EXPERIMENTAL STUDY OF OPTIMUM DISK CLAMP TORQUE BY USING DOE METHOD

SOMSAK TAWEEPUN

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENT FOR THE DEGREE OF
MASTER OF ENGINEERING IN DATA STORAGE TECHNOLOGY
INTERNATIONAL COLLEGE
KING MONGKUT'S INSTITUTE OF TECHNOLOGY LADKRABANG
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Thesis Certification

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Thesis Title	Experimental Study of Optimum Disk Clamp Torque by Using DOE Method
Student	**Mr.Somsak Taweepun**
Student ID.	53600607
Degree	Master of Engineering
Program	Data Storage Technology (English Program)
Thesis Advisor	Asst.Prof.Dr.Monsak Pimsarn
Thesis Reference Number	KMITL-2014-IC-M-005-002

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Place : International College, 8th floor, 55th Anniversary Chalermprakiat Building

KING MONGKUT'S INSTITUTE OF TECHNOLOGY LADKRABANG

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July 20 , 2015

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Abstract

The screw-fastening assembly process is one of the most widely used fastening methods in industrial assembly that including hard disk drive (HDD) industrial assemble. The screw-fastening process on assembly at media installation (MI) and auto gang bias installation (AGB) are critical operations to achieve the accuracy of disk clamp screw torque. The purpose of this study was to study the factors which affect to the disk clamp screw torque in hard disk drive: the different preliminary-torque (PT) at media installation, input torque (IT) and gain (G) control of screw-fastening process at auto gang bias by performing an experiment and using design of experiment (DOE) method. From the experimental study, it was found that the input torque parameter is the most significantly affect to the disk clamp screw torque. The gain is slightly significant affect to the disk clamp screw torque. The preliminary torque parameter has no affected to the disk clamp screw torque. However, this factor had interaction affected with the input torque. After that the DOE method was employed to predict the relationship between these factors and disk clamp screw torque. The disk clamp screw torque proportionally depends on the input torque and gain control in the quadratic manner. Finally, the optimum setting for these parameters were investigated by using desirability function. Moreover, the correlation between actual experiment and predicted models of disk clamp screw torque were validated. It showed very good correlation, with R-square 98%. It is able to prove that this is an appropriate setting of inputs torque and gain control which result in the accuracy of disk clamp screw torque.

ชื่อหัวข้อวิทยานิพนธ์	การทำการทดลองเพื่อศึกษาหาจุดที่ดีที่สุดของแรงทอร์คดิสก์แคลมส์สกรูในฮาร์ดดิสก์ ผ่านวิธีการของ DOE
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บทคัดย่อ

โรงงานอุตสาหกรรมทั่วไปนิยมกันมากในการใช้เครื่องขันสกรู (Screw fastener) ในกระบวนการผลิตรวมถึงอุตสาหกรรมผลิตฮาร์ดดิสก์ด้วย เครื่องขันสกรูในกระบวนการยึดแผ่นมิเดียด้วยสกรูของกระบวนการผลิตฮาร์ดดิสก์มีสองกระบวนการที่สำคัญคือเครื่องจับยึดขั้นต้นระหว่างแผ่นมิเดียเข้ากับแกนมอเตอร์และเครื่องจับยึดแน่นระหว่างแผ่นมิเดียเข้ากับแกนมอเตอร์ วัตถุประสงค์ของการศึกษาในครั้งนี้คือหาปัจจัยที่มีผลกระทบต่อการยึดแผ่นมิเดียด้วยสกรูในฮาร์ดดิสก์เพื่อที่จะได้ค่าที่ดีที่สุดของแรงทอร์คดิสก์แคลมส์สกรูในฮาร์ดดิสก์ มีทั้งหมดสามปัจจัยที่ได้ทำการศึกษาคือ การกำหนดให้ค่าของแรงทอร์คในการขันสกรูเบื้องต้น (Preliminary torque) ที่เครื่องจับยึดขั้นต้นระหว่างแผ่นมิเดียเข้ากับแกนมอเตอร์ สองการกำหนดให้ค่าของแรงทอร์คที่แหล่งจ่าย (Input torque) ของเครื่องจับยึดแน่นระหว่างแผ่นมิเดียเข้ากับแกนมอเตอร์ และสามการจ่ายกระแสไฟ (Gain) ของเครื่องจับยึดแน่นระหว่างแผ่นมิเดียเข้ากับแกนมอเตอร์ ซึ่งได้ทำการทดลองผ่านวิธีการของ Design Of Experiment (DOE) จากการทำการทดลองพบว่าตัวแปรที่มีผลกระทบต่อการยึดแผ่นมิเดียด้วยสกรูของฮาร์ดดิสก์มากที่สุดคือการกำหนดให้ค่าของแรงทอร์คที่แหล่งจ่ายที่เครื่องจับยึดแน่น การจ่ายกระแสไฟมีผลกระทบเพียงเล็กน้อยเท่านั้น ส่วนการกำหนดให้ค่าของแรงทอร์คในการขันสกรูเบื้องต้นไม่มีผลกระทบโดยตรงต่อการยึดแผ่นมิเดียด้วยสกรูในฮาร์ดดิสก์แต่จะมีผลกระทบร่วมกันกับการกำหนดให้ค่าของแรงทอร์คที่แหล่งจ่ายของเครื่องจับยึดแน่น หลังจากที่ได้ศึกษาผ่านวิธีการของ DOE ได้เห็นความสัมพันธ์อย่างมีนัยยะสำคัญและสามารถที่จะนำไปทำนายการหาค่าที่ดีที่สุดของแรงทอร์คดิสก์แคลมส์สกรูโดยผ่านเครื่องขันสกรูในฮาร์ดดิสก์จากตัวแปรทั้งสามตัว ซึ่งมีความสัมพันธ์กันแบบสมการสองชั้น ในที่สุดแล้วได้ค้นหาจุดที่ดีที่สุดของการยึดแผ่นมิเดียด้วยสกรูในฮาร์ดดิสก์โดยผ่านการหาความสัมพันธ์ทางคณิตศาสตร์ด้วย Desirability function ยิ่งไปกว่านั้นได้ทำการทดลองจริงเพื่อเปรียบเทียบความสัมพันธ์กับสมการความสัมพันธ์ทางคณิตศาสตร์แล้วทำการวิเคราะห์ด้วยสมการถดถอยพบว่ามีความสัมพันธ์ดีมากด้วย R^2 = 98% ซึ่งพิสูจน์ได้ว่าการกำหนดให้ค่าของแรงทอร์คที่แหล่งจ่ายและการจ่ายกระแสไฟที่ที่ถูกต้องที่เครื่องจับยึดแน่นระหว่างแผ่นมิเดียเข้ากับแกนมอเตอร์จึงจะสามารถได้ค่าที่ดีที่สุดของแรงทอร์คดิสก์แคลมส์สกรูในฮาร์ดดิสก์ต่อไป

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Finally, I would like to thanks my family that everyone gives unfailing encouragement; especially, my parents. I would like to dedicate this thesis to them and say thank to everyone again for encouraging me to pursue higher education.

Somsak Taweepun

Contents

Contents (Cont.)

Page

List of Tables

Table Page

LIST OF FIGURES

Abbreviations

AIAG = Automotive Industry Action Group
AGB = Auto Gang Bias
D = Desirability
DOE = Design of Experiment
HAA = Head Arm Assembly
HDA = Hard Disk Assembly
HDD = Hard Disk Drive
In-lbs = Pounds-Inch
IT = Input Torque
G = Gain
GR&R = Gage Repeatability and Reproducibility
LCL / UCL = Lower / Upper Control Limit
LSL / USL = Lower / Upper Specification Limit
MI = Media Install
MSA = Measurement System Analysis
NDC = Number of Distinct
OLS = Ordinary Least Squares
PT = Preliminary Torque
P/T = Precision to Tolerance
P/TV = Precision to Total Variation
RPM = Revolution per Minute
RSM = Response Surface Method

Nomenclature and Notations

T = Torque (lbf-in, Nm)

F = Force (lbf, N.)

K = Nut Factor for basic equation

D = Nominal diameter of nut head (in.)

F_M = Initial clamping load (assembly preload); the values in the table are calculated with a 90 percent utilization of the elastic limit using red (lb., N.)

P = Pitch of the bolt thread (in., mm)

d = Bolt diameter is outside diameter of thread (nominal diameter) (in., mm)

d_h = Bore diameter of the clamped parts; inner diameter of the cylinder (in., mm)

d_r or d_1 = Minor diameter is the narrowest on a thread (in., mm)

d_p or d_2 = Pitch diameter is the diameter between the major and minor diameter (in., mm)

μ_G = Coefficient of friction in thread

μ_{ges} = Average coefficient of friction for thread and bolt head bearing surface

μ_K = Coefficient of friction for bolt head bearing surface

Chapter 1
Introduction

1.1 Statement and significance of the problem

Assembly process is a common step in most of general industrial manufacturing which is the final step in a manufacturing process. It is very important to directly influence to the product's quality and reliability. The screw fastening is a machine for driving screws and rotating other engine elements with the mating driver system. It is the one of the most widely used fastening methods in industrial assembly. Hard disk drive (HDD) industry is also adopted the screw-fastening assembly process for variety of component assembly.

In hard disk drive technology, the motor's speed is now up to 10,000 revolution per minutes (RPM) and number of magnetic disks are more stacking in order to increase the speed and capacity simultaneously. Therefore, the accuracy or optimum point of disk clamp screw torque target is required which the magnetic disk assembly process by screw fastener is very important factors. The inaccuracy of disk clamp screw torque can cause many problems, such as, mechanical failure of resonance, disk slipping and disk imbalance. Further sensitive operation, such as, clamping a stack of magnetic disks, spacers, screw, disk clamp and motor base or motor hub as shown in Figure 1.1 that needs a precise clamp load produced by a set of fasteners.

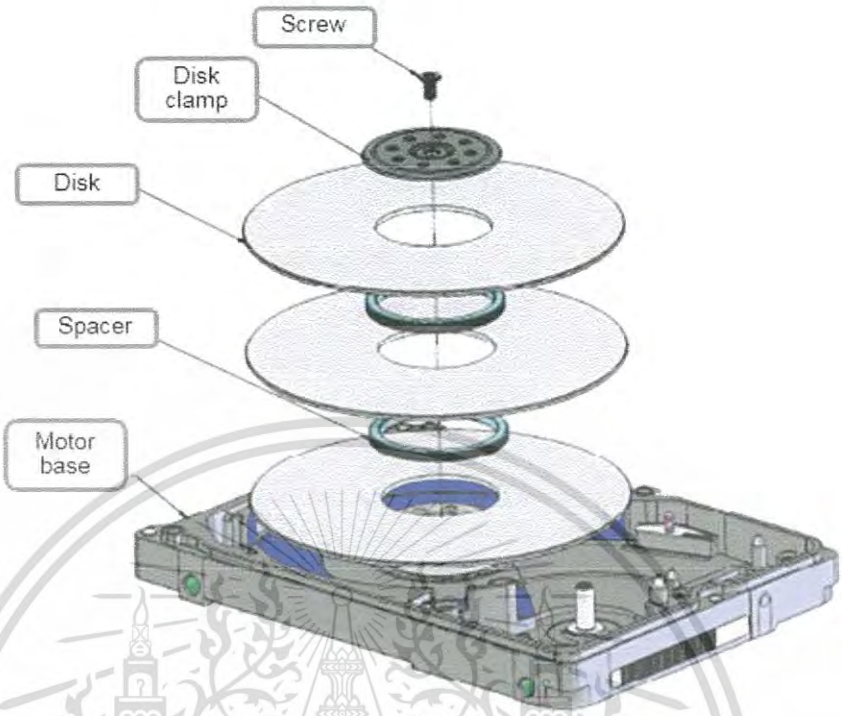


Figure 1.1 Disks pack assembly in a hard disk drive [1]

The process of disk clamp screw torque fastening consists of two operations, as illustrated in Figure 1.2. The first operation is media installation (MI), where the screw fasteners performs preliminary disk clamp screw torque in order to hold all components together. The second operation is auto gang bias (AGB), where the screw fasteners perform the final disk clamp screw torque and media balancing. The requirement of MI and AGB assembly are an installation all these components together with accuracy of disk clamp screw torque and balancing of disks.

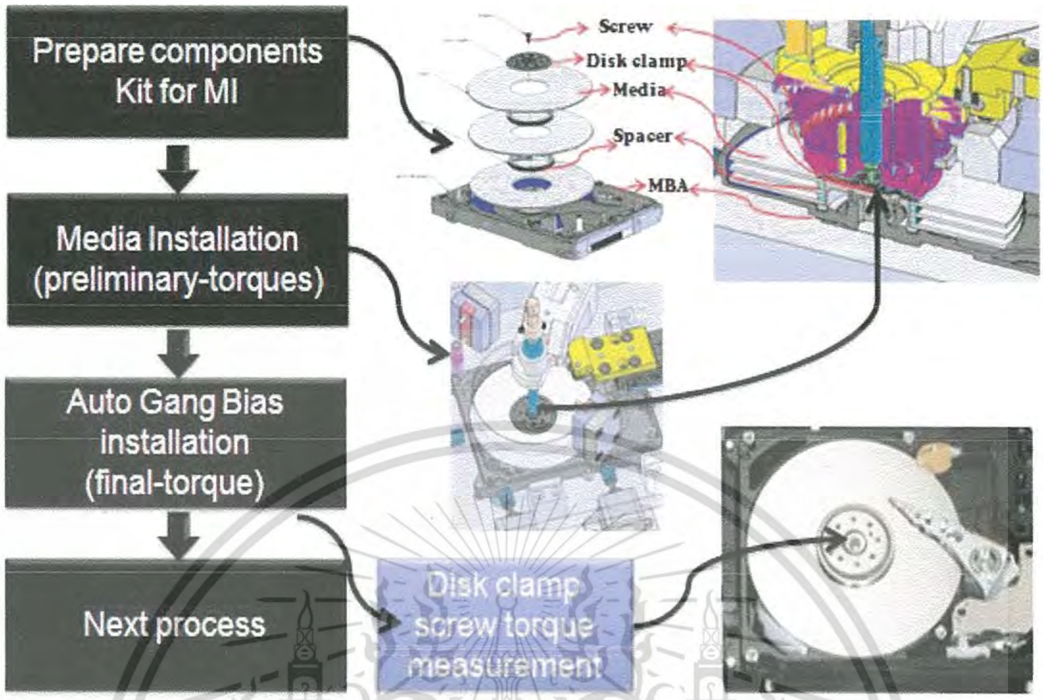


Figure 1.2 Process step of disk clamp screw fastening at MI and AGB [1]

1.2 Objectives

The purpose of this research is to find the optimum setting point of each factor and apply to actual process in order to improve process capability and to minimize the scrap parts of disk clamp screw torque. To achieve this objectives, it is necessary to investigate the effect of the different preliminary torque at media installation, input torque and gain of screw fastening process at auto gang bias. In order to achieve the goal, experiment and DOE will be performed. The obtained result will lead to optimize setting points.

1.3 Scope and limitations

To understand the accuracy of the screw fastening assembly process, both MI and AGB operations are on this study.

1. In this research, one product 2.5” at Western Digital (Thailand) company limited will be selected to demonstrate the effect of disk clamp screw fastening process. In order to

reduce variation or noise by screw fasteners, the MI and AGB machines are dedicated for this studying.

2. In this research, the preliminary torque (PT) setting at MI is selected by following the limitation of machine setting as same as the input torque (IT) and gain (G) at AGB.

3. In this research, Minitab software is used to analyze the experimental data and to find the optimum setting point of disk clamp screw torque.

1.4 Research questions

Firstly, how does the preliminary setting of disk clamp screw torque at media installation affect to the final disk clamp screw torque? Secondly, how does the input torque setting at auto gang bias installation affect to the final screw torque of disk clamp? Lastly, how does the gain control at auto gang bias installation affect to the final screw torque of disk clamp?

1.5 Hypothesis

Firstly, preliminary torque setting at high level will show a higher the final disk clamp screw torque than the preliminary torque setting at low level at media installation. Secondly, input torque setting and gain at high level will show a higher the final disk clamp screw torque than the low level setting at auto gang bias installation. Finally, the optimum setting point of preliminary torque at MI, input torque and gain at AGB respectively in order to improve process capability and to minimize the scrap parts of disk clamp screw torque.

1.6 Expectations

1. To understand the most influential factors that impact to the disk clamp screw torque in hard disk drive.

2. To predict and optimize the disk clamp screw torque with the settings of preliminary torque, input torque and gain at screw fastening process.

3. To apply with actual process in order to improve process capability and to minimize the scrap parts of disk clamp screw torque.

4. The study is to be a guideline for other stations of HDD screw fasteners.

1.7 Research methodology

The accuracy or optimum point of the disk clamp screw torque is required in HDD. Since we have a lot of components stacking together consists of magnetic disk, spacer, disk clamp, motor hub and screw. The experimental study of optimum disk clamp screw torque will be performed by using DOE. The measurement fixture has developed by adding the laser sensor to detect screw slipping. It can solve the human error when reading the value on a panel. It is passed qualification of the calibration and gage repeatability and reproducibility (GR&R).

There were several process steps in this experimental study for the optimal disk clamp screw torque. Firstly, MI and AGB were selected and studied on the screw fastening process. Secondly, the factors that affected to disk clamp screw torque were identified, including level of each factor by referring to the machine limitation and engineering expertise. Thirdly, the statistical design of experiment (DOE) technique was selected for effective planning, appropriate data collection and analyze. Fourthly, the boundary which was likely to obtain the optimal point would be identified. Fifthly, model described the relationship of the response and influential variables (First or second order model) would be created. Finally, model validation would be running to confirm the results.

Chapter 2

Literature Review and Related Theories

2.1 Associated researches

Neville K.S. Lee, Yingfei An, and Fugee Tsung [2] had studied the effects of screw-fastening process to attain the assembly accuracy by using design of experiment (DOE) technique for data analysis. There were 5 factors studying: input-torque, washer, holding force, number of screws and datum pin. They performed 36 runs with 2 replications per run. Lee et al. had developed a multi-dimensional high resolution optical position monitoring system and successfully facilitated the study of the mechanical alignment system. The experiment was carried out in a class 1000 clean room with the temperature controlled to within +/-1 °C. In conclusion, the most accurate screw-fastening condition was using relatively more number of screws with datum pins, washer and larger holding force.

Dhayagude, Zhiqiang Gao, and Fouad Mrad [3] had studied the fuzzy logic control of automated screw fastening. Since high downtime conversion and inflexibility, they had dedicated stations for various types/sizes of screw fastening Artificial neural network (ANN) models to resolve for the fastening problem was the lack of controller's flexibility. In addition, the complexities found in current processes include cross-threading, screw jamming, slippage and the need to apply precise torque. The fuzzy-logic controller (FLC) was designed and analyzed by simulation model. The goal was to achieve a desired torque and detect faulty joining conditions resulting from cross-threading, jamming, slippage and screw gap. In conclusion, the intelligent controller had developed and integrated process of an electric driver mounted on a robotic positioning system to fasten screws, and easier for conversion due to different products. The new scheme controls continuously the motion and driving stages to avoid process failures, to achieve a desired precise torque and to detect bad parts at early stages of the assembly. Furthermore, the robustness of the proposed scheme was demonstrated in the presence of noisy measurements and jerky manipulator motion. The same control scheme was thought to be capable of detection at the beginning step of mistaken found, such as, jamming or slippage situations.

Mr. Samart Mungtoklang, faculty of engineering at King Mongkut's Institute of Technology Ladkrabang [4] had studied the rotating imbalance in Hard Disk Drive due to screw tightening. This research presented that the manufacturing process caused the imbalance of the rotating disks in hard disk drive. The disk-spindle mechanism which disks were assembled to the spindle with screws would be balanced when balancing level within the acceptable limit. The screws were finally tightened with higher torque, and the disk-spindle mechanism was checked for its balance. The imbalance in disk-spindle mechanism was usually found to be increased after the final screw tightening process. From the previous studies on screw tightening, they were found that screws tightened with the same torque might not have the same preload forces. As a result of the difference in screw preload forces, the disk-spindle mechanism might not maintain in its stability. In this research, the cause of increasing–disk-spindle imbalance was investigated under the condition of different screw preload force with the same tightening torque. Finite element technique was used to calculate for the imbalance of the disk-spindle mechanism under the various values of each screw preloads force. The results from computer simulations were then compared with the experimental ones. In the worst case, the result from computer simulation differs from the experiment by 43%. However, both results always are on the same course of action.

D. W. Shu, F. F. Yap, B. Gu and B. J. Shi [5] had studied an effect of Disk Clamping Conditions on the Operational Shock Response of Hard Disk Drives. The mechanical robustness of HDDs during operational state had become increasingly more important [6]. In this research paper, the effect of disk clamping conditions on the operational shock response of a hard disk drive was investigated numerically. A finite element model of the hard disk drive was developed in the available commercial finite element package. The overall model included the head arm assembly (HAA) and the disk. The shock responses of the drive under half-sine acceleration pulses were simulated when the disk was subject to various clamping conditions [7]. It was found that the shock response of the drive was decreased with the more firmly clamped disk.

2.2 Related theories

2.2.1 Engineering fundamentals of the screw fastening process [8]

The screw fastening process, especially for critical bolted joints, alignment, insertion and involves controlling both input torque and angle of turn to achieve the desired result of proper preload of the bolted assembly. The role of friction in both the under head and threaded contact zones is the key to identify the association between torque, angle, and tension. There are too many factors that affect the tension created in the bolt when the tightening torque is applied. By combining the torque-angle curves with a few simple calculations and a basic understanding of the engineering mechanics of screw fastening, it can obtain the practical information needed to evaluate the characteristics of individual fastener tightening processes.

2.2.1.1 Energy transfer

The screw fastening is basically energy transfer process as shown in Figure 2.1. The area under the torque-angle curve is the energy required to tighten the fastening.

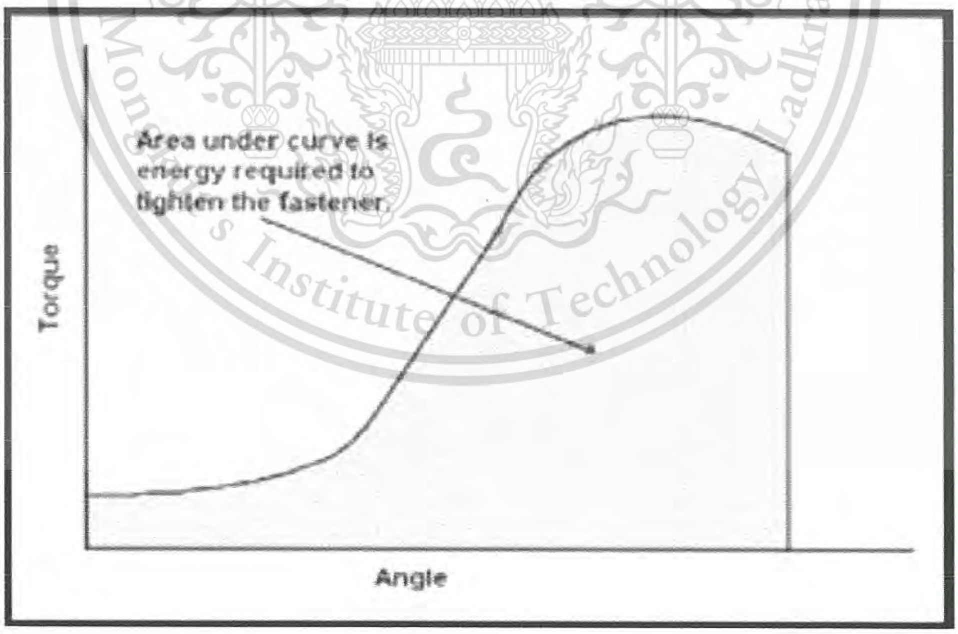


Figure 2.1 Screw fastening transfers energy [8]

2.2.1.2 Modeling the screw fastening process

For accuracy controlling of the screw fastening process is to find the association between torques and turns in the development of tension. Before studying the screw fastening methods, it is necessary to understand what actually happens when a fastener is tightened. The process of tightening a fastener involves turning, advance of the lead screw, and torque, turning moment, so that preload, tension, is produced in the fastener. The desired result is a clamping force to hold components together. There are four zones of the general model for the screw fastening process as shown in Figure 2.2.

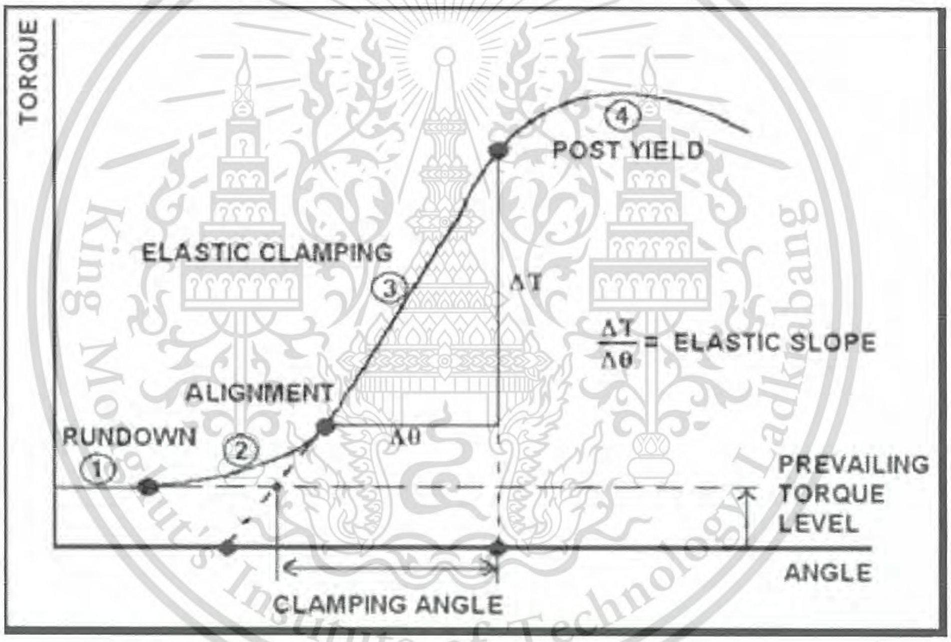


Figure 2.2 Four zones of the screw fastening process [8]

The first zone is the rundown or prevailing torque zone that occurs before the fasteners head or nut touches on the object surface. The second zone is the alignment zone which the fasteners and joint mating surfaces are drawn into alignment to achieve a comfortable condition. The third zone is the elastic clamping area, which the slope of the torque-angle curve is unchanging. The fourth zone is the post-yield zone, which begins with an inflection point at the end of the elastic area. This fourth zone can be due to yielding in the joint or others factors somewhat than to yield of the fasteners.

The main or macro effects of alignment zone is the poor alignment of the mating threads, bending together of mating parts, and bending of the fasteners to the fasteners under head surface. The micro effects are included of contacting stress defections of plating and coatings as well as surface and thread deformations. These two effects are shown in Figure 2.3.

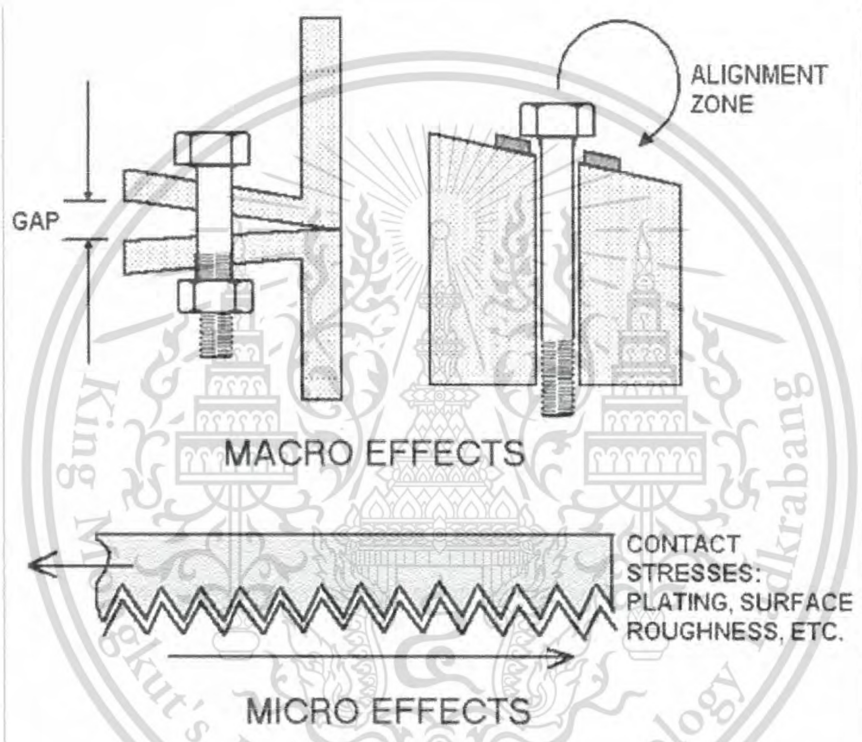


Figure 2.3 Alignment zone effect [8]

2.2.1.3 Where does the input or apply torque go?

The basic torque distribution for the screw fastening is shown in Figure 2.4. The input torque applied to a fastener is lost in three main areas of under head friction, thread friction, and clamping force. Under head friction may lost 50 percent or more of the total input torque. Thread friction lost as much as 40 percent of the input torque. The last lost 10 percent of the input torque is on the clamping force that holds the components together.

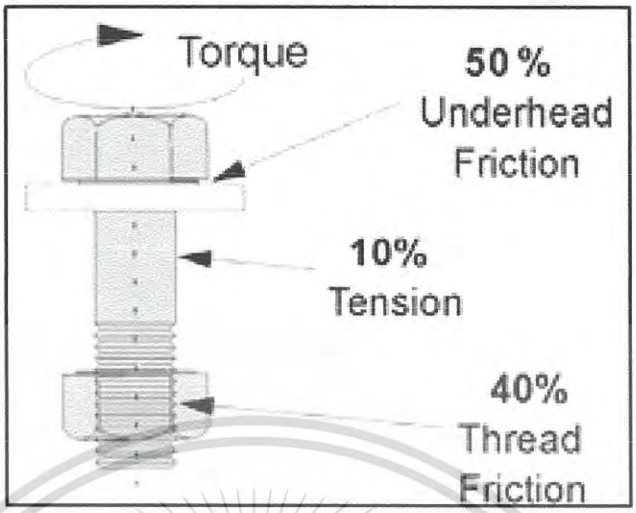


Figure 2.4 Where does the input torque go? [8]

Per earlier explanation, total energy required to tighten a screw fasteners are the area under the torque-angle curve. As shown in Figure 2.5, the above area 10 percent of the area on the curve is the elastic clamping energy that is providing the holding power to clamp the parts together. The elastic clamping energy shown on the torque-angle plot has the same value as the areas under the bolt and clamped component lines in the force-deformation diagram (Refer to Figure 2.9.)

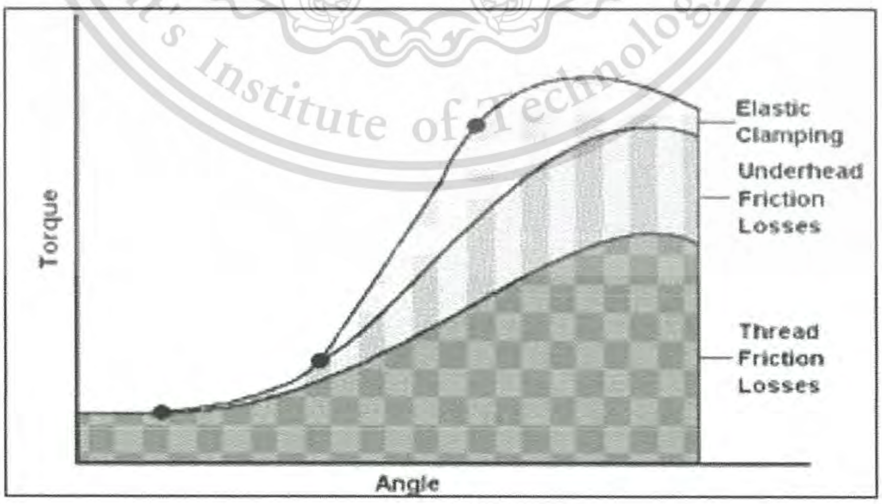


Figure 2.5 Where does the fastening energy go? [8]

The post-yield response can affect from the number of components clamping force are shown in Figure 2.6.

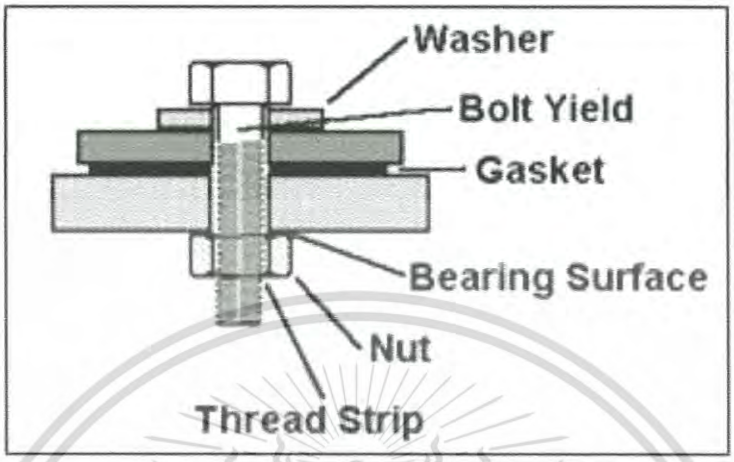


Figure 2.6 Sources of post-yield response [8]

2.2.1.4 Elastic torque-tension association

The basic elastic torque-tension as shown in Equation (2.1), is to use for the analysis to predict the associated magnitudes of torque and clamp force. This equation can determine a relationship between torque and tension which finally the models can be come out for the screw fastening process.

$$T = K \times D \times F \tag{2.1}$$

Where

T = Torque (lbf-in)

K = Nut Factor (Ranges from 0.03 to 0.35)

D = Nominal Diameter (inch)

F = Force (lb)

2.2.1.5 Stress/strain vs. torque/tension

The estimated equivalence of the stress-strain curve to the torque versus angle curve as shown in Figure 2.7 (Note that the alignment zone has been removed from the torque angle diagram). Deformation or damaging of the fasteners and angle of turn are geometrically associated by the following formula.

$$\delta = \frac{\alpha}{360} \times P \tag{2.2}$$

Where

δ = deformation

α = angle

P = pitch of thread

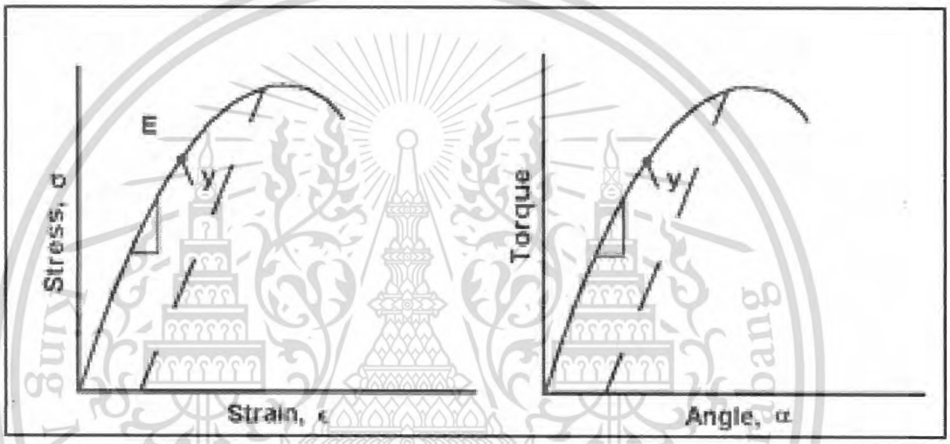


Figure 2.7 Association of stress-strain vs. torque-angle [8]

This association directly involves with the stress caused by total strain in the fasteners only when the fasteners are fastened on a joint with infinite stiffness. From further experiment, the tension generated can be shown to be directly to the angle of turn from the elastic origin. The elastic origin is located by projecting a line tangent to the elastic portion of the torque-angle curve backward to zero torque. The total angle of turn is equal to the compression of the clamped components plus the stretch of the fasteners as shown in Figure 2.8.

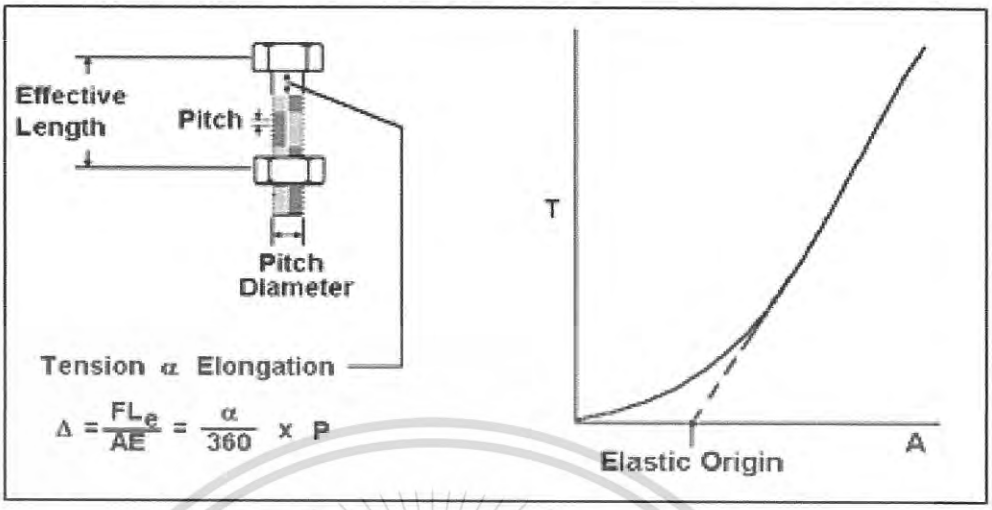


Figure 2.8 Angle of turn is proportional to clamp force [8]

2.2.1.6 Association of stress-strain and turn

The basic association of stress to strain in the elastic region is given by the following equation.

$$\sigma = \varepsilon \times E \tag{2.3}$$

Where

σ = Stress (psi)

ε = strain (in/in)

E = Young's Modulus (psi)

The following equation is calculated for the stretch of a bolt of metal rod loaded in tension.

$$\Delta = \frac{F \times L}{A \times E} \tag{2.4}$$

The below equation is the association of the Force Angle turn.

$$\frac{\Delta F}{\Delta \Theta} = \left(\frac{K_b K_c}{K_B K_C}\right) \frac{P}{360} \tag{2.5}$$

Where

K_B = bolt spring rate (lb/in)

K_C = joint spring rate (lb/in)

Taking the first derivative of the original equation (2.1), it gives the below association.

$$\Delta T = K \times D \times \Delta F or \Delta F = \frac{\Delta T}{K \times D} \tag{2.6}$$

As a result of substituting ΔF in the force-angle of turn equation in a torque-angle slope, the spring rate of bolted joints can be calculated approximately shown as the following equation.

$$\frac{\Delta T}{\Delta \Theta} = \left(\frac{K_B K_C}{K_{B+} K_C}\right) \frac{P \times K \times D}{360} \tag{2.7}$$

The spring rate of the bolt is approximated by the following equation.

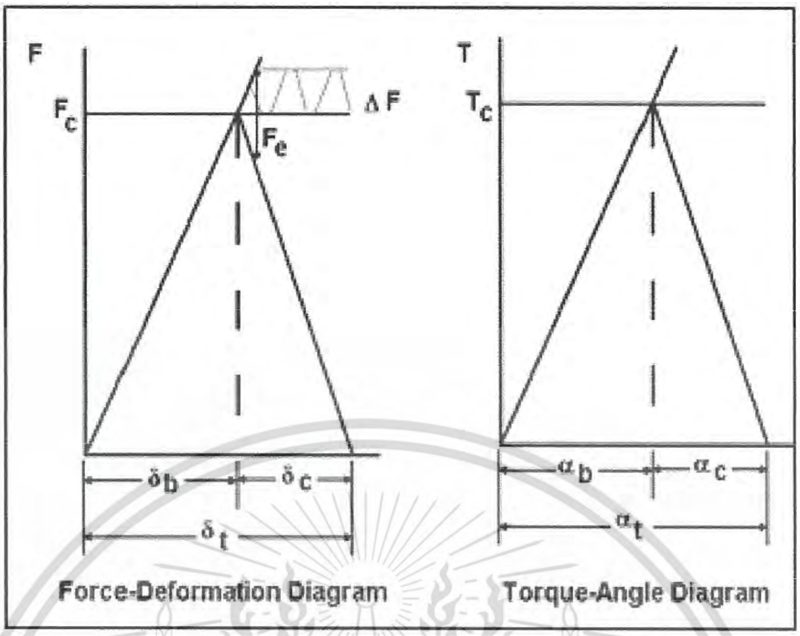
$$K_B = \frac{F}{\Delta} \frac{LB}{\varepsilon} = \frac{A \times E}{Le} \tag{2.8}$$

Then, the slope of the elastic clamping region of the torque-angle Curve, ΔT/ΔΘ, is defined from the curve. If a value for K is presumed, then the spring rate for the joint is calculated as following.

$$K_C = \frac{\Delta T / \Delta \Theta}{\frac{K \times D \times P}{360} \times K_B - \frac{\Delta T}{\Delta \Theta}} \times K_B \tag{2.9}$$

2.2.1.7 Forcer-deformation and torque-angle diagrams

The basic force-deformation diagram and a special torque angle diagram as shown in Figure 2.9 is the same as the association between the material torque-angle diagram and the stress-strain diagram. This special diagram shows the associate angular motion required to both stretch the fasteners and compress the joint. The factors defined in Figure 2.9.



Factor	Definition
δ_t	Total Elastic Deformation
δ_b	Bolt Stretch
δ_c	Parts Compression
α_t	Total Elastic Moment
α_b	Bolt Stretch Moment
α_c	Parts Compression Angle

Figure 2.9 Force-deformation and torque-angle diagrams [8]

2.2.1.8 Preload-preload efficiency factor

According to force-deformation diagram, the bolted joint feedbacks can be forecasted when involving to the external working loads. There are two key factors important to the analysis of the fatigue resistance safety factor, Preload efficiency factors, and clamped elements. Preload efficiency factor based upon the desirable spring rates of the bolt is determined using the following formula.

$$\Phi = \frac{K_B}{K_{B+}K_C} \tag{2.10}$$

The spring rate for the clamped components can be estimated from calculation by assuming the preload efficiency factor. The accuracy of the computed values for joint stiffness and clamping efficiency factor are dependent upon the degree of accuracy of the predicted value for K and the desirable length, L_e, predicted for the bolt. The preload efficiency factor can be predicted by computing the elastic angle of turn to stretch the bolt, α_b, and the angle of turn, α_c, over the same torque range needed to compress the joint.

$$\Phi = \frac{1}{1+\frac{ab}{ac}} \tag{2.11}$$

The preload efficiency factor, Φ, when multiplied by the external applied load, is used to compute the maximum change in bolt loading that can be suspected when an external load is input to the assembly.

2.2.1.9 Torque-tension association coefficient

The basic equation, as shown in Equation (2.1), applies to the linear elastic zone of the torque-angle fastening curve. The factor K, represented to as the nut factor, as three factors are combination: K_1, a geometric factor; K_2, a thread friction; and K3, an under head friction. Figure 2.10 shows the equation for each of factors. The friction coefficients μ_t and μ_c are key variables in the equation. While there are published tables for K, these are combined values. It is very important to determine the specific data on the under head and thread friction factors for further analysis or solving a particular problems or when designing special fasteners.

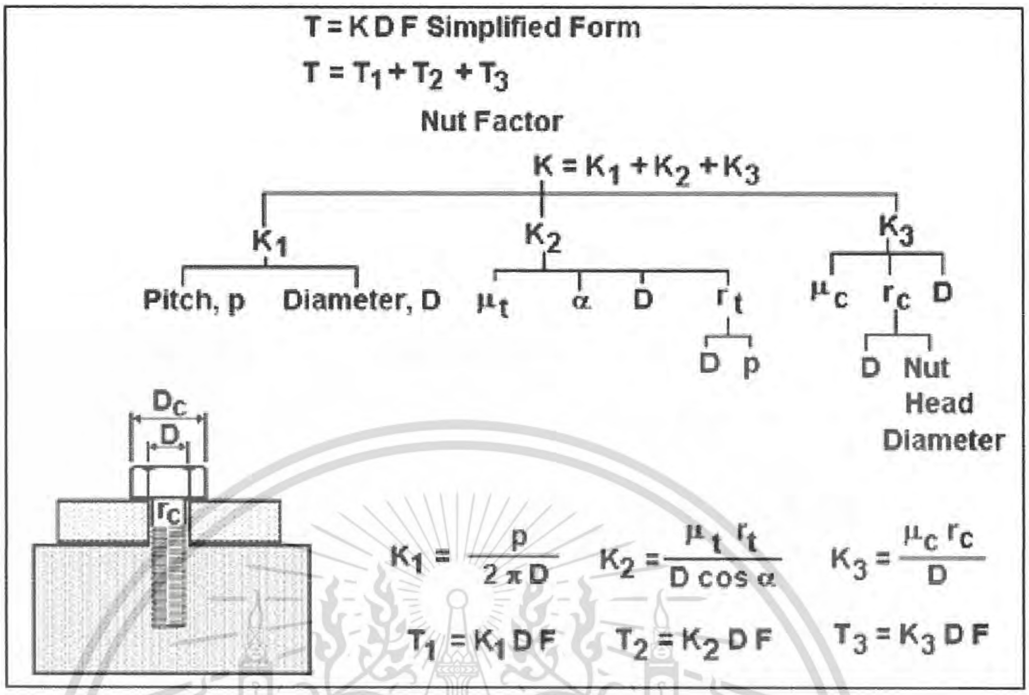


Figure 2.10 Frictional coefficients [8]

To measure for the frictional losses in the threads and under head area of fasteners, a specially designed torque-tension load cell which measures clamp force and thread torque will be used.

2.2.1.10 Thread/Under head friction measurements

In the advancement of fasteners locking components, such as, locknuts, serrated under heads, thread structures, or thread locking compounds, it is essential that intent to measure both thread friction and under head friction. The frictional characteristics in the thread and under head area are the areas essential to be controlled in order to ensure overall reliable performance or screw fasteners. During installation, the specific clamp force should be determined in the experiment in order to get the stable and data accuracy for further analysis.

Figure 2.11 shows a torque-tension research head in cross-section, it is a special load cell constructed to measure thread torque, T_G, and clamp load, F_V. It is used together with the measurement of the input torque, T_A, to determine the under head friction torque and the thread friction torque.

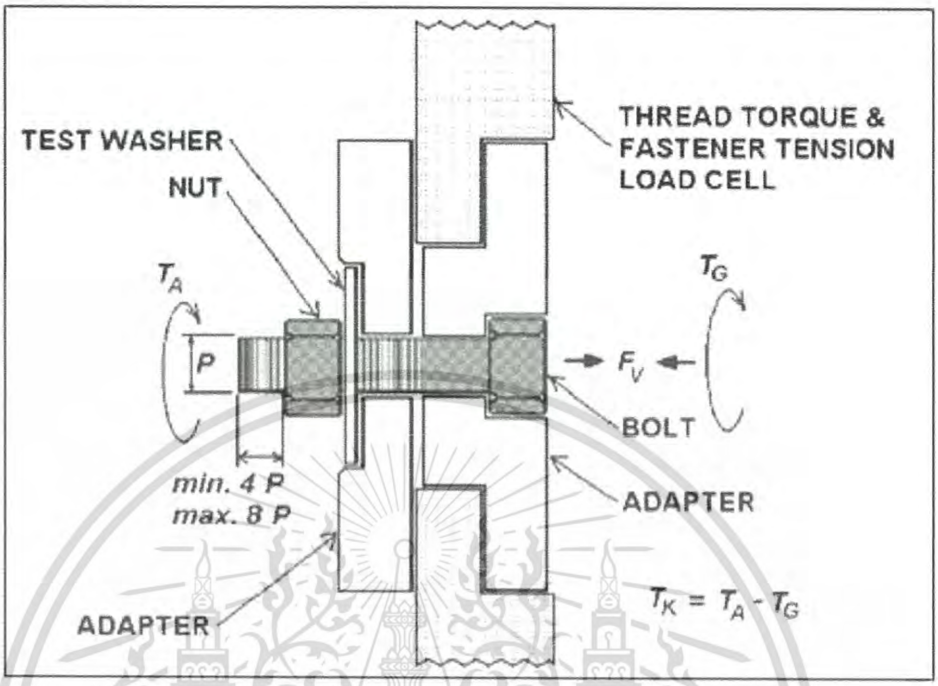


Figure 2.11 Torque-tension research head [8]

As clamp force is developed, the pitch torque is calculated and subtracted from the thread torque to compute the thread friction torque. Pitch torque = pitch x clamp Force/2X. The testing plot as shown in Figure 2.12, the locknut is initially driven onto a bolt the thread friction torque is equal to the input torque until contact with the under head-bearing surface is made. Once contact is made with the under head area, the under head friction torque is measured as the difference between the total input torque and the thread torque.

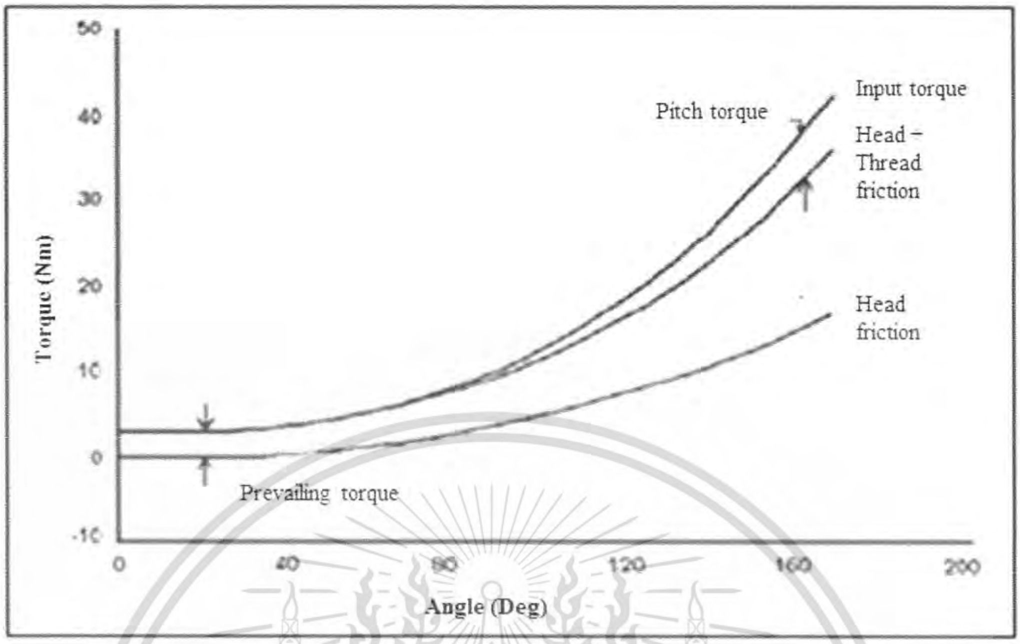


Figure 2.12 Determine frictional forces [8]

2.2.1.11 Automated fastening process

The capability of a fasteners to deliver torque is the primary criteria for selection of tools for critical assembly operations. The energy transfer and controlling the fasteners requirement are established by torque-angle curves. When applied the same input torque, the short stiff fasteners is less absorb than long flexible fasteners. With the same torque, the stiff-hard joints absorb less energy than stiff-soft joints. The various monitoring strategies include: torque monitoring, torque monitoring with control, torque angle monitoring, torque angle monitoring with control, torque rate monitoring and yield control (Variation of rate monitoring). All of these processes are dependent upon measurement of the dynamic torque or torque and angle profiles during the fastening process.

2.2.2 Part of a screw and a thread

A screw is an important device in fastening pieces together. Sometimes, screws are used to finely adjust gauges for better measurement. Fastening by the screws really appropriates in many kinds of appliance including small tools. Besides, screws are cheap and easy to use due to their standard sizes, easy for rework process, and make high effective production. However, there is a disadvantage in screw fastening. That is dense stress in crest and root area where are the weak points under the changing-force usage.

A thread is helical surface wrapping around a cylinder or cone. The helical surface is formed by a right triangle which has a base side AA_1 having the same length as the cylinder's circumference (πd), the height A, C = L as in the Figure 2.13, and the hypotenuse AC forms a thread on the cylinder surface. Then move this plane figure along the helical surface while the figure is still on axial sectional. The laterals of the plane figure will form the helical surface on the cylinder λ which is the angle between the triangle base and the hypotenuse called a circular thread, while the one on a cone is called a conic thread [4].

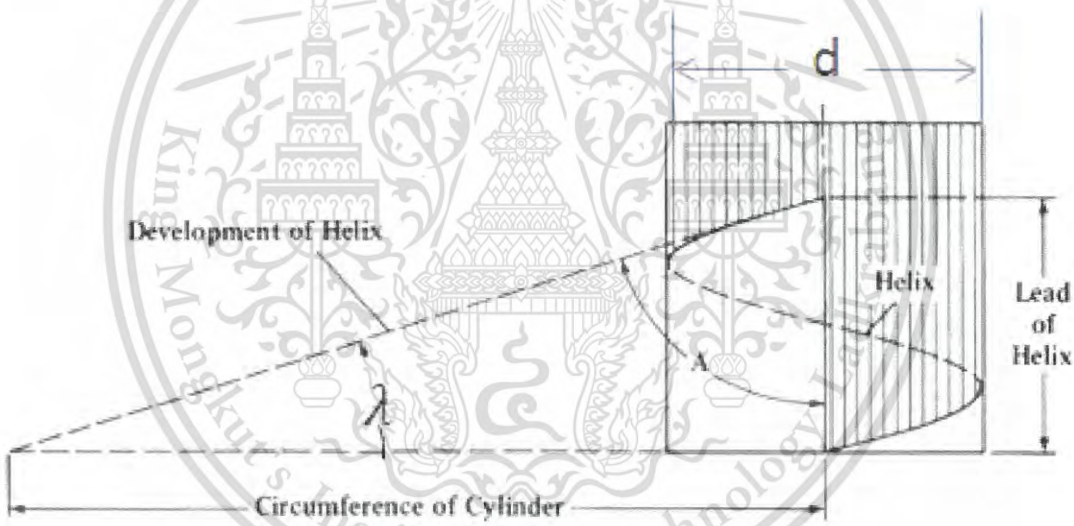


Figure 2.13 Characteristics of a thread [4]

A part of a screw and a thread can be defined and shown in Figure 2.14.

Pitch (p) is the width from one crest to next crest, measured as the number of threads per inch.

Major diameter (d) is the widest diameter on a thread.

Minor diameter (d_r or d_1) is the narrowest diameter on a thread.

Pitch diameter (d_p or d_2) is the diameter between the major and minor diameter.

Lead (L) is the distance parallel to the axis when the screw is turned one resolution.

Thread angle (2α) is the angle occurring between the sides of a thread.

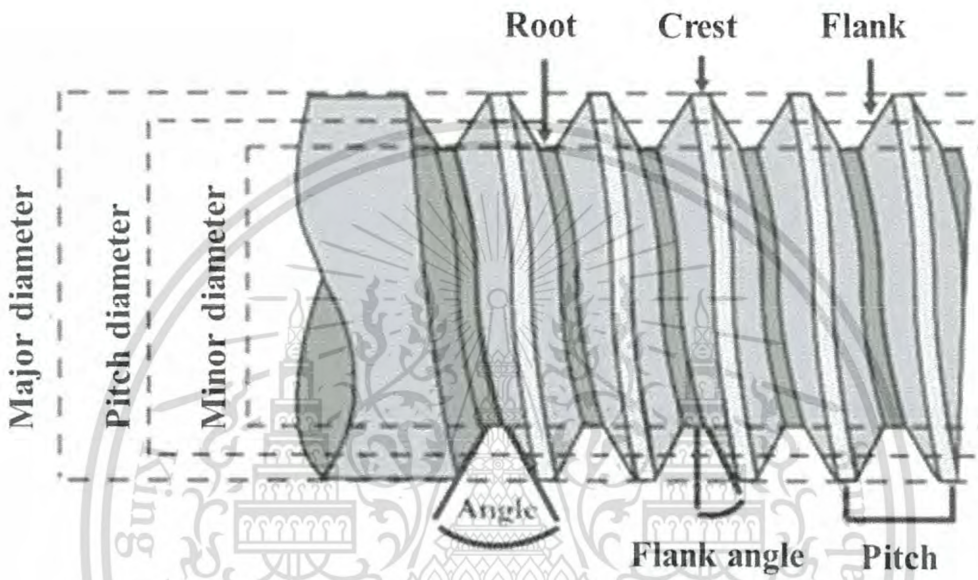


Figure 2.14 Parts of a screw [13]

2.3 Design of experiments (DOE)

Design of experiments (DOE) capabilities provide a method for simultaneously investigating the effects of multiple variables on an output variable (Response). These experiments consist of the series of runs, or tests, in which purposeful changes are made to input variables or factors, and data are collected at each run. DOE method is a systematic approach to modeling and optimizing a process. A response surface method (RSM) was selected for experiment designing and data analysis. RSM is a set of advanced design of experiments (DOE) techniques that help for better understanding and optimize the response. Response surface method is used to examine the relationship between one or more response variables and a set of quantitative experimental variables or factors. These methods are often employed after a "vital few" controllable factors have been identified and the factor settings that optimize the response are required to be determined. Design of this type is usually chosen when the suspect curvature is in the response surface. Response surface methods may be employed to find factor settings (Operating conditions) that produce the best responses, find factor settings that satisfy operating or process specifications.

2.3.1 Design of experiment – General model

The design of experiment is to make a meaningful modification of the inputs or factors into the process of product to obtain the desirable changes of the outputs or responses as shown in Figure 2.15. Noise is variables that affect product or process performance, those values cannot be controlled or are not controlled for economic reasons.

Figure 2.15 General model of design of experiment [9]

2.3.2 Design of experiment – Terminology

2.3.2.1 Responses are variables of interest in an experiment (Those are measured or observed) which depends on the input or factors.

2.3.2.2 Predictor, Explanatory or Independent variables are other variables in the experiment which are not responses, but they can be measured by the experimenter.

2.3.2.3 Factors can be a categorical variable or a continuous variables. Experimenters select factors and factor level to vary purposely in the experiment in order to determine the effect of the responses. Factors are limited to only some numbers, known as factor levels.

2.3.2.4 Treatment is a set of specified factor levels of an experiment

2.3.2.5 Noise is the variables that impacts to the responses, whose values cannot be controlled or are not controlled for financial purposes.

2.3.2.6 Main effect or Main effect plot are used together with an analysis of variance and design of experiments to examine differences among level means for one or more factors. A main effect is used the response are varied differently according to the different levels of a factor. The line which is connected together each factor level in the main effect plot graph is the mean of the response. When this connected line is horizontal or parallel to the x-axis, it means no main effect involved. This can be further explained that each level of the factor affects the response in the same way, and the response mean is the same across all factor levels. When the line is not horizontal, then there is a main effect present. That means different levels of the factor affect the response differently. The steeper the slope of the line, the greater the magnitude of the main effect.

2.3.2.7 An interaction plot is a plot of means for each level of a factor with the level of a second factor held constant. The interaction plot can be created from two factors, called a single interaction plot. A matrix of interaction plots are created by a single interaction plot from three to nine factors combined together. Interaction plot is the useful tool to analyze if any two factors are interacted together.

2.3.2.8 Surface plot is used to examine how the fitted response relates to two continuous variables. A response surface model is used to create either a response surface plot for a single pair of variables or separate surface plots for all possible pairs of variables. A surface plot can well explain for the three-dimensional relationship in two dimensions. The variables are on the x and y axis, and the response variables are on the z axis display in a smooth surface.

2.3.2.9 Contour plot is used to examine the potential relationship between three variables. The contour plot displays the three-dimensional relationship in two dimensions. The graphical contour plot is formed by x and y factors plotted on the x and y axis, and z (Response) on the contour line.

2.4 Response surface method (RSM)

Response Surface Method (RSM) is used to explain the relationship between the response and the control factors. A sequence of design of experiments are used for optimizing the process or product by starting from current operating conditions and moving towards the optimum condition where the response is either maximized or minimized. The spot on the response surface, such as, the current setting condition if is far from the optimum condition, the curvature is often slightly. On the case as this, a first-order model will be adequate. The second order model will be necessary to help find a more exact location of the peak in the region of the optimum.

2.4.1 Type of second order models [9]

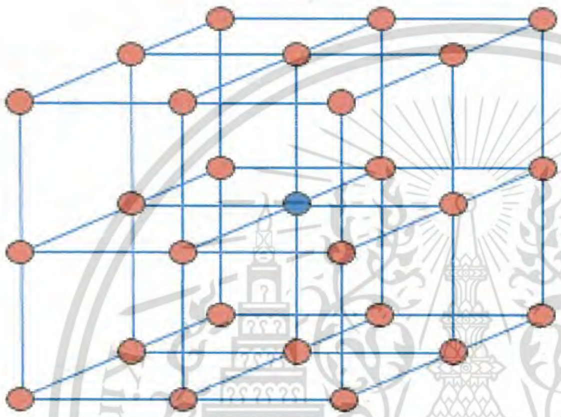
2.4.1.1 3^k Full Factorial Design

2.4.1.2 Box-Behnken Design

2.4.1.3 Central Composite Design (CCD)

2.4.1.1 3^k full factorial design

3k full factorial design; 3 is a number of factor level and k is a number of factor. It means that k factors are considered, each at 3 levels. The responses of 3^k Full Factorial are measured at all combinations of the experimental factor levels. Each experimental condition is called a run and the response is measured on each run. The entire set of runs is the design of experiment. The following diagrams show three factor and three factor level design. Each points is the unique combinations of factor levels. The example below shows total of 27 runs which each points of red color represents an experimental run. All combinations of factor levels will be set up and run the experiment as shown in Figure 2.16.



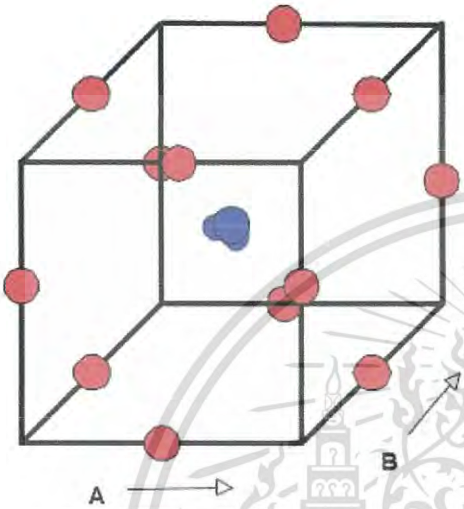
StdOrder	A	B	C
1	1	1	1
2	1	1	2
3	1	1	3
4	1	2	1
5	1	2	2
6	1	2	3
7	1	3	1
8	1	3	2
9	1	3	3
10	2	1	1
11	2	1	2
12	2	1	3
13	2	2	1
14	2	2	2
15	2	2	3
16	2	3	1
17	2	3	2
18	2	3	3
19	3	1	1
20	3	1	2
21	3	1	3
22	3	2	1
23	3	2	2
24	3	2	3
25	3	3	1
26	3	3	2
27	3	3	3

Figure 2.16 3^k Full Factorial Design [9]

The 3^k full factorial is very useful. It is able to estimate all linear and quadratic effects as well as all simple and higher order interactions. The only disadvantages is the number of run is excessive which concerns to cost and effort. This method is chosen for this experiment studying on disk clamp screw torque optimization.

2.4.1.2 Box-Behnken design

Box-Behnken design is the combinations of treatment where each factor is at the midpoints of the edges of the experimental space. Box-behnken design requires at least three factors. As shown example below in Figure 2.17 shows total of 15 runs, a three-factor Box-Behnken design which each points represents the experimental runs. These designs allow efficient estimation of the first-order and second-order coefficients. With the same number of factors, Box-Behnken design have fewer runs which will be less expensive comparing to the Central Composite Designs. However, because Box-Behnken design does not contain an embedded factorial or fractional factorial design, it is not suited for sequential experiments.



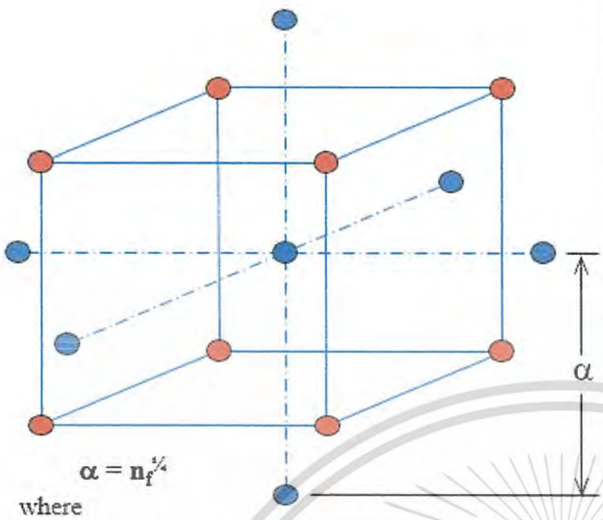
Run	A	B	C
1	-1	-1	0
2	1	-1	0
3	-1	1	0
4	1	1	0
5	-1	0	-1
6	1	0	-1
7	-1	0	1
8	1	0	1
9	0	-1	-1
10	0	1	-1
11	0	-1	1
12	0	1	1
13	0	0	0
14	0	0	0
15	0	0	0

Figure 2.17 Box-Behnken design [9]

The advantages of Box-Behnken are able to estimate all main effects, 2-way interactions and pure quadratic terms. Besides, it requires less runs compared to 3k Factorial Designs and useful when curvature is known to exist. However, it cannot be built-up from a 2 level factorial design, and usually performed as a non-sequential experiment.

2.4.1.3 Central composite design (CCD)

Central composite design is the most commonly used response surface method. Central composite design consists of a factorial or fractional factorial design with center points, adding a group of axial points that the curvature can be estimated. Central composite design can be used efficiently to estimate first and second order terms. It is especially useful in sequential experiments because the previous factorial experiments can be utilized and build on by adding axial and center points as shown in Figure 2.18.



$\alpha = n_f^{1/4}$

where

$n_f^{1/4}$ is number of run in factorial portion of CCD

α is a rotatability where is a number of set $(n_f)^{1/4}$

Run	A	B	C
1	-1	-1	-1
2	1	-1	-1
3	-1	1	-1
4	1	1	-1
5	-1	-1	1
6	1	-1	1
7	-1	1	1
8	1	1	1
9	-1.682	0	0
10	1.682	0	0
11	0	-1.682	0
12	0	1.682	0
13	0	0	-1.682
14	0	0	1.682
15	0	0	0
16	0	0	0
17	0	0	0
18	0	0	0
19	0	0	0
20	0	0	0

Figure 2.18 Central composite design (CCD) [9]

Rotatability (α) is a desire design proper; In order to satisfy rotatability, α will take value greater than 1. The value of α is set of $(n_f)^{1/4}$ which n_f is the number of runs in the factorial portion of the design. These value are chosen to produce rotatability, which simplify implies that the predicted response is capable of being estimate with equal of variance. [9]

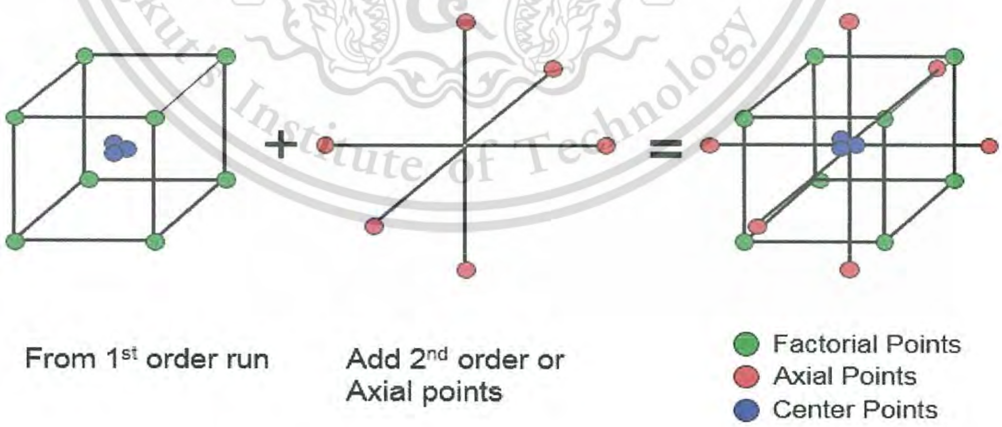


Figure 2.19 Compare 1st and 2nd of central composite design (CCD) [9]

The advantages of central composite design (CCD) are able to estimate all factors affected, and selected quadratic effects and interaction. The disadvantages is that each factor need to be at 5 levels and some axial points may be in non-desirable conditions.

Chapter III
Research Methodology

The most recent assembly on the screw fastening process has been reviewed. The previous studies were really helpful in understanding the principles and the advantages of the fasteners. The key fasteners parameters setting that affected to the final screw torque, such as, input torque, number of screws, datum pins, washer, holding force, size of the screw, work piece material, screw head geometry, linear speed of the positioning system manipulate the driver, the parts-coating lubricant characteristics and all parameters as shown in Figure 2.10. From the previous researches all these factors have been studied but they had not been studied in hard disk drive process. Therefore, the purpose of this research was to study the factors that affect to the disk clamp screw torque in hard disk drive by performing an experiment and using design of experiment (DOE) method. It could provide a better understanding for the accuracy of disk clamp screw torque by screw fastening process. There were three interesting factors were the preliminary torque at media installation, input torque parameter and gain control at auto-gang-bias installation.

3.1 Materials to support the experiment

In order to minimize variation of the material characteristic or dimensions, the same vendor, shipment and built date were selected. There were 81 sets of material preparation to support the experiment as following details.

1. Motor Base Assembly (MBA) 81 pieces

2. Media Disk 162 pieces

3. Disk Clamp 81 pieces

4. Spacer 81 pieces

5. Screw 81 pieces

3.2 Calibration and GR&R of instruments

The reading value of disk clamp screw torque in Hard Disk Drive (HDD) 2.5" was very problematic because the disk clamp screw torque was very low value and the current measurement tool was manually operated by an operator. So, it was difficult to find an accurate and precise value reading. To enhance in the measurement before starting the experimental study, a forward torque of 2.5" product was developed in order to measure disk clamp screw torque by using the laser sensor to detect screw slipping. It could solve the human error when reading the value on a panel.

The calibration and gage repeatability and reproducibility (GR&R) of measurement system had been qualified and passed per the guideline of Automotive Industry Action Group (AIAG). For more details of the qualification are in Appendix A.

3.3 Experiment setup

There are 3 factors which all of them are variable data, 3 levels at each of factors. An experimental design involves making purposeful changes of the inputs (Pre-torque, Input torque and Gain) to a HDD screw fastening in order to observe the corresponding changes in the outputs (Disk clamp screw torque) as shown in Figure 3.1.

To predict and optimize the disk clamp screw torque with the settings of preliminary torque, input torque and gain at screw fastening process. Product 2.5" at Western Digital (Thailand) Company Limited was demonstrated and studied the effect of disk clamp screw fastening at MI and AGB Installation. Machines were dedicated for this studying and optimization of the final disk clamp screw torque in hard disk drive.

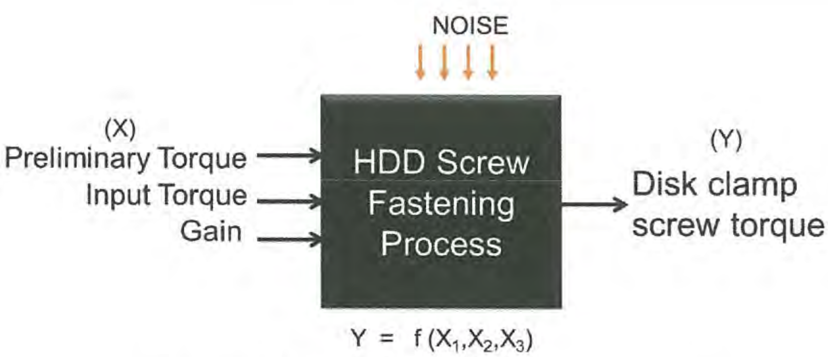


Figure 3.1 DOE model of disk clamp screw torque

Disk clamp screw torque is purposed to secure the magnetic disc by screw fastening to a spindle hub on a disc drive motor base assembly (MBA). The screw fastening is a mechanism to apply torque by rotating the tip, and position to support the fastening which can be either by manual screw fastening or by an electric motor or other motor. The manual screw fastening is a typical method which use human hand to control the cylindrical handle. The axial shaft of cylindrical handle is fitted to the head or tip of a specific type of screw. The manual screw fastening can be positioned and supported when rotated to apply torque.

To investigate the parameters of preliminary torque, input torque and gain that affect to disk clamp screw torque by using DOE method. The factor and factor level were defined as following;

Preliminary torque at MI is the given amount of torque applied preliminarily to hold the components together before sending the drive to AGB for final disk clamp screw torque assembly. The range setting of this experiment was between 0.80 – 1.20 lbf-in, the factor level were setting 0.80, 1.00 and 1.20 lbf-in respectively, and the low level of preliminary could not set below 0.80 lbf-in because the screw could not hold the set of pack disks with the motor hub. Also the high level of preliminary could not set higher than 1.20 lbf-in because it was difficult to reverse screw before fastening screw at AGB (At AGB, screw fasteners reverse screw a bit before screw fastening in order to balance the media). The middle of preliminary torque was 1.0 lbf-in that was the normal production setting.

Input torque at AGB is the given amount of torque applied to motor speed of the screw fasteners at AGB in order to tighten the final disk clamp screw torque. The input torque setting usually reduced after transmission to the output. The range setting of this experiment was between 1.40 – 2.40 lbf-in, the factor level were setting at 1.40, 1.90 and 2.40 lbf-in respectively, and the lowest and highest level setting of the input torque were AGB machine capability. The middle of input torque setting was 1.90 Lbf-in that was the normal production setting.

Gain (ampere) is a current which applied to motor speed of screw fasteners at AGB in order to tighten the final disk clamp screw torque. The range setting of this experiment was between 0.50 – 0.90 ampere, the factor level were setting at 0.50, 0.70 and 0.90 ampere respectively, and the low level of gain could not set below 0.50 ampere that could cause screw high or gap between disk clamp and under head of screw head. The maximum setting of this model was 1 ampere but the high level of this gain was setting at 0.90 ampere for safety factor that recommended by machine expertise. The middle of the gain was 0.70 ampere that was the normal production setting.

The factor and factor level of the experiment were shown in Table 3.1, to plan the testing conditions.

Table 3.1 The factor and level for the experiment

Factor/Level	Pre-torque (lbf-in)	Input torque (lbf-in)	Gain (Ampere)
Level 1	0.8	1.4	0.5
Level 2	1.0	1.9	0.7
Level 3	1.2	2.4	0.9

Before analyzing the result of data in Minitab, firstly an experimental design must be created and stored in a worksheet. Based on the design of experiment, the experimental ran include all 81 combinations of data set. Three replications of experiment were conducted to provide more precise estimation of mean level effects and provided a relatively reliable estimation of experimental error.

Chapter IV
Result and Data Analysis

An experiment setup, result and data analysis of this study were performed at Western Digital Bangpa-in plant. The DOE analysis was done using the commercially available "Minitab" software. In this section, statistical and graphical of DOE tools, such as, the main effect plots, interaction plots, contour plots, response optimizer, regression and residual plots analysis were used for the investigation. It is so that appropriate of experiment set up and data analysis could be collected and analyzed.

4.1 Experiment Result

In order to achieve the appropriate experimental design, data collection and data analysis the second-order model of 3^k full factorial design of response surface method (RSM) would become necessary for testing the conditions. The result of disk clamp screw torque based on the experiment design conditions were shown in Table 4.1.

Table 4.1 Experiment setup and results of disk clamp screw torque

Replication	Run	Pre-torque (lbf-in)	Input torque (lbf-in)	Gain (Ampere)	Disk Clamp screw-torque (lbf-in)
1	1	0.8	1.4	0.5	1.25
1	2	0.8	1.4	0.7	1.30
1	3	0.8	1.4	0.9	1.35
1	4	0.8	1.9	0.5	1.70
1	5	0.8	1.9	0.7	1.75
1	6	0.8	1.9	0.9	2.20
1	7	0.8	2.4	0.5	1.65
1	8	0.8	2.4	0.7	1.75
1	9	0.8	2.4	0.9	1.85

1	10	1.0	1.4	0.5	1.25
1	11	1.0	1.4	0.7	1.35
1	12	1.0	1.4	0.9	1.35
1	13	1.0	1.9	0.5	2.20
1	14	1.0	1.9	0.7	2.20
1	15	1.0	1.9	0.9	2.25
1	16	1.0	2.4	0.5	2.20
1	17	1.0	2.4	0.7	2.25
1	18	1.0	2.4	0.9	2.35
1	19	1.2	1.4	0.5	1.20
1	20	1.2	1.4	0.7	1.25
1	21	1.2	1.4	0.9	1.30
1	22	1.2	1.9	0.5	1.75
1	23	1.2	1.9	0.7	1.85
1	24	1.2	1.9	0.9	1.90
1	25	1.2	2.4	0.5	2.25
1	26	1.2	2.4	0.7	2.30
1	27	1.2	2.4	0.9	2.35
2	28	0.8	1.4	0.5	1.35
2	29	0.8	1.4	0.7	1.40
2	30	0.8	1.4	0.9	1.50

2	31	0.8	1.9	0.5	1.65
2	32	0.8	1.9	0.7	1.75
2	33	0.8	1.9	0.9	1.95
2	34	0.8	2.4	0.5	2.15
2	35	0.8	2.4	0.7	2.35
2	36	0.8	2.4	0.9	2.25
2	37	1.0	1.4	0.5	1.25
2	38	1.0	1.4	0.7	1.35
2	39	1.0	1.4	0.9	1.45
2	40	1.0	1.9	0.5	1.75
2	41	1.0	1.9	0.7	1.85
2	42	1.0	1.9	0.9	1.95
2	43	1.0	2.4	0.5	2.25
2	44	1.0	2.4	0.7	2.25
2	45	1.0	2.4	0.9	2.35
2	46	1.2	1.4	0.5	1.35
2	47	1.2	1.4	0.7	1.40
2	48	1.2	1.4	0.9	1.45
2	49	1.2	1.9	0.5	1.65
2	50	1.2	1.9	0.7	1.75
2	51	1.2	1.9	0.9	1.85

2	52	1.2	2.4	0.5	2.15
2	53	1.2	2.4	0.7	2.30
2	54	1.2	2.4	0.9	2.35
3	55	0.8	1.4	0.5	1.10
3	56	0.8	1.4	0.7	1.20
3	57	0.8	1.4	0.9	1.30
3	58	0.8	1.9	0.5	1.50
3	59	0.8	1.9	0.7	1.60
3	60	0.8	1.9	0.9	1.60
3	61	0.8	2.4	0.5	2.00
3	62	0.8	2.4	0.7	2.10
3	63	0.8	2.4	0.9	2.10
3	64	1.0	1.4	0.5	1.20
3	65	1.0	1.4	0.7	1.20
3	66	1.0	1.4	0.9	1.20
3	67	1.0	1.9	0.5	1.60
3	68	1.0	1.9	0.7	1.80
3	69	1.0	1.9	0.9	1.70
3	70	1.0	2.4	0.5	1.90
3	71	1.0	2.4	0.7	1.95
3	72	1.0	2.4	0.9	1.95

3	73	1.2	1.4	0.5	1.20
3	74	1.2	1.4	0.7	1.30
3	75	1.2	1.4	0.9	1.25
3	76	1.2	1.9	0.5	1.85
3	77	1.2	1.9	0.7	1.75
3	78	1.2	1.9	0.9	1.75
3	79	1.2	2.4	0.5	2.10
3	80	1.2	2.4	0.7	2.15
3	81	1.2	2.4	0.9	2.10

4.2 Data analysis

In this section, statistical and graphical of DOE tools, such as, the main effect plots, interaction plots, contour plots, response optimizer were used for the investigation. Use the results from the fitted model and graphs to understand which factors were important for disk clamp screw torque.

4.2.1 DOE session window result

A session window displays the text output of the statistical test results and related notes or error messages. Both the session window output and the graphical plots are used to determine which effects were important to the disk clamp screw torque.

Response surface regression: Disk clamp torque versus pre-torque, input-torque, gain. The analysis was done using coded units. Estimated the regression coefficients for result-torque.

```
Term                         Coef   SE Coef       T      P
Constant                  1.86420   0.04582  40.689  0.000
PreTorque                 0.04074   0.02121   1.921  0.059
InputTorque               0.41944   0.02121  19.777  0.000
Gain                      0.06481   0.02121   3.056  0.003
PreTorque*PreTorque      -0.05926   0.03673  -1.613  0.111
InputTorque*InputTorque  -0.10093   0.03673  -2.747  0.008
Gain*Gain                -0.00926   0.03673  -0.252  0.802
PreTorque*InputTorque     0.05278   0.02597   2.032  0.046
PreTorque*Gain           -0.02639   0.02597  -1.016  0.313
InputTorque*Gain          0.00000   0.02597   0.000  1.000
```

```
S = 0.155850    PRESS = 2.21702
R-Sq = 85.53%  R-Sq(pred) = 81.39%  R-Sq(adj) = 83.69%
```

Analysis of variance for Result-Torque

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	10.1903	10.1903	1.13226	46.62	0.000
Linear	3	9.8169	9.8169	3.27230	134.72	0.000
PreTorque	1	0.0896	0.0896	0.08963	3.69	0.059
InputTorque	1	9.5004	9.5004	9.50042	391.14	0.000
Gain	1	0.2269	0.2269	0.22685	9.34	0.003
Square	3	0.2481	0.2481	0.08270	3.40	0.022
PreTorque*PreTorque	1	0.0632	0.0632	0.06321	2.60	0.111
InputTorque*InputTorque	1	0.1833	0.1833	0.18335	7.55	0.008
Gain*Gain	1	0.0015	0.0015	0.00154	0.06	0.802
Interaction	3	0.1253	0.1253	0.04178	1.72	0.171
PreTorque*InputTorque	1	0.1003	0.1003	0.10028	4.13	0.046
PreTorque*Gain	1	0.0251	0.0251	0.02507	1.03	0.313
InputTorque*Gain	1	0.0000	0.0000	0.00000	0.00	1.000
Residual Error	71	1.7245	1.7245	0.02429		
Lack-of-Fit	17	0.1545	0.1545	0.00909	0.31	0.995
Pure Error	54	1.5700	1.5700	0.02907		
Total	80	11.9149				

From above data analysis, the model of disk clamp screw torque is

$$\textit{Disk clamp screw torque} = 1.8642 + (0.0407 \times PT) + (0.4194 \times IT) + (0.0648 \times G) - (0.0593 \times PT \times PT) - (0.1009 \times IT \times IT) - (0.0093 \times G \times G) + (0.0528 \times PT \times IT) - 0.0264 \times PT \times G) \quad (4.1)$$

4.2.2 DOE main effect plot

A main effects plot is a plot of the average data at the various levels of each factor for comparing magnitudes of the main effects. To plot average data to compare multiple factors, with a reference line drawn at the grand the average of the response data. The main effect plot for disk clamp screw torque on these 3 factors are preliminary torque, input torque and gain control as shown in Figure 4.1.

Figure 4.1 (Top left) displays the disk clamp screw torque that completely remained when moving from the low level to the high level of preliminary torque factor.

Figure 4.1 (Top right) displays the disk clamp screw torque that significantly increasing when moving from the low level to the high level of input torque factor.

Figure 4.1 (Bottom left) displays the disk clamp screw torque that slightly increasing when moving from the low level to the high level of gain factor.

Therefore, the input torque is the most significant effect while the gain is slightly significant effect but the preliminary torque is insignificant effect to the disk clamp screw torque.

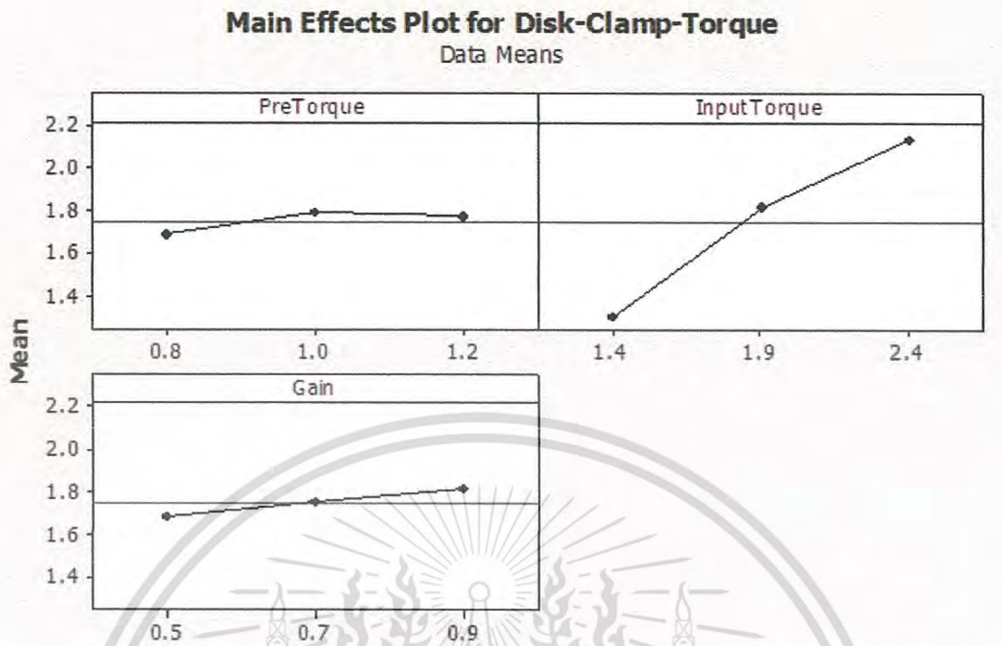


Figure 4.1 Main effect plot for disk clamp screw torque

4.2.3 DOE interaction plot

An interactions plot is a plot of the average data at the various levels of each factor for comparing the relative strength of the effects across factors. An interaction between factors will be occurred when the change in the result from the low level to the high level of one factor is not the same as the change in the result at the same two levels of the other factors. The interaction plot for disk clamp screw torque on these three factors are shown in Figure 4.2.

Figure 4.2 (Top left) shows slightly interaction between preliminary torque and input torque. The change in disk clamp screw torque when moving from the low level to the high level of preliminary torque is slightly different in magnitude of increasing at each level of Input torque.

Figure 4.2 (Top right) does not show interaction between preliminary torque and gain. The change in disk clamp screw torque when moving from the low level to the high level of preliminary torque is about the same among three levels of gain.

Figure 4.2 (Bottom right) does not show interaction between input torque and gain. The change in disk clamp screw torque when moving from the low level to the high level of input torque is about the same among increasing or parallel with three levels of gain.

Therefore, only preliminary torque and input torque are an interaction together. Although preliminary torque is insignificantly different on the main effect plot as shown in Figure 4.2. It is also needed a proper control in order to get optimal disk clamp screw torque.

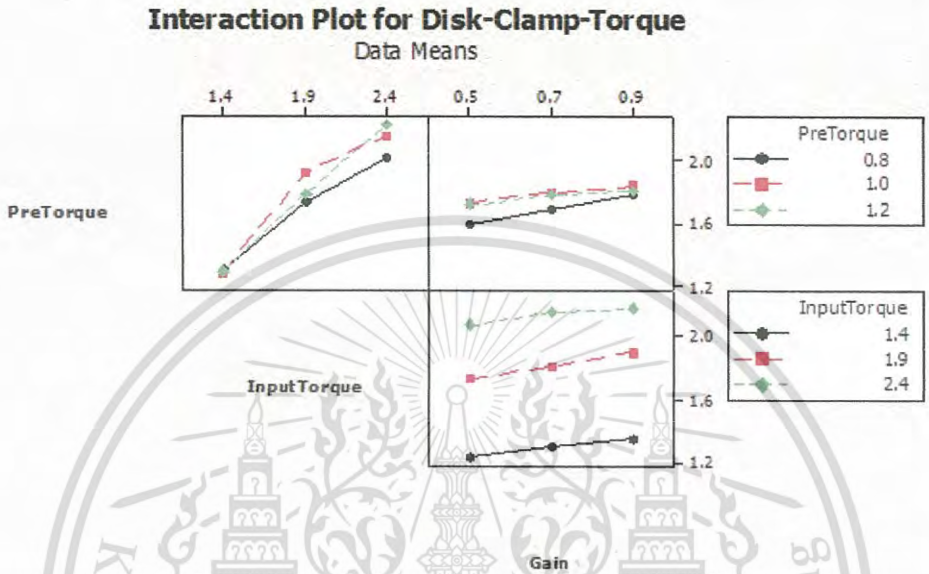


Figure 4.2 Interaction plot for disk clamp screw torque

4.2.4 DOE contour plot and surface plot

Contour and surface plot are useful establishing desirable response values and factors setting conditions.

1. A contour plot provides a two-dimensional view where use to explore the potential association between response value and variable factors.

2. Surface plot provides 3 dimensional that should provide clearer picture of response value and variable factors.

Figure 4.3 and Figure 4.4 display the contour plot and surface plot of disk clamp screw torque that show positive relationship among disk clamp screw torque, preliminary torque, input torque and gain. A higher the final disk clamp screw torque are required high level setting of preliminary torque, input torque and gain.

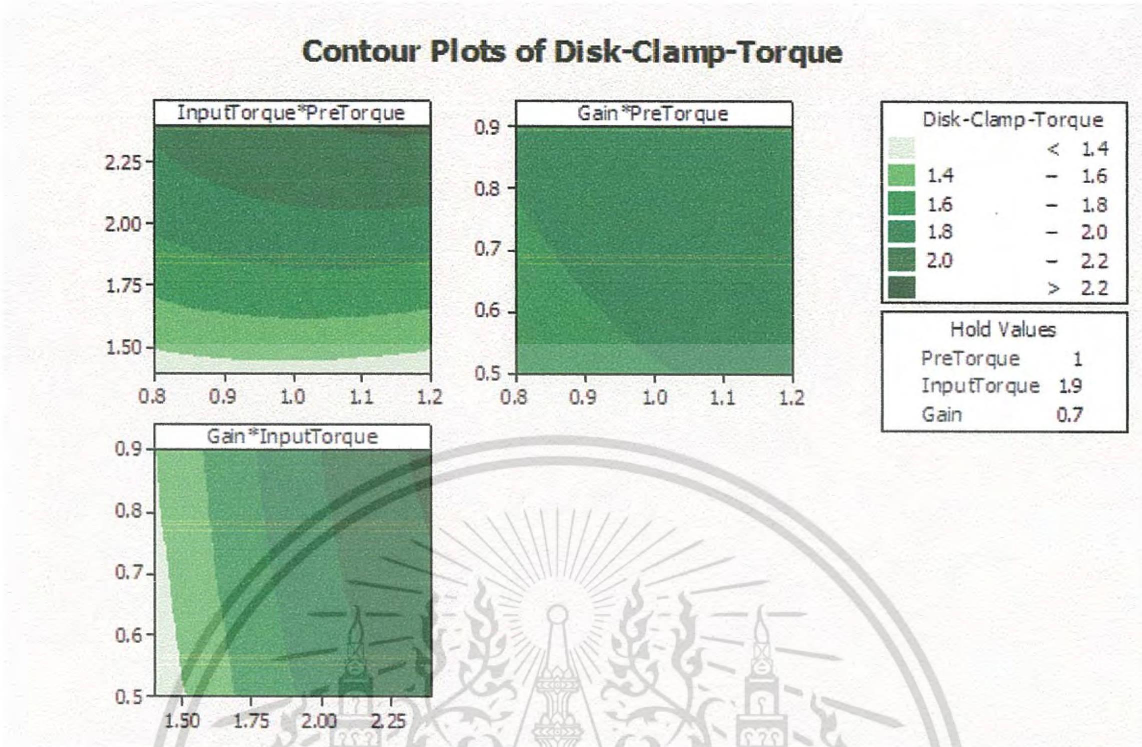


Figure 4.3 Contour plots for disk clamp screw torque vs input-torque and gain

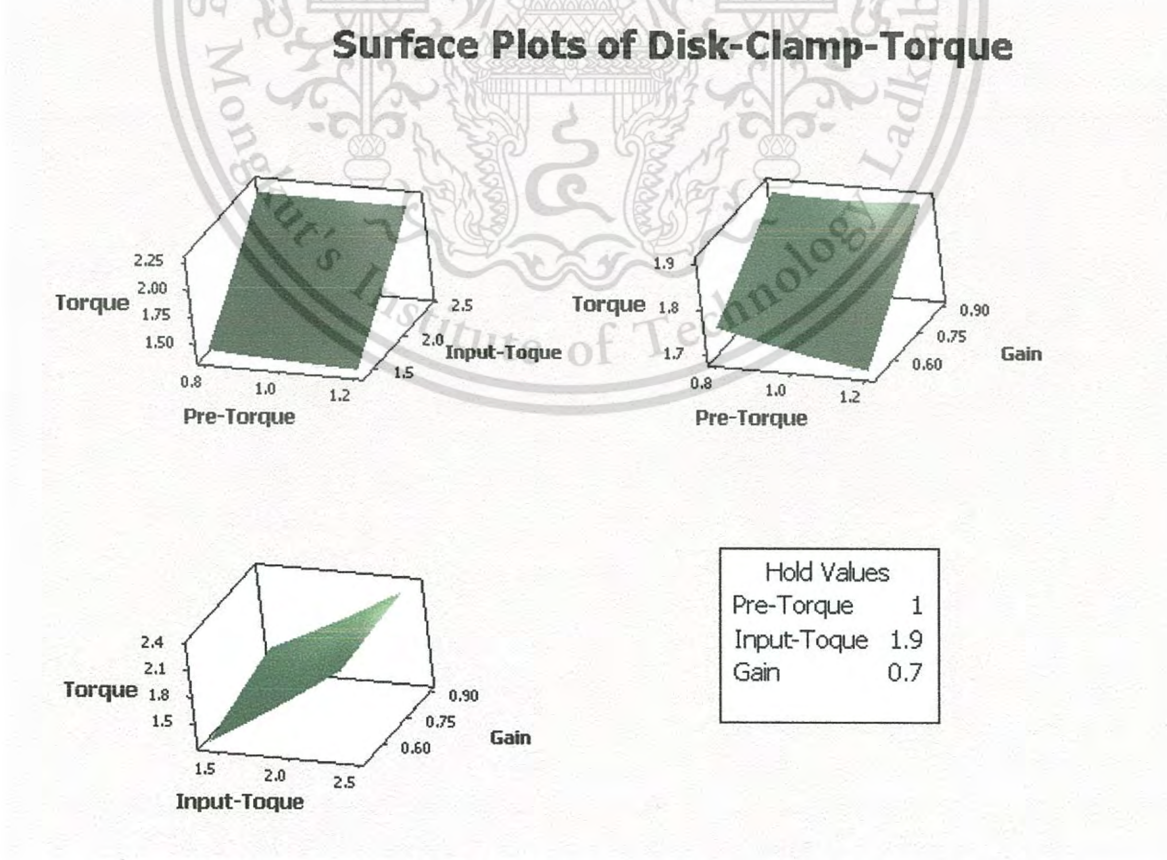


Figure 4.4 Surface plots for disk clamp screw torque vs input-torque and gain

4.2.5 DOE optimization and desirability function

The industry commonly utilized the useful technique of design of experiment for multiple inputs and outputs are to simultaneously optimize multiple input variables based on the quality concept that any inputs if are outside the required limits is absolutely unacceptable. Its approach is to convert the each response (y_j) into the desirability function that varies from zero to one ($0 \le d_i(y_j) \le 1$) and increases as the corresponding response value becomes more desirable [11]. Different desirability function $d_i(y_j)$ is obtained depending on whether the determined response, is to be maximized, minimized, or reached to a target value. The individual desirability $d_i(y_j)$ will be as follows: [12]

Target is the best (TB), the objective is min *($y_j(x)$-T_i)* or max *$d_i(y_j)$*

$$d_i(y_j) = \begin{cases} 0 & if\ y_j(x) \le L_i \\ \left(\frac{y_j(x)-L_i}{T_i-L_i}\right) & if\ L_i \le y_j(x) \le T_i \\ \left(\frac{y_j(x)-U_i}{T_i-U_i}\right) & if\ T_i \le y_j(x) \le U_i \\ 0 & if\ y_j(x) > U_i \end{cases} \tag{4.2}$$

Smaller better (SB), the objective is min *$y_j(x)$* or max *$d_i(y_j)$*

$$d_i(y_j) = \begin{cases} 1 & if\ y_j(x) < T_i \\ \left(\frac{y_j(x)-U_i}{T_i-U_i}\right) & if\ L_i \le y_j(x) \le U_i \\ 0 & if\ y_j(x) > U_i \end{cases} \tag{4.3}$$

Larger better (LB), the objective is max *$y_j(x)$*, or max *$d_i(y_j)$*

$$d_i(y_j) = \begin{cases} 0 & if\ y_j(x) < L_i \\ \left(\frac{y_j(x)-L_i}{T_i-L_i}\right) & if\ L_i \le y_j(x) \le T_i \\ 1 & if\ y_j(x) > T_i \end{cases} \tag{4.4}$$

Where $\mathbf{x}$ is the factors while y_j; j = 1, 2, .., n and d_i; i = 1, 2, .., m. The L_i and U_i are lower and upper specification of y_j, while T_i is target of specification, where $L_i \le T_i \le U_i$ respectively. The individual desirability (d_i) is then combined using the geometric mean, which gives the overall desirability D as shown in below function [11].

$$D = (d_1(y_1) \times d_2(y_2) \times \ldots \times d_m(y_m))^{1/m} \quad (4.5)$$

Where *m* denotes the number of responses, m = 1.

$$D = d_1(y_1) \quad (4.6)$$

Equation (4.2) is applied for the disk clamp screw torque due to target is best and two side of specification. The objective is to maximize $d_i(y_i)$ measured by the composite desirability (d) as following step:

1. After that the DOE method was employed to predict the relationship between these factors and disk clamp screw torque. The disk clamp screw torque (y_j) proportionally depends on the preliminary torque (X_1), the input torque (X_2) and gain (X_3) in the quadratic manner. To find the optimum setting parameters, mathematical statement can be shown as following.

$$y_j(x) = 1.8642 + (0.0407 \times X_1) + (0.4194 \times X_2) + (0.0648 \times X_3) - (0.0593 \times X_1 \times X_1) - (0.1009 \times X_2 \times X_2) - (0.0093 \times X_3 \times X_3) + (0.0528 \times X_1 \times X_2) - 0.0264 \times X_1 \times X_3) \quad (4.7)$$

2. The objective to minimize $(y_j(x) - T_i)$ or maximize $d_i(y_j)$

$$\textit{Design variable } \vec{X} = \begin{Bmatrix} X_1 = PT \\ X_2 = IT \\ X_3 = G \end{Bmatrix} \quad (4.8)$$

Where

PT = Preliminary torque

IT = Input torque

G = Gain

Subjected to $0.8 \le X_1 \le 1.2$

$1.4 \le X_2 \le 2.4$

$0.5 \le X_3 \le 0.9$

3. To define the total number of response (y_n) computed from the setting number of each variable input as shown in equation (4.9)

$$y_n = Number\ of\ X_1\ setting \times Number\ of\ X_2\ setting \times Number\ of\ X_3\ setting \quad (4.9)$$

Where n denotes the total number of setting

$$Number\ of\ PT\ setting\ (X_1) = \frac{Maximum\ value\ setting - Minimum\ value\ setting}{Increasing\ unit\ value} \quad (4.10)$$

From Equation (4.10)

$$(X_1) = \frac{1.20 - 0.80}{0.01}$$
$$(X_1) = 40$$

$$Number\ of\ IT\ setting\ (X_2) = \frac{\text{Maximum value setting - Minimum value setting}}{\text{Increasing unit value}} \quad (4.11)$$

From Equation (4.11)

$$(X_2) = \frac{2.40 - 1.40}{0.01}$$
$$(X_2) = 100$$

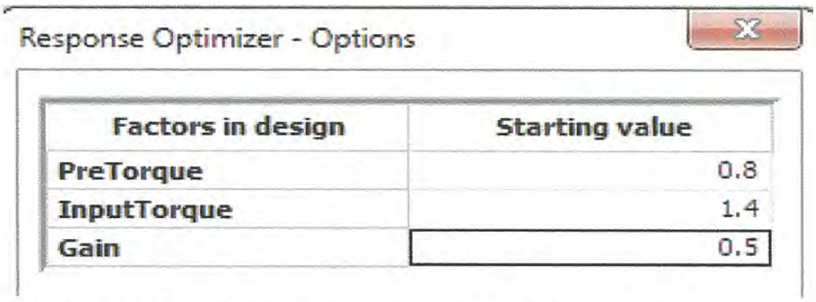
$$Number\ of\ G\ setting\ (X_3) = \frac{\text{Maximum value setting - Minimum value setting}}{\text{Increasing unit value}} \quad (4.12)$$

From Equation (4.12)

$$(X_3) = \frac{0.90 - 0.50}{0.01}$$
$$(X_3) = 40$$

Therefore, y_n = 40 x 100 x 40 = 160,000 which is representing total number of response.

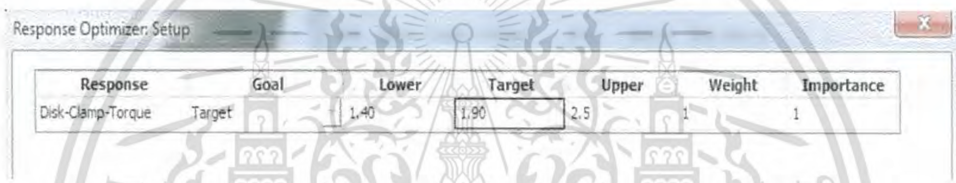
4. To define the start point of each factor which the starting value must be in DOE setting range, PT sets start point from 0.8 lbf-in., IT sets start point from 1.4 lbf-in. and G sets start point from 0.5 ampere as shown in Figure 4.5.



Factors in design	Starting value
PreTorque	0.8
InputTorque	1.4
Gain	0.5

Figure 4.5 Setting start point of each factor in Minitab

5. To select the response optimizer, choose the target is the best for disk clamp screw torque due to two side of specification. The lower specification is 1.4 lbf-in., the upper specification is 2.4 lbf-in and the target is 1.9 lbf-in. as shown in Figure 4.6.



Response	Goal	Lower	Target	Upper	Weight	Importance
Disk-Clamp-Torque	Target	1.40	1.90	2.5	1	1

Figure 4.6 Select the target is the best for disk clamp screw torque in Minitab

6. To calculate the response (y_j) and an individual desirability (d_i) for each factors setting, then calculate the overall composite desirability (D) per Equation (4.5) where m=1, therefore $D = d_1(y_1)$. The corresponding outcome level is measured by the maximum d_i.

7. To find for factors variable setting with y_j is the most closely to the target or the maximum composite desirability (d_i) as shown in Table 4.2 in red color. The variable data in Table 4.2 is just random with 30 different settings, for example Y29 is the most close to the target 1.90 lbf-in or the most maximize d_i (d_{29} = 0.9976, is very close to 1), which indicates these factors setting are the optimal results of disk clamp screw torque.

Table 4.2 Example for factors settings and response with an individual desirability

i and j	X_1	X_1^2	X_2	X_2^2	X_3	X_3^2	X_1*X_2	X_1*X_3	X_2*X_3	$y_j(x)$	$(y_j(x)-T_i)$	$y_j<L_i$	$L_i<y_j<T_i$	$T_i<y_j<U_i$	$y_j<U_i$	$D_i(y_n)$
1	0.80	0.64	1.40	1.96	0.50	0.25	1.12	0.40	0.70	1.20	-0.7039	1.00				0.00
2	0.81	0.66	1.41	1.99	0.51	0.26	1.15	0.42	0.72	1.22	-0.6771	1.00				0.00
3	0.83	0.68	1.48	2.19	0.53	0.28	1.22	0.43	0.78	1.32	-0.5844	1.00				0.00
4	0.84	0.70	1.52	2.31	0.54	0.29	1.28	0.45	0.82	1.37	-0.5271	1.00				0.00
5	0.85	0.73	1.56	2.43	0.55	0.30	1.33	0.47	0.86	1.43	-0.4712		1.00			0.06
6	0.87	0.75	1.60	2.56	0.57	0.32	1.38	0.49	0.90	1.48	-0.4169		1.00			0.17
7	0.88	0.77	1.64	2.69	0.58	0.33	1.44	0.51	0.95	1.54	-0.3642		1.00			0.27
8	0.89	0.79	1.68	2.82	0.59	0.35	1.50	0.53	0.99	1.59	-0.3130		1.00			0.37
9	0.90	0.82	1.72	2.96	0.60	0.36	1.55	0.55	1.04	1.64	-0.2633		1.00			0.47
10	0.92	0.84	1.76	3.10	0.62	0.38	1.61	0.57	1.09	1.68	-0.2152		1.00			0.57
11	0.93	0.86	1.80	3.24	0.63	0.40	1.67	0.59	1.13	1.73	-0.1686		1.00			0.66
12	0.94	0.89	1.84	3.39	0.64	0.41	1.74	0.61	1.18	1.78	-0.1236		1.00			0.75
13	0.96	0.91	1.88	3.53	0.66	0.43	1.80	0.63	1.23	1.82	-0.0801		1.00			0.84
14	0.97	0.94	1.92	3.69	0.67	0.45	1.86	0.65	1.28	1.86	-0.0381		1.00			0.92
15	0.97	0.94	1.99	3.96	0.68	0.47	1.93	0.66	1.36	1.92	0.0213			1.00		0.96
16	1.00	0.99	2.00	4.00	0.70	0.48	1.99	0.69	1.39	1.94	0.0411			1.00		0.92
17	1.01	1.02	2.04	4.16	0.71	0.50	2.06	0.71	1.44	1.98	0.0784			1.00		0.84
18	1.02	1.04	2.08	4.33	0.72	0.52	2.12	0.74	1.50	2.01	0.1142			1.00		0.77
19	1.03	1.07	2.12	4.49	0.73	0.54	2.19	0.76	1.56	2.05	0.1484			1.00		0.70
20	1.05	1.10	2.16	4.67	0.75	0.56	2.26	0.78	1.61	2.08	0.1810			1.00		0.64
21	1.06	1.12	2.20	4.84	0.76	0.58	2.33	0.81	1.67	2.11	0.2122			1.00		0.58
22	1.07	1.15	2.24	5.02	0.77	0.60	2.40	0.83	1.73	2.14	0.2417			1.00		0.52
23	1.09	1.18	2.28	5.20	0.79	0.62	2.48	0.85	1.79	2.17	0.2698			1.00		0.46
24	1.10	1.21	2.30	5.29	0.80	0.64	2.53	0.88	1.84	2.19	0.2851			1.00		0.43
25	1.11	1.24	2.31	5.34	0.81	0.66	2.57	0.90	1.88	2.19	0.2939			1.00		0.41
26	1.13	1.27	2.32	5.38	0.83	0.68	2.61	0.93	1.91	2.20	0.3019			1.00		0.40
27	1.14	1.30	2.33	5.43	0.84	0.70	2.65	0.95	1.95	2.21	0.3093			1.00		0.38
28	1.15	1.32	2.34	5.48	0.85	0.72	2.69	0.98	1.99	2.22	0.3158			1.00		0.37
29	0.80	0.64	2.11	4.46	0.70	0.49	1.69	0.56	1.48	1.9012	0.0012			1.00		0.9976
30	1.20	1.44	2.40	5.76	0.90	0.81	2.88	1.08	2.16	2.25	0.3462			1.00		0.31

y_{29} is minimum while d_{29} is maximum

$\min(y_j(x) - T_i)$ $\max d_i(y_i)$

The input variable setting can be adjusted to obtain the desirable response in the optimal plot. For mixture designs, component, process variable and amount variable settings can be adjusted. These input variable settings on the optimization plot can be changed for many reasons, for example,

1. To search and find the solution for the input variable setting in the local area.
2. Explore an input variable setting and obtain higher composite desirability (d).
3. To explore for less effort and lower cost input variable setting close to the optimal solution.
4. To search for the sensitivity of response variables following the adjusted input variable setting.
5. To calculate the predicted responses from the adjusted input variable setting.

Using the response optimization is to help identify the combination of three factors variable settings for disk clamp screw torque. The corresponding outcome level is measured by the composite desirability (d).

Figure 4.7 shows an optimization plot of disk clamp screw torque which the optimizer produces the subsequent graph showing the optimal factor settings in red, and the predicted response for disk clamp screw torque in blue. For example, disk clamp screw torque of product a target is 1.90 lbf-in. As Figure 4.5, Y = 1.902 lbf-in, desirability (D) = 0.99764, Input torque = 2.0 lbf-in and Gain = 0.7 Ampere. D= 0.99764, is very close to 1, which indicates the settings appear to reach favorable results of disk clamp screw torque.

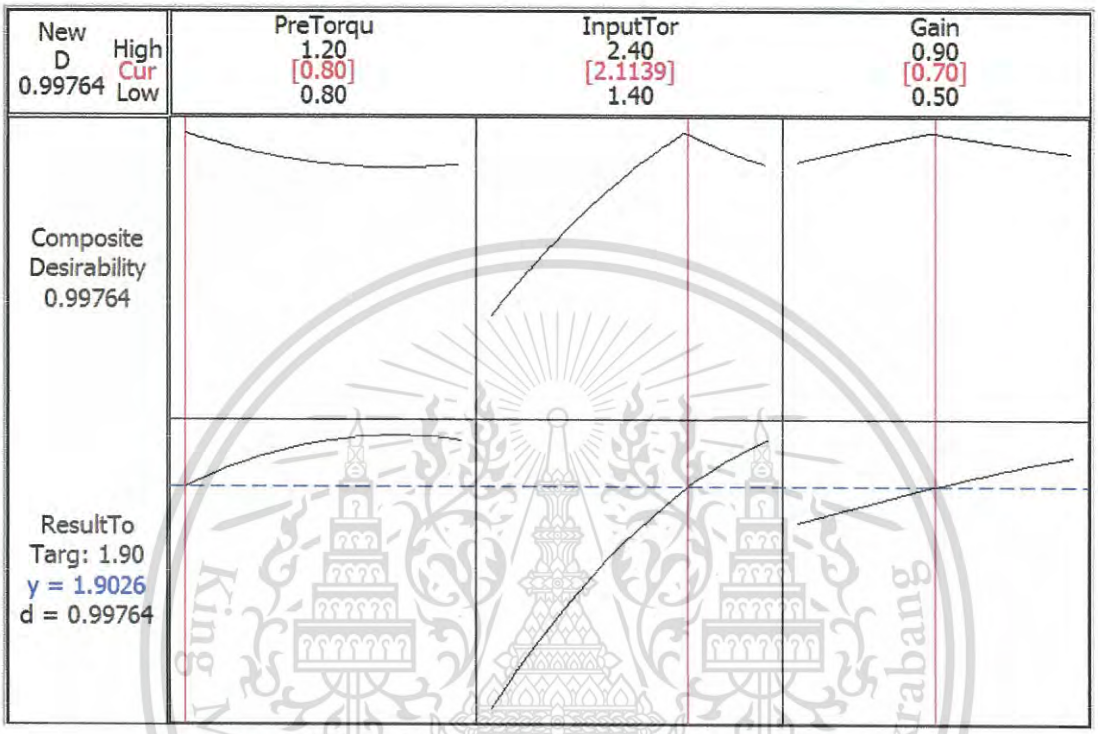


Figure 4.7 Optimization plots for disk clamp screw torque

4.3 Data validation

In this section, it is to verify the model by doing the experiment again then compare the result of disk clamp screw torque between predicted models as shown in Equation (4.13) and revalidate the experiment as shown in Table 4.3.

$$Equation\ of\ disk\ clamp\ screw\ torque = 1.8642 + (0.0407 \times PT) + (0.4194 \times IT) + (0.0648 \times G) - (0.0593 \times PT \times PT) - (0.1009 \times IT \times IT) - (0.0093 \times G \times G) + (0.0528 \times PT \times IT) - 0.0264 \times PT \times G) \quad (4.13)$$

Table 4.3 Actual experiment and predicted models of disk clamp screw torque comparison

No	PT	PT^2	IT	IT^2	G	G^2	PT*IT	PT*G	IT*G	Actual Torque	Predicted Model	Delta
1	0.80	0.64	1.40	1.96	0.50	0.25	1.12	0.40	0.70	1.30	1.20	-0.10
2	0.81	0.66	1.44	2.07	0.51	0.26	1.17	0.42	0.74	1.35	1.26	-0.09
3	0.83	0.68	1.48	2.19	0.53	0.28	1.22	0.43	0.78	1.40	1.32	-0.08
4	0.84	0.70	1.52	2.31	0.54	0.29	1.28	0.45	0.82	1.40	1.37	-0.03
5	0.85	0.73	1.56	2.43	0.55	0.30	1.33	0.47	0.86	1.40	1.43	0.03
6	0.87	0.75	1.60	2.56	0.57	0.32	1.38	0.49	0.90	1.45	1.48	0.03
7	0.88	0.77	1.64	2.69	0.58	0.33	1.44	0.51	0.95	1.55	1.54	-0.01
8	0.89	0.79	1.68	2.82	0.59	0.35	1.50	0.53	0.99	1.60	1.59	-0.01
9	0.90	0.82	1.72	2.96	0.60	0.36	1.55	0.55	1.04	1.65	1.64	-0.01
10	0.92	0.84	1.76	3.10	0.62	0.38	1.61	0.57	1.09	1.70	1.68	-0.02
11	0.93	0.86	1.80	3.24	0.63	0.40	1.67	0.59	1.13	1.75	1.73	-0.02
12	0.94	0.89	1.84	3.39	0.64	0.41	1.74	0.61	1.18	1.75	1.78	0.03
13	0.96	0.91	1.88	3.53	0.66	0.43	1.80	0.63	1.23	1.85	1.82	-0.03
14	0.97	0.94	1.92	3.69	0.67	0.45	1.86	0.65	1.28	1.90	1.86	-0.04
15	0.98	0.96	1.96	3.84	0.68	0.47	1.92	0.67	1.34	1.90	1.90	0.00
16	1.00	0.99	2.00	4.00	0.70	0.48	1.99	0.69	1.39	1.95	1.94	-0.01
17	1.01	1.02	2.04	4.16	0.71	0.50	2.06	0.71	1.44	1.95	1.98	0.03
18	1.02	1.04	2.08	4.33	0.72	0.52	2.12	0.74	1.50	2.00	2.01	0.01
19	1.03	1.07	2.12	4.49	0.73	0.54	2.19	0.76	1.56	2.05	2.05	0.00
20	1.05	1.10	2.16	4.67	0.75	0.56	2.26	0.78	1.61	2.10	2.08	-0.02
21	1.06	1.12	2.20	4.84	0.76	0.58	2.33	0.81	1.67	2.15	2.11	-0.04
22	1.07	1.15	2.24	5.02	0.77	0.60	2.40	0.83	1.73	2.20	2.14	-0.06
23	1.09	1.18	2.28	5.20	0.79	0.62	2.48	0.85	1.79	2.25	2.17	-0.08
24	1.10	1.21	2.32	5.38	0.80	0.64	2.55	0.88	1.85	2.20	2.20	0.00
25	1.11	1.24	2.36	5.57	0.81	0.66	2.62	0.90	1.92	2.25	2.22	-0.03
26	1.13	1.27	2.40	5.76	0.83	0.68	2.70	0.93	1.98	2.35	2.24	-0.11
27	1.14	1.30	2.44	5.95	0.84	0.70	2.78	0.95	2.04	2.30	2.27	-0.03
28	1.15	1.32	2.48	6.15	0.85	0.72	2.85	0.98	2.11	2.35	2.29	-0.06
29	1.16	1.35	2.52	6.35	0.86	0.75	2.93	1.01	2.18	2.40	2.31	-0.09
30	1.18	1.39	2.56	6.55	0.88	0.77	3.01	1.03	2.25	2.40	2.32	-0.08

The value shown in Predicted model is calculated from the equation of disk clamp screw torque as shown in (4.14). The Actual torque is the value which came from the real experiment by varying the variable factors in each run. The different value between Actual Torque and Predicted Model is shown in the delta which is used to calculate for % discrepancy.

$$\% \, Discrepancy \quad = \frac{\text{(Predicted Value – Actual Torque)}}{\text{Predicted Value}} \times 100 \qquad (4.14)$$

% Discrepancy is the guideline to assess on the how accuracy the value can be predicted directly from the formula. When % discrepancy is huge, it means there are some variable factors may not yet been studied or included, or some noise is not in control.

Figure 4.8 shows very good correlation between actual experiment and predicted models of disk clamp screw torque. It is able to prove that this is an appropriate setting of each factor that able to reach the target of disk clamp screw torque.

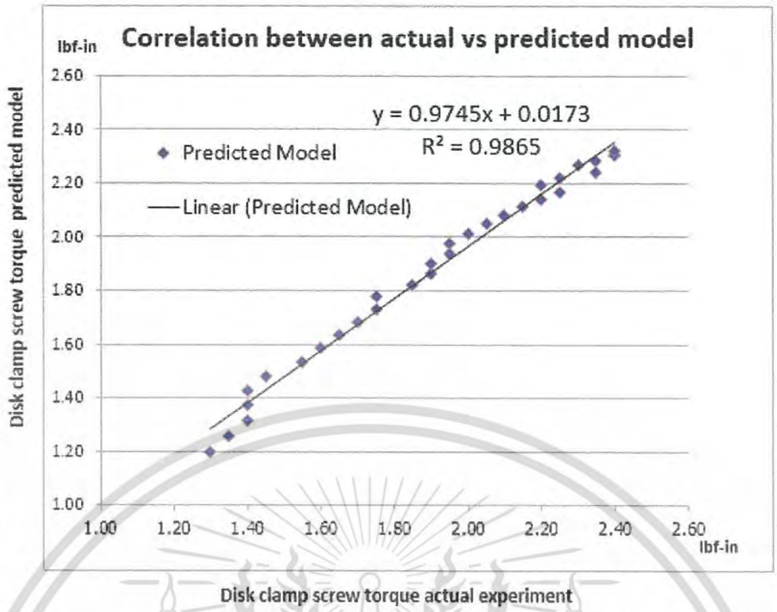


Figure 4.8 Actual experiment and predicted models of disk clamp screw torque correlation

The obtained setting values have been applied at one product at the company which it was found that the actual process capability (Cpk) of disk clamp screw torque is significantly improved from 1.0 to 2.17 as shown in Figure 4.9. Moreover, the scrap parts of disk clamp screw and labor overhead cost are significant reduction from drives teardown and rework. The normality test is required before running the process capability [13]

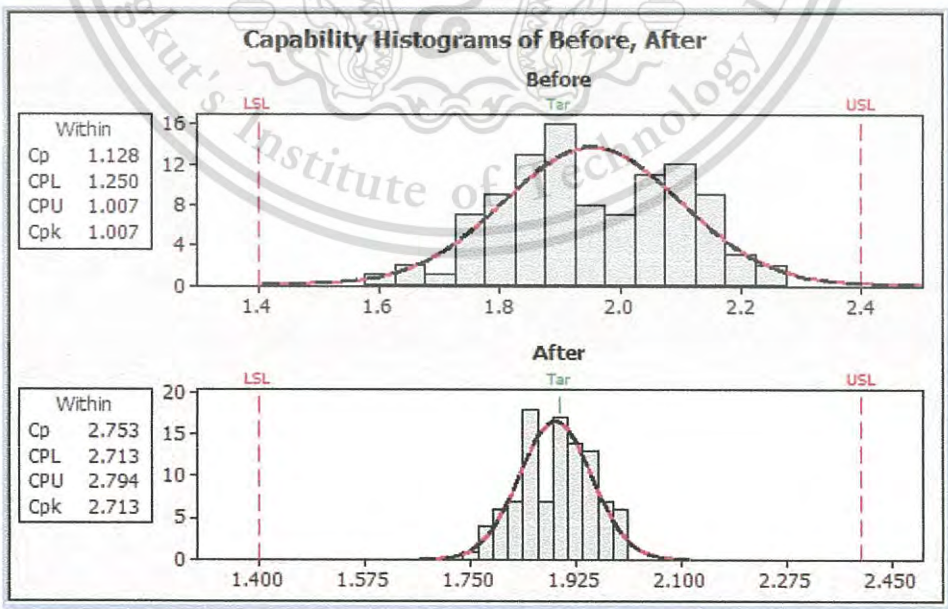


Figure 4.9 Process capability before and after the optimum setting point

Chapter 5
Conclusion and Suggestion

5.1 Conclusion

The experimental study of optimum disk clamp screw torque by using DOE in this paper are composed of two screw fastening processes; media installation (MI) and auto gang bias installation (AGB). The conclusions of this study are as following;

1. The input torque parameter is the most significant effect to the disk clamp screw torque. The gain is slightly significant effect to the disk clamp screw torque. The preliminary torque parameter is insignificant difference on the main effect plot, but it has interaction with input torque. So, it is needed to control as well in order to achieve the optimum point of disk clamp screw torque. As a result, the preliminary torque is able to set at minimum level in order to save energy and give faster cycle time.

2. The disk clamp screw torque proportionally depends on the input torque and gain control in the quadratic manner. High value of disk clamp screw torque is required high level setting of these factors too.

3. The optimum point of disk clamp screw torque needs to find the optimum setting of input torque and gain at auto gang bias. From the model and optimization plot, in order to achieve the target of disk clamp screw torque 1.90 lbf-in the setting of these 3 parameters are as following; Preliminary torque at 0.8 lbf-in, Input torque 2.1 lbf-in and Gain at 0.7 Ampere respectively. However, the optimum point of setting is depended on product specification of the disk clamp screw torque which is based on products capacity and number of media stacks in a drive.

4. The obtained setting values have been applied on hard disk drive 2.5” product. It was found that the actual process capability of disk clamp screw torque is significantly improved. Moreover, scrap parts and labor overhead cost are significant reduction from drives tearing and repairing.

5.2 Suggestion

1. The screw fastening process of hard disk drive manufacturing is more than 50% of overall operations in cleanroom, such as, bottom voice coil magnetic screw fastening, ramp screw fastening, pivot screw fastening, top cover screw fastening and other fastening screw. The selected parameters in this thesis for studying in disk clamp screw torque could be a very good guideline.

2. Process engineering can consider applying statistical process control monitoring on the input torque and gain instead of disk clamp screw torque monitoring. It should help to early trigger for fixing at the root cause of problem.

3. The media installation and auto gang bias are able to combine into one operation because there is no significant effect on preliminary toque at Media installation. Therefore, cleanroom space could be reduced. However, the machine time or the bottleneck of operation should be considered.

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Appendix

Appendix A.

Measurement System Analysis (MSA) and Calibration

1. Measurement System Analysis (MSA)

The reading value of disk clamp screw torque in 2.5" HDD (Hard Disk Drive) is very problematic because disk clamp screw torque value is very low and the current measurement tool is manually operated by an operator. So, it is difficult to find an accurate and precise value reading. To enhance in the measurement before starting the experimental study, a Forward torque of 2.5" product is developed in order to measure disk clamp screw torque as shown in Figure 1. By using the laser sensor to detect screw slipping, it can solve the human error when reading the value from a panel.

Figure 1 Forward torque for 2.5" Disk clamp screw torque

There are three main components of measurement tools; torque gauge, sensor and fixture.

1. **Torque gauge**

There are many types of torque gage, depending on use per product specification. For 2.5" product at Western Digital Company, 2 types are used: 3.6 BTG-A-S for product specification 1.5 - 2.4 lbf-in as shown in Figure 2 and 9.0 BTG-A-S for product specification 2.5 - 4.0 lbf-in.

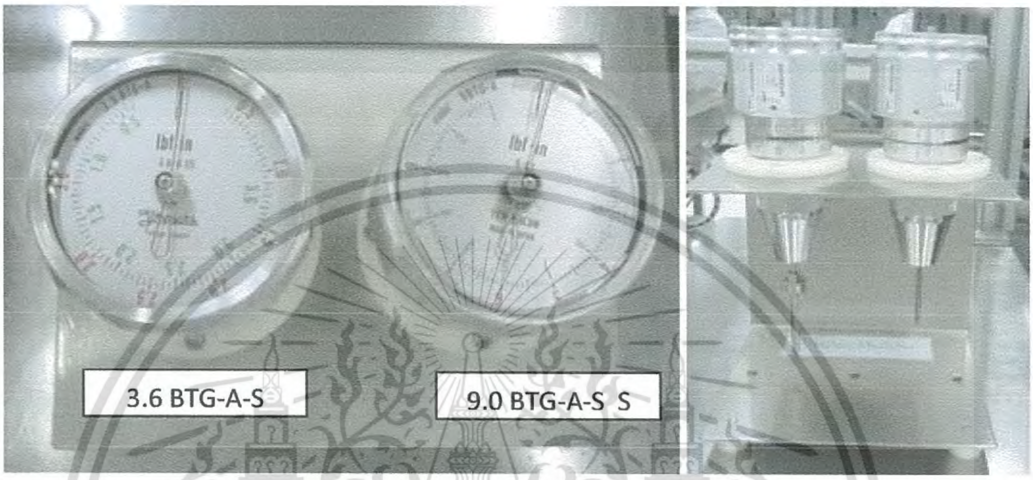


Figure 2 Torque gauge for 3.6 BTG-A-S and 9.0 BTG-A-S

2. **Sensor**

Because the resultant torque of disc clamp screw is very sensitive finding, therefore laser sensor will be used in place to detect screw slipping. The Sensor FU-20 for reflection detection and amplifier FS-V31 for analog signal (Light source) conversion to digital as shown in Figure 3.

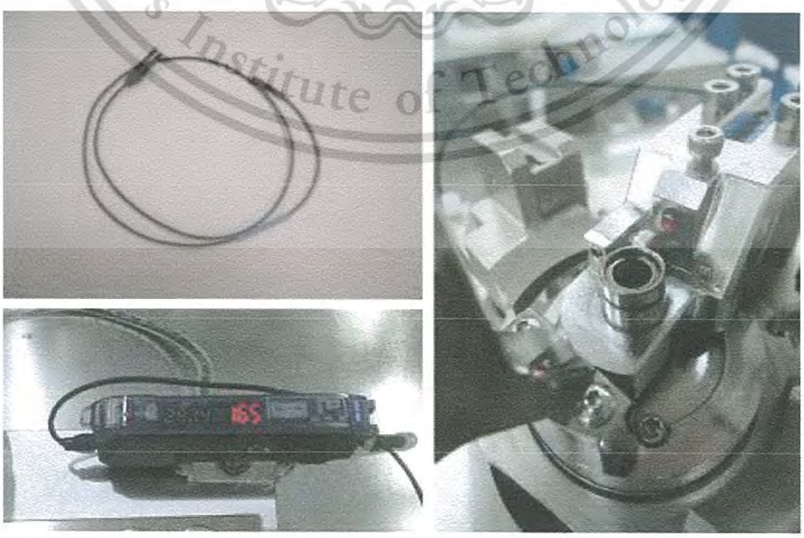


Figure 3 Sensor and Amplifier of the torque gauge

3. **Fixture**

The base supports the measurement disk clamp screw torque drive that need to strong and balance as shown in Figure 4.

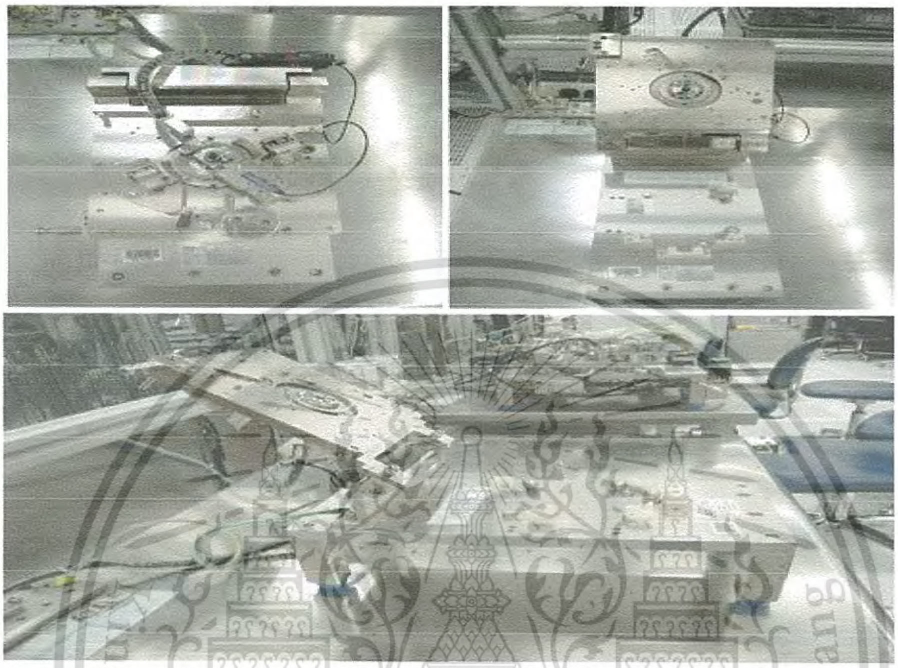


Figure 4 Fixture support

The disk clamp screw torque measurement method

1. To open the cover, to put the HDA (Hard disk Assembly) on nest of fixture and close the cover as shown in Figure 5.

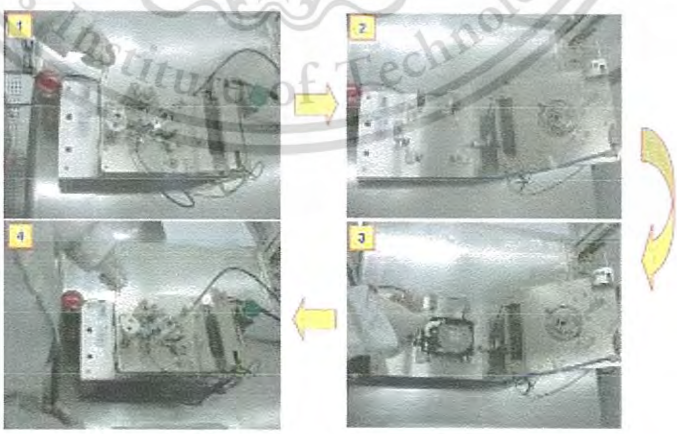


Figure 5 Putting HDA on nest of fixture

2. To locate a hole position of disk clamp before pushing it down to lock disk clamp. Then rotate the arm (Clockwise) to lock the position as shown in Figure 6.

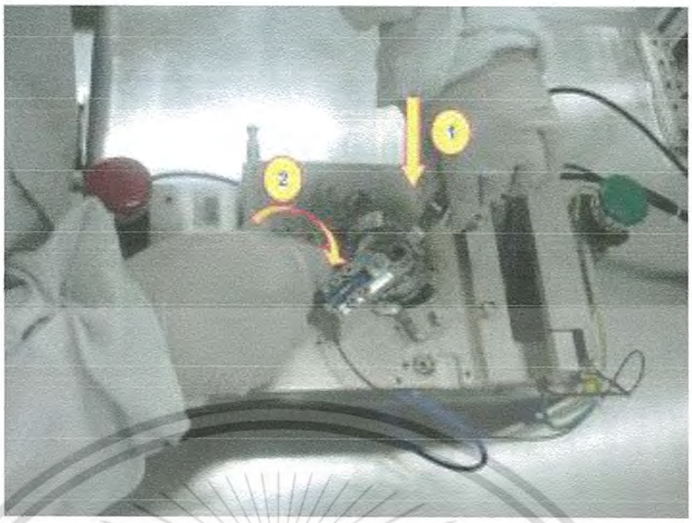


Figure 6 The disk clamp locking

4. Gently put torque gauge (bit with sleeve) in the hole of bearing, and then locate the head of screw by rotating slightly as shown in Figure 7.

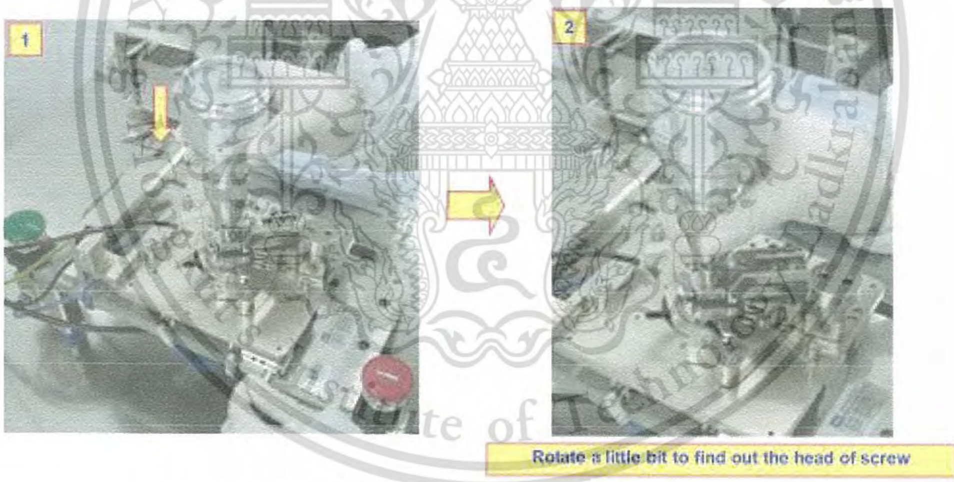


Figure 7 Putting torque gauge into the hole of bearing

5. After the head of screw is detected, rotate the torque gauge and hold on at value torque about 0.5 lbf-in to reset the torque as shown in Figure 8. Then, rotate (Counterclockwise) the ring to set the notch to align with light sensor. RED LED sensor will be off.

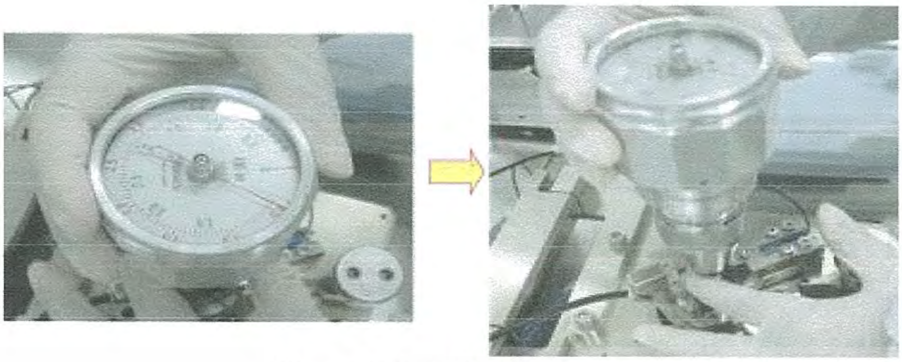


Figure 8 Reset the torque before rotating

6. When the RED LED light off, slowly start to rotate torque gauge by clockwise to check resultant torque as shown in Figure 9.

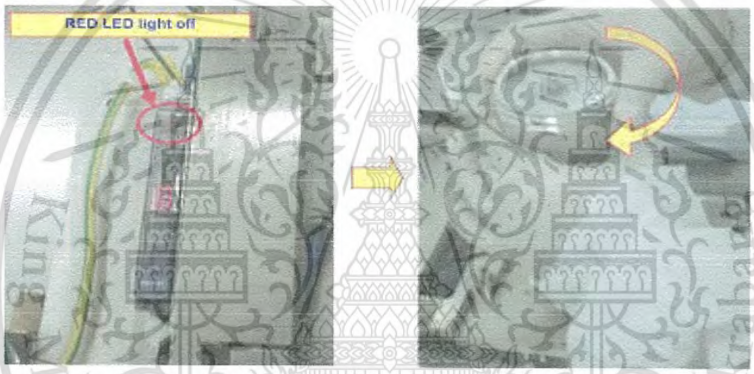


Figure 9 Rotation the torque gauge

7. Slowly rotate torque gauge (Clockwise) and watch the LED light. Stop to rotate the torque gauge when the RED LED light on. Then, read value of the torque gauge as shown in Figure 10.

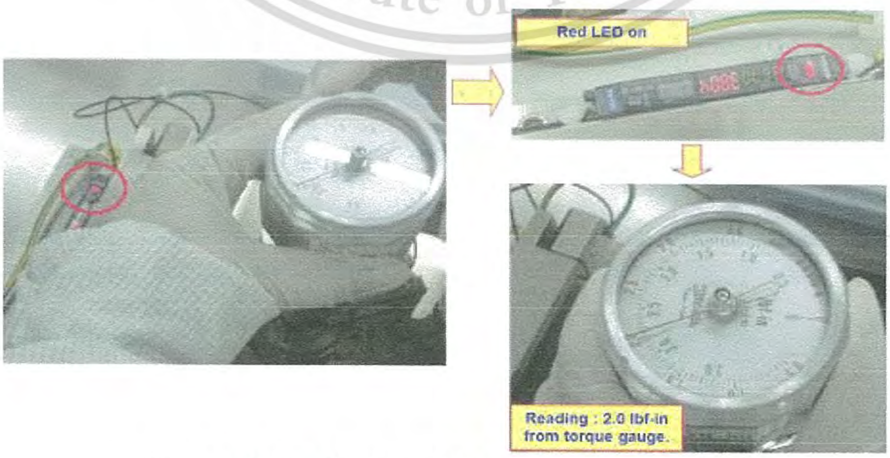


Figure 10 Read value of the resultant on torque gauge

8. After reading the torque, the torque gauge is pulled up and put into the torque holder.

9. Open the cover, then pick up HDA from the nest to HDA's tote and repeat the same method on next HDA. The cover should be closed, when the fixture is not used.

2. Disk clamp screw torque calibration

To qualify disk clamp torque measurement fixture with the calibrated standard device.

2.1 Tool and Equipment

2.1.1 Torque Calibration Analyzer (Spring Type) as show in Figure 11

2.1.2 Electronic Torque Calibration Analyzer as show in Figure 12

2.1.3 Torque gauge for 3.6 BTG-A-S

2.1.4 Air Gun

2.1.5 Hex L-Wrench Key

2.1.6 Blank adapter 3/8"

2.2 Check torque force reading

2.2.1 Remove Hex head bit from Torque body and insert hex to 1/4" Male square convector into Torque

2.2.2 Adjust red hand of torque calibration analyzer scale to Zero (0) N-m/Lbf-in or Set Zero for Electronic torque analyzer.

2.2.3 Insert square side of convector into torque calibration analyzer socket and rotate torque handle to clockwise direction. Spring type torque Calibration analyzer as shown in Figure 11 and Electronic Torque Calibration Analyzer (Mount M10) as shown in Figure12. The Black hand of analyzer scale will push Red hand of analyzer scale move together. When apply the torque force until set force limit, the screw driver will reset the torque force and the black hand of analyzer scale will move Backwards to Zero (0) N-m/Lbf-in but red hand still at the maximum force Read the torque force value at pointed by red hand of analyzer scale as shown in display Figure 11.

2.2.4 Ensure the torque force is in specification

2.2.5 Repeat item 2.2.3 two times and record the average reading in data sheet or Calibration report.

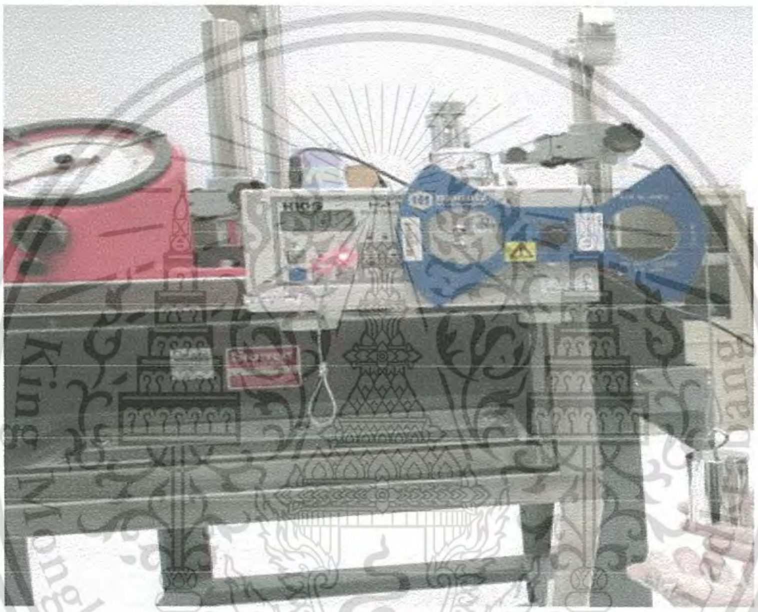


Figure 11 Torque Calibration Analyzer (Spring Type) [14]

Figure 12 Electronic Torque Calibration Analyzer (Mount M10) [14]

1.3 Adjust torque force if the torque force reading out of specification

1.3.1 Remove cover screw from bottom of the torque force handle.

1.3.2 Adjust torque force by using L-Wrench key size 3/16 inches adjust screw in torque handle. Turn L-Wrench key to clockwise direction when we want to increase torque force and move backwards when we want to decrease torque.

1.3.3 Test torque force by follow item 2.2.1 to 2.2.4

1.4 Remove old calibration sticker and clean torque by IPA and air gun

1.5 Attaches new calibration due date sticker which write Calibration Date, Due date and name of calibrator as shown in Figure 13.

1.6 Remove convector and install Hex head into torque

Figure 13. Calibration sticker [14]

4. Correlation with standard value

The objective is to qualify disk clamp torque measuring fixture with the calibrated standard device. Ordinary least squares (OLS) correlation is a method used for this qualification; the estimated equation is calculated by determining the equation that minimizes the sum of the squared distances between the sample's data points and the standard values by the equation. Figure 14 shows OLS correlation with standard values, the sum of the squared distances from each point to the line is as small as possible.

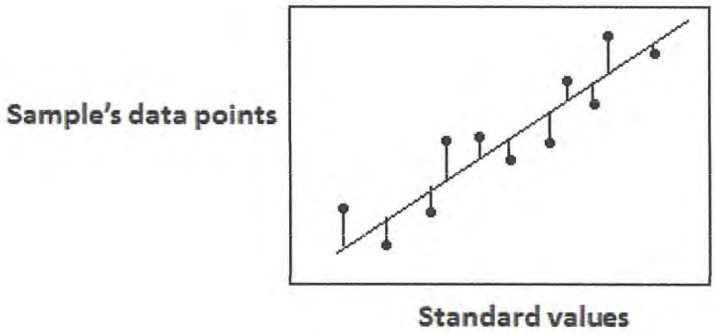


Figure 14 Ordinary least squares (OLS) correlation method.

1. Step of correlation method for Torque Gauge performed on HDA screw

1.1 Prepare 10 drives for correlation.

1.2 Select range of input torque for each drive.

1.3 Checking resultant torque by performing on the disk clamp fixture.

1.4 Measure 3 trials for each input torque in order to check repeatability and if average value are out of the measurement error.

1.5 Repeat step 1.2-1.4 until 10 samples as shown in Table 1.

1.6 Compare correlation between the input torque of torque gauge (Standard value) and resultant torque (Sample's data) from the developed disk clamp fixture.

1.7 Verify whether R-Square is acceptable with factory standard?

Table 1 Raw data of 3 trials measurement each sample's data point

No.	Standard values	Sample data point
1	1.50	1.55
2	1.60	1.60
3	1.70	1.75
4	1.80	1.80
5	1.90	1.90
6	2.00	2.05
7	2.10	2.10
8	2.20	2.20
9	2.30	2.35
10	2.40	2.40

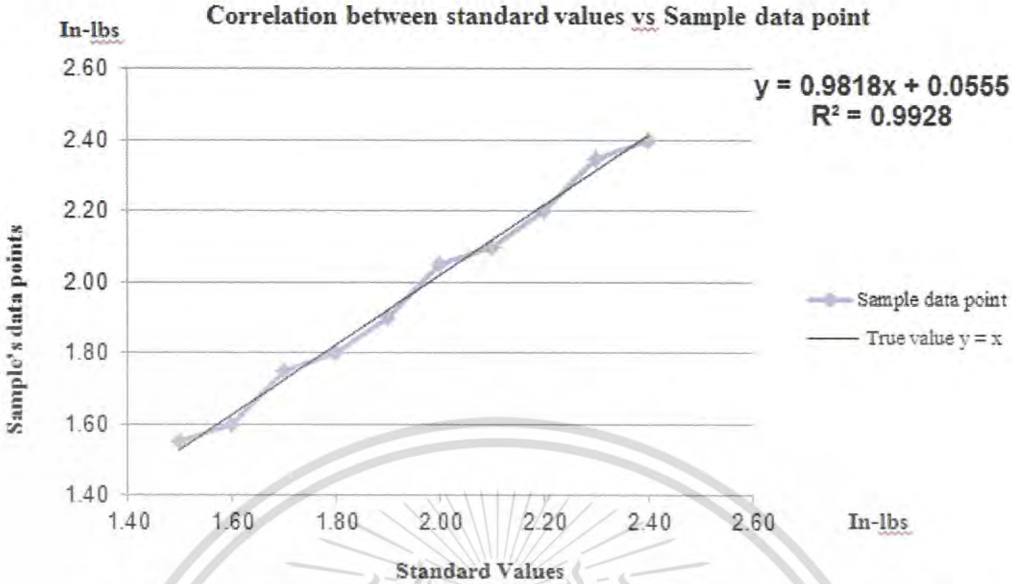


Figure 15 Ordinary least squares (OLS) correlation between standard values versus sample's data point

The correlation study between disk clamp screw torque and standard values that calibration system is acceptable; with R-square of model 99.28% as shown in Figure 15. These Disk clamp torque measurement fixture is expected to match up well. So, the study on precision of measurement both repeatability and reproducibility is planned before releasing this measurement and the experiment.

4. Gage precision or gage repeatability and reproducibility (GR&R)

According to the Automotive Industry Action Group (AIAG), the measurement system is determined whether it is acceptable using the following guidelines.

If the Total Gage R&R contribution in the % Tolerance is:

1. Less than 10% - the measurement system is acceptable.
2. Between 10% and 30% - the measurement system is acceptable depending on the application, the cost of the measuring device, cost of repair, or other factors.
3. Greater than 30% - the measurement system is unacceptable and should be improved.

If you are looking at the %Contribution column, the corresponding standards are:

1. Less than 1% - the measurement system is acceptable.

2. Between 1% and 9% - the measurement system is acceptable depending on the application, the cost of the measuring device, cost of repair, or other factors.

3. Greater than 9% - the measurement system is unacceptable and should be improved.

Automotive Industry Action Group (AIAG); A global organization founded by managers from DaimlerChrysler, Ford Motor Company, and General Motors in 1982 with the purpose of providing an open forum for sharing information benefiting the automotive industry. Today, there are more than 1600 member companies which cooperate in developing and sharing solutions that enhance the prosperity of the automotive industry. The AIAG publishes reference materials aimed at improving the quality of products and are used by many suppliers and manufacturers, not just those in automotive industries. Among them, the Measurement System Analysis manual and the Statistical Process Control manual have been used by many quality practitioners to improve their processes. *For more information, see www.aiag.org.*

Gage precision, or measurement variation, can be broken down into two components:

1. Repeatability is the variation due to the measuring device. It is the variation observed when the same operator measures the same part repeatedly with the same device.

2. Reproducibility is variation due to the measurement system. It is variation observed when different operators measure the same parts using the same device.

Gage repeatability and reproducibility studies determine how much of our observed process variation is due to measurement system variation. The X and R method breaks down the overall variation into three categories: part-to-part, repeatability, and reproducibility as shown in Figure 16.

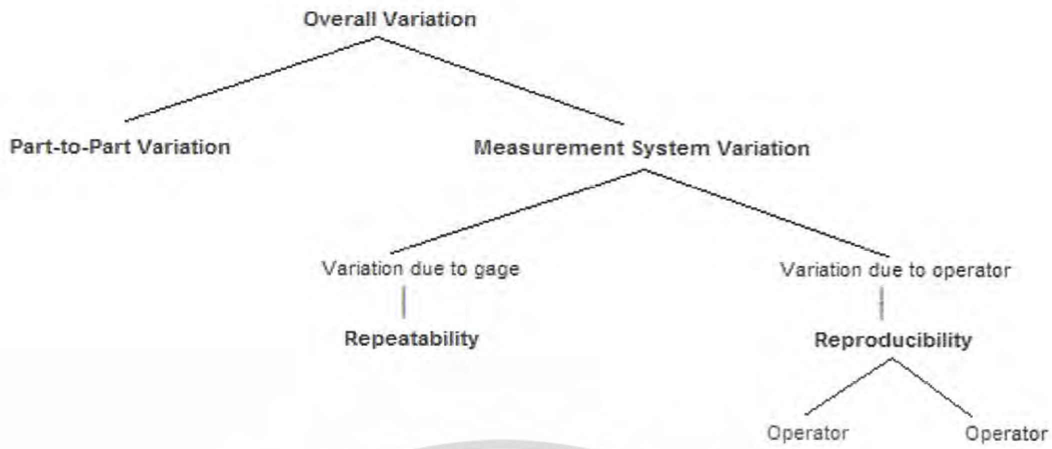


Figure 16 Source of overall variations that caused of measurement error

1. Step of GR&R method for torque gauge performed on HDA screw

1.1 Prepare sample HDA 10 samples

1.2 Use torque gauge to input torque a screw for each HDA

1.3 Continue for 10 samples by varying each screw torque value to cover process range.

1.4 Operators use torque gauge to measures for 10 samples.

1.5 Repeat step 1.2 to 1.4 until 3 trials for each operator.

1.6 Repeat step 1.5 for operator #2 and operator #3.

2. Method of GR&R calculation

2.1 Gage R&R calculation in Excel as shown in Table 2.

2.1.1 Enter Part/Product Name, Parameter, Date, Name and etc.

2.1.2 The numbers fields will fill in automatically.

2.1.3 Enter process Specification Tolerance = Upper specification limit (USL) – Lower specification limit (LSL).

2.1.4 Completed enter all measurements data in blue field, all result will be automatically calculation.

Table 2 Gage R&R calculation in Excel file

Western Digital

Measurement System Analysis Worksheet - Gauge Repeatability and Reproducibility (ANOVA)

Part/Product Name	Hubble Product	Instrument Name	Disk clamp fixture	Date of Study	20 Aug'13	Number of Opr.	3
Parameter	Resultant torque	Instrument Number	BT-90003	Originator	wanna_t	Number of Parts	10
		Total Tolerance	1.20	Location	CR phase 2	Number of Trials	3
		Historical Sigma		Sample Range(>90%)			

Comparison	Operator 1 name: Laeiad L EN: 100073					Operator 2 name: Juree P EN: 112269					Operator 3 name: Sasithorn EN: 177190				
Sample#	Trial 1	Trial 2	Trial 3	Avg.	Range	Trial 1	Trial 2	Trial 3	Avg.	Range	Trial 1	Trial 2	Trial 3	Avg.	Range
1	1.4000	1.4000	1.3500	1.3833	0.0500	1.4000	1.4500	1.5000	1.4500	0.1000	1.4500	1.4000	1.5000	1.4500	0.1000
2	1.5000	1.5000	1.4500	1.4833	0.0500	1.5000	1.5000	1.5000	1.5000	0.0000	1.4500	1.4500	1.5000	1.4667	0.0500
3	1.5500	1.6000	1.5000	1.5500	0.1000	1.5500	1.5500	1.6000	1.5667	0.0500	1.6000	1.5500	1.6000	1.5833	0.0500
4	1.6500	1.6500	1.6000	1.6333	0.0500	1.6000	1.6500	1.6500	1.6333	0.0500	1.6500	1.6500	1.6500	1.6500	0.0000
5	1.6500	1.6500	1.7000	1.6667	0.0500	1.6500	1.6500	1.6500	1.6500	0.0000	1.7000	1.6500	1.7000	1.6833	0.0500
6	1.7000	1.7000	1.7500	1.7167	0.0500	1.6500	1.7500	1.7500	1.7167	0.1000	1.7500	1.6500	1.7500	1.7167	0.1000
7	1.7500	1.7500	1.7500	1.7500	0.0000	1.8000	1.7500	1.7500	1.7667	0.0500	1.8000	1.7500	1.8000	1.7833	0.0500
8	1.8500	1.8000	1.9000	1.8500	0.1000	1.8500	1.8500	1.8500	1.8500	0.0000	1.9000	1.8500	1.9000	1.8833	0.0500
9	1.9500	1.9000	2.0000	1.9500	0.1000	1.9500	1.9500	2.0000	1.9667	0.0500	2.0000	1.9500	2.0000	1.9833	0.0500
10	2.0000	2.0500	2.0000	2.0167	0.0500	2.1000	2.0500	2.0000	2.0500	0.1000	2.1000	2.1000	2.1000	2.1000	0.0000
Total	17.0000	17.0000	17.0000	17.0000	0.6000	17.0500	17.1500	17.2500	17.1500	0.5000	17.4000	17.0000	17.5000	17.3000	0.5000
Avg.	1.7000	1.7000	1.7000	**1.7000**	**0.0600**	1.7050	1.7150	1.7250	**1.7150**	**0.0500**	1.7400	1.7000	1.7500	**1.7300**	**0.0500**
StDev.	0.1929	0.1886	0.2261	0.2009	0.0316	0.2166	0.1944	0.1814	0.1960	0.0408	0.2171	0.2186	0.2028	0.2122	0.0333
Max	2.0000	2.0500	2.0000	2.0167	0.1000	2.1000	2.0500	2.0000	2.0500	0.1000	2.1000	2.1000	2.1000	2.1000	0.1000
Min	1.4000	1.4000	1.3500	1.3833	0.0000	1.4000	1.4500	1.5000	1.4500	0.0000	1.4500	1.4000	1.5000	1.4500	0.0000
Range	0.6000	0.6500	0.6500	0.6333	0.1000	0.7000	0.6000	0.5000	0.6000	0.1000	0.6500	0.7000	0.6000	0.6500	0.1000

Test for Control (Data Qualification)

Upper Control Limit for the Range (UCL-Range) = D4*Average R-bar : D4=3.267 for 2 trials and D4=2.575 for 3 trials.
If any individual range exceeds this limit, the measurement or reading should be reviewed, repeated, corrected or discarded as appropriate. Then new averages & ranges should be re-computed.

Average R-bar	0.06333
UCL-Range	0.13733

In control

Two-Way ANOVA Table (With Interaction) Alpha to remove interaction term (default is 0.25) => 0.25

Source	DF	SS	MS	F	p-value
Parts	9	3.3286944	0.3698327	390.1010	0.00000
Operators	2	0.0135000	0.0067500	7.1238	0.00526
Interaction	18	0.0170556	0.0009475	0.8122	0.67886
Repeatability	60	0.0700000	0.0011667	*Interaction is Not Significant*	
Total	89	3.4272500	0.0011161		

Average X-bar	1.71500
UCL - X-bar	1.76956
LCL - X-bar	1.66044

Out control : 76.67%

Measurement System Analysis : By ANOVA method Input Process Distribution Width(typically 5.15 or 6.00) 6.00 sigma's

Source	StDev. (SD)	Study Variation (SV = 6*SD)	Variance (SD^2)	%Tolerance (SV/Tolr.)	% by Study Var (%SV)	% by Process Var (SV/Process)	%Contribution (% by Total Variance)
Total Gage R&R	0.036109	0.216657	0.0013039	**18.05%**	**17.57%**	**N/A**	**3.09%**
Repeatability	0.033408	0.200448	0.0011161	**16.70%**	**16.25%**	**N/A**	**2.64%**
Reproducibility	0.013704	0.082223	0.0001878	**6.85%**	**6.67%**	**N/A**	**0.44%**
Operators	0.013704	0.082223	0.0001878	6.85%	6.67%	N/A	0.44%
Op*Pa Interaction	-	-	-	#VALUE!	-	-	-
Part-To-Part	0.202352	1.214111	0.0409463	101.18%	98.44%	<= Optional	96.91%
Total Variation	0.205548	1.233291	0.0422502	102.77%		Input Historical Sigma	

Summary (by ANOVA)

Summary (by ANOVA)		Value	Result	Criteria			
- P/T Ratio or %Tolerance	=	18.05%	Conditional	Approved ≤	10%	< Conditional ≤	30%
- Number of Distinct Categories (NDC)	=	7	Approved	Approved ≥	5		
- Precision to Total Variation: (%P/TV)	=	17.57%	Conditional	Approved ≤	10%	< Conditional ≤	30%
- % Contribution	=	3.09%	Conditional	Approved ≤	2.0%	< Conditional ≤	7.7%
- Range chart	=	In control	Approved	Approved =	In control		
- Xbar chart	=	76.67%	Approved	Approved ≥	50%		
	Judgment:		Conditional				
	Review/Approved by:		Chanchai C				

Gage repeatability and reproducibility show process variation as following result; The total Gage R&R contribution in the % Tolerance is 18.05% and the %Contribution column is 3.09%, the corresponding AIAG standards are conditional acceptable.

2.2 The graphical Output

2.2.1 Figure 17 shows R-Chart graph by operator

2.2.1.1 All samples range should be within upper control limit (UCL) and lower control limit (LCL). It is to represent the range of measurement are within control.

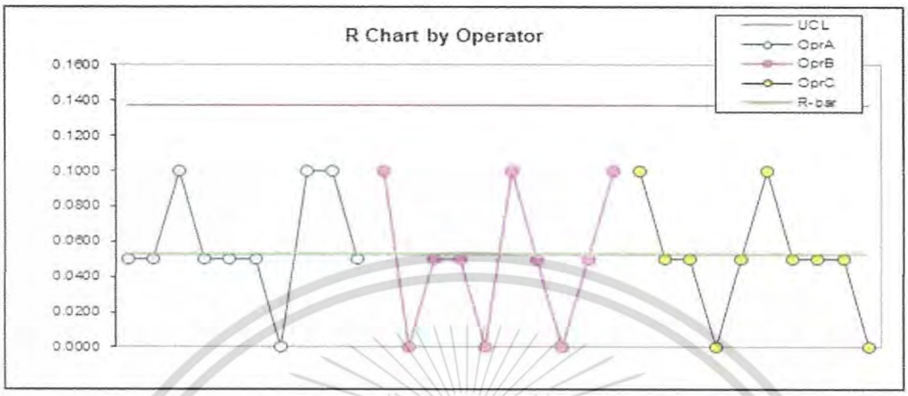


Figure 17 R-Chart graph by operator

2.2.2 Figure 18 shows X-bar chart graph by operator

2.2.2.1 Each point shows average of measured part.

2.2.2.2 Over a half of data should be out of control. It is to represent variation of part or how many groups of selected parts.

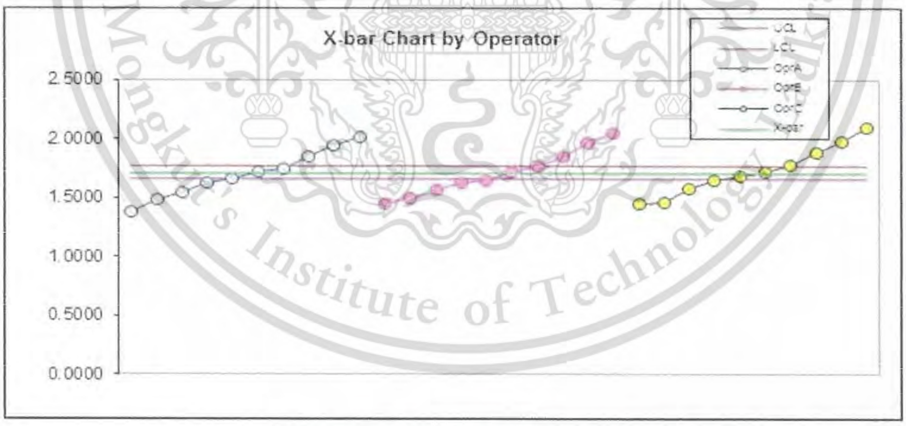


Figure 18 X-bar chart graph by operator

2.2.3 Figure 19 shows measurement graph by Part

2.2.3.1 Each point shows the ability of our operators to obtain the same readings for each part

2.2.3.2 Each point also shows the ability of our measurement system to distinguish between parts (Amount of overlap)

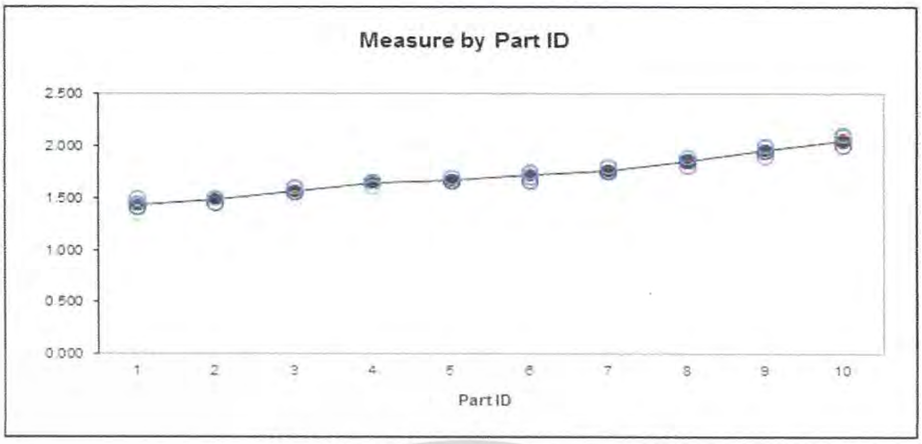


Figure 19 Measurement graph by Part

2.2.4 Figure 20 shows measurement graph by Operator.

2.2.4.1 Each point shows the ability of our operators to obtain the same readings for each part

2.2.4.2 The line shows the different of operator readings (Average)

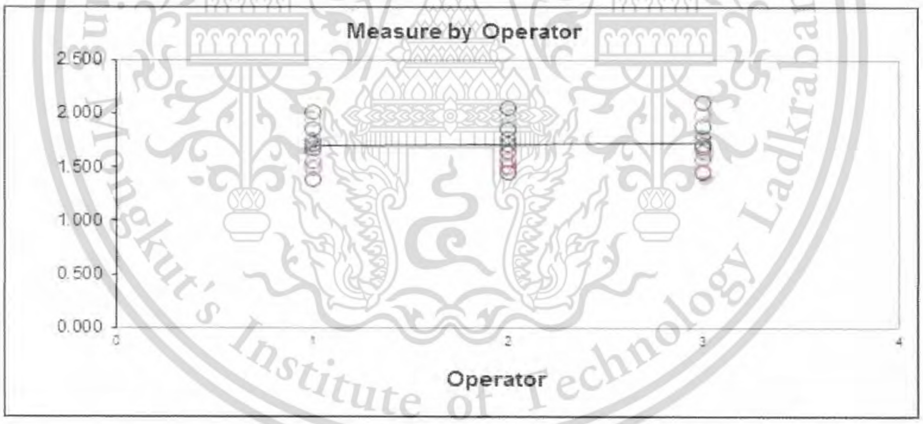


Figure 20 Measurement graph by operator

2.2.5 Figure 21 shows operator * Part interaction

2.2.5.1 Each line shows the ability of our operators to obtain the same readings for each part.

2.2.5.2 It also shows the ability of our measurement system to distinguish between parts (Amount of overlap)

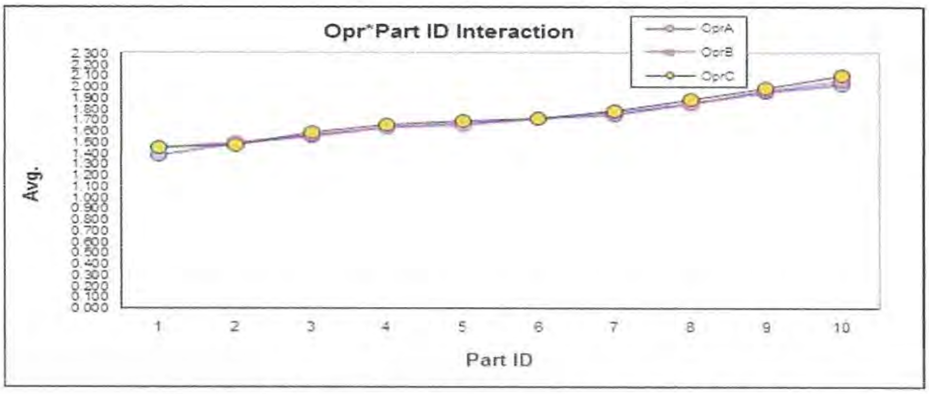


Figure 21 Measurement graph by operator * Part interaction

In conclusion, fixture measurement is acceptable to measure disk clamp screw torque. The measurement has passed qualification on both accuracy and precision.

3. Gage R&R formula

3.1 P/T (Precision to Tolerance) Ratio or % Tolerance. Process distribution width is 6.0 sigma that represents 99.73% of all measurements.

$$P/T = \frac{6.0\sigma_{MS}}{USL-LSL} \quad (1)$$

3.2 Number of Distinct Categories (NDC)

$$NDC = 1.41\frac{\sigma_{part}}{\sigma_{MS}} \quad (2)$$

3.3 Precision to Total Variation: (P/TV)

$$P/TV = \frac{\sigma_{MS}}{\sigma_{TOTAL}} \quad (3)$$

3.4 % Contribution

$$Contribution = \frac{\sigma^2{}_{MS}}{\sigma^2{}_{TOTAL}} \quad (4)$$

4. GR&R criteria

GR&R conclusion will be made by review result of %P/T, NDC, %P/TV, %Contribution and graphical result.

4.1 Below are the criteria for the equipment: Refer MSA-3rd edition of AIAG manual

4.1.1 %P/T Ratio

%R&R <=10 %	APPROVED
%R&R >10-30%	CONDITIONAL
%R&R > 30%	REJECTED

4.1.2 Number of Distinct Categories (NDC)

NDC >=5	APPROVED
NDC< 5	CONDITIONAL

4.1.3 Precision to Total Variation: (%P/TV)

%R&R <=10 %	APPROVED
%R&R >10-30%	CONDITIONAL
%R&R > 30%	REJECTED

4.1.4 % Contribution

%R&R <=2 %	APPROVED
%R&R >2 - 7.7%	CONDITIONAL
%R&R > 7.7%	REJECTED

5. GR&R action guideline.

GRR studies rated as 'conditional' or 'rejected' require corrective action implementation and repeated GRR studies with reporting

5.1 %P/T or %P/TV or % Contribution is 'conditional' or 'rejected'.

5.1.1 If a dominant source of variation is repeatability (Equipment): need to replace, repair or otherwise adjust the equipment.

5.1.2 If a dominant source of variation is operator (Reproducibility): must address this via training and definition of the standard operating procedure. You should look for differences between operators to give you some indication as to whether it is a training, skill, and/or procedure problem.

5.2 Number of Distinct Categories (NDC) not meet requirement.

5.2.1 This number represents groups of part variation that the measurement system can discern. If you want to distinguish a higher number of distinct categories, you need a more precise gage.

5.2.2 Reduce gage variation by follow item# 5.1.1 and 5.1.2

5.2.3 Collect new sample which more variation and represent process variation.

Appendix B.

Creating an Experimental Design in Minitab

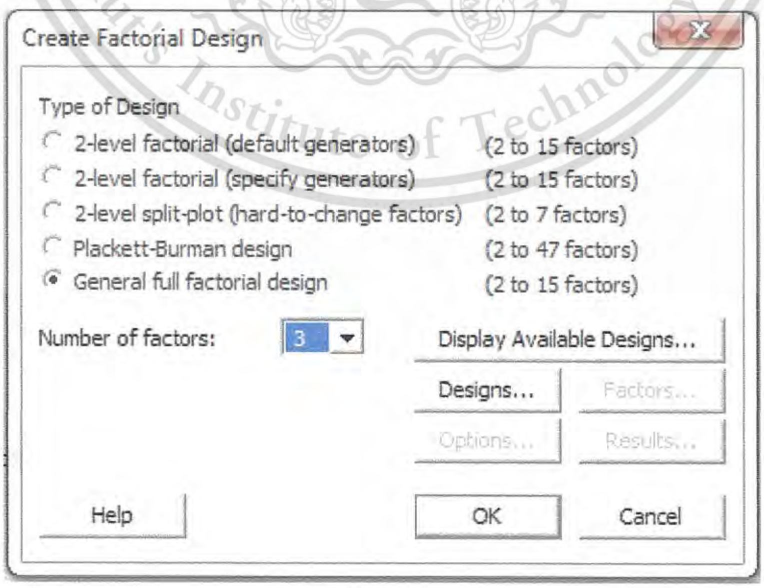
1. Creating an Experimental Design

Before entering or analyzing measurement data in Minitab, firstly an experimental design must be created and stored in a worksheet. Depending on the requirements of the experiment, a variety of designs can be chosen. Minitab helps to select a design by providing a list of all the available designs. Once it has chosen the design and its features, Minitab automatically creates the design and stores it in the worksheet.

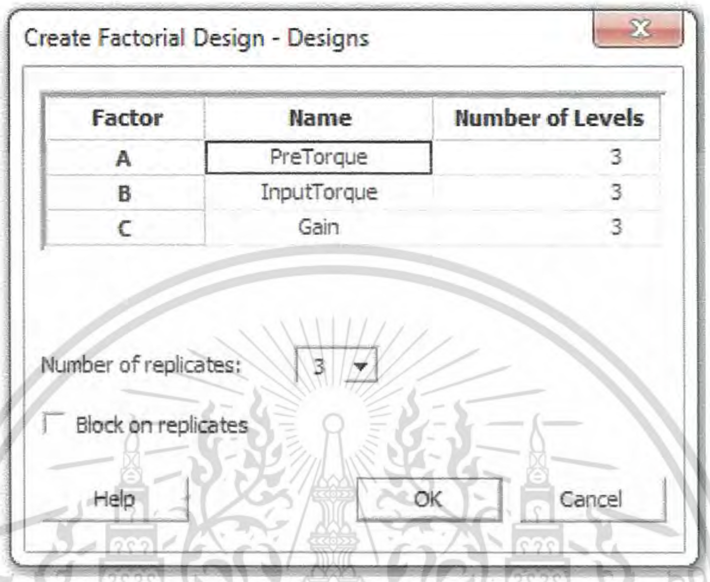
To create a factorial design to examine the relationship between two factors, order processing system and packing procedure, and the time it takes to prepare an order for shipping.

1. Choose **File** ➤ **New**, then choose **Minitab Project**. Click **OK**. Otherwise, just start Minitab.
2. Choose **Stat** ➤ **DOE** ➤ **Factorial** ➤ **Create Factorial Design**
3. Choose **General full factorial design**
4. **In number of factors,** choose 3

When creating a design in Minitab, initially only two buttons are enabled, **Display Available Designs** and **Designs**. The other buttons are enabled after complete the **Designs** sub-dialog box.



5. Click **Designs**. The box at the top shows all available designs for the design type and the number of factors. In this experiment, a factorial design with 3 factors and 3 levels is conducted.



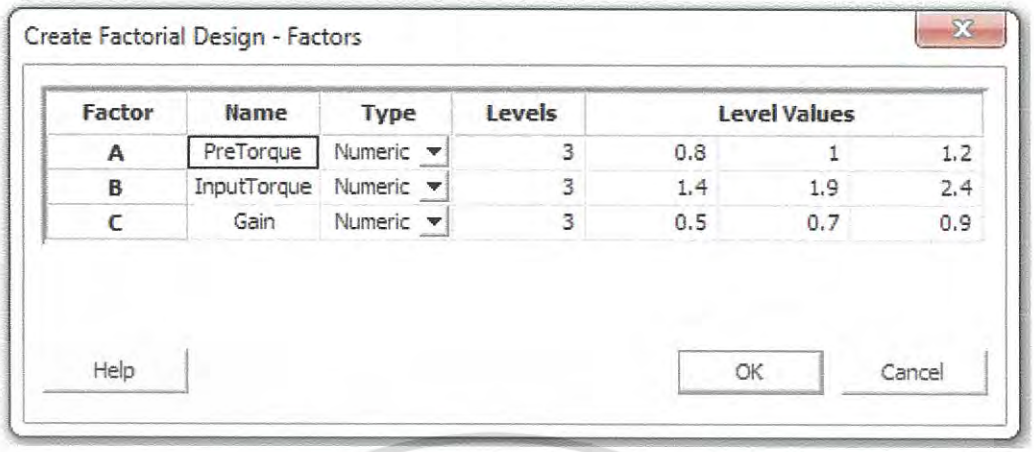
6. Creat name of factor A= PreTorque (Preliminary Torque), B=InputTorque and C=Gain.

7. In **Number of Levels**, choose 3 at each of factor.

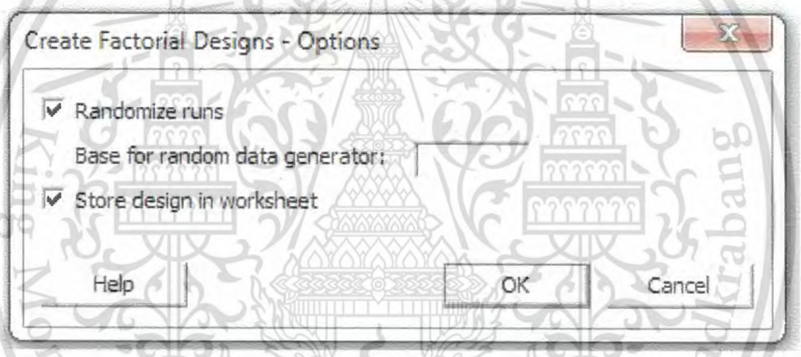
8. In **Number of replicates**, choose *3*.

9. Click **OK** to return to the main dialog box. Notice that Minitab enables the remaining buttons.

10. Name factors and set factor levels, Minitab enters the names and levels enter for each factor into the worksheet and uses the names as the labels for the factors on the analysis output and graphs. Choose numeric for **Type** of each factor, and then create actual **Level Values** for each factor. Level values of factor A is 0.8, 1.0 and 1.2, factor B is 1.4, 1.9 and 2.4 and factor C is 0.5, 0.7 and 0.9.



11. Click **OK** to return to the main dialog box.
12. Click **Option** to Random run and store design in worksheet



By default, Minitab randomizes the run order of all design types. Randomization helps to ensure that the model meets certain statistical assumptions and can also help reduce the effects of factors not included in the study. Setting the base for the random data generator ensures the same run order every time the design is created. While this practice is not usually used, setting the base gives the same run order that is used in this example.

13. Click **OK** to return to the main dialog box.

14. Viewing the design of experiment, every time create a design, Minitab stores design information and factors in worksheet columns. Open the Data window to see the structure of a typical design.

↓	C1 StdOrder	C2 RunOrder	C3 PtType	C4 Blocks	C5 PreTorque	C6 InputTorque	C7 Gain
1	61	1	1	1	0.8	2.4	0.5
2	70	2	1	1	1.0	2.4	0.5
3	51	3	1	1	1.2	1.9	0.9
4	74	4	1	1	1.2	1.4	0.7
5	23	5	1	1	1.2	1.9	0.7
6	64	6	1	1	1.0	1.4	0.5
7	30	7	1	1	0.8	1.4	0.9
8	24	8	1	1	1.2	1.9	0.9
9	47	9	1	1	1.2	1.4	0.7
10	46	10	1	1	1.2	1.4	0.5
11	40	11	1	1	1.0	1.9	0.5
12	78	12	1	1	1.2	1.9	0.9
13	69	13	1	1	1.0	1.9	0.9
14	29	14	1	1	0.8	1.4	0.7
15	19	15	1	1	1.2	1.4	0.5
16	50	16	1	1	1.2	1.9	0.7
17	6	17	1	1	0.8	1.9	0.9
18	15	18	1	1	1.0	1.9	0.9
19	5	19	1	1	0.8	1.9	0.7
20	77	20	1	1	1.2	1.9	0.7
21	52	21	1	1	1.2	2.4	0.5
22	7	22	1	1	0.8	2.4	0.5
23	56	23	1	1	0.8	1.4	0.7
24	14	24	1	1	1.0	1.9	0.7
25	10	25	1	1	1.0	1.4	0.5
26	60	26	1	1	0.8	1.9	0.9
27	71	27	1	1	1.0	2.4	0.7

15. Choose Window ➤ Worksheet 1. The StdOrder column (C1), which is randomly determined, indicates the order in which the data will be collected. If you do not randomize a design, the StdOrder and RunOrder columns are the same. In this example, because you did not add center points or block the design, Minitab sets all the values in C3 and C4 to 1. The factors are stored in columns C3 and C4, labeled PtType and Blocks. Columns C5, C6 and C7 are the main factors studying in next step. Because the factor levels are entered in the Factors sub-dialog box, the actual levels in the worksheet are seen.

Appendix C.
Normalized Unit Calculation

1. Normalized unit calculation

Normalized unit is to define the factor levels on a common scale when want to determine which factor is the biggest effect on the disk clamp screw torque. By default, Minitab uses normalized unit or coded units to perform the analysis. From Equation (5) shows how to calculate the normalized unit [9]. For example, to determine which combination of preliminary torque (PT) settings, input torque (IT) and gain. The low settings of experiment (PT = 0.80, IT = 1.40 and gain 0.5) are indicated by -1 in normalized unit or coded units and the high settings (PT = 1.20, IT = 2.40 and gain 0.9) are indicated by +1 in normalized unit or coded units.

$$X_{normalized} = \frac{X - Mid\ Po\text{int}}{\frac{1}{2}\ Range} = \frac{X - \frac{1}{2}\left(X_{Max} + X_{Min}\right)}{\frac{1}{2}\left(X_{Max} - X_{Min}\right)} \tag{5}$$

PT	=	0.80	1.00	1.20
Midvalue	=		1.00	
Range/2	=	(1.20-0.80)/2 = 0.2		
Normalized	=	-1	0	+1
IT	=	1.40	1.90	2.40
Midvalue	=		1.90	
Range/2	=	(2.40-1.40)/2 = 0.5		
Normalized	=	-1	0	+1
Gain	=	0.50	0.70	0.90
Midvalue	=		0.70	
Range/2	=	(0.90-0.50)/2 = 0.2		
Normalized	=	-1	0	+1

Figure 22 Normalized unit calculation

Table 3 Normalized and un-normalized unit comparison

Actual data

Run	PT	IT	Gain	Final-Torque
1	0.80	1.40	0.50	1.25
2	0.80	1.40	0.70	1.30
3	0.80	1.40	0.90	1.35
4	0.80	1.90	0.50	1.70
5	0.80	1.90	0.70	1.75
6	0.80	1.90	0.90	2.20
7	0.80	2.40	0.50	1.65
8	0.80	2.40	0.70	1.75
9	0.80	2.40	0.90	1.85
10	1.00	1.40	0.50	1.25
11	1.00	1.40	0.70	1.35
12	1.00	1.40	0.90	1.35
13	1.00	1.90	0.50	2.20
14	1.00	1.90	0.70	2.20
15	1.00	1.90	0.90	2.25
16	1.00	2.40	0.50	2.20
17	1.00	2.40	0.70	2.25
18	1.00	2.40	0.90	2.35
19	1.20	1.40	0.50	1.20
20	1.20	1.40	0.70	1.25
21	1.20	1.40	0.90	1.30
22	1.20	1.90	0.50	1.75
23	1.20	1.90	0.70	1.85
24	1.20	1.90	0.90	1.90
25	1.20	2.40	0.50	2.25
26	1.20	2.40	0.70	2.30
27	1.20	2.40	0.90	2.35

Normalized data

Run	PT	IT	Gain	Final-Torque
1	-1	-1	-1	-0.91
2	-1	-1	0	-0.83
3	-1	-1	1	-0.74
4	-1	0	-1	-0.13
5	-1	0	0	-0.04
6	-1	0	1	0.74
7	-1	1	-1	-0.22
8	-1	1	0	-0.04
9	-1	1	1	0.13
10	0	-1	-1	-0.91
11	0	-1	0	-0.74
12	0	-1	1	-0.74
13	0	0	-1	0.74
14	0	0	0	0.74
15	0	0	1	0.83
16	0	1	-1	0.74
17	0	1	0	0.83
18	0	1	1	1.00
19	1	-1	-1	-1.00
20	1	-1	0	-0.91
21	1	-1	1	-0.83
22	1	0	-1	-0.04
23	1	0	0	0.13
24	1	0	1	0.22
25	1	1	-1	0.83
26	1	1	0	0.91
27	1	1	1	1.00

Appendix D

Publication

Certificate of Participation

The 29th International Technical Conference on Circuit/Systems Computers and Communications (ITC-CSCC 2014)

Somsak Taweepun

is thanked for their phenomenal participation on

ITC-CSCC 2014, Phuket, Thailand July 1-4, 2014

LUNCHAKORN WUTTISITTIKULKIJ, PH.D.
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JUN HEO, PH.D.
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Experimental study of optimum disk clamp screw torque by using DOE method

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***Abstract*—The screw-fastening assembly process is one of the most widely used fastening methods in industrial assembly that included hard disk drive (HDD) assembly. The screw-fastening process at media installation (MI) and auto gang bias (AGB) of HDD assembly are the critical operations to attain the accuracy of disk clamp screw torque. In this paper, the design of experiment (DOE) had been performed to study the optimization of disk clamp screw-fastening process. The analysis revealed that input torques and gain current are the key factors affecting the disk clamp screw torque accuracy during the screw fastening process.**

***Keywords*—disk clamp; media; spacer; screw; motor base**

I. INTRODUCTION

In hard disk drive technology, the motor's speed is now up to 10,000 rounds per minute (RPM) and stacking number of magnetic disk is increasing in order to increase speed and capacity respectively. We addressed the concerns of the sensitive assembly operations. More sensitive applications, such as clamping a stack of magnetic disks, spacer, disk clamp on a motor hub in a hard disk drive needs a precise clamp load produced by a set of fasteners. There are two operations in the process of disk clamp fastening. The first operation is media installation (MI), where the screw fastener performs preliminary disk clamp screw torque. The second operation is auto gang bias (AGB), where the screw fastener performs the final disk clamp screw torque and disk balancing. Disk pack assemblies in a hard disk drive as shown Fig. 1 are the material component factors that affect to disk clamp screw torques. They are screw thread dimension, angle, tolerance specification of each component, screw head geometry and the material coating lubricant characteristics excluding screw fastening process setup. Dhayagude, Zhiqiang Gao and Fouad Mradt [2] studied the fuzzy logic control of automated screw fastening found problems in normal processes which were cross-threading, screw jamming and slippage, etc. The fuzzy-logic controller (FLC) was designed and analyzed by simulation model to develop the screw fastening process. With this intelligent controller integrated the process of an electric driver mounted on a robotic positioning system, it helped to fasten screws, be easy to convert products and detect faulty joining conditions, mechanical failure. Neville K.S. Lee, Yingfei An and Fugee Tsung [1] studied the effects of screw-fastening process and assembly accuracy by using design of experiment (DOE) technique for data analysis. Based on the experimental result, the most accurate screw-fastening condition was using relatively more screws, with datum pins, washer and larger holding force. Samart Mungtoklang [3] studied the unbalance rotating in hard disk drive due to screw tightening. This research revealed the unbalance of the rotating disks in hard disk drive caused from the difference in disk clamp screw torque. The screw fastening process is very sensitive. Even though we set in the same condition, it still produces the different disk clamp screw torque value.

Previous studies were really helpful in understanding the principles and the advantages of the screw-fastener. The key screw-fastener parameters were input torque, number of screws, datum pins, washer, holding force, size of the screw, work piece material, screw head geometry, linear speed of the positioning system manipulating the driver and the parts-coating lubricant characteristics. Those setting really affected to the final screw torque. Therefore, the purpose of this study is to understand the factors that affect to the disk clamp screw torque in hard disk drive when the preliminary torque at media installation (MI), input torque and gain at auto gang bias (ABG) are varied. This may be useful to perceive the behavior of the disk clamp screw torque from screw-fastening process.

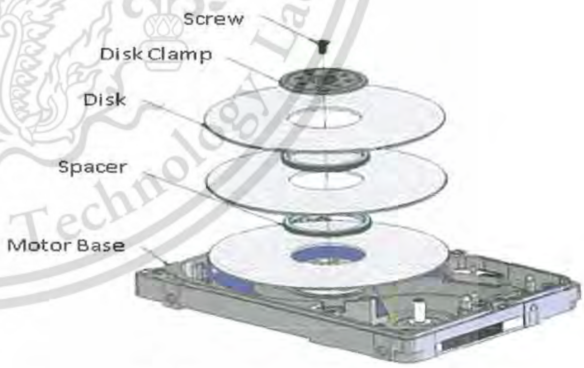

Fig. 1. A disk pack assembly in a hard disk drive

II. THEORY AND METHODOLOGY

To ensure the screw torque be in control when the components are put together and fastened with screws, Micrometer and Torque Wrench must be explored for this study. Micrometer is used to measure the length of the screws while fastening. Then we can calculate the stretch range of the screws, as the result of preloads referring the formula δ = Fl/AE. After the screw is tighten further until they reach the δ range where we can be certain that the fastening is acquired in response to the required preloads.

However, we typically cannot measure the length of a screw while fastening, because the thread at the tip part of the screw is embedded in the component. In this case, if we need the fastening to meet the required force, we have to use a Torque Wrench to tighten the screws until they stretch out as range δ, and then there will be the torsion which causes the primary tension according to the requirement.

$$T = F\frac{d_p}{2}\frac{(\mu+\tan\lambda\cos\alpha)}{(\cos\alpha-\mu\tan\lambda)} + F\frac{d_c}{2}\mu_c \quad (1)$$

T is the screw torque; F is the force in a screw. Due to there is a very small difference between dp and d, then dp is considered to be equal to d, dc is 1.5d approximately. The equation can be rewritten as

$$T \cong F\frac{d}{2}\frac{(\mu+\tan\lambda\cos\alpha)}{(\cos\alpha-\mu\tan\lambda)} + F\frac{(1+1.5)d}{2}\mu_c \quad (2)$$

And

$$T \cong KFd \quad (3)$$

K is the coefficiency of the torsion which can be calculated from

$$K \cong \left[0.50\frac{\mu+\tan\lambda\cos\alpha)}{(\cos\alpha-\mu\tan\lambda)} + 0.625\mu_c\right] \quad (4)$$

Equation (4) shows that K depends on the coefficiency of friction μ and μc. Hence, each screw's coefficiency of friction will affect each screw's torsion.

In the experiment two processes affected disk clamp screw torques which were media installation (MI) and auto gang bias (AGB) as shown in Fig. 2. The preliminary-torque at media installation, input torque and gain control at auto gang bias were studied by using statistic design of experiment method. Design of experiments (DOE) is an appropriate technique for effectively planning, collecting, analyzing the experimental data by statistical methods and producing in valid conclusion.

We used full-run of DOE to plan for the testing conditions. The number of run was designed per number of factors and level. We also conducted the replication of experiment to understand the error of screw-fastening process when we did change the setting. The experiment was carried out in a cleanroom class 100 with the temperature and humidity control.

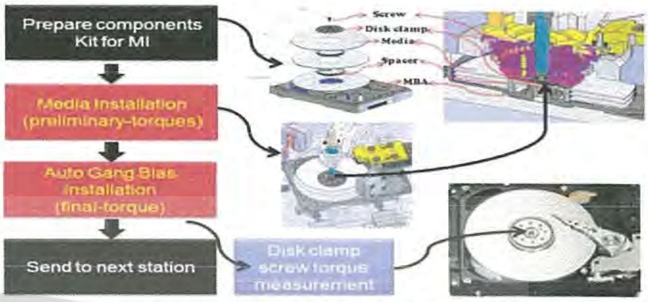

Fig. 2. The process step when assembled motor base, media, spacer, disk clamp and screw by media installation and auto gang bias.

We also solved a problem on the normal measurement quite manual operating with uncertain repeatability and reproducibility. It's too difficult to find the very low value of disk clamp screw torque 2.5". The new fixture designing that provides better precision and easy to use by using the sensor in place to detect screw slipping. This measurement tool is Forward torque for disk clamp screw torque as shown in Fig. 3.

Fig. 3. Disk clamp screw torque measurement fixture

III. Experimental Method

The statistical analysis was done by using the commercially available "Minitab" software. The statistical result and graphical DOE tools such as the main effect plots, interaction plots, contour plots, response optimizer, regression and residual plots analysis were used for the investigation.

Factors and levels of the experiment as shown in Table I, were planned for the testing conditions. The first factor was preliminary-torque, three levels (0.9, 1.0 and 1.2 inch-pounds); the second factor was input torque, 3 levels (1.4, 1.9 and 2.4 inch-pounds); and the third factor was gain control, 3 levels (0.5, 0.7 and 0.9 Ampere). Based on the 3^K full factorial experiment, there were 81 runs totally as shown in Table II. We also conducted 3 replications of experiment runs to give more precise values of mean level effects and provide a relatively reliable estimation of experimental error.

TABLE I. THE FACTOR AND LEVEL OF THE EXPERIMENT

Levels	Factors		
	Pre-torque (Inch-Pounds)	*Input torque (Inch-Pounds)*	*Gain (Ampere)*
1	0.8	1.4	0.5
2	1.0	1.9	0.7
3	1.2	2.4	0.9

TABLE II. The experimental design metrics and results

Run	Pre-torque (Inch-Pounds)	Input torque (Inch-Pound)	Gain (Ampere)	Disk clamp screw torque #1	*Disk clamp screw torque #2*	*Disk clamp screw torque #3*
1	0.8	1.4	0.5	1.25	1.35	1.10
2	0.8	1.4	0.7	1.30	1.40	1.20
3	0.8	1.4	0.9	1.35	1.50	1.30
4	0.8	1.9	0.5	1.70	1.65	1.50
5	0.8	1.9	0.7	1.75	1.75	1.60
6	0.8	1.9	0.9	2.20	1.95	1.60
7	0.8	2.4	0.5	1.65	2.15	2.00
8	0.8	2.4	0.7	1.75	2.35	2.10
9	0.8	2.4	0.9	1.85	2.25	2.10
10	1	1.4	0.5	1.25	1.25	1.20
11	1	1.4	0.7	1.35	1.35	1.20
12	1	1.4	0.9	1.35	1.45	1.20
13	1	1.9	0.5	2.20	1.75	1.60
14	1	1.9	0.7	2.20	1.85	1.80
15	1	1.9	0.9	2.25	1.95	1.70
16	1	2.4	0.5	2.20	2.25	1.90
17	1	2.4	0.7	2.25	2.25	1.95
18	1	2.4	0.9	2.35	2.35	1.95
19	1.2	1.4	0.5	1.20	1.35	1.20
20	1.2	1.4	0.7	1.25	1.40	1.30
21	1.2	1.4	0.9	1.30	1.45	1.25
22	1.2	1.9	0.5	1.75	1.65	1.85
23	1.2	1.9	0.7	1.85	1.75	1.75
24	1.2	1.9	0.9	1.90	1.85	1.75
25	1.2	2.4	0.5	2.25	2.15	2.10
26	1.2	2.4	0.7	2.30	2.30	2.15
27	1.2	2.4	0.9	2.35	2.35	2.10

IV. EXPERIMENTAL RESULTS

We used the general full factorial design of design of experiment (DOE) to test the conditions in order to achieve the appropriate experimental design, data collection and data analysis. The resulting of disk clamp screw torque based on the experiment conditions in the experiment design matrix were shown in Table II.

From the data analysis, Fig. 4 displays the main effect plot of disk clamp screw torque with three factors of pre-torque, input torque and gain control. The input torque is the most significant effect while pre-torque is insignificant effect to the disc clamp screw torque. The gain is slightly significant effect.

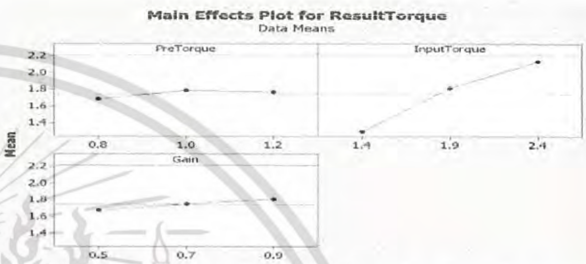

Fig. 4. Main effect plot for disk clamp screw torque

The interactions of all three factors are shown in Fig. 5. They are interacted together, except input torque and gain. Although pre-torque is insignificant different on the main effect plot as shown in Fig. 4, it's also needed a proper control in order to get the best optimization of disk clamp screw torque.

Fig. 5. Interaction plot for disk clamp screw torque.

Fig. 6 displays the surface plot of disk clamp screw torque that shows positive correlation among disk clamp screw torque, input torque and gain. High disk clamp screw torque is required high level setting of these 3 factors as well.

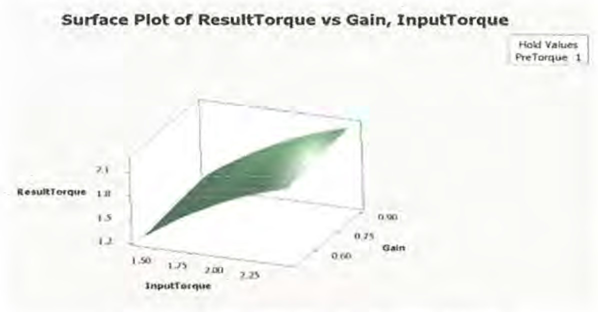

Fig. 6. Surface plot for disk clamp screw torque

Using the response optimization is to help identify the combination of three factors variable settings for disk clamp screw torque. The corresponding outcome level is measured by the composite desirability (d).

Fig. 7 shows an optimization plot of disk clamp screw torque. The optimizer produces the following graph showing the optimal factor settings in red, and the predicted response for disk clamp screw torque in blue. Example: Disk clamp screw torque of product A is 1.90 in-lbs. As Fig. 7, we can get Y= 1.902 inch-pounds, desirability = 0.99764, Input torque = 2.0 inch-pounds and Gain = 0.7 Ampere. The composite desirability (0.99764) is very close to 1, which indicates the settings appear to achieve favorable results of disk clamp screw torque.

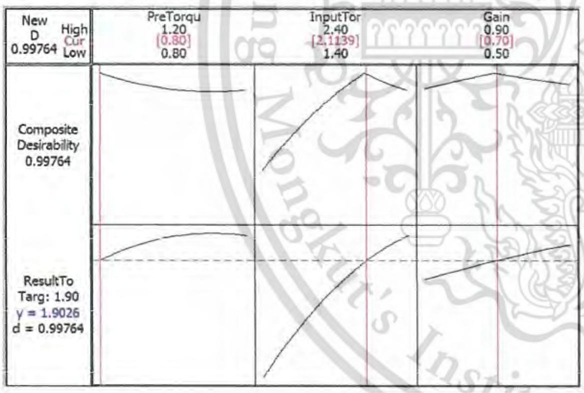

Fig. 7. Optimization plot for disk clamp screw torque

V. CONCLUSIONS

By the experimental study of optimum disk clamp screw torque using DOE on this paper, the input torque and gain were the key factors affecting to the disk clamp screw torque accuracy during the screw fastening process. The best optimization of disk clamp screw torque needs to optimize the setting of input torque and gain at auto gang bias (AGB). Pre-torque at media installation (MI) was insignificant but it had interaction with both input torque and gain. Therefore, we can set the Pre-torque at minimum level in order to save energy and faster cycle time. However, the setting optimization is depended on the disk clamp screw torque product specification based on product capacity and number of media stacking on a drive.

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