TRACK-SEEKING CONTROL USING INPUT-SHAPING METHOD TO REDUCE VIBRATION IN HARD DISK DRIVE

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หัวข้อวิทยานิพนธ์	การควบคุมการค้นหาวงของตัวขับเคลื่อนหัวอ่านเขียนในจานบันทึกแบบแข็งด้วยวิธีการดัดแปลงสัญญาณขาเข้า
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บทคัดย่อ

ฮาร์ดดิสก์ไดรฟ์ใช้สำหรับจัดเก็บข้อมูลลงในดิสก์ โดยมีแขนกล (Actuator arm) ทำหน้าที่เคลื่อนหัวอ่านจากแทร็คหนึ่งไปยังอีกแทร็คที่ต้องการด้วยความรวดเร็ว และแม่นยำ ตัวแปรสำคัญในการควบคุมตำแหน่งของแขนกล ได้แก่สัญญาณที่ถูกต้อง และเวลาในการเข้าถึงของหัวอ่าน ซึ่งเป็นปัจจัยในการหาสัญญาณที่ถูกต้อง และมีความรวดเร็วในการเข้าถึง ในวิทยานิพนธ์นี้นำทฤษฎีดัดแปลงสัญญาณขาเข้าเพื่อใช้ในการปรับเปลี่ยนโครงสร้างของสัญญาณเพื่อลดค่าพลังงานกระตุ้นในช่วงที่เกิดการสั่นพ้อง โดยการใช้ฟังก์ชันพื้นฐาน คือการกำจัดแรงกระตุ้นของระบบ (Impulse response cancellation) สาเหตุของการสั่นสะเทือนโดยปรับเปลี่ยนโครงสร้างของสัญญาณจากการอ้างอิงที่มีความเร่ง ความเร็ว และตำแหน่งที่มีพลังงานคลื่นในช่วงความถี่ธรรมชาติเป็นตัวสร้างสัญญาณ สัญญาณที่การออกแบบอย่างถูกต้องจะเป็นสัญญาณที่ผลิตสัญญาณที่จะยกเลิกการสั่นสะเทือนจากนั้นผลที่ได้คือ ความนุ่มนวล และการสั่นสะเทือนจะหายไป ดังนั้นการสั่นสะเทือนควรจะลดลงโดยการใช้เทคนิคอินพุทเชฟปิง

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ABSTRACT

Hard disk drives are used to store information in its recording disk or media. An actuator arm is a mechanical part to move heads that fly over a track from any positions to the target track. Accuracy signal and access time are the key parameters to control the actuator seeking position. However, the accuracy signal and access time are adverted when the actuator moves fast, the system will create the residual vibration at the target track. The causes of vibration by changing structure of signal from reference signals with acceleration, velocity, and position with high power spectrum energy over wide frequency range including over the actuator's natural frequency are signal creator. The input shaping is convolved two signals at reference position signal and properly designed impulse signal. The impulse sequence produces an input signal to cancel residual vibration, then the result is smoother and the residual vibration is cancelled in actuator-arm movement. Hence the residual vibration should be reduced by the recommended input shaping.

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ACRONYMS, DEFINITIONS AND SYMBOLS

This thesis document uses the following set of Acronyms, Definitions and Symbols

HDD	Head Disk Drive
VCM	Voice Coil Motor
R/W Head	Read or Write Head
TMR	Track Misregistration
e.m.f	Electromotive force
ABS	Air Bearing Surface
TPI	Track per inch
BPI	Bit per inch
AD	Area Density
ID	Innermost Disk
OD	Outermost Disk
PES	Position Error Signals
PA	Power Amplifier
DAC	Digital to Analog Computer
ZOH	Zero-Order Hold
CL	Close Loop
PID	Proportional Integral Derivative
CNF	Composite Nonlinear feedback
LQG	Linear Quadratic Gaussian
LTR	Loop Transfer Recovery
EM	Electro Magnetic
$\hat{F}$	Magnitude of an impulse
ξ	Damping Ratio
ω_n	Natural Frequency
m	Mass
t	Time the impulse applies
L	Arm length
θ	Angle between current track and target track

CHAPTER 1
Introduction

Hard disk drives are used as data storage device which are for storing and retrieving digital information by rapidly rotating disks coated with magnetic material. The main component in hard disk drive consists of heads and disks. The head is arranged on a moving actuator arm to read and write data to the surface. When hard disk drive is powered up, the disks are spun to precisely regulated speed, and the head is allowed to move radially over the disk surfaced when hard disk drive retrieves or reads data. The limited movement within a very small range, self-regulating on the format of an air bearing surface between head and slider is allowed, is controlled. Accuracy or precise control of radial position of the head slider is controlled by the head positioning servomechanism. This servomechanism is a feedback system ,consisting of a sensing element that measures the displacement of the head, a servo motor and actuator, an amplifier, and a controller which is controlling the movement of the actuator [1]. The parallel movement of the head to disk surface is controlled by the torque that is generated by voice coil motor (VCM). The VCM actuator moves the read-write head (R/W head) between tracks, called track seeking mode, and regulates the position head, called track following mode. The head must be followed by the reference marks that define to the center of the track. The reference marks are created on the disk at the time of servo track writing. The current hard disk drives use a combination of classical control techniques and add the notch filters to reduce the effects of high frequency resonance modes. The switch of induced vibration can be removed by using input shaper. The reference track is not changed abruptly at the beginning of the seeking operation but a filtered reference command is injected into servo loop. This command generation scheme convolves the reference command with a sequence of impulse. The input shapers create a command signal that cancels the vibration produces by the system, which is applied. For the intro chapter, it is organized as following the motivation, scope in this research, and problem statement on this topic.

1.1 Motivation

This thesis is designed for track-seeking controller and using the input shaping technique to control the shape of model response. The method is offered to cancel the impulse on the model. When the head is still far from the target, the control system will put more impulse on the step response if the impulse magnitude and timing are designed properly. The response should be cancelled in the first impulse produce, so the controller can generate the new step response to reduce overshoot on system. The objectives of track-seeking in servo system control are requirements as list below:

1. The overshoot on the system should be less than 5%,

2. The steady-state error should be less than 3%,

3. The gain margin and phase margin of the overall design are greater than 6 dB and 30 degrees, and

4. The 2% of settling time is less than 3 ms.

As mentioned, these objectives will be constrained which the thesis will have to conquer and improve in each parameter compare to the previous system.

1.2 Problems Description

The servo system must be maintained the position of the R/W head on track near the center of the target track in the following mode. The track seeking mode is required to achieve fast and quiet head seek from one track to another track. The seeking and following mode are used for the different method, and the overall servo system should be involved with 2 switching modes. The scheme is referred to the switching control. Currently, the seeking mode has 2 sources of the resonance: the head actuator assembly, and the rotation speeds of disk. The issue on the head actuator assembly is caused by the pivot bearing, when the major design factor are limited the higher servo control bandwidth, so the resonance is found. The resonances are roused during the track seeking mode, when the control is transferred to the track following mode, and the vibrations result will increase the settling time. The rotational speeds of modern disk drives are progressively increasing, and hence the effects of the vibration of individual disk platters at their natural frequency are a significant contributing factor to track misregistration (TMR) in high-density disk drives. These resonances are driven primarily by internal windage excitation, and their behavior is dominated by the disk-material properties and geometry, but not by the spindle, enclosure, or structural design.

This research scope for seeking mode, called "Mode switching control of seek controller", has 2 majors on design;

1) Mode switching condition, and

2) Velocity profiles.

Track seeking mode is contained the transition from the seeking to the following mode and switching between tracks, so that requires are fast, smooth, and minimize the residual vibration. The vibrations may exacerbate the head settling, make the effective seek time longer, and cause acoustics problems. A settling mode is often used to smooth the transition between change seeking mode and following mode.

Track seeking is required to be as fast as possible. Meanwhile, the transition from the seeking to the following mode is also required to be smooth to minimize the residual vibrations. The vibrations may exacerbate the head settling, make the effective seek time longer, and cause acoustics problems. A settling mode is often used to smooth the transition. The velocity reference profiles should utilize the full power, including the back e.m.f. effects, for the velocity control of the head. The ideal case in the end of seek mode is achieved; the head velocity reaches zero, the head position is right above the target track center, and the VCM current is also zero.

However, the plant is more complicated. There have pivot friction, flexible cable bias, resonance modes, back e.m.f. effects, PA dynamics and saturation, electronic noises, and power supply voltage variations. Those make the pure inertia plant model over simplified. As a result, both the velocity profiles and the switching mode are designed by using rigid body model but do not yield optimal, and head settling.

1.3 Scope of the Thesis

This research proceeds to design track-seeking controllers for a single- stage actuator in hard disk drive (HDD) that should be given the high speed of seeking performance. The system is utilized the linear techniques to carry out the design of track seeking controlled for a Maxtor (model 51536U3) HDD [1] so the VCM is a single actuator. More specifically, this research is designed to the servo system by using the PID, notch filter, and input shaping to reference signal for reducing the residual vibration. However, the order will make our design more realistic, and our simulation results are done using the tenth order model. Of cause, the final implementation is carried out on the actual system.

1.4 Outline of the research

There are 5 chapters. Firstly, Chapter 1 introduces the hard disk drives, the servo system controller in HDD, the problem in servo system control for seeking mode, and the scope in this research. Next is Chapter 2 describes about the previous researches that concern about HDD and input shaping technique for learning in this project. The hard disk drives and servo system are described in Chapter 2 also. Then, Chapter 3 presents the modeling of HDD servo system; the controller design from a model and the result simulation for HDD is presented in Chapter 4. The last is Chapter 5, the conclusion and the proposed research projects.

CHAPTER 2

Hard Disk Drive System and Literature Review

In the recent five decades, The HDD servo systems have been playing an important role in the development of HDD technology. For increasing the HDD performance has provided a lot of challenges for the HDD servo system control. The HDD servo system have one of the most important parts is the track seeking in servo system which is utilized the residual vibration and get smooth signal.

In this thesis, that offers a tutorial on the control design of the HDD servo system, Input shaping controller, and input shaping is applied in HDD track seeking controller.

Besides, this chapter presents two topics; firstly HDD system and secondary will talk about input shaping method.

2.1 HDD System Overview

The HDD is important for all devices that need to storage data storage, such as computers, refrigerator, washer, to oven. HDD is a data storage device used for storing and retrieving digital information using rapidly rotating disks or platters coated with magnetic material. An HDD can retain when powered off. Data is read in a random-access manner, meaning individual blocks of data can be stored or retrieved in any order rather than sequentially. An HDD consists of one or more head rapidly rotating disks or platters with magnetic heads arranged on a moving actuator arm to read and write data to the surfaces. The physical structure of a HDD is described in Figure 2.1. Hard disk drives are contained;

1. Disk or Platter - The platter shaped like a record with a magnetic surface. Its job is to store the data contained on the hard disk drive. HDD can be installing one or multiple platters depending on the disk capacity.
2. Spindle motor - The spindle holds the platters together and the motor rotates the platters at their designated speed, which is measured in RPM.
3. VCM (voice coil motor) - This is designed to move the read/write head to the correct position on the platter to read/write the data. The VCM is the torque

producing component of the head positioning servomechanism. When current is passed through the coil of VCM suspended in the magnetic field produced by permanent magnets, a force (torque) is generated. The force (torque), proportional to coil current, can be controlled by changing the amplitude and polarity of the current.

4. Read/Write Arm - The read/write arm contains many "heads" on the end of the arm which are designed to float above the platter and read data from the platter.
5. Flex cable – This is designed to connect with PCB for control the VCM and input power electricity.

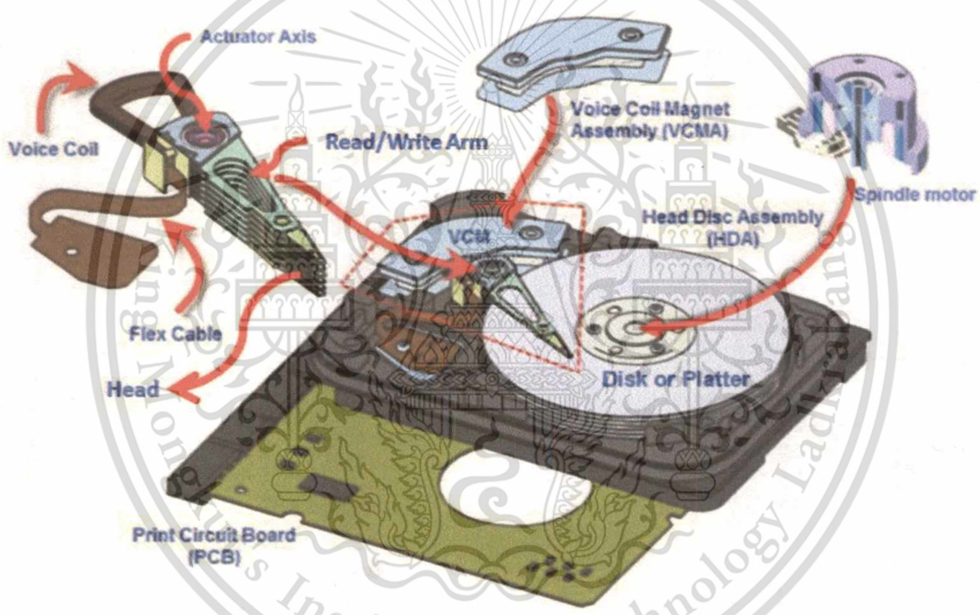

Figure 2.1 : The physical structure of a Hard disk drive [2]

In hard disk drives, a binary bit is stored in a tiny segment of the surface of a circular disk by magnetizing the medium coated on the surface with the help of an inductive head. In a majority of hard disk drives, the disk is spun at constant angular velocity by a spindle motor when the bits are written, and the head traces a circular path (Track) on the spinning disk. Saturated magnetization of the media is used and it is magnetized in one of the two possible polarizations. The transitions between two opposite polarizations in the magnetic medium can be sensed by a sensor held over the track of a spinning disk. Figure 2.2 show the magnetic bit transition. The disks are spun at the same speed during both writing and reading.

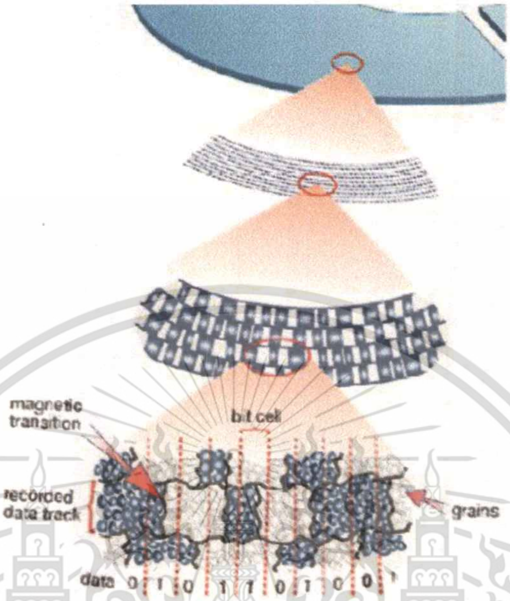

Figure 2.2 : Magnetic bit transition [3].

The read head and write head are fabricated on a single slider whose surface facing the disk is profiled such that an air bearing surface (ABS) is produced between the spinning disk and the slider. As a result, the slider is lifted and is not in contact with the disk. The separation between the slider and the spinning disk, known as the flying height, is maintained as constant as possible. Characteristics of the flying height depend on many factors such as profile of the slider surface, smoothness of the disk surface, rotating speed of the disk etc. Flying height has direct effect on the achievable areal density a key parameter defining the storage capacity and is equal to the number of bits recorded in unit area of the disk surface [4]. The common word that call in any calls are describe below:

1. Data Track- Concentric circular (not perfectly) tracks on the disk where binary bits are stored sequentially.
2. Track Pitch - Distance between two adjacent tracks.

3. Track Density - Inverse of track pitch, i.e., the number of tracks in unit length of radius of the disk. It is usually defined in units of Tracks per Inch (TPI)
4. Bit Density - Number of bits recorded per unit length of a track, defined in units of Bits per Inch (BPI).
5. Areal Density (AD) - Number of bits recorded per unit area of the disk surface. It is equivalent to the product of track density and bit density, and is defined in units of bits per square inch.

Demand for higher areal density has always been and still is the driving force behind the dramatic growth of the magnetic storage technology. Areal density in magnetic recording has grown by a factor of 5,000,000 over last four decades. The Figure 2.3 is shown the track, sector, and actuator.

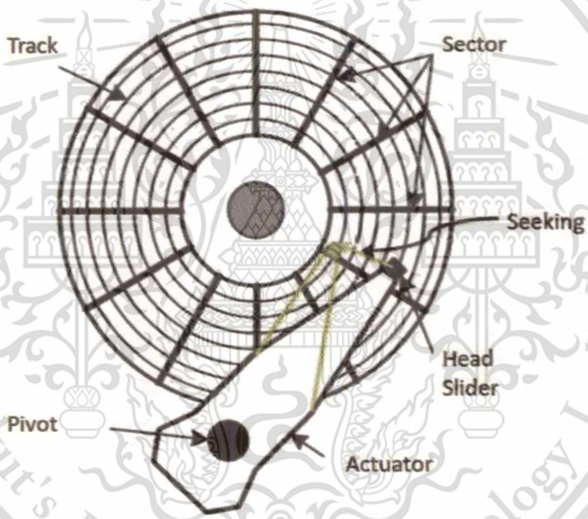

Figure 2.3 : Tracks, Sectors, and Actuator [5].

The access time is the time required to retrieve a block of data from the disk and is equal to sum of seek time and average latency, The servo system of the disk drive plays a vital role to increase the internal performance of HDDs. Some key internal performance factors are explained as follow.

1. Seek time is the amount of time required for the read/write heads to move between tracks, normally in an order of milliseconds. Average seek time is the average seek time from one random track (cylinder) to any other. Track-to-track seeks time, or

track switch time is the amount of time that is required to seek between adjacent tracks. This can be less than 1 ms. Full stroke seek time is the amount of time to seek the entire width of the disk, from the innermost disk (ID) to the outermost disk (OD).

2. Latency is the amount of time that the R/W heads must wait to reach the target sector. The average latency is half the time of a full disk rotation. The worst case happens when the R/W head has to wait a full revolution to reach the target track. E.g., the average latency is 5.6ms for 5400 RPM drive, 4.2ms for 7200 RPM, and 2.8ms for 10K RPM drive. Increasing the spindle speed will reduce latency. Faster spindle speed also increases data transfer rate in a given BPI.
3. Settling Time is time settle in HDD that ready to read or write data the settle time is lower than 0.1 ms.
4. Command Overhead Time is start when have command to HDD count until HDD process follow that command. The command overhead time is around 0.5ms.

During the process of seek from one track to another, the error between the position of the head and the destination track gradually becomes smaller However, it is practically impossible to bring the error to zero and maintain it there from that time onward. Even though the head positioning servomechanism tries to make the head follow the center of a track while reading or writing data, it is practically not possible to make the error zero. So the end of a seek process does not imply zero position error. In fact, track seeking is assumed to come to an end if the position error remains less than some pre-specified limit for few consecutive samples. The limit is typically 15% of the track pitch before a reading operation is allowed, and 10% of track pitches for seeking prior to writing data. This is a major difference from the typical definition of settling time in control system step responses. In HDD servo mechanism, the error must be less than 10% (writing) or 15% (reading) of a single track irrespective of the number of tracks traversed by the seek operation. In Figure 2.4 is show the Time Response Specifications for both track seeking and following.

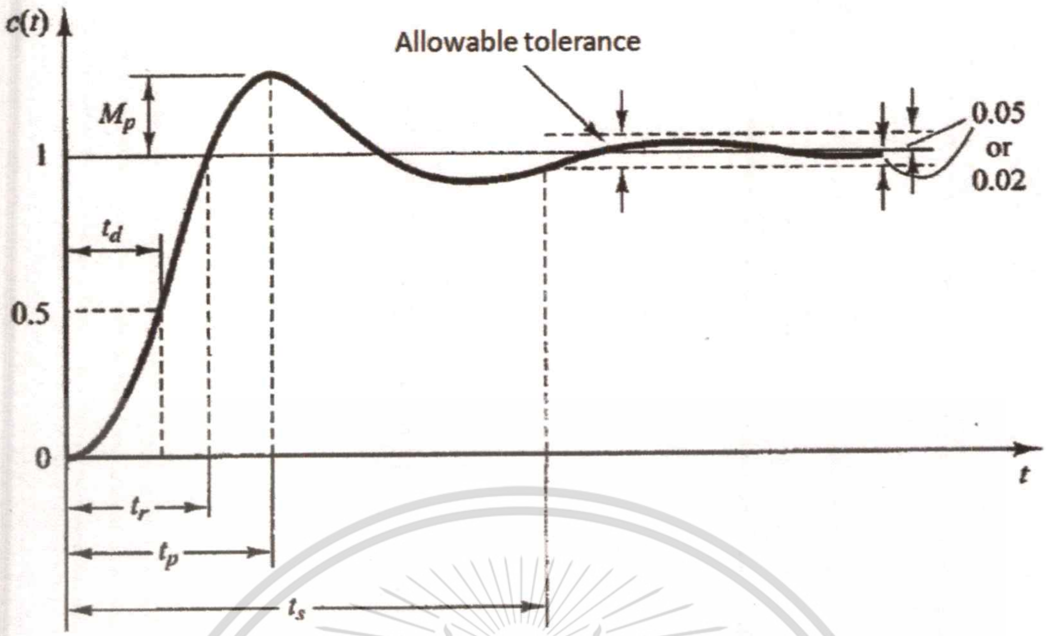

Figure 2.4 : Transient and Steady-State Response Analyses [6].

When a HDD is powered up, the disks will be spun to a precisely regulated speed and the heads are allowed to move radically over the disk surfaces. Limited of the head movement can move with vertical with a very small range, self-regulating by the format of an air bearing surface (ABS) between the head and slider is allowed. Accurate and precise control of radial position of the head slider is done by the head positioning servomechanism. This servomechanism is a feedback system consisting of a sensing element that measures the displacement of the head, a servo motor and actuator, an amplifier, and a controller controlling the movement of the actuator. In the early generations of HDD, the controller used to be implemented using analog electronics but all modern drives come with digital controller.

The position of the read/write head is controlled by a closed loop servomechanism that uses the feedback signal generated by decoding the information written on the disks. There are two modes of operation for this control loop firstly moving the head from one track to another track in shortest possible time, and secondly regulate the position of the head such that the relative offset between the head and the track-center is as small as possible. The first of these modes is known as Track Seek while the second mode is called the Track Following. The track seeking and following on HDD servo system is showed in Figure 2.5.

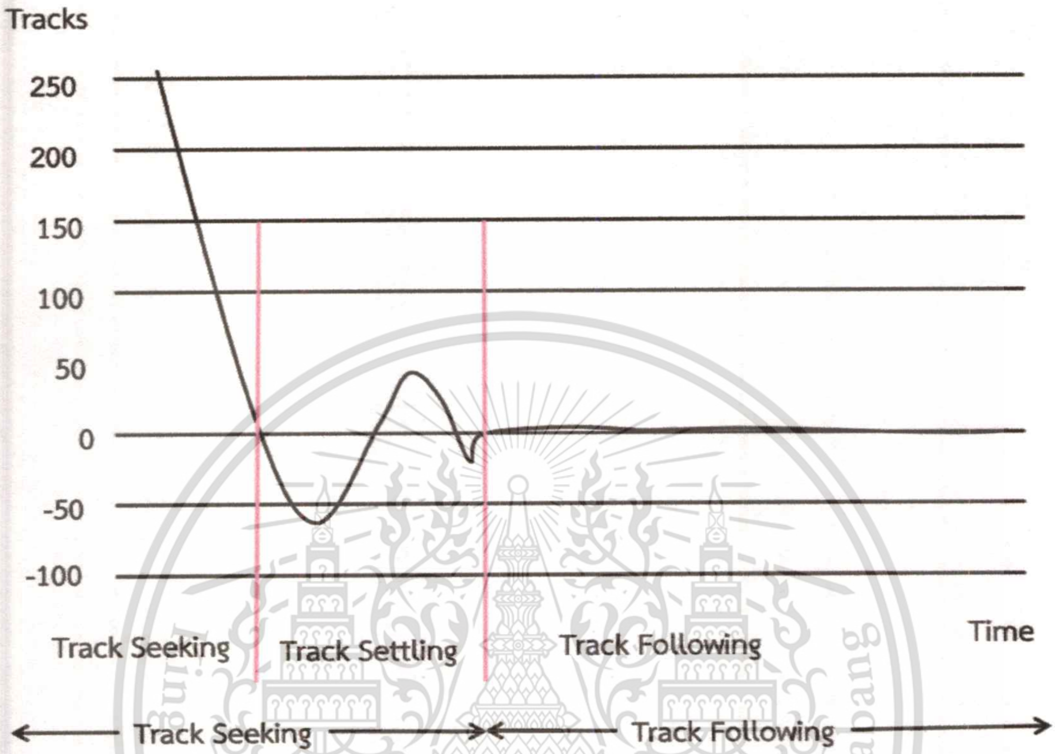

Figure 2.5 : The track seeking/following on HDD.

Design objectives of these two modes of operation are significantly different. Besides, there must be a smooth transfer between the two modes. It is impossible to meet the specifications of both modes using a single control law. Two controllers can be made to produce desired performances if each is designed and tuned independent of the other. However, while designing and implementing such controller, special attention must be paid to ensure that sudden change in the amplitude of control signal does not occur at the time of switching between modes. Sharp discontinuity in the control signal excites the lightly damped resonances of the actuator. Occurrence of such jerk increases the time it takes to settle and, therefore, must be avoided.

The trend in hard disk design is towards smaller hard disks with increasingly larger capacities. This implies that the track width has to be smaller, which leads to lower error tolerance in the positioning of the head. The controller for both tracks seeking and following has to achieve tighter regulation in the control of the servomechanism for accurate move to the destination track.

2.1.1 Hard disk drives servo system

The servo system is consists of two main points the spindle motor servo system and the actuator servo system there are real-time embedded systems. The disks rotate at a constant speed and the actuator moves over the disk surface. The task of the spindle servo is to keep the constant rotation speed. This research is mainly concern with the actuator servo system. The term of servo system on this research are refers to the actuator servo system unless otherwise stated.

The servo system calculates voltage command based on position error signals (PES) demodulated from servo sectors [7]. The voltage command is then fed through an analog power amplifier (PA) via a DAC. The DAC acts as a zero-order hold (ZOH). The output current of PA passes the coils of the VCM, and the resulted torque drives the actuator for track following and seeking. Figure 2.6 is shown closed loop (CL) head positioning servomechanism. The closed loop servomechanism uses the feedback signal generated be decoding the information written in these sectors.

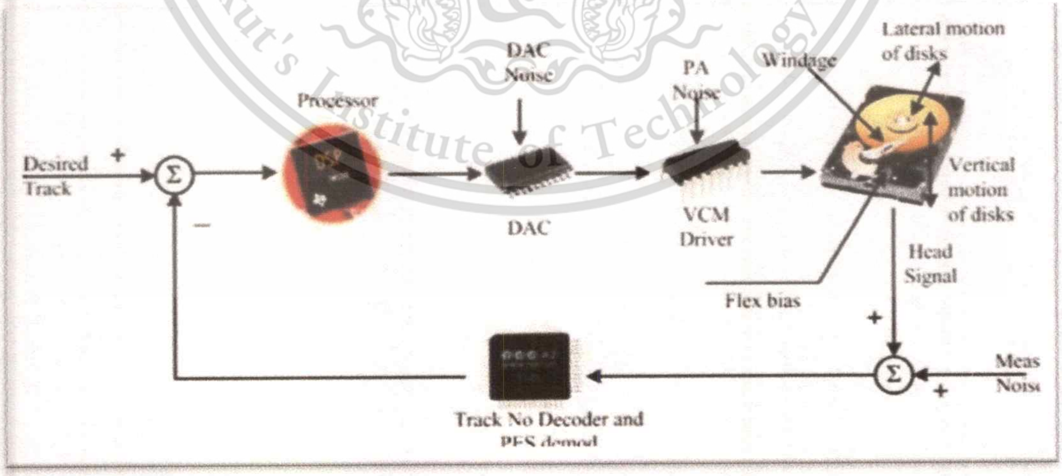

Figure 2.6 : Close loop Head Position on Servo system [2].

Track seeking is a mechanical process that involves using the actuator to physically move the read/write heads. Track switch time is important because switches to adjacent tracks occur much more frequently than random seeks. With a fixed mechanical design, servo system is responsible for reducing seek time and track switch time, without increasing acoustics noises [1]. Higher RPM and more sectors per track provide higher sampling rate. In general, higher sampling rate results in higher HDD internal performance. However, high RPM HDDs consume more power, generate more heat, and introduce more self-induced noises. High sampling rate servo system also demands faster DSP speed, and reduces the formatting efficiency. Trade-offs has to be made.

2.1.2 Research for the servo system on hard disk drives

Current HDDs servo system have developed a combination of classical control techniques, such as the proximate time-optimal control technique in the track-seeking stage, and lead-lag compensators, proportional-integral-derivative (PID) compensators in the track following stage, plus some notch filters to reduce the effects of high-frequency resonance modes. These classical methods can no longer meet the demand for HDDs of higher performance. To improve the performance of hard disk drive, various control method are applied from simple controller to advance controller to hard disk drives The hard disk drive is applied many techniques to reduce the effect of high-frequency resonance modes such as Composite Nonlinear Feedback (CNF) Control with Optimal Nonlinear Gain Tuning Methods [8]. Track seeking and track following are achieved for any seek length within ±20 µm with a single CNF control law. The optimal nonlinear gain tuning method is applied to design the CNF control law for an HDD servo system. Simulation and experimental results show that the HDD servo system has satisfied performance for both track seeking and track following. A method to cancel self-induced vibrations is presented by T. Semba [9]. The vibration effects are cancelled by adding a vibration model in the servo loop. Since the vibration gain and frequency vary due to the properties of the soft mounting mechanism, an adaptive technique is developed to adjust the model in real-time to ensure robustness [10]. Ishikawa used an accelerometer attached to the actuator to sense the pivot friction torque to compensate for the nonlinear friction effects [11]. White and Tomizuka attached an accelerometer on the disk drive base cover and implemented an adaptive feed forward control to reject external vibrations [11] [12]. Thus, many control approaches have been tried, such as the linear quadratic Gaussian (LQG) [13] with the loop transfer recovery (LTR) approach, control approach and adaptive control and so on [14]. Although much work has been conducted to date, more studies need to be done to achieve better performance in HDDs. The scope of this thesis is to provide a systematic treatment on the design of HDD servo systems for seeking controller. The emphasis is on HDD servo systems with a single-stage VCM actuator to provide faster response and robustness in track seeking. Most of the results presented in this thesis use the model HDD in Chan book [1] and run experiment for validate the result.

2.2 Input Shaping Method

Input Shaping is a control technique for reducing vibrations in any machines controller. The method works by creating a command signal that cancels its own vibration. That is, vibration caused by the first part of the command signal is canceled by vibration caused by the second part of the command. Input shaping is implemented by convolving a sequence of impulses, an input shaper, with any desired command. The shaped command that results from the convolution is then used to drive the system. If the impulses in the shaper are chosen correctly, then the system will respond without vibration to any unshaped command. The amplitudes and time locations of the impulses are obtained from the system's natural frequencies and damping ratios [15]. Shaping can be made very robust to errors in the system parameters. Input shaping is easier to derive and implement than time-optimal control schemes and does not require the feedback mechanisms of closed-loop and adaptive controllers. Input shaping is implemented in real time by convolving the command signal with an impulse sequence. This process is illustrated in Figure 2.7 with a step input and an input shaper containing two positive impulses.

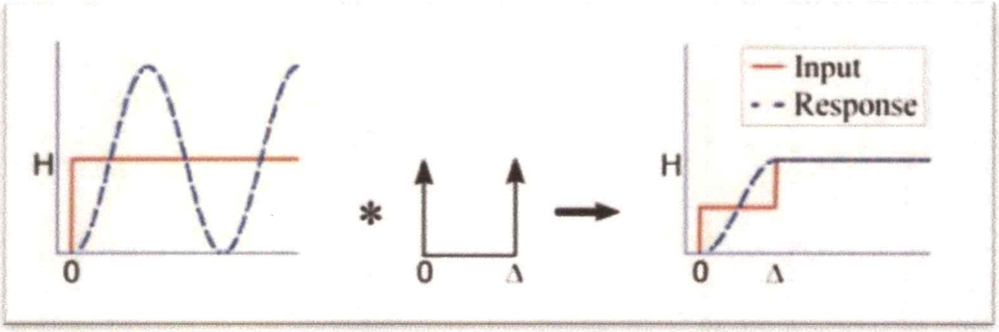

Figure 2.7 : Input Shaping a Pulse Input [14].

2.2.1 Impulse Responses Cancellation

For a one-degree-of-freedom unforced linear system with damping, the response to an impulse with magnitude $\hat{F}_1$ is given by

$$y(t) = \frac{\hat{F}_1 e^{-\xi\omega_n(t-t_1)}}{m\omega_n\sqrt{1-\xi^2}} sin\sqrt{1-\xi^2}\omega_n(t-t_1) \tag{2.1}$$

Where y is the response, ξ is damping ratio, ω_n is natural frequency, m is mass, and t_1 is the time the impulse applies. The response $y(t)$ above can be plotted as a solid line in Figure 2.8(a). Suppose there is another impulse $\hat{F}_2$ applied at time t_2 when magnitude and timing are designed properly, its response (the dash line in Figure 2.8(a)) would be canceled with that of the first impulse producing vibration-free response Figure 2.8(b). Instead of N impulse, it can solve by trigon equation (2.2) and shown that the amplitude of the sum of N impulse responses is given by

$$A = \sqrt{\left(\sum_{i=1}^{N} A_i cos\beta_i\right)^2 + \left(\sum_{i=1}^{N} A_i cos\beta_i\right)^2} \tag{2.2}$$

When

$$A_i = \frac{\hat{F}_i e^{-\xi\omega_n(t-t_1)}}{(m\omega_n\sqrt{1-\xi^2})} \tag{2.3}$$

$$\beta_i = \sqrt{1-\xi^2}\omega_n t_i \tag{2.4}$$

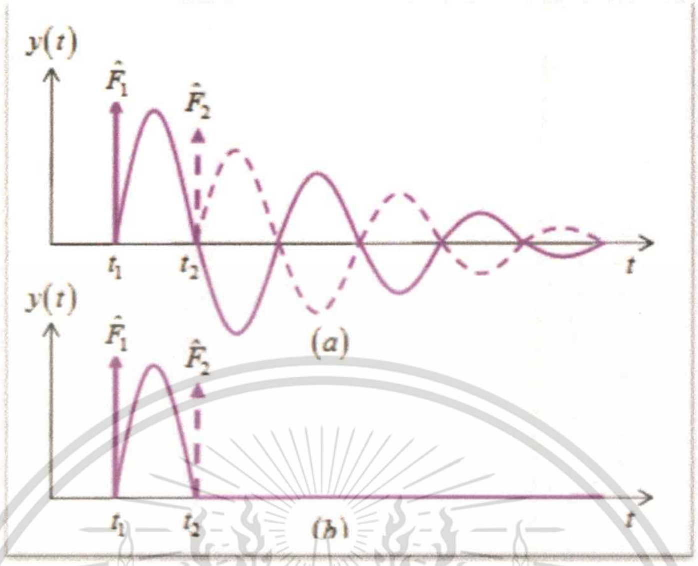

Figure 2.8 : System response of two impulses.

Since the system want to have zero vibration, setting equation (2.2) to zero and t to t_N results in two constraints

$$\sum_{i=1}^{N} \hat{F}_i e^{-\xi\omega_n(t_N-t_i)} cos\sqrt{1-\xi^2}\omega_n t_i = 0 \tag{2.5}$$

and

$$\sum_{i=1}^{N} \hat{F}_i e^{-\xi\omega_n(t_N-t_i)} sin\sqrt{1-\xi^2}\omega_n t_i = 0 \tag{2.6}$$

For two impulses, of which the first one applies at $t_1 = 0$ and its impulse magnitude normalizes to $\hat{F}_1 = 1$, $\hat{F}_2$ and t_2 can be found from the two equations (2.5-2.6) above.

$$\hat{F}_2 = e^{-\frac{\xi n}{\sqrt{1-\xi^2}}} \tag{2.7}$$

$$t_2 = \frac{\pi}{\omega_n\sqrt{1-\xi^2}} \tag{2.8}$$

2.2.2 Robustness to Uncertainties in Natural Frequency and Damping Ratio

Since the amount of residual vibration left depends on the accuracy of the natural frequency (ω_n) and the damping ratio (ξ) used to compute $\hat{F}_2$ and t_2 to increase the robustness of the input under variations of the natural frequency, we can set the derivatives, with respect to ω_n of (2.2) and (2.5) to zeros to obtain two more constraints

$$\sum_{i=1}^{N} \hat{F}_i t_i e^{-\xi\omega_n(t_N-t_1)} \cos(\sqrt{1-\xi^2}\omega_n t_i) = 0 \tag{2.9}$$

and

$$\sum_{i=1}^{N} \hat{F}_i t_i e^{-\xi\omega_n(t_N-t_1)} \sin(\sqrt{1-\xi^2}\omega_n t_i) = 0 \tag{2.10}$$

The constraints (2.9) and (2.10) are reduced the sensitivity of the constraints (2.2) and (2.5) to change in ω_n and can be used to solve for two additional unknowns t_3 and $\hat{F}_3$ of the third impulse. It can be shown that these constraints also apply to the robustness of the input under variations of the damping ratio. Letting $t_1 = 0$ and $\hat{F}_1 = 1$, we can compute t_2, $\hat{F}_2$, t_3 and $\hat{F}_3$ from (2.2)-(2.10) to be equation (2.11)-(2.14) respectively.

$$t_2 = \frac{\pi}{\omega_n\sqrt{1-\xi^2}} \tag{2.11}$$

$$\hat{F}_2 = 2e^{-\frac{\xi\pi}{\sqrt{1-\xi^2}}} \tag{2.12}$$

$$t_3 = \frac{2\pi}{\omega_n\sqrt{1-\xi^2}} \tag{2.13}$$

$$\hat{F}_3 = e^{-\frac{2\xi\pi}{\sqrt{1-\xi^2}}} \tag{2.14}$$

Increasing the robustness of the input shaping under variations of the damping ratio requires setting derivatives of (2.2) and (2.5) with respect to zeros. It turns out that this produces the same constraints as (2.5) and (2.6). To obtain even more robustness, we can continue to differentiate (2.5) and (2.6) to produce a new set of constraints for the fourth impulse and so on. However, more impulse so result could be robustness but in slower trajectory when implementing in the closed-loop system.

2.2.3 Research on input shaping method

While active controls have proliferated, passive controls, especially that use reference input shaping, are less well know. Meckl and Seering (1988) [16] reconstructed a bang-bang reference acceleration signal using ramped sine or versine basis functions. A cost function is penalized, weighing over removing the spectrum energy around the natural frequencies and approaching the bang-bang shape. Chatlatanagulchai et al. (2006) [17] applied this method with a two-link flexible-joint robot. Another shaping method was devised by Singer and Seering (1990) [18] Instead of shaping the reference acceleration, this method shapes the reference position directly by convoluting it with a properly designed impulse sequence. In theory, this impulse sequence is designed such that all impulse responses cancel each other producing vibration-free movement. Since the convolution with an impulse can be conveniently performed in real time, this method has received more attentions than the former method, even though its appearance is still rare.

This thesis applies the input shaping method to hard disk drives track seeking system. This servo system is made to follow any arbitrary angular position. It can be viewed as a model of actuator arm seeking movement only. A simple PID controller is used in the closed-loop system. The result is that the actuator arm can move with significantly less vibration when the shaped reference position is applied instead of an unshaped square-wave reference position.

CHAPTER 3
Research Methodology and Simulation experiment

Track seeking controller is designed for a single stage actuator in HDD that would give high-speed seeking performance and reduce the residual vibration. This thesis is design the servo systems by using the PID controller add the notch filter and use the parameter with Maxtor (Model 51536U3) [1], the special model we will add the input shaping method to the system for reducing vibration. Figure 3.1 is shown the Closed-loop-system block diagram with an input shaper.

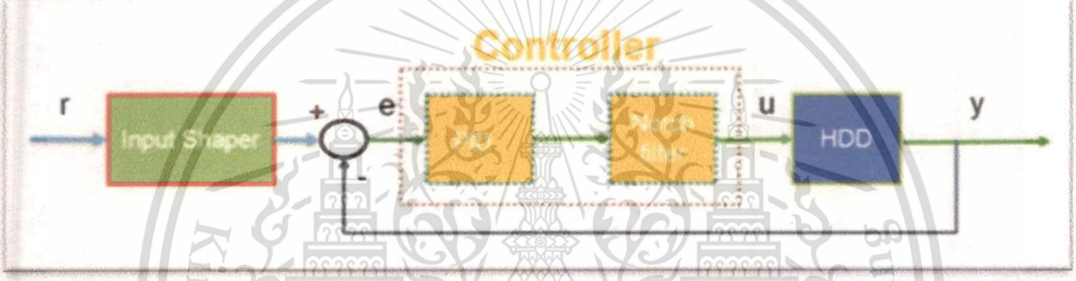

Figure 3.1 : Closed-loop-system block diagram with an input shaper.

The input shaper will generate the impulse sequence to convolve with the reference position to create a new reference signal that will cancel the residual vibrations.

This thesis focuses on the track seeking on servo control which is challenge design for reducing vibration when the head move any tracks to target track. The designed servo controller that has the following physical constraints and design specification:

1. The control input does not exceed ±3 Volts owing to physical constraints on the actual VCM actuator.
2. The overshoot and undershoot of track seeking are kept to less than 0.5 μm, the limit of our measurement device for large displacement.

3. The gain margin and phase margin of the overall design are, respectively, greater than 6 dB and 30°.

3.1 Hard Disk Drive Model

The simulation used Maxtor HDD (Model 51536U3)[1]. Figure 3.2 shows the diagram of a single actuator arm seeking from any tracks to the target track.

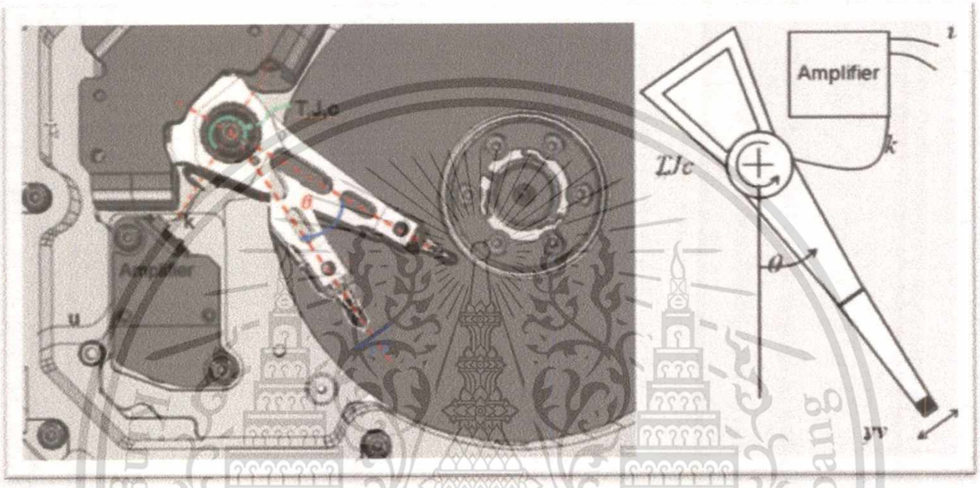

Figure 3.2 : Diagram of a head move to another track.

The relationship between head move from current track to target track is shown in equation (3.1) and (3.2) is equation on torque of system:

$$y = L\theta \tag{3.1}$$

$$T = k_1 u - k_2 \dot{\theta} \tag{3.2}$$

So that we can get the ODE equation (3.3):

$$\frac{J}{L}\ddot{y} + \frac{(c+k_2)}{L}\dot{y} + \frac{k}{L}y = k_1 u \tag{3.3}$$

Thus the control design model is $\ddot{y} + 282.6\dot{y} + 3.9933 \times 10^6 y = 2.35 \times 10^8 u$, where the term $282.6\dot{y}$ is the viscous friction part of $\tilde{T}_f$ and the term $3.9933 \times 10^6 \dot{y}$ is a straight line estimate of $\tilde{T}_c$. However, if consider the high-frequency resonance modes for more realistic model for the VCM actuator is shown in Figure 3.3.

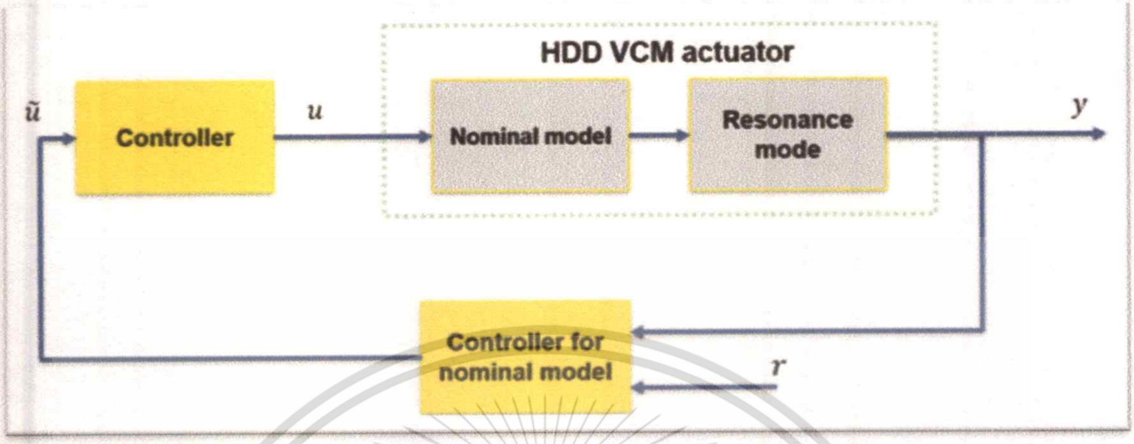

Figure 3.3 : The control system for hard drive VCM.

The nominal plant [1] is a tenth-order model for the actuator is obtained in equation (3.4) with the resonance mode is provided the equation (3.5) – (3.8).

$$G_v(s) = \frac{6.4013 \times 10^7}{s^2} \prod_{i=1}^{4} G_{r,i}(s) \tag{3.4}$$

$$G_{r,1}(s) = \frac{0.912s^2+457.4s+1.433 \times 10^8}{s^2+359.2s+1.433\times10^8} \tag{3.5}$$

$$G_{r,2}(s) = \frac{0.7586s^2+962.2s+2.491 \times 10^8}{s^2+789.1s+2.491\times10^8} \tag{3.6}$$

$$G_{r,3}(s) = \frac{9.917 \times 10^8}{s^2+1575s+9.917\times10^8} \tag{3.7}$$

$$G_{r,4}(s) = \frac{2.731 \times 10^8}{s^2+2613s+2.731\times10^8} \tag{3.8}$$

The controller had separated into 2 controllers firstly is Proportional-Integral-Derivative (PID) Control and secondary is notch filter. The PID control is classical technique used in industry [1] because it is easy and simple to design and implement. To be more specific, we consider the control system as depicted in Figure 3.4, in which

G_s is the plant to be controlled and K_s is the PID controller characterized by the following transfer function in equation (3.9)

$$K_{(s)} = K_p(1 + \frac{1}{T_i s} + T_d s) \quad (3.9)$$

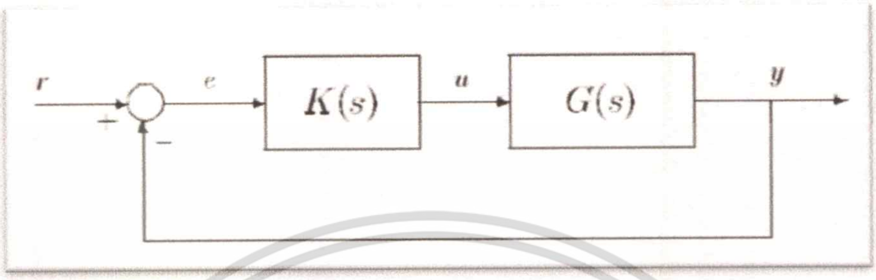

Figure 3.4 : The typical PID control configuration.

The control system is design is then to determine the parameters K_p, T_i, T_d such that the resulting closed-loop system yields a certain desired performance. The PID control has many method for tuning [16] such as, Trial and Error, Ziegler-Nichols Method, Cohen-Coon Method and others. In this thesis use Ziegler-Nichols Method [5] for finding the K_p, T_i and T_d. The K_{cr} = 0.0001, K_{cr} is a critical value that start from 0 to the output first exhibits sustained oscillations. The P_{cr} = 0.0788, is P_{cr} the system's output will oscillate with period. K_p= 0.6*K_{cr}, T_i = 0.5*P_{cr}, and T_d = 0.125*P_{cr}. After get plan from Ziegler-Nichols Method author add find tune for finding the best spec by multiply 1.2 to Ti and 50 to Td

The notch filter to minimize the effect of the high frequency resonance mode, this thesis will add a notch filter [1] to the plant to cancel as much as possible of the unwanted responses. The notch filter is provided in equation (3.10)

$$G_{notch(s)} = \left(\frac{s^2+238.8s+1.425x10^8}{s^2+2388s+1.425x10^8}\right) + \left(\frac{s^2+314.2s+2.467x10^8}{s^2+3142s+2.467x10^8}\right) + \left(\frac{s^2+628.3s+9.87x10^8}{s^2+12570s+9.87x10^8}\right) \quad (3.10)$$

The frequency response of the identified model is shown in Figure 3.5. The bode diagram is plotted when open loop system.

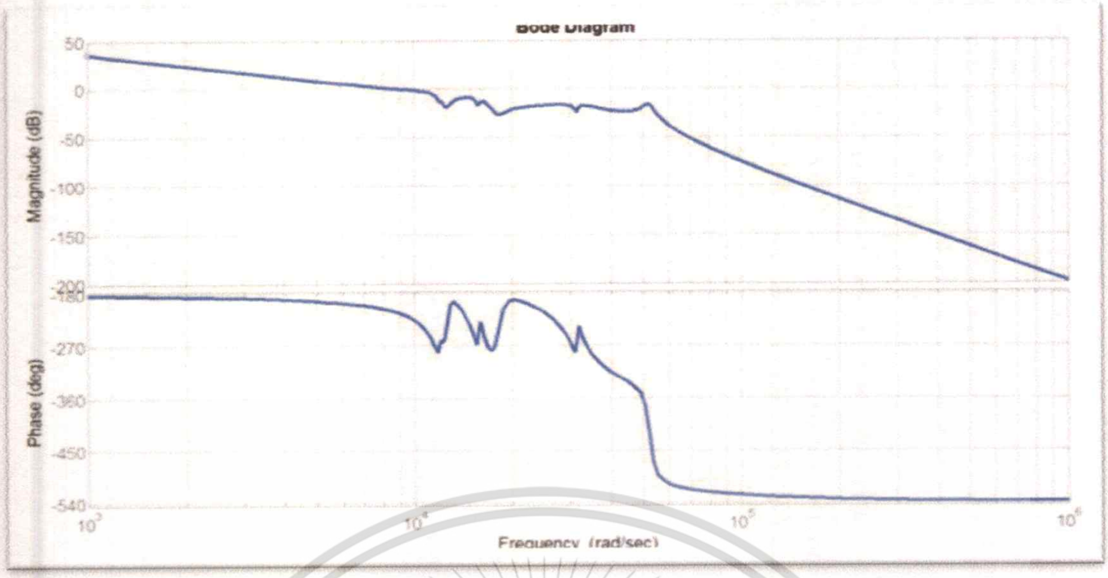

Figure 3.5 : The frequency response with resonance mode.

Normally, if the controller does not add any under-damped poles to the closed-loop system, the natural frequency and damping ratio still follow those of the plants so that can get from Figure 3.6. The simulation select natural frequency (ω_n) and damping ratio (ξ_n) from the poles are closely to zero poles: *(1.2e⁴, 0.0154), (1.58e⁴, 0.0292), (3.15e⁴, 0.028).* The impulse sequence is developed by applying the closed-loop system identifications using simple PID controller add an input shaping in Figure 3.1. The impulse sequence can be convolved with the reference position to create a shaped input that will cancel the residual vibrations.

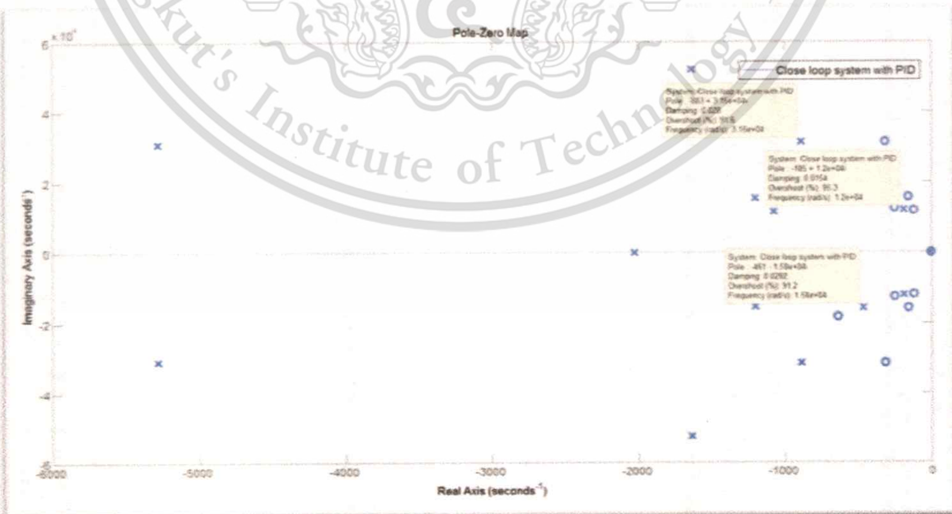

Figure 3.6 : Pole-Zero mapping in HDD close loop system.

3.2 Input Shaping of a Hard Disk Drive

The Input shaping is a powerful control techniques to reduce residual vibration including HDD. Normally, the close-loop Input shaping is applied in Servo system of HDD, the proposed to apply Input shaping in HDD due to control seeking process. In Figure 3.7 shows the position response of reader heads before and after applied input shaping. The key of Input shaping is applied to HDD due to be greatly reduced settling time. To precisely position the read/write head, a feedback controller is needed to control motion of the actuator arm.

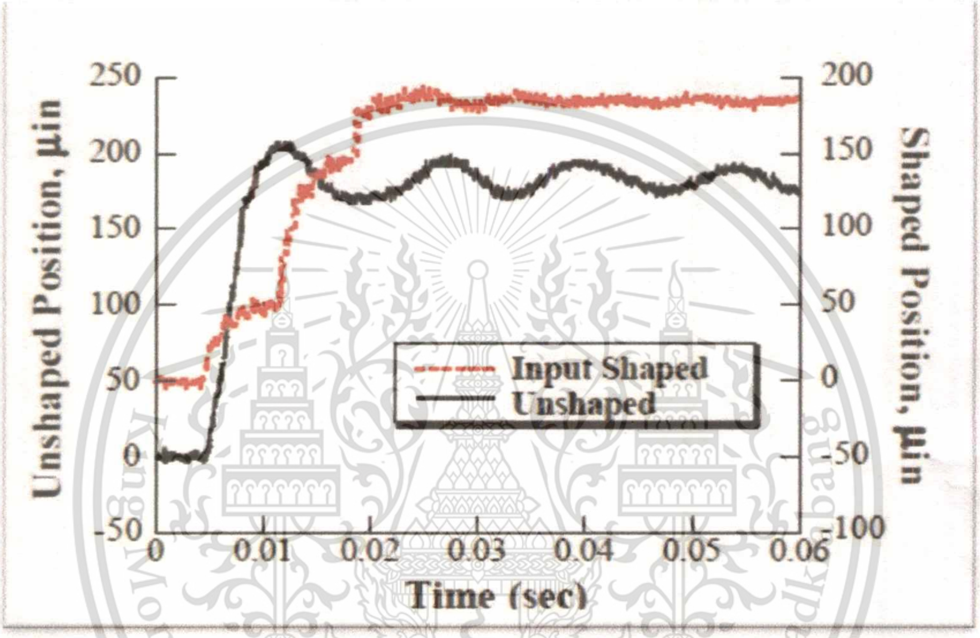

Figure 3.7 : Position response of heads with input shaping [19].

For track seeking, we need all impulse amplitudes to sum to one so that the shaped reference position will have the same end point as the original reference position. Therefore, in the three impulses case, the amplitudes and timing given in can be plotted as Figure 3.7, where K is equal equation (3.11)

$$K = e^{-\frac{\xi\pi}{\sqrt{1-\xi^2}}} \tag{3.11}$$

Figure 3.8 and 3.9 are shown the shaped step reference position, which is a result of convolving a step reference position r with the three-impulse sequence.

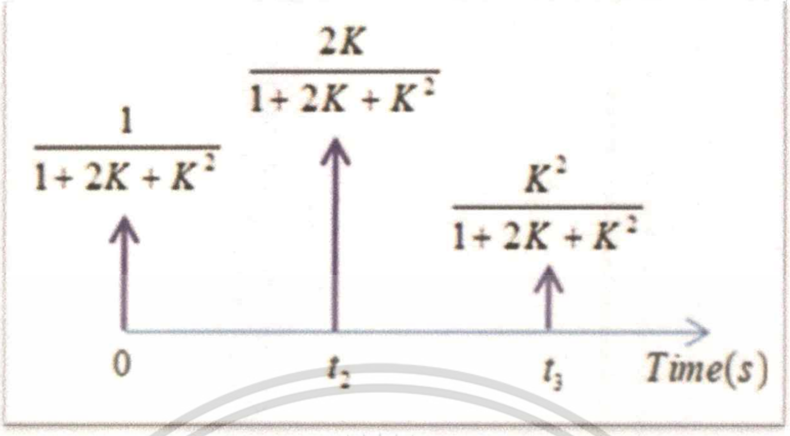

Figure 3.8 : Three impulses for adding the plan.

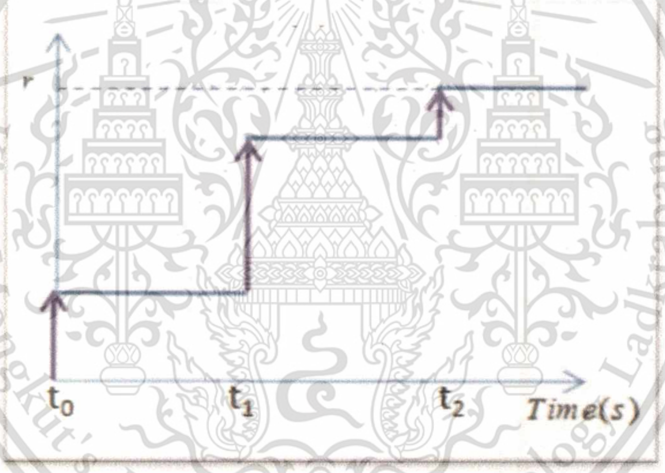

Figure 3.9 : Convolution of the impulse.

This also shows that even though using more impulses provides more robustness, the shaped reference position will reach the end point slower at a later time t_N where N is the number of impulses used. The step response is shown in Figure 3.10 after added input shaping is smoother than normal PID, and the overshoot is lower than PID. The gain and phase margin are shown in Figure 3.11 and 3.12.

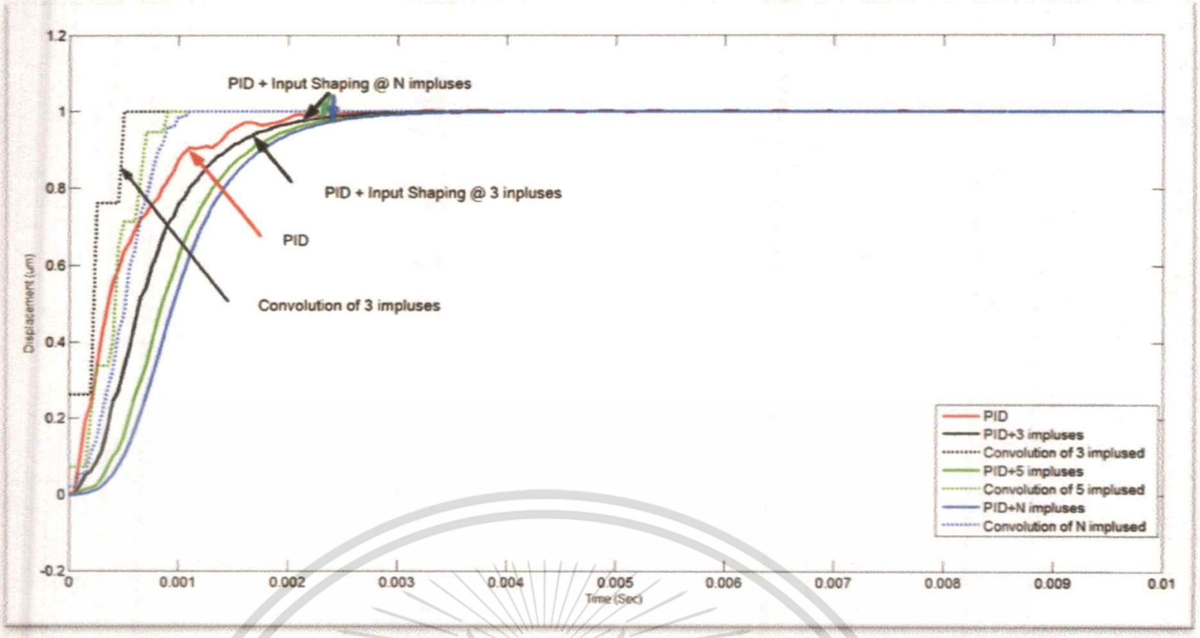

Figure 3.10 : Output response of PID and Input shaping.

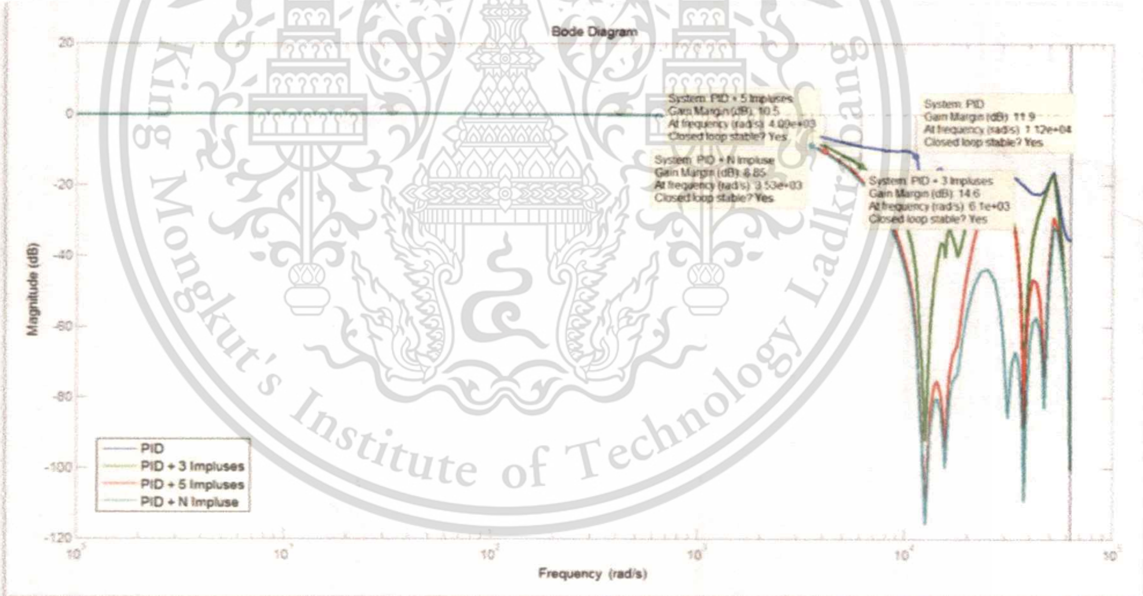

Figure 3.11 : Gain margin plot from bode diagram.

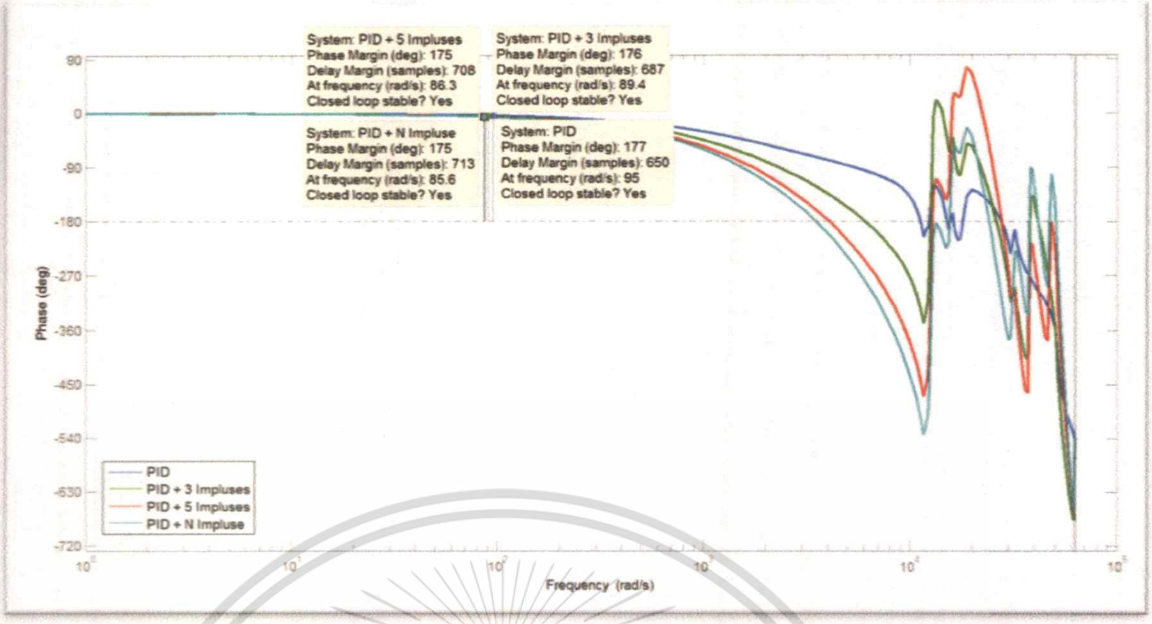

Figure 3.12 : Phase margin plot from bode diagram.

The simulation of time response is shown in Table 1. The time response is related to the number of impulses. If adding more impulse, the test time will be increased. The simulation result suggests to add 3 impulses for minimizing the robustness, overshoot, and to add the time response is not much. The overall result can meet motivation targets. Chapter 4 will show the experimental when run this method to HDD drives and author expected the result near the simulation result.

Controller/ Time response	Delay time (ms)	Rise time (ms)	Peak time (ms)	Maximum overshoot (um)	Settling time (2%)	Gain/Phase margin	Steady-state error (t=0.1 ms)
Target	3.00	-	-	0.01	-	>6dB/30Degree	0.03
PID	0.35	2.05	3.30	0.003	2.24	11.9dB/177Deg	0.0001
PID + Input Shaping 3 impluse	0.65	2.50	2.65	0.001	2.40	14.6dB/176Deg	0.0001
PID vs PID + Input Shaping 3 impluse	0.30	0.45	-0.65	-0.002	0.17	-2.70dB/1Deg	0.0000
PID + Input Shaping 5 impluses	0.85	3.05	3.05	0.001	2.45	10.5dB/175Deg	0.0001
PID + Input Shaping N impluses	0.95	3.15	3.15	0.001	2.55	8.85dB/175Deg	0.0001

Table 3.1 : The test time response.

CHAPTER 4
Experiment and Implementation

This chapter describes about experiment that is modified for applying the input shaping method to hard disk drive. This thesis uses the LABVIEW program for design the system connection devices, adding controller, and reading the input and output signals. The MATLAB is used for simulation. The equipment connections are shown in Figure 4.1.

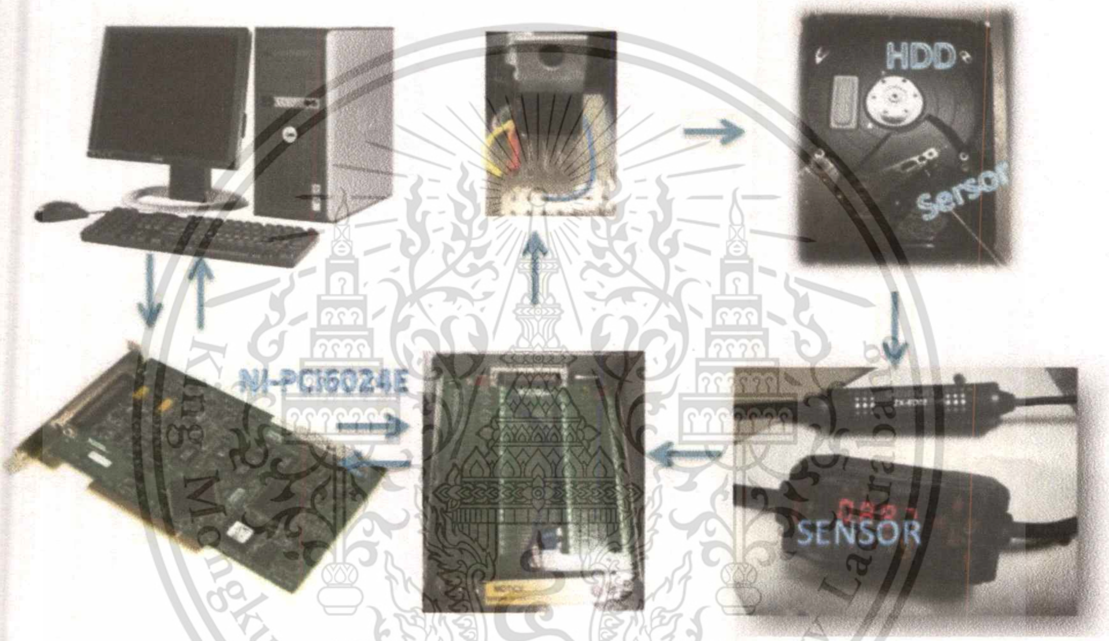

Figure 4.1 : The connection of the experimental device.

4.1 The equipment detail

The computer is used for controlling, commanding, and displaying the result by connect with NI PCI6024E card. The computer is installed the LABVIEW program on windows 7 professional OS. The computer station is shown in Figure 4.2

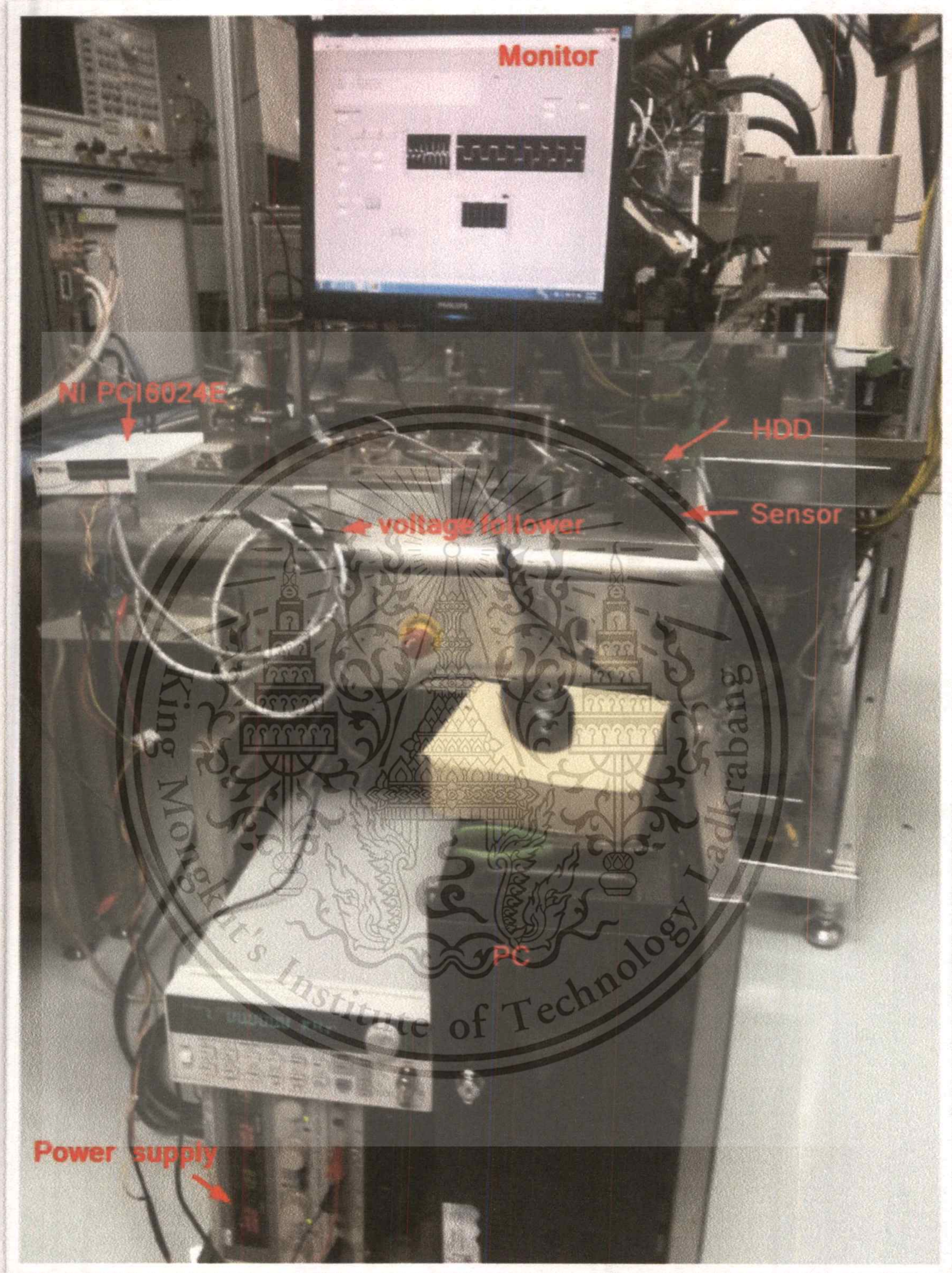

Figure 4.2 : Computer work station.

The NI PCI6024E card processes all command and transfers the signal to voltage follower circuit for control the hard disk drive. The NI PCI6024E has 2 cards; first card is installed inside computer for transferring and processing command, second card is connected with power supply for input the current to hard disk drive. Figure 4.3 shows the NI PCI6024E card, which connects with computer and Figure 4.4 shows the NI PCI6024E card, which connects with the voltage follower circuit for input current to hard disk drive.

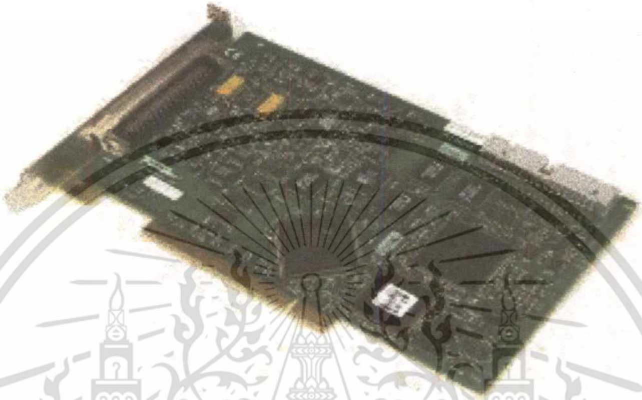

Figure 4.3 : The NI PCI6024E is installed inside computer.

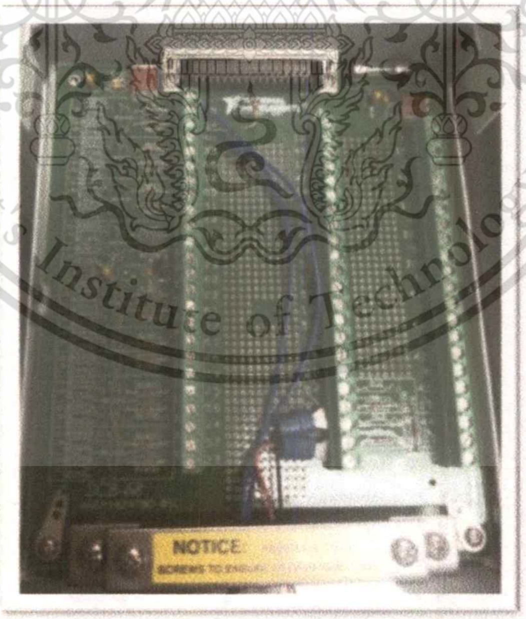

Figure 4.4 : NI PCI connects to voltage follower circuit.

The voltage follower circuit is amplifier signal because the signal from NI PCI60204E is not enough to control the hard disk drives. The Figure 4.5 shows the voltage follower circuit with gain equal 1.

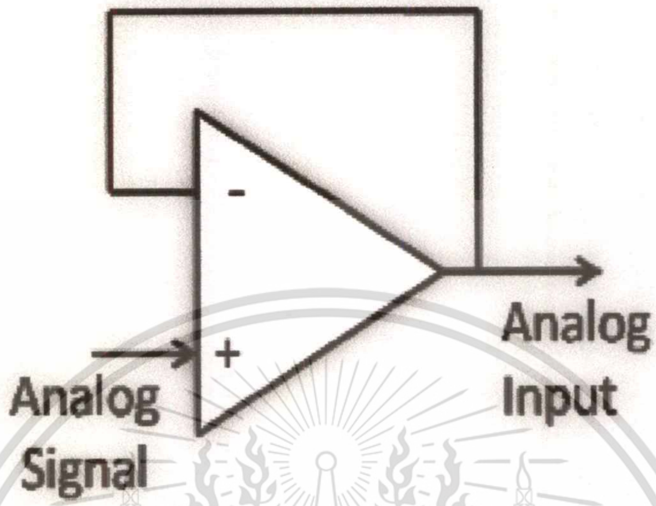

Figure 4.5 : The voltage follower circuit.

The Sensor on this experiment is recommended to use omrom X-ED02T [20] because the sensor measurement range is 0-2 mm, which has high resolutions scale. When signal inputs to Hard disk drives, the head will move and then the sensor will read the distance between head and sensor.

4.2 The method on experiment

The method on this experiment flow is shown in Figure 4.6. The Figure 4.7 shows the analog signals input and Figure 4.8 shows the analog signal reading from Hard disk drive and the unit is voltage. From the Figure 4.8 the signal is incomplete because the range is over sensor limit. Author uses trial and error to get the best input signal follow up in Table 4.1. The voltage that uses to find the system identification for driving the voice coil signal amplitude uses the sine wave, which amplitude is equal to 0.023 volt and offset 19.25 volt. The frequency input equal 0.1Hz in 10 sec. Then author puts the zero offset and sets normalize to the system for finding the hard disk drive system identification. The system identification is shown in Figure 4.9.

Variable	Value
Amplitude/Offset	**0.023 Volt / 19.25 Volt**
Frequency	**0.1 Hz.**
Sampling Rate	**100 sample/sec**
Time	**10 Sec**

Table 4.1 : Value for finding the system identification.

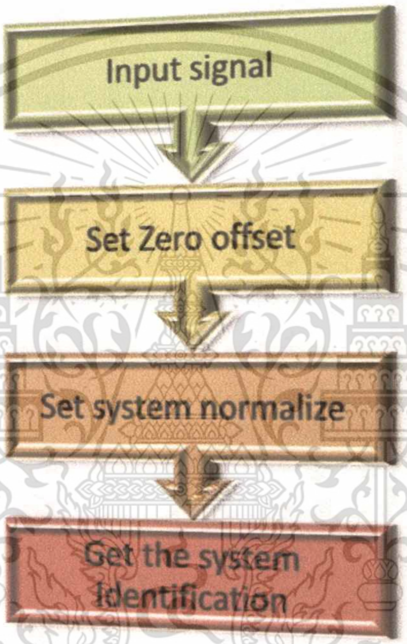

Figure 4.6 : The experimental flow.

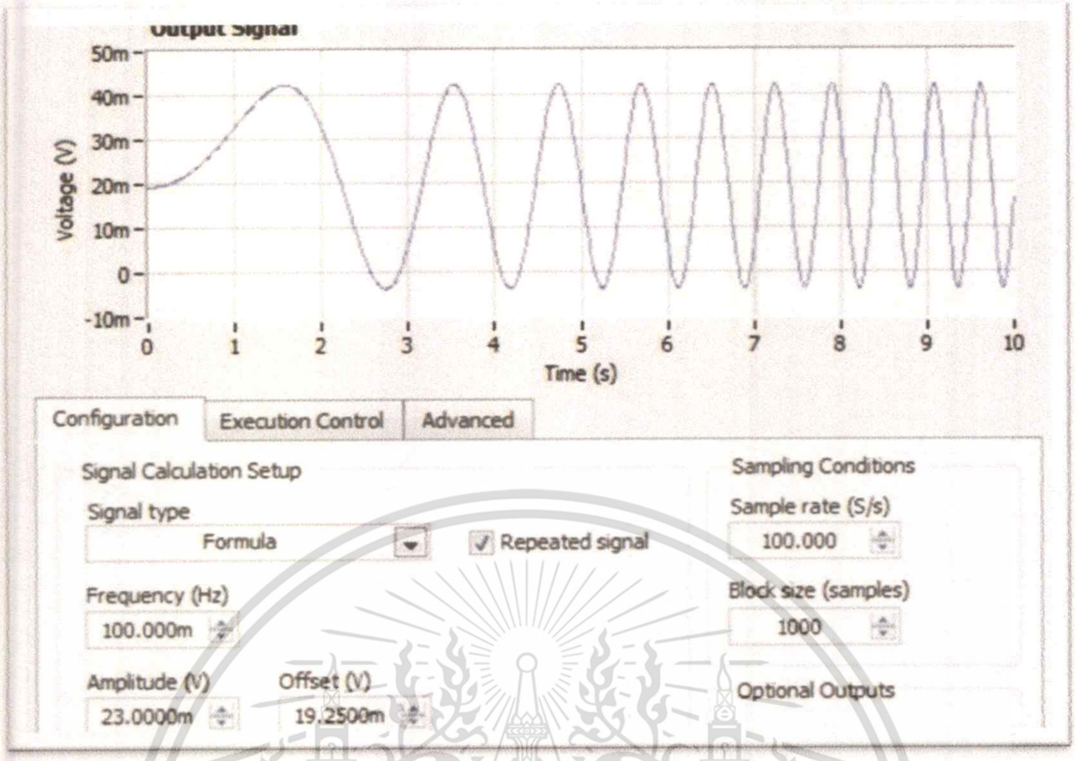

Figure 4.7 : The analog signal input.

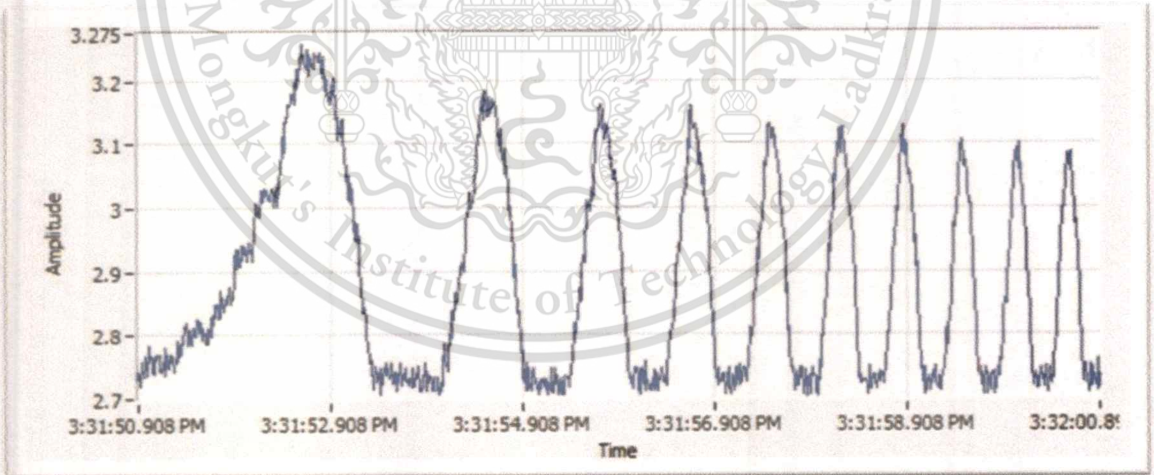

Figure 4.8 : The analog signal read from HDD.

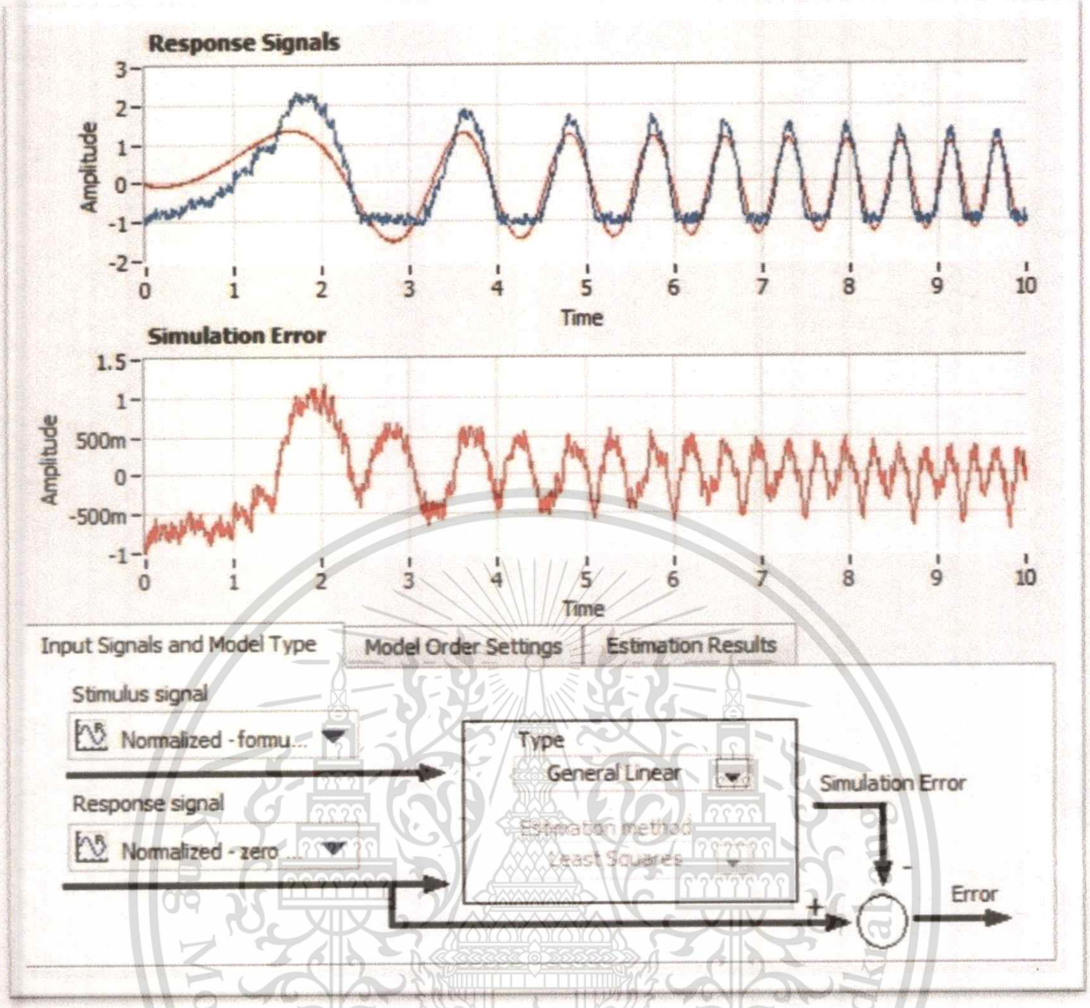

Figure 4.9 : The system identification on HDD system.

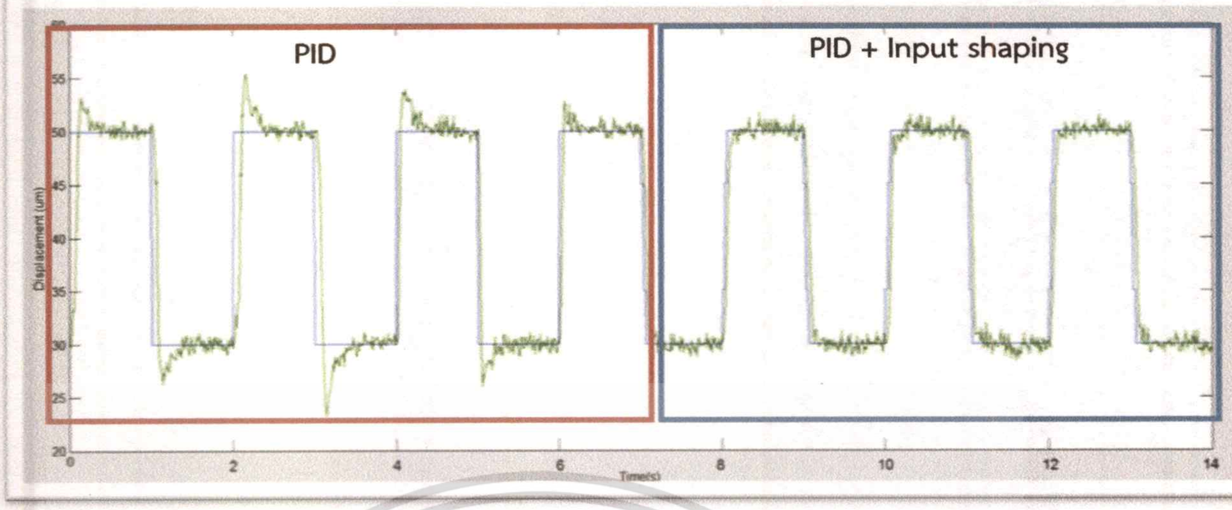

Figure 4.10 : Output responds between PID and input shaping with 3 impulses.

This system have 2 poles and zeroes so author will select pole that nearest the zero to get the natural Frequency (ω_n) = 314.1656, and Damping Ratio (ξ_n) = 0.0063. From LabView program. The circuit connection will be shown in Appendix. The system applies the simple PID controller and adds an input shaping method to convolute the reference position for canceling the residual vibrations. The Figure 4.10 shown the output responds compare between normal PID and input shaping with 3 impulses. The steps respond in picture they show the input shaping can reduce the overshoot significance. Chapter 5 will brief the conclusions and suggestions for the future research.

CHAPTER 5
Conclusions and Suggestions for the Future Research

The convolution between the reference position and the impulse designed by input shaping technique that cancelled the residual vibration. The result showed the head moved smoother than none shaping. The convolution was completed in real time. The arbitrary reference position was convolved with a sequence of 3 impulses in real time producing a shaped input that cancels residual vibration of the system. Base on the simulation result in Chapter 3 and Experimental in Chapter 4 are shown the input shaping method can implement to any machines that have vibration but adding some delay time on that system. The simulation result is shown the input shaping can cancel all vibration and look very smooth than PID. When the system try to implement the input shaping method into HDD the system have some residual vibration but overall result still meet motivation target.

There are many components and systems inside the HDD that are combined and the servo system is very small and important for HDD. It is the main controller which is used to control the R/W head. This thesis presented only track seeking system, movement of the head and measurement of the vibration when head is moving. Input shaping technique is applied to HDD (small portion to HDD development) so developer can use this technique to apply with new technology on HDD. This technique can be applied to dual actuator head or any systems which is suffering from vibrations during slewing. Nevertheless, this technique relies on the superposition principle of the linear system, no generalization over the nonlinear systems. Besides, the accuracy of the system's natural frequency and damping ratio is vital to the effectiveness of the technique.

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APPENDIX

Sensor spec: Amron ZX-ED02T

ZX-ED02T

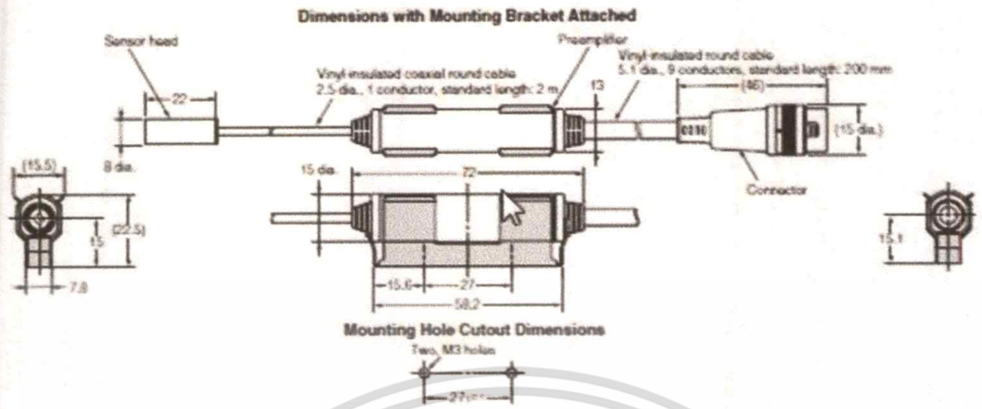

Figure Appendix 1 : ZX-ED02T

Sensor Heads

Model		ZX-EDR5T	ZX-ED01T	ZX-ED02T/ EM02T	ZX-EM07MT	ZX-EV04T	ZX-EM02HT
Measurement range		0 to 0.5 mm	0 to 1 mm	0 to 2 mm	0 to 7 mm	0 to 4 mm	0 to 2 mm
Sensing object		Magnetic metals (Measurement ranges and linearities are different for non-magnetic metals. Refer to Engineering Data on See Engineering Data (Typical).)					
Standard reference object		18 × 18 × 3 mm		30 × 30 × 3 mm	60 × 60 × 3 mm		45 × 45 × 3 mm
		Material: ferrous (S50C)					
Resolution *1		1 µm					
Linearity *2		± 0.5% F.S.					± 1.0% F.S. *5
Linear output range		Same as measurement range.					
Temperature characteristic *3 (including Amplifier Unit)		0.15 % F.S./°C	0.07% F.S./°C				0.1% F.S./°C
Ambient temper-ature	Operating *4	0 to 50°C (with no icing or con-densation)	-10 to 60°C (with no icing or condensation)				-10 to 200°C (with no icing or condensa-tion)
	Storage *4		-20 to 70°C (with no icing or condensation)				

<table>
<tr><th colspan="3">Ambient humidity</th><td colspan="6">Operating and storage: 35% to 85% (with no condensation)</td></tr>
<tr><th colspan="3">Insulation resistance</th><td colspan="6">50 MΩ min. (at 500 DC)</td></tr>
<tr><th colspan="3">Dielectric strength</th><td colspan="6">1,000 VAC, 50/60 Hz for 1 min between charged parts and case</td></tr>
<tr><th colspan="3">Vibration resistance (destruction)</th><td colspan="6">10 to 55 Hz with 1.5-mm double amplitude for 2 h each in X, Y, and Z directions</td></tr>
<tr><th colspan="3">Shock resistance (destruction)</th><td colspan="6">500 m/s^2, 3 times each in X, Y, and Z directions</td></tr>
<tr><th colspan="3">Degree of protection (Sensor Head)</th><td>IEC60529, IP65</td><td colspan="4">IEC60529, IP67</td><td>IEC60529, IP60 *6</td></tr>
<tr><th colspan="3">Connection method</th><td colspan="6">Connector relay (standard cable length: 2 m)</td></tr>
<tr><th colspan="3">Weight (packed state)</th><td>Approx. 120 g</td><td colspan="2">Approx. 140 g</td><td>Approx. 160 g</td><td>Approx. 130 g</td><td>Approx. 160 g</td></tr>
<tr><th rowspan="5">Materials</th><th rowspan="4">Sensor Head</th><th>Case</th><td>Brass</td><td>Stainless steel</td><td colspan="2">Brass</td><td>Zinc (nickel-plated)</td><td>Brass</td></tr>
<tr><th>Sensing surface</th><td colspan="5">Heat-resistant ABS</td><td>PEEK</td></tr>
<tr><th>Tightening nut</th><td colspan="2">---</td><td colspan="2">Brass (nickel-plated) (except ZX-ED02T)</td><td>---</td><td>Brass (nickel-plated)</td></tr>
<tr><th>Toothed washer</th><td colspan="2">---</td><td colspan="2">Iron (zinc-plated) (except ZX-ED02T)</td><td>---</td><td>Iron (zinc-plated)</td></tr>
<tr><th colspan="2">Preamplifier</th><td colspan="6">PES</td></tr>
<tr><th colspan="3">Accessories</th><td colspan="6">Amplifier Mounting Brackets (ZX-XBE1), Instruction Manual</td></tr>
</table>

*1: Resolution: The resolution is the deviation (±3σ) in the linear output when connected to the ZX-EDA Amplifier Unit. The above values indicate the deviations observed 30 minutes after the power is turned ON. (The resolution is measured with OMRON's standard reference object at 1/2 of the measurement range with the ZX-EDA set for the maximum average count of 4,096 per period.) The resolution is given at the repeat accuracy for a stationary workpiece, and is not an indication of the distance accuracy. The resolution may be adversely affected under strong electromagnetic fields.

*2: Linearity: The linearity is given as the error in an ideal straight line displacement output when measuring the standard reference object. The linearity and measurement values vary with the object being measured.

*3: Temperature characteristic: The temperature characteristic is measured with OMRON's standard reference object at 1/2 of the measurement range.

*4: The ambient temperature given is only for the sensor head. It is -10 to 60°C for the preamp.
*5: The value given is for an ambient temperature of 25°C.

*6: Do not use in moist environments because the case is not waterproof.

Amplifier Units

Model	ZX-EDA11	ZX-EDA41
Measurement period *1	150 μs	
Possible average count settings	1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1,024, 2,048, or 4,096	
Linear output *2	Current output: 4 to 20 mA/F.S., Max. load resistance: 300 Ω Voltage output: ± 4 V (± 5 V, 1 to 5 V *3), Output impedance: 100 Ω	
Judgement outputs (3 outputs: HIGH/PASS/LOW)	NPN open-collector outputs, 30 VDC, 50 mA max. Residual voltage: 1.2 V max.	PNP open-collector outputs, 30 VDC, 50 mA max. Residual voltage: 2 V max.
Zero reset input, timing input, reset input, judgement output hold input	ON: Short-circuited with 0-V terminal or 1.5 V or less OFF: Open (leakage current: 0.1 mA max.)	ON: Supply voltage short-circuited or supply voltage within 1.5 V OFF: Open (leakage current: 0.1 mA max.)
Function	- Number of display digit changes - Sample hold - Peak hold - Bottom hold, peak-to-peak hold - Self-peak hold - Self-bottom hold - Average hold - Delay hold - Zero reset - Initial reset - Linearity initialization - ON-delay timer - OFF-delay timer - One-shot timer - Previous value comparison - Non-measurement setting - Direct threshold value setting - Position teaching - Automatic teaching - Hysteresis width setting - Timing inputs - Reset input - Judgement output hold input - Monitor focus - Linear output correction - (A-B) calculations *4 - (A+B) calculations *4 - K-(A+B) calculation *4 - Mutual interference prevention *4 - Sensor disconnection detection - Zero reset memory - Zero reset indicator - Key lock	
Indications	Judgement indicators: High (orange), pass (green), low (yellow), 7-segment main digital display (red), 7-segment sub-digital display (yellow), power ON (green), zero reset (green), enable (green)	
Voltage influence (including Sensor)	0.5% F.S. of linear output value at ±20% of power supply voltage	
Power supply voltage	12 to 24 VDC ± 10%, Ripple (p-p): 10% max.	
Current consumption	140 mA max. with power supply voltage of 24 VDC (with Sensor connected)	
Ambient temperature	Operating and storage: 0 to 50°C (with no icing or condensation)	
Ambient humidity	Operating and storage: 35% to 85% (with no condensation)	
Insulation resistance	20 MΩ min. (at 500 DC)	
Dielectric strength	1,000 VAC, 50/60 Hz for 1 min	
Vibration	10 to 150 Hz with 0.7-mm double amplitude for 80 min each in X, Y, and Z directions	

resistance (destruction)	
Shock resistance (destruction)	300 m/s^2, 3 times each in 6 directions (up, down, left, right, forward, backward)
Connection method	Prewired (standard cable length: 2 m)
Weight (packed state)	Approx. 350 g
Materials	Case: PBT (polybutylene terephthalate), Cover: Polycarbonate
Accessories	Instruction Manual

*1: The response time for the first linear output or judgment output is calculated as follows (with fixed sensitivity): Measurement period × (Average count setting + 1). The response time for the second and later outputs is the measurement period specified in the table.

*2: The output can be switched between a current output and voltage output using a switch on the bottom of the Amplifier Unit.

*3: Setting is possible via the monitor focus function.

*4: A Calculating Unit (ZX-CAL2) is required.

Last update: April 25, 2013

MATLAB Code for simulation the servo in HDD with input shaping and PID.

```
clc
%close all
clear
warning off all

%time
ts = 1/20e3; %20kHz sampling
tend = 0.01;
t = 0:ts:tend;

%Plant
s = tf('s');
GvL = 6.4013e7/s^2; %nominal plant
Gr1 = (0.912*s^2+457.4*s+1.433e8)/(s^2+359.2*s+1.433e8); %resonances
Gr2 = (0.7586*s^2+962.2*s+2.491e8)/(s^2+789.1*s+2.491e8);
Gr3 = 9.917e8/(s^2+1575*s+9.917e8);
Gr4 = 2.731e9/(s^2+2613*s+2.73e9);
Gn1 = (s^2+238.8*s+1.425e8)/(s^2+2388*s+1.425e8); %notch filters
Gn2 = (s^2+314.2*s+2.467e8)/(s^2+3142*s+2.467e8);
Gn3 = (s^2+628.3*s+9.87e8)/(s^2+12570*s+9.87e8);
%G = GvL;
%G = GvL*Gr1*Gr2*Gr3*Gr4;
G = GvL*Gr1*Gr2*Gr3*Gr4*Gn1*Gn2*Gn3;
y = lsim(G, 1*ones(length(t),1), t);
 figure(1),bode(G)
 figure(2),plot(t,y)
 figure(3),pzmap(G)

%-------------------%Ziegler%--------------------%
kcr = 0.0001;
pcr = 0.0788;
%PID
Kp = 0.6*kcr;
Ti = 0.5*pcr;
Td = 0.125*pcr;

%-------------------%Find Tune%--------------------%
% Kp = kcr;
 Ti = Ti*1.2;
 Td = Td*50;

Kpid = Kp*(1+1/(Ti*s)+Td*s);

%Closed-loop system
CL = feedback(Kpid*G,1);
y1 = lsim(CL, 1*ones(length(t),1), t);
figure(4),plot(t,y1)
```

```
figure(5),pzmap(CL)
[Wn,Z] = damp(CL)

%Input shaping
z = tf('z',ts);
wn(1) = 1.2e4; %natural frequency of a mode
zt(1) = 0.0154; %damping ratio of a mode

wn(2) = 1.58e4;
zt(2) = 0.0292;

wn(3) = 3.15e4;
zt(3) = 0.028;


for i = 1:3
    K = exp(-(zt(i)*pi/sqrt(1-zt(i)^2)));
    Fhat1(i) = 1/(1+2*K+K^2);
    Fhat2(i) = 2*K/(1+2*K+K^2);
    Fhat3(i) = K^2/(1+2*K+K^2);
    t2(i) = pi/wn(i)/sqrt(1-zt(i)^2);
    t3(i) = 2*pi/wn(i)/sqrt(1-zt(i)^2);
    IS(i) = Fhat1(i) + Fhat2(i)*z^-round(t2(i)/ts) + Fhat3(i)*z^-
round(t3(i)/ts);
end


IS3 = IS(1)*IS(2)*IS(3);
IS2 = IS(1)*IS(2);
IS = IS(1);

%Closed-loop system with input shapers
CL = c2d(CL,ts);

CLIS = IS*CL;
CLIS2 = IS2*CL;
CLIS3 = IS3*CL;

ris = lsim(IS, 1*ones(length(t),1), t);
ris2 = lsim(IS2, 1*ones(length(t),1), t);
ris3 = lsim(IS3, 1*ones(length(t),1), t);

y2 = lsim(CLIS, 1*ones(length(t),1), t);
y3 = lsim(CLIS2, 1*ones(length(t),1), t);
y4 = lsim(CLIS3, 1*ones(length(t),1), t);

figure(6),plot(t,y1,'r-'),hold on,
          plot(t,y2,'m-'),hold on,
          plot(t,ris,'r:'),hold on,
          plot(t,y3,'g-'),hold on,
          plot(t,ris2,'b:'),hold on,
          plot(t,y4,'k-'),hold on,
          plot(t,ris3,'y:'),hold off
```

```
figure(7),bode(CL),hold on,
          bode(CLIS),hold on,
          bode(CLIS2),hold on,
          bode(CLIS3),hold off
```

Diagram of Hardware connection

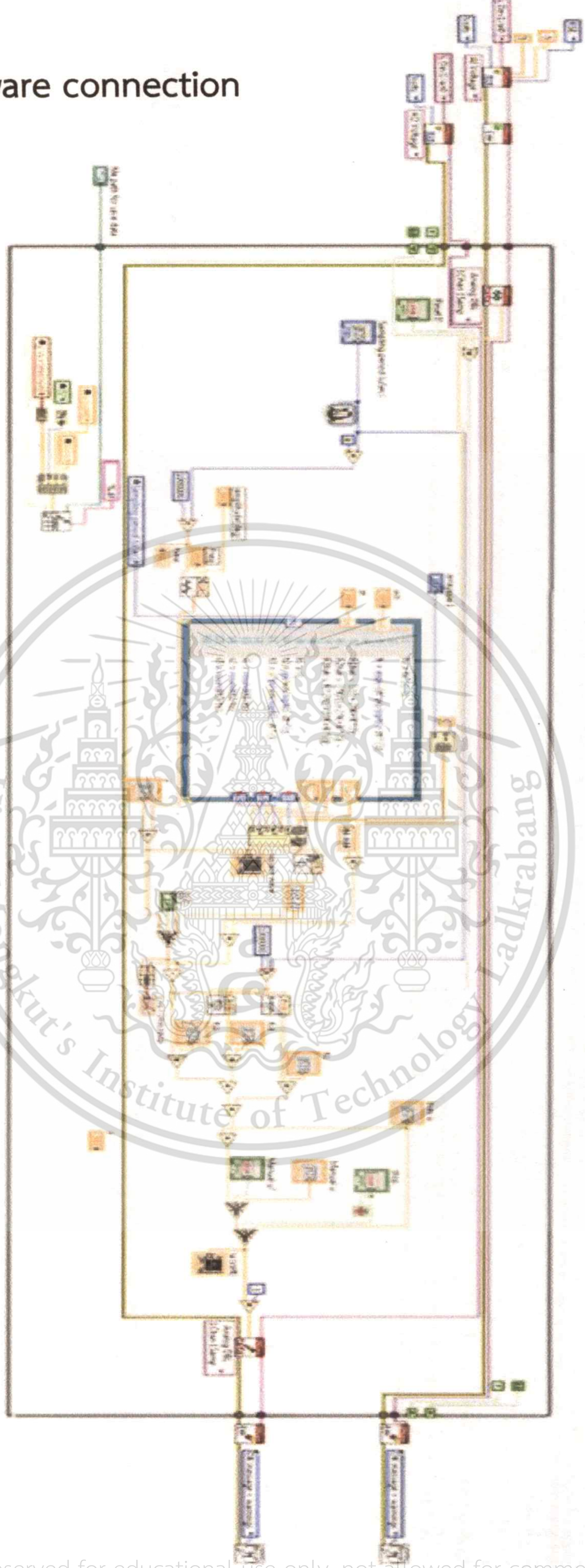

Figure Appendix 2 : Diagram of Hardware connection

Publication list

[1] Wimonrat Runghimmawan, Asst.Prof.Dr. Withit Chatlatanagulchai
, Assoc.Prof.Dr. Pitikhate Sooraksa, "Track-Seeking Control using Input-Shaping Method to Reduce Vibration in HDD," The 13th international Symposium on Communications and Information Technologies (ISCIT2013), Samui Island, Thailand, Sep 2013.

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Track-Seeking Control using Input-Shaping Method to Reduce Vibration in HDD

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***Abstract*— Hard disk drives are used for storage information in its recording disk or media. Actuator arm is mechanical part to move heads that fly over a track from any position to the target track. Accuracy signal and access time are the key parameters to control the actuator seeking position. However, the accuracy signal and access time are adverse when actuator moves faster and then the system create the residual vibration at the target track. The causes of the vibration are part from the fact that the reference signals, which are acceleration, velocity, and position, have high power spectrum energy over wide frequency range including over the actuator's natural frequency. The input shaping is convolved two signals at referent position signal and properly designed impulse signal. The impulse sequence produces an input signal to cancel residual vibration, then the result is smoother and the residual vibration is canceled in actuator-arm movement. Hence the residual vibration should be reduced by the recommended input shaping.**

***Keywords*—Hard disk drive; Track seeking; Vibration; Input shaping;**

I. INTRODUCTION

Nowadays, hard disk drives use a combination of classical control, such as, PID compensators including notch filters to reduce the effects of high-frequency resonant modes. The actuator arm is mechanical part for moving head that fly over a track from any position to target track. The servo system of a hard disk drive is divided into three categories: 1) the track seeking, 2) the track settling, and 3) the track following stage. Figure 1 shows the Head Stack Assembly (HSA) and VCM Magnet in Hard disk drives. The gimbals and the suspensions help the heads for maintaining the constant flying height on an air bearing over the disks rotation. The heads fly over the disk surface is positioned by an actuator, which controls the movement of HSA is called servo system control. Voice coil motor (VCM) is widely used as the actuator in hard disk drives. VCM controls HSA and a selected head to follow a track (track following stage) or to switch from one track to another (track seeking). The servo system is consisted of two main points: 1) the spindle motor servo system and 2) the actuator servo system; there are real-time embedded systems. The disks rotate at a constant speed and the actuator moves over the disk surface. This research scope to seeking mode that have 2 majors on design. Firstly mode switching contidion is used for changing from seeking mode to the following mode that also required to smooth and minimize the resudual vibration. Secondary velocity profiles require to be fast and robustness. The vibrations may exacerbate the head settling, make the effective seek time longer, and cause to acoustic problems. A settling mode is often used to smooth the transition.

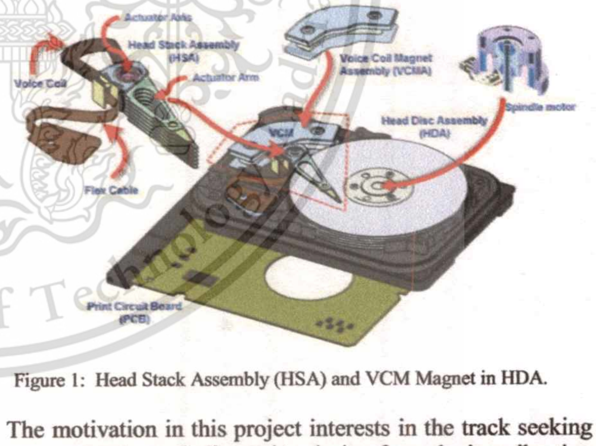

Figure 1: Head Stack Assembly (HSA) and VCM Magnet in HDA.

The motivation in this project interests in the track seeking on servo control are challenged to design for reducing vibration when the head move any track to target track. The design a servo controller that has the following physical constraints and design specification: 1) the control input does not exceed ±3 Volts owing to physical constraints on the actual VCM actuator. 2) The overshoot and undershoot of track seeking are kept to less than 0.5 μm, the limit of our measurement device for large

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displacement. 3) The gain margin and phase margin of the overall design are, respectively, greater than 6 dB and 30^o.

In active controls have proliferated, passive controls, especially those that use reference input shaping, are less well-known. Meckl and Seering (1988) reconstructed a bang-bang reference acceleration signal using ramped sine or versine basis functions. A cost function is penalized, weighing over removing the spectrum energy around the natural frequencies and approaching the bang-bang shape. Chatlatanagulchai et al. (2006) applied input shaping method with a two-link flexible-joint robot. Another shaping method was devised by Singer and Seering (1990.) Instead of shaping the reference acceleration, this method shapes the reference position directly by convoluting it with a properly designed impulse sequence. In theory, this impulse sequence is designed such that all impulse responses cancel each other producing vibration-free movement. Since the convolution with an impulse can be conveniently performed in real time, this method has received more attentions than the formal method, even though its appearance is still rare [2]. This paper applies the input shaping method to hard disk drives track seeking system. This servo system is made to follow any arbitrary angular position. It can be viewed as a model of actuator arm seeking movement only. A simple PID controller is used in the closed-loop system. The result is that the actuator arm can move with significantly less vibration when the shaped reference position is applied instead of an unshaped square-wave reference position.

II. INPUT SHAPING BASIC

A. Impulse Responses Cancellation

For a one-degree-of-freedom unforced linear system with damping, the response to an impulse with magnitude $\hat{F}_1$ is given by

$$y(t)=\frac{\hat{F}_1 e^{-\zeta\omega_n(t-t_1)}}{m\omega_n\sqrt{1-\zeta^2}}\sin\sqrt{1-\zeta^2}\,\omega_n\left(t-t_1\right), \quad (1)$$

Where y is the response, ζ is damping ratio, ω_n is natural frequency, m is mass, and t_1 is the time the impulse applies.

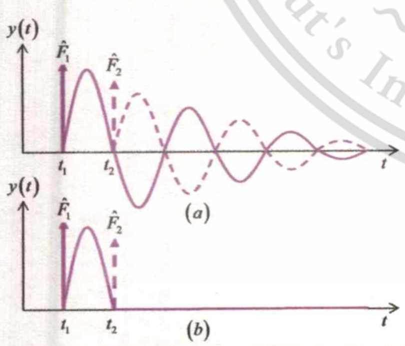

Figure 2: System response of two impulses [2].

The response $y(t)$ above can be plotted as a solid line in Figure 2(a). Suppose there is another impulse $\hat{F}_2$ applied at time t_2. when magnitude and timing are designed properly, its response (the dash line in Figure 2(a)) would be cancel with that of the first impulse producing vibration-free response Figure 2(b). Instead of N impulse, it can solve by trigon equation and shown that the amplitude of the sum of N impulse responses is given by

$$A=\sqrt{\left(\sum_{i=1}^{N}A_i\cos\beta_i\right)^2+\left(\sum_{i=1}^{N}A_i\sin\beta_i\right)^2} \quad (2)$$

with $A_i=\hat{F}_i e^{-\zeta\omega_n(t-t_i)}/\left(m\omega_n\sqrt{1-\zeta^2}\right)$ and $\beta_i=\sqrt{1-\zeta^2}\,\omega_n t_i$.

Since the system want to have zero vibration, setting (2) to zero and t to t_N results in two constraints

$$\sum_{i=1}^{N}\hat{F}_i e^{-\zeta\omega_n(t_N-t_i)}\cos\sqrt{1-\zeta^2}\,\omega_n t_i=0 \quad (3)$$

and $$\sum_{i=1}^{N}\hat{F}_i e^{-\zeta\omega_n(t_N-t_i)}\sin\sqrt{1-\zeta^2}\,\omega_n t_i=0. \quad (4)$$

For two impulses, of which the first one applies at $t_1=0$ and its impulse magnitude normalizes to $\hat{F}_1=1$, $\hat{F}_2$ and t_2 can be found from the two equations above.

$$\hat{F}_2=e^{-\frac{\zeta\pi}{\sqrt{1-\zeta^2}}} \text{ and } t_2=\frac{\pi}{\omega_n\sqrt{1-\zeta^2}}.$$

B. Robustness to Uncertainties in Natural Frequency and Damping Ratio

Since the amount of residual vibration left depends on the accuracy of the natural frequency (ω_n) and the damping ratio (ζ) used to compute $\hat{F}_2$ and t_2, to increase the robustness of the input under variations of the natural frequency, we can set the derivatives, with respect to ω_n, of (2) and (3) to zeros to obtain two more constraints

$$\sum_{i=1}^{N}\hat{F}_i t_i e^{-\zeta\omega_n(t_N-t_i)}\cos\left(\sqrt{1-\zeta^2}\,\omega_n t_i\right)=0 \quad (4)$$

and $$\sum_{i=1}^{N}\hat{F}_i t_i e^{-\zeta\omega_n(t_N-t_i)}\sin\left(\sqrt{1-\zeta^2}\,\omega_n t_i\right)=0. \quad (5)$$

The constraints (4) and (5) are reduced the sensitivity of the constraints (2) and (3) to change in ω_n and can be used to solve for two additional unknowns t_3 and $\hat{F}_3$ of the third impulse. It can be shown that these constraints also apply to the robustness of the input under variations of the damping ratio. Letting $t_1=0$ and $\hat{F}_1=1$, we can compute $t_2, \hat{F}_2, t_3$, and $\hat{F}_3$ from (2)-(5) to be

$$t_2=\frac{\pi}{\omega_n\sqrt{1-\zeta^2}},\ \hat{F}_2=2e^{-\frac{\zeta\pi}{\sqrt{1-\zeta^2}}},\ t_3=\frac{2\pi}{\omega_n\sqrt{1-\zeta^2}},\ \text{and}\ \hat{F}_3=e^{-\frac{2\zeta\pi}{\sqrt{1-\zeta^2}}}. \qquad (6)$$

Increasing the robustness of the input shaping under variations of the damping ratio requires setting derivatives of (2) and (3) with respect to zeros. It turns out that this produces the same constraints as (4) and (5). To obtain even more robustness, we can continue to differentiate (4) and (5) to produce a new set of constraints for the fourth impulse and so on. However, more impulse so result could be robustness but in slower trajectory when implementing in the closed-loop system.

III. Input Shaping of a Hard disk drive

A. Hard disk drive model

The simulation used Maxtor HDD (Model 51536U3)[1]. Figure 3 shows the diagram of a single actuator arm seeking from any track to the target track.

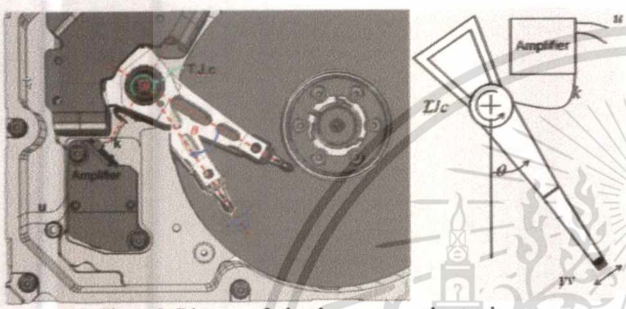

Figure 3: Diagram of a head move to another track.

The relationship between $y = L\theta$ and $T = k_1 u - k_2\dot{\theta}$ that can get ODE equation= $\frac{J}{L}\ddot{y} + \frac{(c+k_2)}{L}\dot{y} + \frac{k}{L}y = k_1 u$. Thus the control design model is $\ddot{y} + 282.6\dot{y} + 3.9933\times10^6 y = 2.35\times10^8 u$, where the term $282.6\dot{y}$ is the viscous friction part of $\tilde{T}_f$, and the term $3.9933\times10^6\dot{y}$ is a straight line estimate of $\tilde{T}_c$.

However, if consider the high-frequenct resnance modes for more realistic model for the VCM actuator is shown in figure 4 .

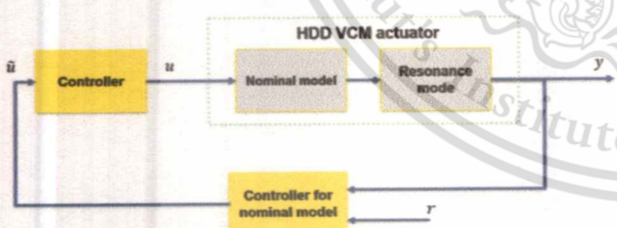

Figure 4: The control system for hard drive VCM

The norminal plan [1] is a tenth-order model for the actuator is obtained in equation (6.1) with the resonance mode is provided the equaltion (6.2) – (6.4).

$$G_v(s) = \frac{6.4013\times10^7}{s^2}\prod_{i=1}^{4} G_{r,i}(s) \qquad (6.1)$$

$$G_{r,1}(s) = \frac{0.912s^2+457.4s+1.433\times10^8}{s^2+359.2s+1.433\times10^8} \qquad (6.2)$$

$$G_{r,2}(s) = \frac{0.7586s^2+962.2s+2.491\times10^8}{s^2+789.1s+2.491\times10^8} \qquad (6.3)$$

$$G_{r,3}(s) = \frac{9.917\times10^8}{s^2+1575s+9.917\times10^8} \qquad (6.4)$$

$$G_{r,4}(s) = \frac{2.731\times10^8}{s^2+2613s+2.731\times10^8} \qquad (6.5)$$

The frequency response of the identified model is shown in figure 5.

Figure 5: The frequency response of the plan with resonance mode.

B. Closed-Loop Application

Normally, if the controller does not add any under-damped poles to the closed-loop system, the natural frequency and damping ratio still follow those of the plant so that can get from figure 4. The simulation select natural frequency (ω_n) and damping ratio (ζ_n) from the poles are closely to zero poles: (1.21e^4, 0.015), (3.15e^4, 0.029), (1.58e^4, 0.03), (1.15e^4, 0.09).

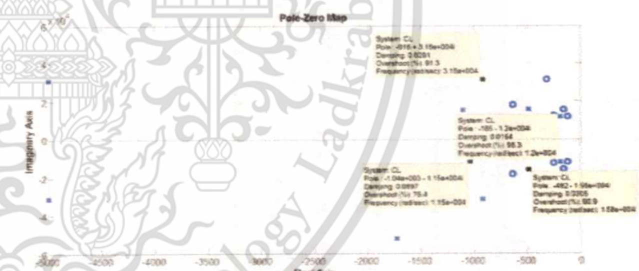

Figure 6 : Pole-Zero mapping.

The impulse sequence is developed by applied to the closed-loop system identifications using simple PID controller as an input shaper in Figure 7. The impulse sequence can be convolved with the reference position to create a shaped input that will cancel the residual vibrations.

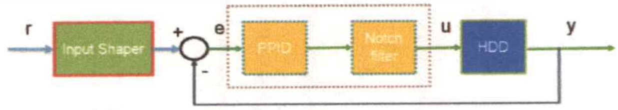

Figure 7 : Closed-loop-system block diagram with an input shaper.

For tracking, we need all impulse amplitudes to sum to one so that the shaped reference position will have the same end point as the original reference position. Therefore, in the three impulses case, the amplitudes and timing given in can be plotted as figure 8(a), where

$$K = e^{-\frac{\zeta\pi}{\sqrt{1-\zeta^2}}}.$$

Figure 8(b) is shown the shaped step reference position, which is a result of convolving a step reference position r with the three-impulse sequence.

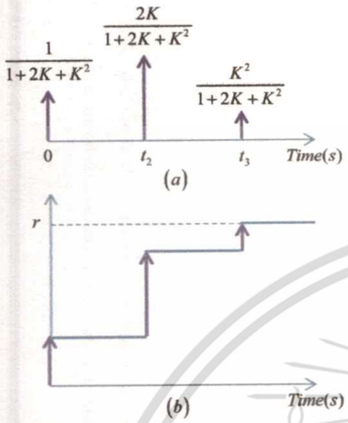

Figure 8 : (a) Three impulses. (b) Convolution of the impulse sequence with a step reference position [2].

This also shows that even though using more impulses provides more robustness, the shaped reference position will reach the end point slower at a later time t_N, where N is the number of impulses used.

IV. RESULS AND CONCLUSION

The step response is shown in figure 9 after added input shaping is smoother than normal PPID, and the overshoot is lower than PPID. The simulation of time response is shown in table 1. The time response is related to the number of impulses. If adding more impulse, the test time will be increased. The simulation result suggests to add 1 impulse for minimizing the robustness, overshoot, and to add the time response is not much. The overall result can meet motivation targets.

Controller/ Time response	Delay time (ms)	Rise time (ms)	Peak time (ms)	Maximum overshoot (um)	Settling time (2%)	Steady-state error (t=0.25 ms)
PPID	0.000276	0.000717	0.001600	0.222000	0.003825	0.001000
PPID + Input Shaping 1 impluse	0.000540	0.000977	0.001720	0.203000	0.004050	0.001000
PPID vs PPID + Input Shaping 1	0.000264	0.000260	0.000120	-0.019000	0.000225	0.000000
PPID + Input Shaping 2 impluses	0.000730	0.001193	0.001957	0.198000	0.004250	0.001000
PPID + Input Shaping 3 impluses	0.000821	0.001289	0.002032	0.197000	0.004350	0.001000
PPID + Input Shaping 4 impluses	0.001039	0.001562	0.002313	0.191000	0.004600	0.001000

Table 1: The test time response.

The arbitrary reference position was convolved with a sequence of one impulse in real time producing a shaped input that cancels residual vibration of the system. The application of this technique is vast. It can be applied to dual actuator head or any systems suffering from vibrations during slewing. Nevertheless, the technique relies on the superposition principle of the linear system. No generalization over the nonlinear systems. Besides, the accuracy of the system's natural frequency and damping ratio is vital to the effectiveness of the technique.

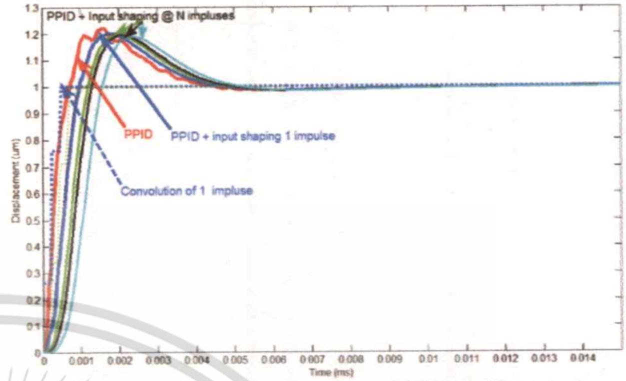

Figure 9 : Output response compare between normal PPID and Input shaping.

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