Numerical Investigation of Geometrical Tolerance Effect on Torque and Power Output of Slip-On Sprocket

by

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24737

Dissertation submitted in partial fulfilment of

the requirements of the

Bachelor of Engineering (Hons)

(Mechanical)

JANUARY 2020

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CERTIFICATION OF APPROVAL

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Approved by,

____

(AP Dr Ahmad Majdi B A Rani)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

JANUARY 2020

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

(LOH XI LI)

Abstract

During manufacturing, each step will inevitably create variation. Geometrical dimensioning and Tolerancing is one example of manufacturing variation. Since variations lead to unstable performance of a system, this project focuses on establishing the co-relationship between geometrical tolerance and performance output of a slip-on sprocket. The performance will be in terms of torque and power output. The torque and power output will be measured by third party using a dynamometer. By comparing various samples of the slip-on sprocket with different GD&T, the relationship can be established.

Acknowledgements

I would like to express my gratitude towards my supervisor, AP Dr Ahmad Majdi for his guidance throughout the entirety of this project. I would like to thank the coordinator for Final Year Project II, Dr Tamiru Lemma for his patience in conducting various seminar sessions that helped me in writing this dissertation.

Acknowledgment to Malaysia Education Ministry for providing the PRGS/1/2017/TK03/UTP/02/3 (Functional Prototype of Slip-on Sprocket System) with the cost centre 0153AB-L47 used for this research project.

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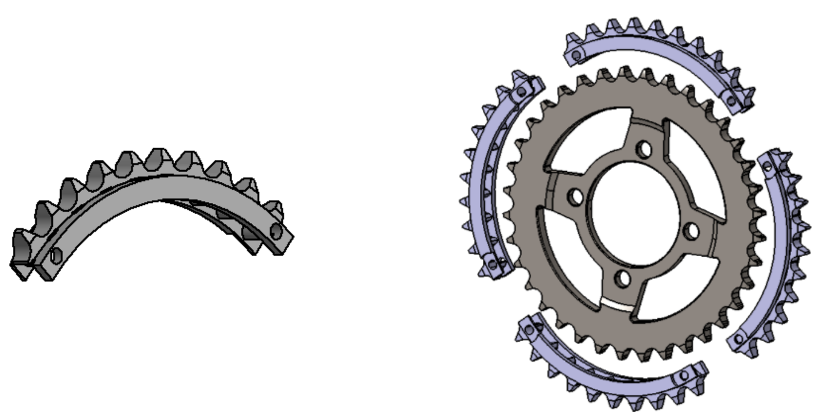
1. Introduction

1.1. Background Study

The slip-on sprocket is a torque boosting device that can be slipped on a regular sprocket on a motorcycle to increase torque output. This sprocket is designed for people in rural or suburban areas that uses motorcycle regularly to commute. The usual motorcycle chain drive system consists of chains, front sprocket and rear sprocket. The slip-on sprocket is installed at the rear sprocket in less than 30 minutes but can boost torque by up to 30%. The sprocket is an easy solution to boost torque without much effort, saving cost, manpower and time [1].

(a) (b) (c)

Figure 1-1: A 40-teeth sprocket (a), 38-teeth sprocket (b) and 38-teeth sprocket installed with Slip-On Sprocket (c).



(a) (b)

Figure 1-2: Illustration of (a) a quadrant of the slip-on sprocket and (b) the exploded view of the assembly between the slip-on sprocket and the rear sprocket.

1.2. Problem Statement

During manufacturing, each step will inevitably create imprecision and the produced parts may vary [2]. Examples of such variation are Geometrical Dimensioning and Tolerancing (GD&T) and surface roughness. Excessive variation is the variation that lies outside the defined upper and lower acceptable limits of a product specification [3]. However, the range of acceptable variation is difficult to determine since it varies with the manufacturing process. It requires a large amount of time, effort and cost to detect non-conforming parts and ensure they do not reach the market [2]. The purpose of doing so is to ensure product quality, where the variability in product in controlled to ensure the characteristics of the final product are consistent with its specifications [3]. Manufacturing variation leads to unstable mechanical performance such as torque and power. In some cases, it can also affect the performance output of a system [4].

Currently, the co-relationship between the geometrical tolerance and torque output of the slip-on sprocket is unknown. There were four samples of Slip-on Sprocket manufactured, which are sample A, B, C and D. For this study, sample B, C and D will be compared.

1.3. Objective

- To analyse the effect of geometrical dimensioning and tolerance on torque output of a slip-on sprocket
- To establish the co-relationship between geometrical tolerance and torque output of a slip-on sprocket

2. Literature Review

2.1. Geometric Dimensioning and Tolerance (GD&T)

GDT is a system used for defining engineering tolerances. It uses symbolic language on engineering drawings or computer generated 3-dimensional drawings that states its geometry and the allowable variation. It states the required accuracy and precision on each feature of a part. The dimensioning refers to the nominal geometry, which is purposely modelled and intended. The tolerancing refers to the variation allowed for the form, size or location. Tolerancing includes linear dimensions and datum reference. GDT ensures repeatability in manufacturing which will save cost and time while producing multiple parts of the same design.

GDT standards include American Society of Mechanical Engineers (ASME) Y14.5 and International Organization for Standardization (ISO) [5]. There are 14 different types of geometric tolerances, mainly divided into three categories. The three categories of tolerance are for individual features, for related features, or for both individual and related features [6]. The range of tolerance for each assembly varies depending on their manufacturing and working characteristics [7].

The types of tolerances are shown in table 2-1.

Table 2-1: Types of Geometrical Tolerance

	Type of Tolerance	Characteristic
For Individual Features	Form	Straightness
		Flatness
		Circularity
		Cylindricity
For Individual or Related Features	Profile	Profile of a Line
		Profile of a Surface
For Related Features	Orientation	Angularity
		Perpendicularity
		Parallelism
	Location	Position
		Symmetry
		Concentricity
	Runout	Circular Runout
		Total Runout

The symbols are shown in figure 2-1.

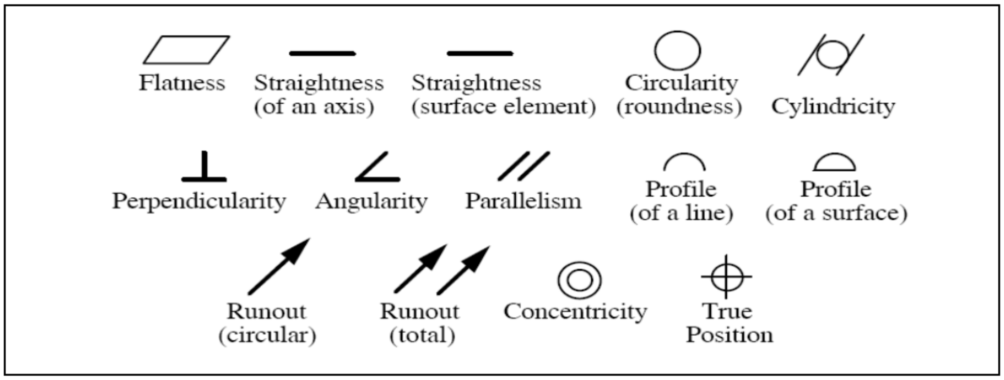


Figure 2-1: Symbol for Geometrical Tolerance

2.2. Tolerance Stack-up Analysis (Worst Case Scenario)

The conventional ways of tolerance analysis are often time consuming and tedious. In order to obtain the stack up of geometrical tolerance of a desired part, it often involves numerous conditions and rules.

The aim of the tolerance stack up analysis is to obtain the dimensional relationships within an assembly. In the case of this project, it allows the slotting part of the slip-on sprocket to be optimized while maintaining its torque and power output.

There are many different graphical approaches in tolerance stack-up analysis, such as Catena, Quickie and Generic Capsule methods. All approaches are used to calculate the cumulative effect of tolerance stack ups at points of interest in a mechanical assembly with the individual tolerances already known. The worst-case and root sum square methods of tolerance stack up are commonly used for the cumulative calculation.

For the project, worst-case approach is used as the slip-on sprocket satisfies the following criteria:

- The number of constituent dimensions in assembly is very small.
- The volume of production is very small.
- 100% acceptance is required.

The weakness, however, is that the prediction of the dimension becomes too conservative, as all individual tolerances are assumed to be at their worst case. On the other hand, the root sum square approach is applicable when the number of constituent dimensions in assembly is sufficiently large, volume of production is high and finite rejection of product assembly is acceptable.

The worst-case method, also known as linear stack-up, is the most basic method for obtaining the predicted effect of individual tolerances in an assembly. All tolerances are assumed to be at their worst limits simultaneously.

$$\Delta Y = \sum_{i=1}^{n} \partial i$$

Where

n = number of constituent dimensions in the dimension chain

δi = tolerance associated with the dimension

The graphical approach chosen for this project is the Generic Capsule approach. For this approach, the steps include labelling, modelling, formulation and evaluation.

Firstly, the surfaces dimensioned are labelled, with an sample assembly as shown in figure 2-2. Surfaces with bilateral flatness tolerance specifications are labelled twice. Labels with an asterisk (*) represents the virtual surfaces created by the presence of geometrical tolerance, while labels without an asterisk represent the basic surfaces. [6]

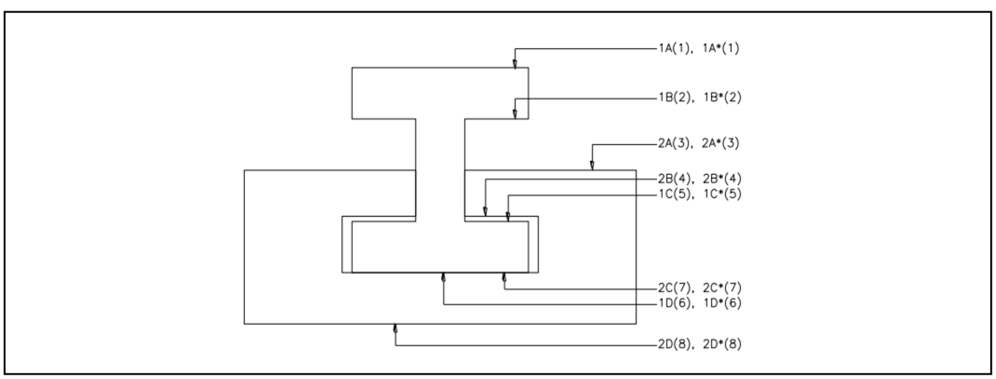


Figure 2-2: Labelling of sample assembly

After labelling, a graphical model can be constructed as shown in figure 2-3. The two parts are linked together with a dash line that represents the surface contact.

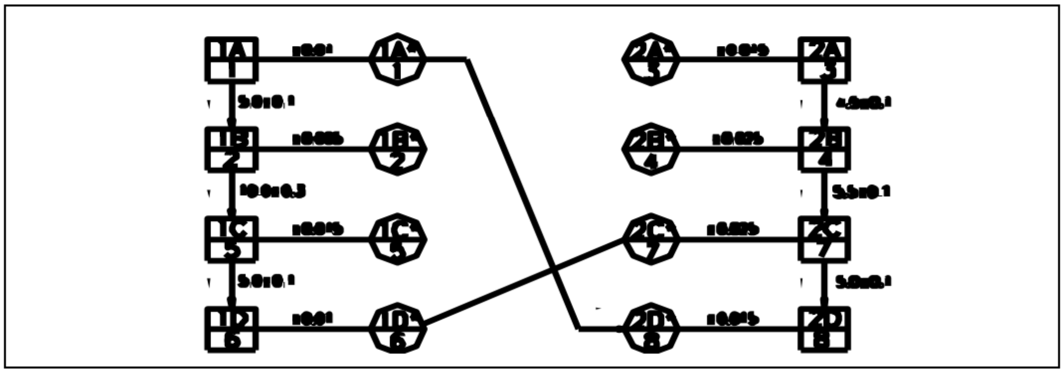


Figure 2-3: Graphical Model

The stack path is identified as the dashed line that connects between 1D* and 2C*, with the expression derived as below:

$$1A^*2D^* + 2D^*2D - 2C2D + 2C2C^* + 2C^*1D^* + 1D^*1D - 1C1D - 1B1C - 1A1B + 1A1A^* = 0$$

Upon substitution and simplification,

$$X = 25.0 \pm 0.66$$
$$X_{MAX} = 25.66$$
$$X_{MIN} = 24.34$$

This method will be used on the slip-on sprocket as discussed in chapter 3.2.

2.3. Relation between Torque and GD&T

The torque output of the slip-on sprocket can be related to its GD&T in terms of vibration [8]. Figure 2-4 shows the free body diagram of the chain drive system. Sprocket A is the driving sprocket and sprocket B is the driven sprocket.

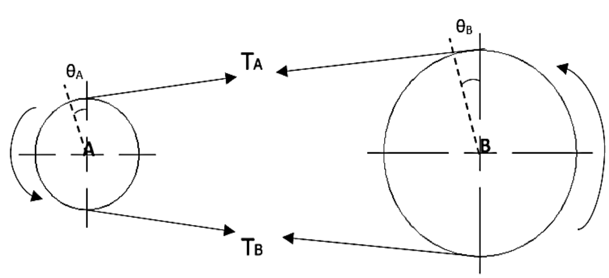


Figure 2-4: Free Body Diagram of the Chain Drive System

The diagram can be analyzed numerically by using the Newton-Euler method to obtain the following equation [1]:

$$\theta_B = \frac{-2Tkr_Ar_B}{I_AI_B\omega^4+2\omega^2k(I_Ar_B{}^2+I_Br_A{}^2)}$$

Where
θ_B is the angular displacement on sprocket B,
T is the torque input from the rotation of the motor of the driver sprocket,
k is the spring stiffness of the chain,
r_A, r_B is the pitch radius of sprocket A and B, respectively,
I_A, I_B is the mass moment of inertia of sprocket A and B, respectively,
ω is the frequency.

Since the slip-on sprocket is installed on the driven sprocket (sprocket B), the vibration response of the slip-on sprocket is based on the excitation of sprocket B as well. This can be expressed as a mass-spring-damper relationship as shown in figure 2-5.

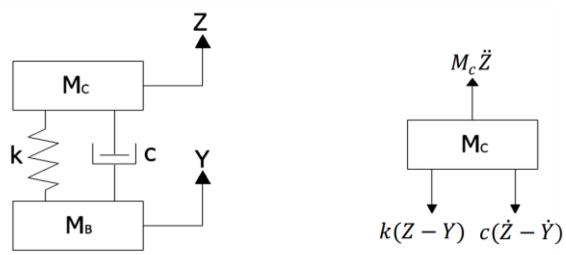


Figure 2-5: The mass-spring-damper of sprocket B and the slip-on sprocket (sprocket C)

Where
M_B, M_C is the mass of sprocket B and slip-on sprocket (sprocket C), respectively,
c is the damper coefficient,
Z, Y are the response directions.

By linearizing the angular displacement of the torque boosting device as Y and substituting into the vibration response of based excitation equation, the response of the slip-on sprocket can be formulated as follows:

$$Z=\left[\frac{-2Tkr_Ar_B^2}{I_AI_B\omega^4+2\omega^2k(I_Ar_B{}^2+I_Br_A{}^2)}\right]\left[\frac{1+\left[2\left(\frac{c}{c_c}\right)\left(\frac{\omega}{\omega_n}\right)\right]^2}{\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)^2+\left(2\left(\frac{c}{c_c}\right)\left(\frac{\omega}{\omega_n}\right)\right)^2}\right]^{\frac{1}{2}}$$

Where
c_c is the critical damping coefficient,
ω_n is the natural frequency.

The k value is influenced by GD&T. A higher tolerance will cause unwanted vibration which will reduce the effective torque output of the whole system.

3. Methodology

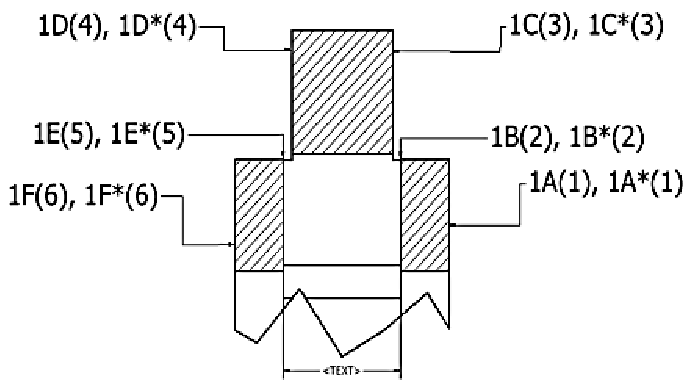
The first phase of this study is to analyse the GD&T of the slip-on sprocket. The design of experiment for the torque and power output were also organised. The second phase will involve the experimental test of the slip-on sprocket for the samples. All the samples will be tested on the same motorcycle model, which is Honda Ex5 110cc. This model normally acts as a benchmark among the community in Malaysia. The specifications of a Honda Ex5 motorcycle is specified in table 3-1.

Table 3-1: Default specification for Honda Ex5 110cc.

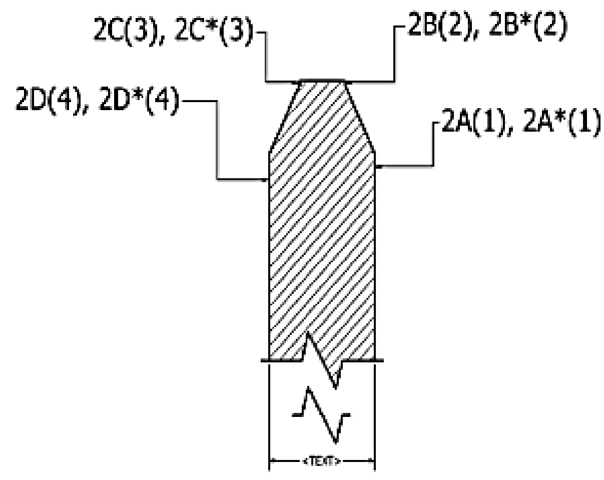
Description	Value
Centre to centre distance (mm)	468.9
Number of chains	96
Length of chain (mm)	467.8
Span Angle (°)	5.39

There were four samples manufactured, which are sample A, sample B, sample C and sample D. Sample A is manufactured using a different material and is used to study the effect of material on the torque and power output of the slip-on sprocket, which is not discussed in this paper. Sample B, sample C and sample D are manufactured using the same material but with different GD&T. A baseline sample that represents the default performance of a 40-teeth sprocket (OEM 40) is also included in this study.

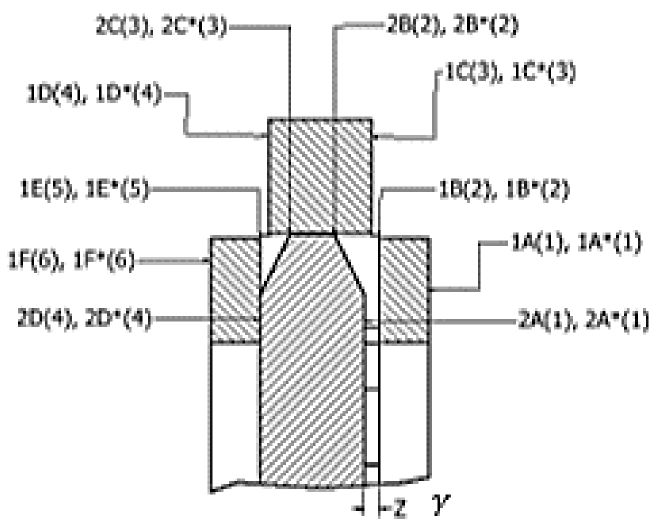
3.1. Tolerance Analysis



(a)



(b)



(c)

Figure 3-1: Graphical model showing (a) Slip-on Sprocket, (b) Rear Sprocket, (c) Assembly.

In order to determine the GD&T of the samples, tolerance analysis was carried out. For the slip-on sprocket, the slotting part is selected as the critical feature for the assembly. Using tolerance stack-up analysis, the dimension in 2D is calculated to obtain the worst-case scenario. The measurements of the samples were measured using the image processing tool in MATLAB and then used to produce the graphical model of the stack-up analysis for each sample. Referring to figure 3-1, the asterisk (*) signifies the virtual surfaces due to the geometrical tolerance.

3.2. Experimental Test for Torque and Power

The torque and power analysis will be handled by Motodynamics Technology Sdn. Bhd. A single gear test will be carried out by them using Bazzaz S125-LC Dynamometer. The standard for this test will be SAE J1349 standard for basic net engine power and torque rating for the spark and compression ignition engines [9]. The setup of the experiment is shown in figure 3-2.

Figure 3-2: The setup of the single gear test

The applied speed for this experiment was 70 rpm for a low-speed run, 140 rpm for medium-speed run, and 240 rpm for a high-speed run. The performance results were automatically plotted as a graph by a computer connected to the dynamometer, running on Dyna Run V3 (2018). The generated results will be used for analysis.

3.3. Gantt Chart

FYP I															
Week		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Task/Activities	Topic Selection														
	FYP Briefing														
	First Meeting with Supervisor														
	Collecting and reviewing of articles/journals														
	Extended Proposal Submission														
	Preparation for Proposal Defence														
	Progress Assessment 1														
	Proposal Defence														
	Submission of Interim Report														
	Meeting with Supervisor														

FYP II															
Week		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Task/Activities	Sample D Obtained														
	MATLAB Image Processing for Sample														
	Single Gear Test by Motodynamics														
	Result Analysis														
	Submission of Video Presentation														
	Submission of Dissertation														
	Meeting with Supervisor														

4. Results and Discussion

4.1. Tolerance Analysis

The graphical model for the slip-on sprocket is constructed with α as the slotting part, β as the teeth thickness of the rear sprocket and γ as the difference between α and β, as shown in figure 4-1.

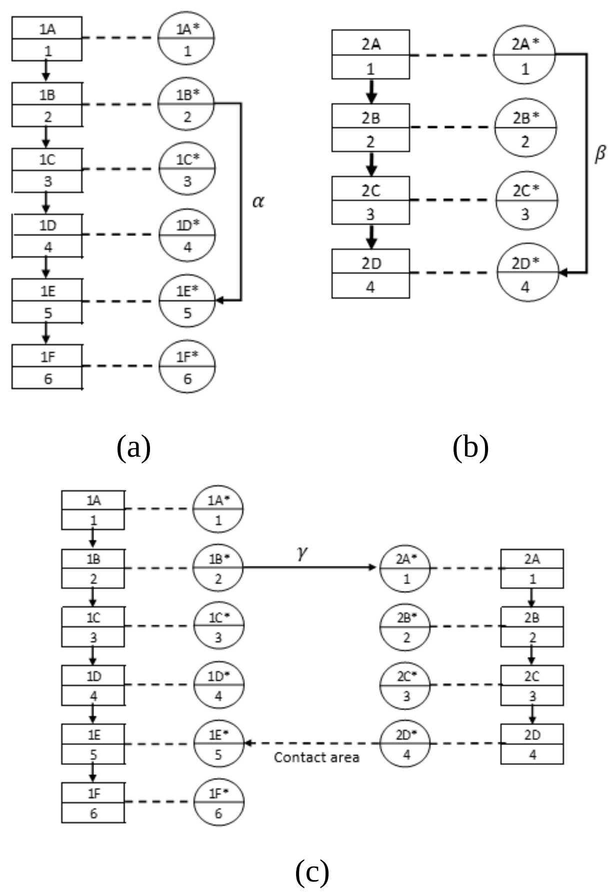


Figure 4-1: Graphical model for (a) α, (b) β and (c) γ

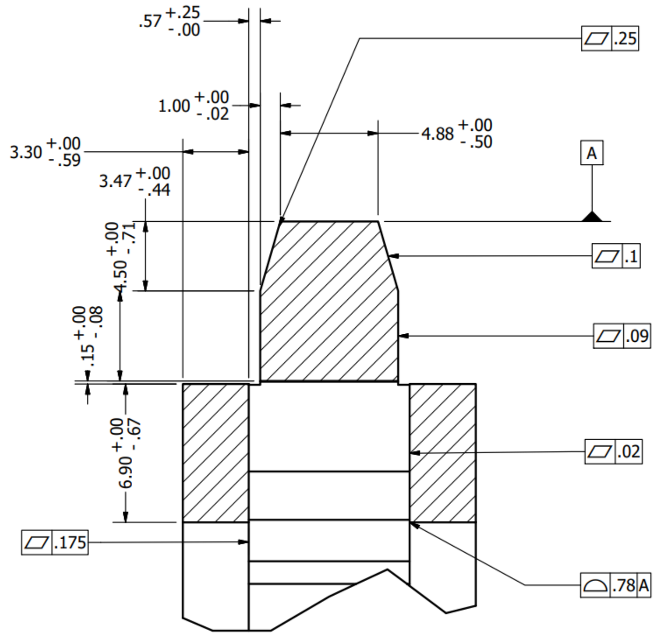
From the graphical model, each of the stack path is derived.

$$\alpha - 1E^*1E - 1E1D - 1D1C - 1C1B - 1B1B^* = 0$$

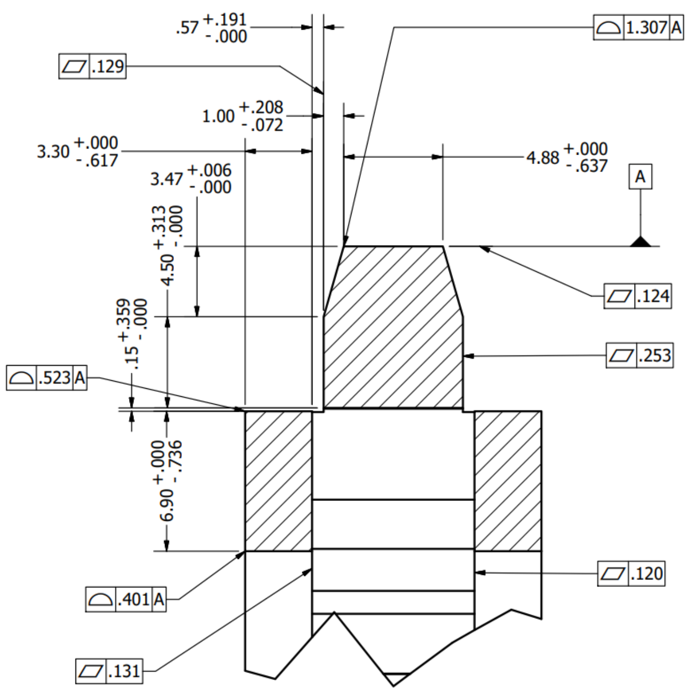
$$\beta - 2D^*2D - 2D2C - 2C2B - 2B2A - 2A2A^* = 0$$

$$\gamma + 2A2B + 2B2C + 2C2D + 2D2D^* + 2D^*1E^* + 1E^*1E - 1E1D - 1D1C - 1C1B - 1B1B^* = 0$$

After MATLAB image processing, the individual tolerance for each sample were drawn in CATIA, as shown in figure 4-2.



Sample B



Sample C

Figure 4-2: Individual tolerances for each sample

The individual tolerance was summed up using the equation derived. The final value of α, β and γ are tabulated in table 4-1.

Table 4-1: Value of α, β and γ for sample B, C and D

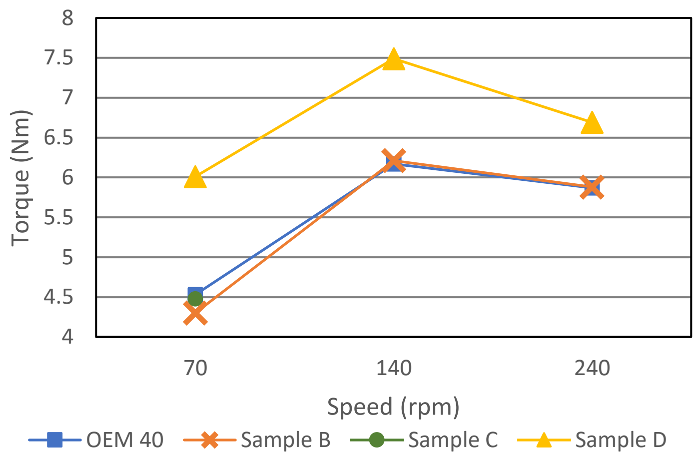
Sample	Distance		
	α	β	γ
B	$8.161^{+0.307}_{-0.000}$	7.000	1.468
C	$8.161^{+0.002}_{-0.000}$	7.000	1.163
D	$8.161^{+0.000}_{-0.433}$	7.000	0.728

4.2. Experimental Test for Torque and Power

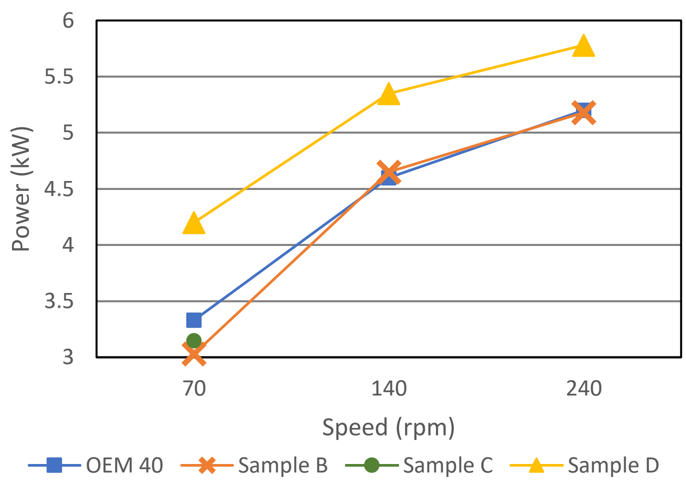
Table 4-2 and figure 4-2 shows the experimental results of the torque and power output for a baseline 40-teeth sprocket, sample B, sample C and sample D. Sample C has undergone plastic deformation at 140 rpm due to high stress from the chain during the experiment. Therefore, there were no results for Sample C at 140 rpm and 240 rpm.

Table 4-2: Results of Single Gear Test

Speed (rpm)	**Torque (Nm)**			
	OEM 40	**Sample B**	**Sample C**	**Sample D**
70	4.53	4.30	4.48	6.01
140	6.17	6.21	-	7.49
240	5.87	5.88	-	6.69
Speed (rpm)	**Power (kW)**			
	OEM 40	**Sample B**	**Sample C**	**Sample D**
70	3.33	3.03	3.16	4.20
140	4.69	4.65	-	5.35
240	5.20	5.18	-	5.78



(a)



(b)

Figure 4-3: Graph of (a) Torque vs. Speed and (b) Power vs. Speed

At 70 rpm, the torque output of Sample D is 24.6% higher than baseline OEM 40, 28.4% higher than Sample B, and 25.5% higher than Sample C. The power output for this speed shows a similar trend, with Sample D being 20.7% higher than baseline OEM 40, 27.9% higher than Sample B, and 24.8% higher than sample C.

For 140 rpm and 240 rpm, Sample B gives the same torque output as baseline, whereas Sample D is 17.1% higher at 140 rpm and 12.1% higher at 240 rpm than both. In terms of power output, Sample B is lower than baseline and Sample D at 140 rpm and 240 rpm.

Based on the results, a decrease in GD&T provided an average of 27.0% increase in torque and power output at low speed but provided 20.0% decrease in terms of increment at medium speed. Although lower GD&T still give higher results output at high speed, it also results in greater decrement of torque and power output. The torque and power output of Sample D drops 58.8% more in terms of torque and 23.2% more in terms of power at 240 rpm when compared to Sample B.

As shown in table 2, Sample D has the lowest value of γ, followed by Sample C and lastly Sample B. From the value at 70 rpm, it can be observed that the lower γ value increases the resultant torque and power output. The results also show similar trend at 140 rpm and 240 rpm, where Sample D has a higher output than sample B.

5. Conclusion and Recommendation

5.1. Conclusion

In this study, the Slip-on Sprocket was analyzed on different manufacturing variation. The GD&T of the slip-on sprocket was varied to obtain its torque and power output under the same operating conditions.

Therefore, it can be concluded that the use of higher GD&T will contribute to lower torque and power output. However, high GD&T will also give a low increment in torque and power at medium speed, and a big decrement in torque and power at high speed. This can be related to the value of stiffness (k) that is affected by γ value in different samples. When γ value increases, k value increases as well. Since increasing stiffness (k) will increase the resonance frequency of the samples, the slip-on sprocket will have more unwanted vibration in the chain drive system if their γ value is higher [8]. The results support this statement as sample D, which has the lowest γ value, gives the highest torque and power output as compared to other samples.

The results obtained from this study can be used to improve and optimize the design of the slip-on sprocket to produce an optimal torque boosting device for motorcycles.

5.2. Recommendation

- Currently, there are only 2 samples at medium and high speeds. Sample C undergone plastic deformation.
- To further relate GD&T and torque/power output, more samples need to be tested.
- The vibration test should also be conducted to support the statement made in the conclusion.

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Appendix

S125LC Load Control

Motorcycle Dynamometer

The S125LC with eddy brake is our main motorcycle dynamometer with its maximum power measured at 600 HP.

*In addition to standard hardware, Package includes:
Gas analyzer, Gas-assisted loading ramp, twin cooling fans, keyboard monitor arm, auto climate monitor.

Vehicle Type: Motorcycle
Loading Type: Inertia & Eddy Brake

Max Power (dynamic): 600 HP
Max Power (static): 270 HP
Max Torque: 500 ftlb
Max Rear Wheel Speed: 200mph

Modeled Mass: 604 lb (274kg)
Drive Roller Diameter: 17.83" (45.3cm)
Drive Roller Width: 17.71" (45cm)
Drive Roller Inertia: 14.0 kg/m2
Drive Roller Surface: Knurled (anti-corrosion zinc)

Max Vehicle Length: 94.33" (239.6cm)
Min Vehicle Length: 47.48" (120.6cm)

Length (w/out ramp): 106.46" (270.4cm)
Width: 70.79" (179.8cm)
Height (deck): 17.68" (44.9cm)
Height (overall): 34.8" (88.4cm)
Weight (approximate, uncrated): 2750lb (1250kg)

Timing Accuracy: 50 nanoseconds
Speed Accuracy: 0.01 pmg
RPM Accuracy: 0.1 rpm
Calibration: Calibrated / Check Weights

Speed Encoder System: Digital Chrome on Glass
Ignition Pick Up: Digital (Intelligent(R) Primary & Secondary)
Data Aquisition System: Digital High Speed USB

Supply Voltage: 190-240 Volt AC, 50/60Hz
Max Supply Current: 32 Amps
Air Consumption: <1CFM (120psi max) **Standard Hardware Features**

- Eddy Brake with torque monitor
- Eddy brake system fully closed-loop with infrared temperature compensation.
- Fast Dynamic Load Control of eddy brake (no user PID control, self learning)
- Calibration check weight and arm.
- Advanced, intuitive Windows software (free software upgrades)
- Dynamometer-to-PC USB link
- Multifunction remote hand controller.
- Intelligent Ignition Pick-up™ system (primary and secondary)
- Starter system (also used to calibrate dynamometer)
- 12 Auxiliary 0-5 Volt data acquisition inputs, for connection to additional sensors
- Machine construction from 3, 5, and 10mm precision laser cut steel
- Powder coated finish in signature Bazzaz blue and white
- Anti-slip, powder coated, flat black diamond plate
- Manufactured to Bazzaz specifications in the UK
- 1 year replacement parts warranty (excludes consumables)

Optional Accessories

- Twin cooling fan system (high speed and pressure, operated from hand control pendant)
- Wideband air/fuel system (single, double, and quad channel)
- Weather station (temperature, humidity, pressure, and relative air density)
- Gas-assisted loading ramp
- Keyboard monitor shelf
- 4-Channel type K thermocouple unit
- 160MPH Ram Air simulation system (calibrated to road speed)
- Infrared temperature monitor (up to 500ºC)
- Exhaust extraction kit
- Exhaust arms
- Carbide drive roller coating

Figure i: Specification for the Bazzaz S125LC Dynamometer

34, Jalan Wangsa Setia 3, Wangsa Melawati, 53300 Kuala Lumpur, Wilayah Persekutuan Kuala Lumpur

6P5V+QP Kuala Lumpur, Federal Territory of Kuala Lumpur

03-4131 4435

Figure ii: Location of Motodynamics Technology Sdn Bhd

Figure iii: The slip-on sprocket installed on a Honda Ex5

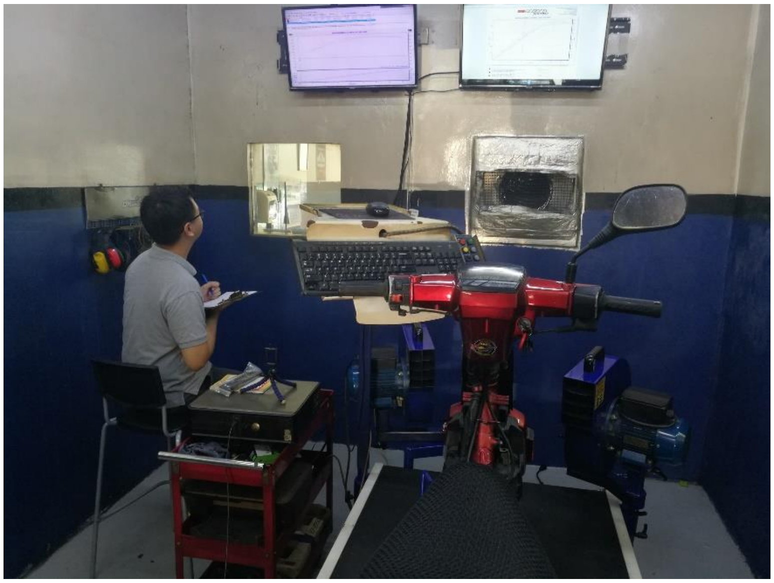

Figure iv: Recording data from the monitor that is connected to the dynamometer