2007). Study on flow-induced vibration of head-disk assembly mechanisms in actual hard disk drive. *Microsyst. Technol. 13(8–10)*, pp. 767–775, doi: 10.1007/s00542-006-0279-8

[16] J. Ishikawa, Y. Yanagita, T. Hattori, and M. Hashimoto. (1996). Head positioning control for low sampling rate systems based on two degree-of-freedom control. *IEEE Trans. Magn. 32(3 PART 2)*, pp. 1787–1792, doi: 10.1109/20.492866

[17] H. Fujimoto, Y. Hori, T. Yamaguchi, and S. Nakagawa. (1999,). Proposal of perfect tracking and perfect disturbance rejection control by multirate sampling and applications to hard disk drive control. *Proc. IEEE Conf. Decis. Control 5(December)*, pp. 5277–5282, doi: 10.1109/cdc.1999.833393

[18] L. Yi and M. Tomizuka. (1999). Two-degree-of-freedom control with robust feedback control for hard disk servo systems. *IEEE/ASME Trans. Mechatronics 4(1)*, pp. 17–24, doi: 10.1109/3516.752080

[19] M. Kobayashi and R. Horowitz. (2001). Track seek control for hard disk dual-stage servo systems. *IEEE Trans. Magn. 37(2 I)*, pp. 949–954, doi: 10.1109/20.917648

[20] S. Skogestad. (2004). Simple analytic rules for model reduction and PID controller tuning. *Model. Identif. Control 25(2)*, pp. 85–120, doi: 10.4173/mic.2004.2.2

[21] B. M. Isayed and M. A. Hawwa. (2007). A Nonlinear PID Control Scheme for Hard Disk Drive Servosystems. *2007 Mediterr. Conf. Control Autom. MED* pp. 0–5, doi: 10.1109/MED.2007.4433790

[22] A. K. Yadav, P. Saxena, P. Gaur, and P. K. Pathak. (2021). Self-tuning fuzzy PID controller for servo control of hard disk drive with time delay. *Int. J. Inf. Technol. 13(1)*, pp. 109–114, doi: 10.1007/s41870-020-00567-w

[23] Surachit. Hard Drive Picture, (2007). https://commons.wikimedia.org/wiki/File:Hard_drive-en.svg (accessed Feb. 24, 2022).

[24] R. T. Ratliff, " Disk drive actuator design and control for robust non-operational shock performance", Oklahoma State University, Stillwater, OK, 2005.