Designing and Modelling of Pivotal Friction Compensator of Actuator of Hard Disk Drives

Muhammad Umer Rana, Syed Irtiza Ali Shah, Muhammad Junaid Ansar, Majid Mehmood
Department of Mechanical & Aerospace Engineering Air University, Islamabad, Pakistan
200544@students.au.edu.pk, 200530@students.au.edu.pk, irtiza@mail.au.edu.pk,majid.25mehmood@au.edu.pk

Abstract

Nowadays, hard disk drives are one of the most common devices for storing data. The growing demand for storing the bulk amount of data and retrieving the data as fast as possible from hard disk drives (HDDs) has posed manufacturers with various challenges. To overcome these hurdles different methods, techniques, and control systems are developed to improve the transient response of the HDDs. The transient response of a system is characterized by numerous specifications such as overshooting, peak time, settling time, delay, and rise time. Transient response of the system can be achieved by using multiple stage actuators which can eventually increase the accuracy of head-positioning of the actuator of hard disk drives. By increasing the accuracy of read/write head actuator there is a challenge to cater the friction at pivot of actuator which can significantly reduce the speed of the actuator and leads to the reduction in the transient responses of the system. This paper aims to design a new modelled-base friction compensator for the servo control of hard disk drives that can compensate the pivotal friction of actuator of HDDs. To achieve this objective, measured and replicated responses will be used as guidance and the friction design of HDD will iteratively improve. This can be done by feeding the measured friction forces back to the voice coil motor so that the frequencies of the actuator's head and current can be linearized. This proposed design will help in the cancelation scheme and the model-based compensator will be implemented. We will test our design system against different types of response and then iteratively modify our system. Then, with the help of MATLAB we will integrate a PID controller into our control system so that we can improve the transient response as much as possible. Our work can be considered important as there are very few frictions compensator control designs that have integrated the PID controller. We are aiming to achieve a significantly improved pivotal friction compensator that can help us to achieve improved transient response of the hard disk drive (HDD).

Keywords— Actuators, friction, hard disk drives, head-positioning, PID controller, transient responses, servomechanisms.

I. INTRODUCTION

Hard disk drive (HDD) is a common device that is used to store data in homes and industries. Hard disk drives use the platters that rotates at a very high speed. As we are moving forward in time, the consumer demands to store large amount of data and to retrieve the data from hard disk drives as fast as possible. To cater these obstacles there is shift in trend by increasing the areal density and decreasing the track pitch of the HDDs. However, the study of vibrations has become more important because of increase in the disturbances. So, to counter these disturbances and to provide better accuracy of the position of the actuator a controller becomes more necessary than ever. There are factors that restricts the areal density growth such as nonlinearities and pivotal friction uncertainties. A compensator that is bound to a certain model will not provide performance up to the requirement if the model is not precise enough. Hence, a sensor is required with the disturbance observer to enhance the performance. A friction compensator is modelled in HDD servo control that uses the estimation of on-line friction torque. The HDD position controller will generate the reference torque and the estimation of friction torque will be added to the reference torque. By successfully implementing the model-based friction compensator in the servo control the transient response of HDD will be improved. For further improvement in the transient response of the hard disk drive we need to look after certain characteristics of the transient responses. [22]

A) Background

Hard disk drives are a mode of storing bulk amount data and it mostly preferred due to its excellent scalability, low cost, high areal density and high transfer rate amidst different storage devices. The very early hard disk drives have the areal density of only 2000 bits/in^2. As we made advancements in the technologies of magnetic recordings, the areal density had been increased by the factor of about 5 million and now the commercial hard disk drives have the areal density of 120 Gb/in^2. With the reduction of component disturbances due to off-track motion and by enhancing the ability of servo controllers track density has been increased. Other factors such as lubricant's quality, air bearing play disk and the surface roughness reduction plays important role in improving the storage bit density. With these advancements, today's hard disk drives can achieve the transfer rate of about 125 Mb/s. As the magnetic recording technology is advancing the disk size

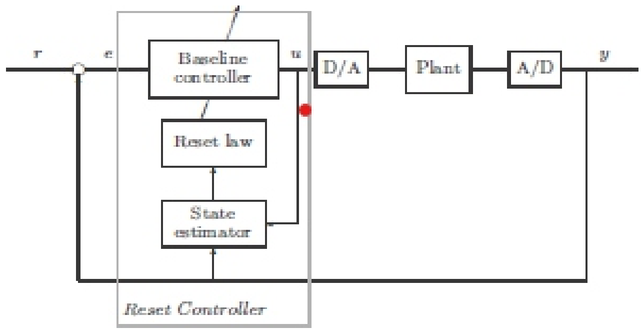


Fig. 1. Block diagram of a reset control system [1]

is reduced significantly and the areal density of disk drives is increased. As more and more data are packaged into smaller space hence, the accuracy of servo positioning for the access of data and other non-linearities become a hurdle for HDD servo system.[24]

B) Literature Review

Clegg introduces the reset controller which is called the Clegg integrator which is used to overcome the limitations of the linear controller. The Clegg integrator consists of an integrator and a reset law is used to reset the output to zero of an integrators when the input values have vanished. The discrete-time reset control system was modelled and that has already stated reset time intervals. Traditionally in hard disk drives, a base linear system is used, the proposed technique by Hui Li improves the transient responses of the hard disk drives (HDDs). The advantages of this technique are that the technique guarantees the stability of the system and reset law solutions are obtained by solving the Riccati equations. The method is applied to both short-span and long-span track seeking of the servo systems of the hard disk drives. The designed technique is used in the controls of seeking track of the single-stage HDD systems. With the help of experiments and simulations, it is proved that this technique is drastically improving the transient responses of the hard disk drives (HDDs) than the control systems that are used in HDDs traditionally.[1]

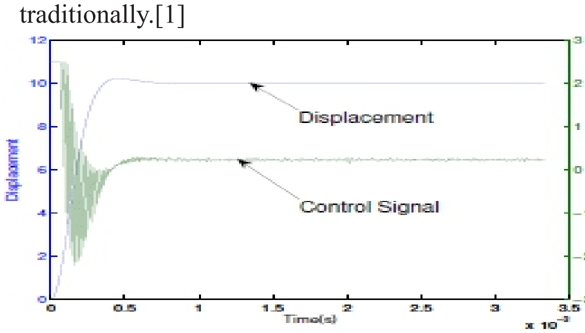


Fig. 2. Displacement and control signal for r=10.[1]

There is a priori performance and stability standard are set that is conditioned to be met in the analysis of modelling of robust control systems. M. Clang in his paper investigated the robust servomechanism problem for sinewave disturbance systems that contains the multi-inputs and outputs and the phase components that are tested have an unknown value of magnitude. In the tuning methods that is dealing with the sinewave harmonic elements, the improved transient responses are shown through the agency of simple initialization and the method can be used in the favor of discrete-time settings. By using this base model, further enhancing techniques are developed and their results show an improvement in the tuning transients. In traditional hard disk drives (HDDs) the harmonic disturbances maybe come to light, for example, fasteners effects. A comparison is drawn between the harmonic damping method that is used conventionally and the solutions approach that is proposed.[2]

A quite familiar servo design tool is applicable for repeating disturbances. This tool is called repetitive control (RC). This new RC scheme is from the observer's perspective and deals with the normal class of the disturbance spectrum. The improved servomechanism is used repetitive control at the primary frequency and the harmonics of higher orders are often succeeded by the unwanted error amplification. Xu Chen conducted an investigation that shows an internal model with new structural configurations in repetitive controls where the model is more flexible in the repetitive loop-shaping design and the amplifications of non-repeating errors are mainly reduced. If control is dealing with the great number of nonrepeating disturbances the proposed technique is quite advantageous as compared to the traditional repetitive control. With this method, an improved transient response is also received and it can be controlled easily steering towards the enhanced transient responses of the hard disk drives with reduced overshoots. The track-seeking tests are conducted in the laboratory and the results are satisfactory.[3]

The performance of transient responses is an attribute of hard disk drives that is considered very important issue to be addressed in problems of tracking controls and its applications are in the output regulations and target tracking. The manufacturer desires for quick responses and overshoots to be as small as possible but it is a well-known thing that as the quick responses always results in the large overshoots. G. Cheng presented a MATLAB toolkit that is quite user-friendly and the purpose of this toolkit is the representation of controls of composite non-linear feedback design. For the group of linear and non

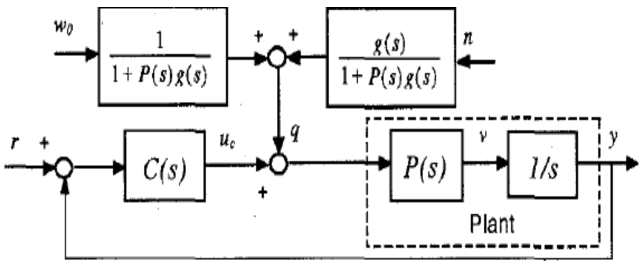


Fig. 3. Equivalent closed-loop block diagram with disturbance observer. [5]

-linear systems involving actuators as well as other exterior disturbances, this MATLAB toolkit is utilized to in the frequency-domain and generates three types of controllers. G. Cheng comprehensively represents the procedure of designing the toolkit and an example of rotational/translational actuator (RTAC) system and the servomechanism of the hard disk drives. The applications of this toolkit are to be used in the designing and modelling of the servo system of hard disk drives for improve transient responses with point-and-shoot fast targeting in the hard disk drives.[4]

Since the idea of the disturbance observer was introduced, the concept is being used in the servo control systems of hard disk drives (HDDs) to make up for the unwanted disturbance of the system. A study was made in 1998 and shows that the disturbance observer model for the servo system of magnetic hard disk drives that have the rotary actuators improves the access time. The major setback of the disturbance observer design that is used traditionally is the rate of disturbance rejection is increased but in the exchange of increased amplification on high frequency noise and that will also affect the stability of the system. Without affecting stability of the system, the capability of compensation for the disturbance is improved with the help of proposed design of disturbance observer. The concept is to replace the constant gain of the controller in the traditional observer of the disturbance with the filter of first order. The comparison shows that the settling time

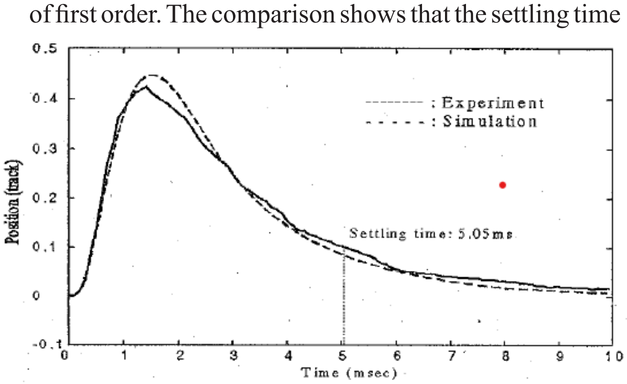


Fig. 4. Step response with advanced disturbance observer. [5]

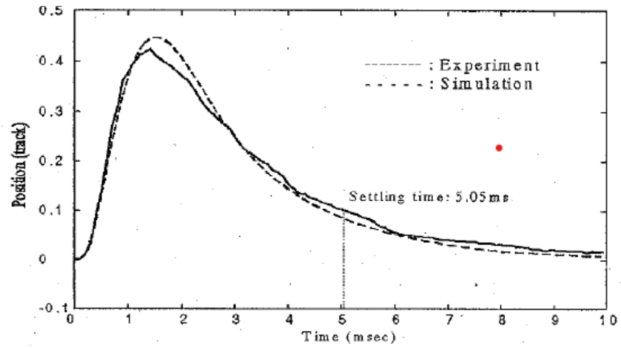


Fig. 5. Step response with conventional disturbance response. [5]

of the suggested disturbance observer is decreased by 40% and the noise attenuation of high frequency is increased by 10db. The simulations and experiments are in accordance with the claim that the performance of the hard disk drives is enhanced.[5]

In 2014, an investigation was made on the composite nonlinear feedback (CNF) that the performance of tracking of the servo systems of hard disk drives are enhanced by using the purposed CNF. The study discusses the idea of composite nonlinear feedback controller by using the filters having set point of arbitrary orders that has the centre point on the starting stage of the transient responses. The filters using set points are used to boost the performance with the help of shortening and rising the settling times of the system. Furthermore, filters are operated outside the feedback loop and thus they don't sacrifice the loop robustness. The proposed design shows how the set point response is enhanced by 10% in terms of settling time. And as the settling time is improved by 10% the transient response of hard disk drives is also improved.[6]

Nano-scale servo controls have various applications and head position controls of hard disk drives are one of them. Yuzu Ohta in its paper showed the improved results regarding the seeking control of hard disk drives. When the system is in higher frequency regions it has instable zeros and resonant terms and the response of the system shows a large overshoot whenever a conventional design of following control scheme is applied. To repress the overshoot and to reduce the settling time an enhanced configured control scheme is proposed and improved results are achieved. An improved seeking control is attained and thus the design enhanced the performance of the hard disk drive.[7]

Large areal density was required in hard disk drives as the growth in demand for storing large amount of data in hard disk drives is increased. A study is made by S. Yabui that introduces an idea of an enhanced method of behavior of convergence for adaptive feed-forward in HDDs. As the storing capacities of hard disk drives is increased the controls of head-position will be disturbed and it must be compensated to avoid bad positioning accuracy. The previous studies shows that the adaptive feed-forward control technique was modelled for the compensation of external disturbances but there were problems in the adaptive algorithm w.r.t convergence. To tackle this problem a method is developed of initial values for the control by using the design that is data-driven. This method is proven to enhanced the behavior of convergence for adaptive algorithm.[10]

A solution is proposed by Alireza Khayatia in which a controller is designed using nonlinear systems that guarantees the enhancement of transient response performance. The controller is using the backstepping controller that is adaptive backstepping controller in which the optimal values are reset. It is ensured that the margin to the error of tracking response is in accordance to the prescribed demands all the time and the rate of convergence is improved.[11]

Seeking time of hard disk drives have been improved with the help of feedforwarding control that uses the data of polynomial which is based upon first order hold (FOH). The algebraic expression ensures the constraints that involves the qualities of first order hold that recoup the errors caused FOH and there is no need of complex calculations. In traditional hard disk drive's control system zero order hold is used, now if we replace ZOH with FOH it significantly improves the seeking time and reduces the tracking errors.[12]

There are numerous disturbances that regresses the accuracy of position of head in the system. For the enhancement of the head-position system these disturbances must be compensated by the control systems. The proposed system of AFC in the algorithm of adaptive control corresponds to the damping factor that reduces the signal of position error and optimizes the control system in accordance of individual variation. The results have been verified and the proposed adaptive feed-forward system can regress the damping and eventually improves the transient performance of the system.[13]

There are numerous problems with the design that is efficient for the control actuators for hard disk drives (HDDs) servo systems. We need to get the set-point tracking with the transient response that we want but this process involves finding the controls method. Robert Schmid in his paper benchmarked the case study that involves the servo system of Hard Disk Drive's (HDD's) tracking control with the help of voice control motors (VCM) actuators. There is a method introduced recently about the linear tracking control and Schmid proposed the comparison in his paper with other linear and non-linear techniques from the literature. The method of NOUS linear state feedback control of two hard disk drives shows that the proposed method provided a better transient response than the PID controller. Not like the RPT method this proposed control linear method can be applied to all types of displacement values of the hard disk drives servo system for read and write R/W head. [14]

In the system of position of the head of the hard disk drives (HDDs), there involves a variable that is controlled which is called head-position signal and that signal is generated with the help of reading special patterns of magnets installed in the hard disk drives. The signal of head-position is obtainable as a signal of discrete time and the control system of the head-position is a sampled data control system. There is a theory proposed by William C. Mesiner that involves the estimation technique for vibrations that are unsettled in the control system of head-positioning and are quite undesirable. This proposal technique involves both the excitability and observability of mechanical vibrations of tracking seeking control. Amplitudes of oscillations that are quite unobservable the method of estimation is used. Simulations and results have shown that the track seeking control is greatly improved by the proposed design and has good estimated solutions for settling vibrations that are unobservable.[15]

The role of vibrations and dynamics becomes more and more prominent in the design of hard disk drives (HDDs) as the demand for storing the bulk amount of data becomes more and more relevant. However, there are several factors that plays the role in the limitations of the servo bandwidth that automatically limits the areal density growth of the hard disk drives. One of the factors is the resonant frequency of the assembly of the head actuator called the head actuator assembly (HAA). There are resonant modes that are caused due to the pivot flexibility and there is also a role head actuator assembly mass. When the hard disk drive is in the operational environment these vibrations modes obstruct the improvement of servo bandwidth that in the end obstructs the areal density growth of HDDs. Therefore, to counter this problem a study was made in Singapore that proposes the passive control technique that can dampen the vibrations of hard disk drives by representing the vibrations as a central rigid body that is affixed with the flexible beam. The study proposes the dual-mass dynamic absorber that is attached to the hollow space in the voice coil motor VCM of HDDs, and the absorber can effectively damp the key vibrations modes with the help of the VCM fork and the vibrations caused by the quasi-rigid of the actuators head in hard disk drives. With this method, the settling time of the track is drastically reduced and that can improve the transient response of the HDDs.[16]

High precision is one of the most important parts of the system that involves positioning control. The performances of hard disk drives (HDDs) are improved by using the actuators of different stages. A famous interdisciplinary research area for different actuator systems involves a control system of high precision position that is designed and optimized. Mostly single-stage actuator systems are used in control applications. Nowadays dual-stage actuators use Voice Control Motors (VCM) as a primary stage and piezoelectric actuator as a secondary actuator in the hard disk drives. However, second- stage actuators show improvements but not significant improvements, therefore, research is being conducted to fabricate the tertiary actuator for triple-stage hard disk drives servo system. These tertiary-stage HDD actuators will help to achieve better bandwidth, track density, track speed, transient responses, and greater error minimization.[17]

The reading time of the data in hard disk drives (HDDs) should be reduced because not only the higher density is in demand but to access the data as quickly as possible is also in demand. Therefore, there is also demand of higher rate of transfer of data. Eguchi investigates the relationship between damping, natural frequency feed forward waveform input and the track- seek control of transient vibrations. The vibrations of head actuators of hard disk drives are designed having transient vibrations in the focus. If the 1 degree of forward (DOF) system is defined as algebraic system expression of function of time and the transient response is solved with the help of Duchamel's integral repeatedly. At the initial and terminal instances of the transient responses are generated and the amplitudes of transient responses are depended on the lowest orders of derivation of non-zero polynomial. The results concludes that damping ratio reduces the transient vibrations for the 4th and 6th order algebraic expressions and not for 5th and 7th order of expression. As the transient vibrations are reduced simulations showed that the required model of vibrations head actuator improved the performance of hard disk drives (HDDs).[19]

A technique was model for a control system by Y. Hattori. A control system for multi-rate in which the holding ranges are not equivalent to sampling intervals. The multi-rate law of control is extended with the help of newly parameters and the sample output of the system is maintained, also the ripples caused in the steady state are maintained to zero using these newly introduced parameters so that they can be chose independently of the sample output. The results have shown that the response of the hard disk drive is improved and transient response becomes more effective.[20]

An important parameter for better performance of hard disk drives is track access time. Due to stiffness of the pivots and the masses of the head actuator assembly the resonances of the HAA are major problem. Sheng Zeng discussed that if the waveform is picked out properly and the time intervals of seeking pulse waveform are deployed then quick access time can be attained. Simulations have showed the effectiveness of the technique and the results are verified through extensive calculations and testing.[21]

C) Research Gap

In the modern era, hard disk drives are one of the most important devices that are used to store data. Hard disk drives become one of the most common devices and are found in homes and industries to storing data purpose. Consumers demands a more compact hard disk drives (HDDs) device with bulk data storing capacities. Research by C. Du shows reset control techniques for the servo systems that contains actuators of dual-stage in hard disk drives (HDDs). This type of actuators consists of voice coiled motor (VCM) as a first stage and Piezoelectric transducer as the second stage actuator. This problem is considered as DISO problem. The study shows the modelling of two optimal reset controllers for VCM and PZT and the elements were combined with the help of structure of decoupled master-slave method. In traditional HDDs the base linear systems are used but with this model discrete-time reset law is solved by using Riccati equations. The performance of HDDs is significantly improved and the simulations and experiments have shown that the track seeking performance of the HDDs of the hard disk drives is also enhanced.[8]

In the last decade, based upon the storage capacity, access time and miniaturization huge improvements have been in hard disk drives although the working principle of HDDs doesn't change. Control systems of head positions control of hard disk drives for read/write (R/W) and it uses adaptive control called MRAC that integrates the PID algorithm in the control system. The demand is to correctly aligned the head of read and write of hard disk drives so that during the operations a proper track is maintained. In the MATLAB environment a MRAC that involves the PID algorithm was modelled that is called the MRAC PID controller. This controller was integrated with the control loop of the model. Simulations are run in the MATLAB environment and the results concluded shows significant enhancement in responses of the system of R/W position of head within the chosen range of adaptive gain.[9]

As we are moving forward in time, the track misregistration of hard disk drives is decreasing and the track density is increasing to meet the demands of the customers, but that doesn't come easy as it brings challenges to the servo mechanism system. There is a technique called anti-wind-up (AW) that is improved is proposed for the hard disk drives that contain a dual-stage actuator system and in this technique, the saturation of the amplitude is solved by the secondary actuator. The approach of secondary decoupling is used for controls of non-linear dual- stage actuator systems of hard disk drives. The compensators that the systems are using are AW compensators and they are modified by solving the optimization matrix of a linear inequality. The filter is used to further improve the anti-windup compensator with the help of a filter that robust the control methodologies with the help of simulations benchmarks of dual-stage actuators.18]

II. METHODOLOGY

The objective of this project is to design a friction compensator for servo control of hard disk drives (HDDs). The approach to achieve this objective is by feeding back the designed-based estimated friction forces into the voice coil motor (VCM) hence the frequency response between the read/write actuator head position and current in the VCM can be linearized. Our aim is to study servo control of hard disk drives (HDDs) under different voltages and observe the effect of different voltage inputs on the servo control. To achieve this, we will model pivot section of the actuator and derive a transfer function for the displacement of the actuator arm with respect to the voltage applied on the pivot of the actuator. A transfer function of the voltage control is also derived that is used to apply voltage on the pivot.

A very similar approach is proposed by Yan [31]. Yan used measured and simulated responses as a guide in both frequency and time domain. The designed a friction model of HDD iteratively and also confirmed the exactness of the hard disk drive measurements in accordance of this new friction model. By feeding the estimated friction into VCM they linearized the frequency response. Furthermore, they also calculated the over shooting in the time responses and compared the results with other voice coil motors without

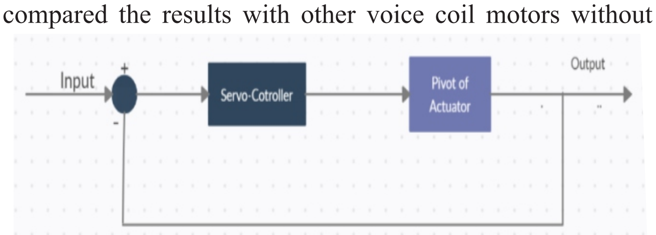


Fig. 6. Block diagram of the system

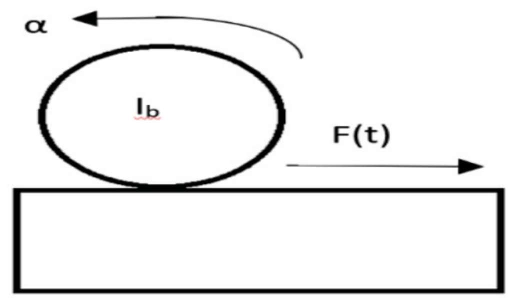


Figure 7: Pivot of actuator model

friction compensators. Yan concluded the effective frequency range is about 0-300 HZ.

Tomizuka [23] described the pivot torque bias due to non-linearities is approximately the difference between VCM current and the carriage angular acceleration. By linearization of VCM current and carriage angular acceleration. Tomikazu made an assumption that the plant dynamics are fixed in the subsequent design stage.

For our approach, we use the friction change as an input and the actuator arm displacement as an output. With this approach we can calculate the arm displacement of the actuator head with respect to friction. However, the friction can be increased with the passage of time and can have an impact on the performance of the actuator. With designed model the output which is the displacement of arm of actuator is fed back to input forming unity feedback.

A) Approach

For the modelling we will use the following approach

$$I_b\alpha - F(t) = 0 \quad (1)$$

The simple ideas of controls engineering are used in ordered to design the mechanics of pivot of the actuator using rotary motor.

where,

I_b = Interia of arm

α = Angular acceleration

Taking Laplace of equation (1)

$$X(s) = \frac{1}{I_b s^2} F(s) \quad (2)$$

The friction control equation can be written as:

$$F = u - F(t) \quad (3)$$

Taking Laplace of equation (3)

$$F(s) = \frac{i(s)\,(s+1)K}{s+10} \qquad (4)$$

Rearranging equation (2) and (4)

$$G(s) = \frac{X(s)}{i(s)} = \frac{(s+1)K}{I_b s^2 (s+10)} \qquad (5)$$

We use following assumptions for the above parameters:
$I_b = 3 \times 10^{-5}$ kgm^2
For representing the system in state space:

$$\begin{bmatrix} x \\ i \end{bmatrix} = \begin{bmatrix} I_b & 0 \\ 0 & -10 \end{bmatrix} \begin{bmatrix} x \\ i \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} f(t)$$

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x \\ i \end{bmatrix}$$

III. IMPLEMENTATION

There are two major software MATLAB and Simulink from where the data is derived for the implementation of the system. MATLAB is used for the data calculation and its verification. The software is preferred as the software has the built-in functions that helps in the designing of control system. MATLAB is a proprietary multi-paradigm programming language and numeric computing environment.

IV. RESULTS

A) System Characteristics:

Following are the characteristics of the system:

B) Comparison Between Step, Ramp and Parabolic Responses:

1) Step Response:

The system is tested against the step input and the results are shown in fig. 16 The system is stable, underdamped and there are oscillations in the system. The overshoot in the system is large which can be seen in the fig. 16. However, the steady state error in the system is significant from the step input.

Table 1. System characteristics table

System Characteristics	
The natural frequency (ω_n)	182.5452
Damping ratio (ζ)	0.0246
Settling time is (T_s)	0.8909 seconds
Peak time (T_p)	0.0172 seconds
%Overshoot	92.5616%

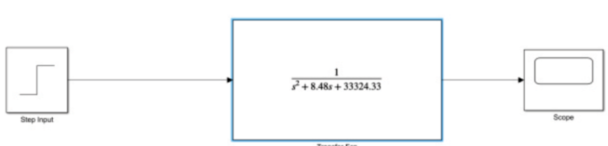


Fig. 8. Reduced transfer function

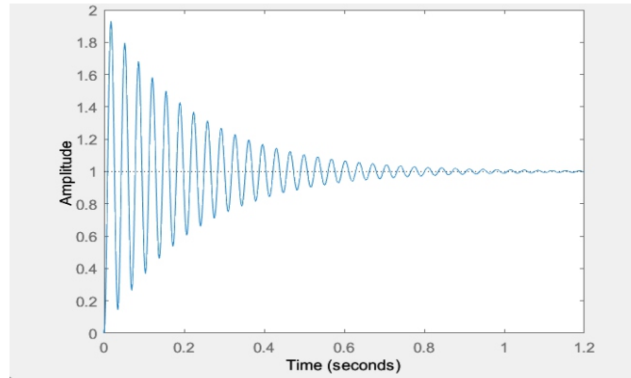


Fig. 9. Step input response

2) Ramp Input:

The system is tested against the ramp input and the results are shown in fig. 17. The system is unstable as it evident from the fig. 17. As the system is approaching to infinity the output of the system becomes undefined.

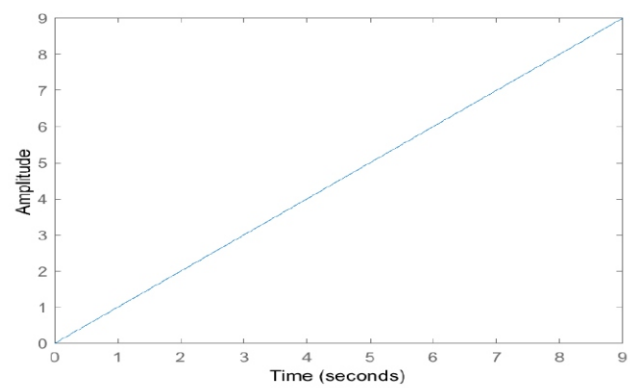


Fig. 10: Ramp input response

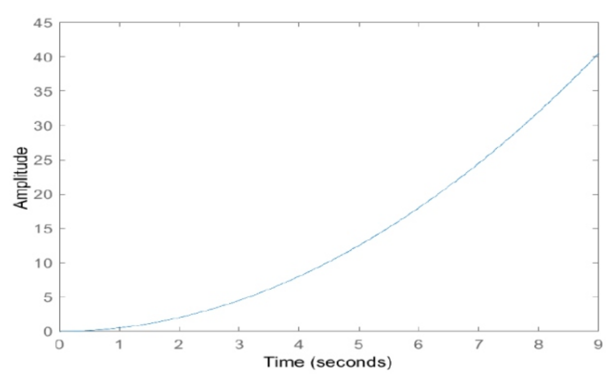


Fig. 11: Parabolic input response

$$G_1(s) = \frac{Ki}{s} + K_d s + K_p$$

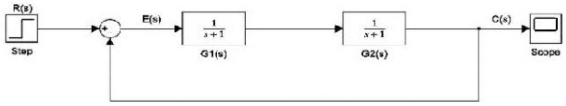


Fig. 12. Block Diagram of the PID controller

3) *Parabolic Input:*

The system is tested against the parabolic input and the results are shown in fig. 18 The system is unstable as it is evident from the fig. 18 that the system response is approaching infinity. As the system is approaching to infinity the output of the system becomes undefined.

From the block diagram of the PID controller in fig. 19:

$$G(s) = G_1(s)G_2(s) \quad (7)$$

While catering for P-controller

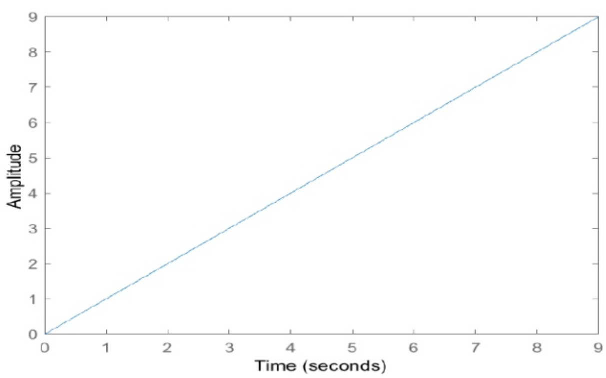


Fig. 13. Ramp input response

The transfer function of PID controller is below:

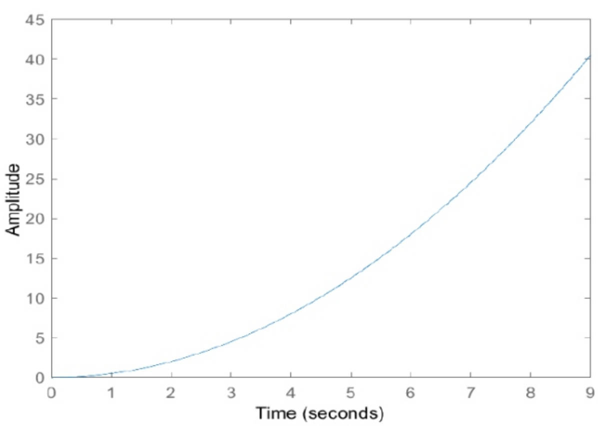


Fig. 14. Parabolic input response

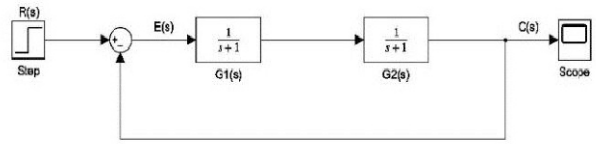


Fig. 15. Block Diagram of the PID controller

The transfer function of PID controller is below:

$$G_1(s) = \frac{Ki}{s} + K_d s + K_p$$

From the block diagram of the PID controller in fig. 19:

$$G(s) = G_1(s)G_2(s) \quad (7)$$

While catering for P-controller

K_i and $K_d = 0$

$$G_2(s) = \frac{1}{s^2+8.98s+33324.33} \quad (8)$$

For a P-controller, K_i and K_d are 0.
Multiplying eq (7) with G2(s)

$$G(s) = \frac{Kp}{s^2+8.98s+33324.33} \quad (9)$$

For unity feedback system we have
C(s)=E(s)G(s)
E(s)=R(s)-C)s)
C(s)=(R(s)-C(s))G(s)

$$T(s) = \frac{C(s)}{1+G(s)}$$

$$T(s) = \frac{G(s)}{1+G(s)}$$

Hence, by putting values of G(s) in the above equation:

$$T(s) = \frac{Kp}{s^2+8.98s+(33324.33+Kp)} \quad (10)$$

C) *Stability*

Following are the poles of the system to check the stability of the system.

TF =

$$\frac{1}{s\text{^}2+8.98\ s + 3.332e04}$$

Continuous - time transfer function

Poles =

1.0e+02 #

-0.0449 + 1.82491
-0.0449 - 1.82491

Fig. 16. System's poles

The result for the stability of the system is generated from the MATLAB code. As we know, for the stability of the system all poles should be in the negative or in the left half plane of the graph. Hence, from fig. 20 we can confirm that our system is stable as all the poles are in the negative or in the left half plane of the system.

Routh Table helps to find the stability of the system. This tool also helps us to evaluate the gain limits of P-controller. By using Routh table, we can find the range of K_p for which the system is stable.

s^2	1	33324.33
s^1	8.98	0
s^0	$\frac{-\begin{vmatrix} 1 & 33324.33+Kp \\ 8.98 & 0 \end{vmatrix}}{8.98}$	0

From row 3 we can see that the term 8.98(33324.33+Kp) should be greater than zero for the system to be stable.

$$8.98(33324.33+Kp) > 0$$
$$Kp > -33324.33$$

Hence, $Kp > -33324.33$ for the system to be stable.

D) Steady-State Error:

To find the steady state error of the system, MATLAB program is generated and the steady state error of the system is found by giving step, ramp and parabolic input to the system. As we know that the system type is 0, therefore the steady state error for ramp and parabolic inputs is infinity. The steady state error for step input is 0.5 which is noticeable from the graph of step input. By using PID controller for the system this error will be removed.

```
kp =

    1

essstep =

    0.5000

kv  -

    0

essramp  =

    Inf

ka  =

    0

essparabolic =

    inf

fx
```

Fig. 17. Steady-state error of the system against step, ramp and parabolic input

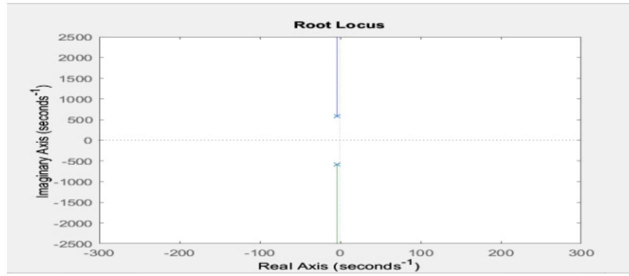


Fig. 18. Root locus of the system

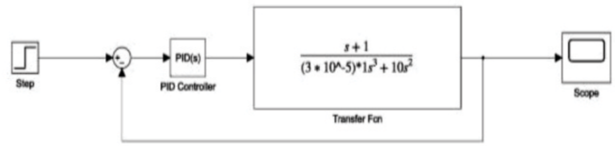


Fig. 18. Block diagram of system

E) Plotting Root Locus:

MATLAB code is used to plot the Root Locus of the system. From the fig. 22 it is observable that our system is stable as both poles of our system lies in the negative or in the left half plane of the graph, and as the system has no zeros the output decays at infinity.

V. CONTROLLER DESIGN

When the system is tested against the step input, an error of 0.5 is observed. When the system is tested against the ramp and parabolic input the error of infinity is observed. As the system is type 0 hence, it was bound to happen. However, an overshoot of 92% is observed when step input is given to the system. The Damping ratio of 0.02 is observed. Both of these characteristics are not desirable and a significant improvement is required to improve the system. As oscillations are observed in the system because the system is underdamped as the value of ζ=0.02. The issues with the system are its %overshoot, damping ratio and steady-state error. These characteristics can be significantly improved by using a PID controller. PID is a very useful controller by which we can improve the system without changing the system's characteristics.

A) PID Tuned Response

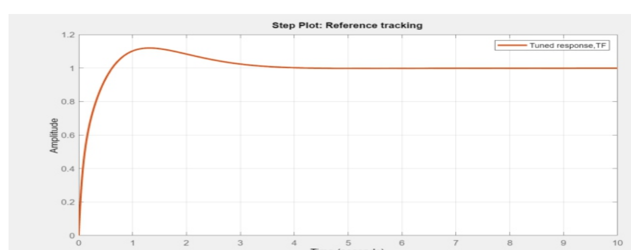
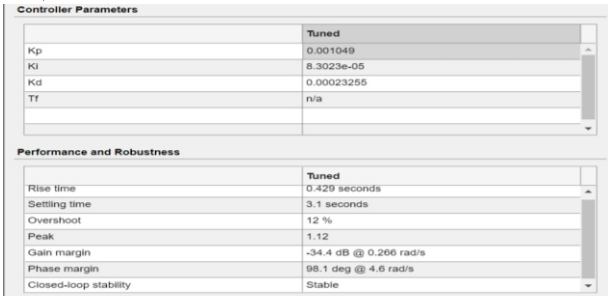


Fig. 19. PID tuned response of the system

B) PID Controller Parameters:



Controller Parameters

	Tuned
Kp	0.001049
Ki	8.3023e-05
Kd	0.00023255
Tf	n/a

Performance and Robustness

	Tuned
Rise time	0.429 seconds
Settling time	3.1 seconds
Overshoot	12 %
Peak	1.12
Gain margin	-34.4 dB @ 0.266 rad/s
Phase margin	98.1 deg @ 4.6 rad/s
Closed-loop stability	Stable

Fig. 20. PID Controller Parameters

C) Final Response of System:

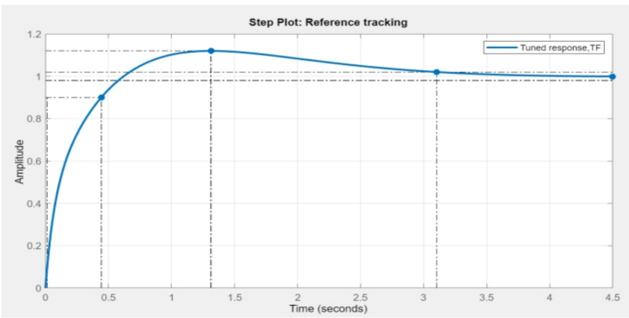


Fig. 21. System response graph

When the PID controller is incorporated with the system we can observed that the overshoot of the system is reduced and the steady-state error is reduced.

VI. CONCLUSION

There are various to improve the transient response of the hard disk drives, but most of the time friction caused by the actuator is neglected. Hence, by damping the actuator's pivot friction we can improve the position of read/write head of the actuator. The aim of this paper is to achieve a compensator of pivotal friction of the actuator of hard disk drives. To achieve this objective a newly proposed dynamic friction model is proposed. There are various ways to achieve this objective but the approach this paper is proposing is the linearization of current and position of

D) Bode Plot of System

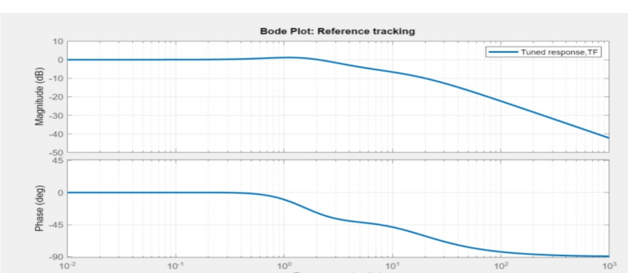


Fig. 22. Bode plot of the system

E) Comparison of Improved and Original Parameters:

TABLE II
Comparison of Un-improved and Improved Systems

Parameters	Un-improved	Improved
Steady-state error	0.5	0
Settling time	0.8909 sec	3.1 sec
Overshoot	92.5616 %	12% (desired)
Rise time	1.232 sec	0.429 sec

head of actuator. A system is modelled by considering the requirements of the problem. The system will feed the estimated friction into the VCM so that the position and current can be linearized. The designed system is 3rd ordered differential system. To simplify the problem the system is reduced to 2nd order. The designed and approximated model of the system is stable as all the poles of the system lies in the left half plane of the graph. The designed system is tested against the step, ramp and parabolic input and the results are observed. As the system is type 0 system hence, we will obtain some error when step input is given to the system. Ramp and parabolic input will show error of infinity. The system is underdamped, also the system has significant overshoot and steady-state error. To counter this a PID controller is incorporated with the system. The PID can help to achieve the desired response of the system. With the help of PID tuner in MATLAB values of K_P, K_I and K_D are evaluated and the results are generated. By using PID controller the %OS and steady-state error is significantly reduced, also the rise time of the system is reduced. Comparisons have been made between the improved and un-improved systems and we can conclude that our proposed modelled-based friction compensator is practically useful.

REFERENCES

[1] H. Li, C. Du, Y. Wang, and Y. Guo, "Discrete-time optimal reset control for the improvement of HDD servo control transient performance," in *Proceedings of the American Control Conference*, 2009, pp. 4153–4158. doi: 10.1109/ACC.2009.5160411.

[2] M. Chang and E. J. Davison, "Transient response improvement of the robust servomechanism problem for sinusoidal signals," in *IFAC Proceedings Volumes (IFAC-PapersOnline)*, 2009, vol. 6, no. PART 1, pp. 319–324. doi: 10.3182/20090616-3-IL-2002.0011.

[3] X. Chen and M. Tomizuka, "New repetitive control with improved steady-state performance and accelerated transient," *IEEE Transactions on Control Systems Technology*, vol. 22, no. 2, pp. 664–675, Mar. 2014, doi: 10.1109/TCST.2013.2253102.

[4] G. Cheng, B. M. Chen, K. Peng, and T. H. Lee, "A MATLAB toolkit for composite nonlinear feedback control - improving transient response in tracking control," *Journal of Control Theory and Applications*, vol. 8, no. 3, pp. 271–279, 2010, doi: 10.1007/s11768-010-0026-7.

[5] Y. Huang and W. Messner, "A novel disturbance observer design for magnetic hard drive servo system with a rotary actuator," *IEEE Trans Magn*, vol. 34, no. 4 PART 1, pp. 1892–1894, 1998, doi: 10.1109/20.706734.

[6] V. P. Pyrhonen and H. Koivisto, "On improvement of transient stage of composite nonlinear feedback control using arbitrary order set point filters," in *Proceedings - 4th IEEE International Conference on Control System, Computing and Engineering, ICCSCE 2014*, Mar. 2014, pp. 147–152. doi: 10.1109/ICCSCE.2014.7072705.

[7] Y. Ohta and H. Guo, "Seek Control of Hard Disk Drives Using Model Following Control: An Improved Result; Seek Control of Hard Disk Drives Using Model Following Control: An Improved Result," 2018.

[8] H. Li, C. Du, and Y. Wang, "Optimal reset control for a dual-stage actuator system in HDDs," *IEEE/ASME Transactions on Mechatronics*, vol. 16, no. 3, pp. 480–488, Jun. 2011, doi: 10.1109/TMECH.2011.2123104.

[9] B. Onyeka Ekengwu, C. Alison Ugoh, P. Chinaenye Eze, C. Patrick Ezeabasili, and L. Emmanuel Aghoghovbia, "Lakpan Emmanuel Aghoghovbia. Servo Position Control in Hard Disk Drive of a Computer Using MRAC Integrating PID Algorithm," *American Journal of Science, Engineering and Technology*, vol. 2, no. 4, pp. 97–105, 2017, doi: 10.11648/j.ajset.20170204.11.

[10] S. Yabui, T. Atsumi, and S. Nakamura, "Improvement of convergence behavior for adaptive feed-forward control with initial values design in hard disk drives," *Microsystem Technologies*, vol. 22, no. 6, pp. 1291–1298, Jun. 2016, doi: 10.1007/s00542-016-28498.

[11] M. Davanipour, A. Khayatian, and M. Dehghani, "Optimal adaptive reset control with guaranteed transient and steady state tracking error bounds," *J Franklin Inst*, vol. 354, no. 14, pp. 5949–5963, Sep. 2017, doi: 10.1016/j.jfranklin.2017.07.031.

[12] K. Igarashi, R. Igarashi, T. Atsumi, and S. Nakadai, "Feedforward control for track-seeking control in hard disk drive with sampled - data polynomial based on first-order hold," Mar. 2021. doi: 10.1109/ICM46511.2021.9385647.

[13] S. Yabui and T. Inoue, "Adaptive feedforward cancellation with damping control system in head positioning systems of HDDs," *Microsystem Technologies*, vol. 25, no. 12, pp. 4547–4558, Dec. 2019, doi: 10.1007/s00542-019-04465-5.

[14] IEEE Staff., *2014 European Control Conference (ECC)*. IEEE, 2014.

[15] T. Atsumi and W. C. Messner, "Estimation method for unobservable settling vibration of head-positioning control in hard disk drives," *Mechatronics*, vol. 23, no. 1, pp. 37–45, 2013, doi: 10.1016/j.mechatronics.2012.10.007.

[16] T. H. Yan and R. M. Lin, "Dual-mass dynamic absorber for the head actuator assembly in hard disk drives," *Mechanics Based Design of Structures and Machines*, vol. 32, no. 2, pp. 119–132, 2004, doi: 10.1081/SME-120030552.

[17] A. Hossain and M. A. Rahman, "Comparative analysis among single-stage, dual-stage, and triple-stage actuator systems applied to a hard disk drive servo system," *Actuators*, vol. 8, no. 3, Sep. 2019, doi: 10.3390/ACT8030065.

[18] S. Zhou and M. Tomizuka, *Enhanced anti-windup compensation for the dual stage hard disk drive systems with amplitude saturation*. 2016. doi: 10.0/Linux-x86_64.

[19] T. Eguchi, "On the relationship of natural frequency, damping, and feedforward acceleration with transient vibrations of track-seek control," *Microsystem Technologies*, vol. 22, no. 6, pp. 1257–1265, Jun. 2016, doi: 10.1007/s00542-015-2760-8.

[20] Y. Hattori, T. Sato, N. Araki, Y. Konishi, and H. Ishigaki, "Improvement in intersample response of HDD head," in *IFAC Proceedings Volumes (IFAC-PapersOnline)*, 2011, vol. 44, no. 1 PART 1, pp. 5286–5290. doi: 10.3182/20110828-6-IT-1002.00592.

[21] S. Zeng, L. Xu, R. Lin, and N. Guo, "Optimization of track seeking pulse waveform in hard disk drives," 2002. doi: 10.1109/APMRC.2002.1037696.

[22] T. Yan and R. Lin, "Experimental modeling and compensation of pivot nonlinearity in hard disk drives," *IEEE Trans. Magn.*, vol. 39, no. 2, pp. 1064–1069, 2003.

[23] R. Chen, G. Guo, T. Huang, T.-S. Low, and S. Weerasooriya, "Optimal multirate control design for hard disk drive servo systems," IEEE Trans. Magn., vol. 34, no. 4, pp. 1898–1900, 1998.

[24] P. Phyo San, "MODELING AND CONTROL OF HARD DISK DRIVE IN MOBILE APPLICATIONS," 2009.