Gear Faults Analysis Using Finite Element Method

by

Rhaishazrin Amirul Iqma Bin Rosli

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

SEPTEMBER 2013

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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Approved by,

____

(Dr Saravanan Karuppanan)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
SEPTEMBER 2013

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.

RHAISHAZRIN AMIRUL IQMA BIN ROSLI

ABSTRACT

In this study, gear faults analysis has been conducted by Finite Element Method (FEM) using ANSYS Software. It was conducted in order to investigate how failure modes in gears affect the gear mechanism. There are many failure modes in gear namely tooth crack, pitting, wear and scuffing. These modes affect gear mechanism in various ways and if not detected in early stage they may lead to a total system failure. The examples of system failure are high vibration state, loud noise, less power transmitted and fracture of teeth. In this study, the author will investigate how each failure modes will affect the frequency response of the system. At the end of the study, the difference of amplitude (deformation of a single tooth) between failure modes was determined to reveal the most risky fault. In this study, two failure modes were investigated, wear and crack. The simulation was validated with previous experiment conducted by Muniyappa Amarnath *et al.* [1]. After the modelling is validated, the simulation was conducted for a gear system with zero faults (healthy gear) followed by two failure modes, wear and tooth crack. They were designed on the gear stage by stage, by increasing the area of failure. For every stage of failure, the frequency response was recorded. The results were analysed to discover the variation of amplitude (deformation) between every failure mode. From this finding, the main failure mode that contributes to the most unsafe condition was determined. The results revealed the crack as the riskiest failure mode since it caused more deformation. A further study can be carried out on how to detect and prevent each of these failure modes from occurring. To save time and money, priority will be given to the one with riskiest condition. This will allow us to solve a major part of the failure problems in gear mechanism.

ACKNOWLEDGEMENT

First of all, I would like to express my gratefulness to Allah S.W.T as I accomplished my project in the duration of 28 weeks. Also a special thanks to Universiti Teknologi PETRONAS for giving me the opportunity to conduct my final year project (FYP).

Furthermore I would like to express my immense appreciation to my FYP supervisor, Dr Saravanan Karuppanan for his kind supervision and fair assessment as well as my co-supervisors, Ir. Idris Bin Ibrahim and Santosh S. Patil for assisting me in these 28 week time.

Without any help from my classmates, I cannot complete this project with ease. Thanks for the assists and supports that you all had given me while accomplishing this project.

Besides I would like to thank my friend and family for their support and encouragements from the beginning of my FYP until the end.

Last but not least, I would like to extend my gratitude to anyone who had assisted me directly or indirectly in making my final year project a success. Thank you and may God bless you all.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

Most of the machines today are using gears as the power transmission mechanism. When two gears mesh together (shown in Figure 1.1), and produce a mechanical advantage through a gear ratio, they may be considered as a simple machine. Gears can act as a system that can change speed, torque and direction of a power source. Gears have more advantages when compared to the wheel and pulley system. Wheel and pulley system have slipping problems; in gear meshing it is prevented with the teeth. They also have other advantages over other drives, like the velocity ratio which is the result of having teeth. This is important for mechanism that requires exact rotational velocity like watches. Besides, gears also have several disadvantages. Despite being a good power transmission mechanism, gears are also costly to manufacture and need lubrication system to prevent them from damage. There are many types of gears such as spur, helical, bevel, hypoid and crown. The simplest gear is the spur gear. It consists of a cylinder disk with teeth projecting radially, as shown in Figure 1.2.

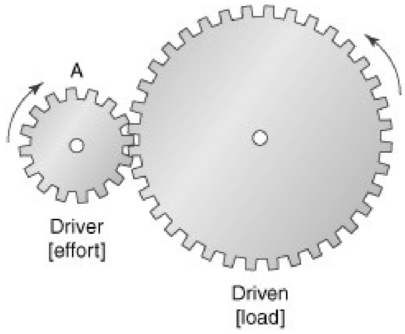

Figure 1.1.The meshing of gears

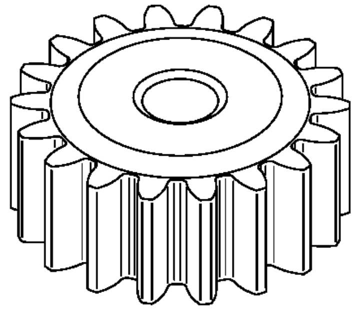

Figure 1.2. A spur gear with 18 teeth

In most of the gear studies, modal analysis is frequently used to determine the frequency response of a gear mechanism during vibration. The most commonly used method for modal analysis is Finite Element Method (FEM). This is because the method is accurate and the results of the calculations are acceptable. It is also possible to find the frequency response based on experiment. A physical gears model are developed and tested to find the frequency response function (FRF). The amplitude of FRF can be noise, pressure and deformation. This is called Experimental Modal Analysis (EMA). Sometime it is used to calibrate FEM, to make sure FEM is correct. However, to conduct an experiment of modal analysis requires lots of time and high cost is involved. Thus the best way to study the frequency response function will be from FEM that has been validated by EMA. Nowadays the most common ways to conduct FEM is using computer simulation like ANSYS, Abaqus, Diffpack, Nastran and S Frame.

Gear systems or gear trains tend to play a vital role in all industries and also in our day to day life. Any failure to the gear system leads to the total system failure. The function of a gear drive is to transmit torque and rotary motion between a prime mover and a driven piece of equipment at acceptable levels of noise, vibration and temperature. When one or more of the preceding operating characteristics exceeded the allowable limits, the drive and its application should be examined to check the gear condition. In most of the cases, faults will occur in gear mechanism. Failure or fault is the state or condition of not meeting a desirable or intended objective, and may be viewed as the opposite of success. Gears can fail in many ways. Except for an increase in noise level and vibration, there is often no indication of difficulty until total failure occurs. In general, each type of failure leaves characteristic clues on the gear teeth, and detailed examination often gives enough information to establish the causes of failure. There are many failure modes in gear systems. The major areas by which the gears tend to fail are shock loading failure, fatigue failure, failure due to wear and failure due to scuffing. A deep understanding of failure modes helps us to overcome or prevent the gear failures.

1.2 PROBLEM STATEMENT

Gear mechanism performance will drop as the time goes by. This is due to the failures that occur on the gears. Every failure has different characteristics and will affect the gear system in different ways. Every fault like tooth crack, pitting, wear and scuffing has different failure causes, degradation rate, noise intensity, vibration, deformation and pressure level. In this study, an investigation on the failure will be carried out in order to determine the riskiest failure mode. Parameters like frequency and deformation of tooth will be used to determine the riskiest fault.

1.3 OBJECTIVE

The objectives of this study are to:

1) Investigate the effect of progressive gear faults to the frequency response function, FRF.
2) Determine the failure modes which give the most unsafe condition to the gear mechanism.

1.4 SCOPE OF STUDY

The study is about failure modes in gear mechanism. The failures will cause high deformation and pressure to the gear teeth and if not prevented at early stage, will lead to the total system failure like the fracture of teeth. These parameters vary for every type of failure. The study will cover the variation of FRF between the failure modes. FRF will tell how failure modes will affect the deformation of gear teeth. It is important to know the effect of each failure types to the gear systems in order to prevent the fracture problem. A computer simulation will be conducted for investigating the effect of every failure modes to the frequency response function. In this simulation model, FEM will be used and validated by previous EMA carried out by Muniyappa Amarnath *et al.* [1].

CHAPTER 2
LITERATURE REVIEW

In the gear field, the most important parameter to study is vibration. Without a doubt, vibration give lots of problems to a gear system like high level of noise produced, less power transmitted and sometime may lead to a total damage. A study about modal analysis of gear housing and mounts had been conducted in 1989 by Teik C. Lim *et al.* [2]. They used Finite Element Method verified by Experimental Modal Analysis for their research. The main purpose of the study was to evaluate the effect of gear housing and mount stiffeners to the dynamic characteristic of gears. They found that the flexibility of the gear housing and mount directly influences the frequency and modal analysis. However, the addition of housing plate stiffeners did not significantly change the nature of the mode shape prediction. Thus it is concluded that, housing plate and mount give little effect to the system vibration.

Another study was done in 2003 that investigate the effect of wear to a gear system [3]. Wear is one of the failures that occur in gear mechanism. The main purpose of the study was to establish a fault detection model. A progressive wear will lead to system failure if it was not prevented at an early stage. A modal analysis on the reduction of gear tooth stiffness was carried out using analytical method and was validated by experimental results. From the results, they constructed a mathematical model that can detect wear at critical stage while monitoring its progress.

Beside wear, there are many other failures. One of the most common fault is crack. It can easily occur due to high load applied to a system. Qinkai Han *et al.* [4] had conducted a dynamic analysis of a geared rotor system considering a slant crack on shaft in 2012. The main objective was to find the effect of crack depth, length and position on dynamic behavior of the gear. They used whirling analysis, parametric instability and steady state response to assist them in their study. Later, they compared all the result for validation purpose. At the end, a variation of stiffness coefficients of cracked shaft element with different cracked length was determined.

Another study on eccentricity error and tooth crack has been conducted in 2008. Mohamed Abbes *et al*. [5] investigated the dynamic behavior modeling of flexible gear system in the presence of defects. The aim was to investigate the influence of wheel rim thickness on the dynamic response. An eccentricity error and tooth crack was also introduced to observe the influence on the dynamic behavior. It was proven that transmission error is affected by the shape of the wheel and presence of natural frequency.

While manufacturing gears, some errors might occur due to machining process. In 2006, Fakher Chaari, Tahar Fakhfah and Rinab Hbaieb investigated the influence of manufacturing errors on the dynamics behaviors of planetary gears [6]. The study involved gears mechanism which was used in transmission of automobile and helicopter. The performance of a healthy gear was compared with the presence of eccentricity and profile error. It has been found that the contact pressure in profile error is higher than in healthy gear.

Another main parameter in gear study is stress and strain state. High stress and strain will affect gear performance in many ways. A dynamic analysis of the stress and strain state of the spur gear pair has been conducted. Dejan Dimitrijevic *et al*. [7] tried to obtain the force in the gear contact. Using analytical method and FEM, they developed a software to calculate parameters of the strain and stress state at every point of the gear.

Stress can also occur due to thermal effect. In 2012, Yuan Hui Quan and Ri Chol Na carried out a research on modal analysis of gear considering temperature using ANSYS [8]. ANSYS software was used to run the thermal effect simulation. From the simulation, the effect of thermal stress on natural frequency has been found. They compared the frequency between having change in temperature and not having change in temperature. From the study, it was discovered that the thermal stress produced by variation of temperature is the main reason for the natural frequency to alter. While changing the gear material, thermal stress effect on the frequency also changes. The largest thermal effect on the frequency is for steel and alloy gears.

Errors in gear mechanism are likely to be chosen as a study area by researchers. They are interested to investigate the failure characteristics, effects of failure to gear mechanism and the causes of each failure modes. Some of the studies focus on detection of the failure since it is important to detect gear fault at early stage. However none of the studies focused on comparing all the failure types. Most of them focused on one type of failure only. By comparing all the failure modes, we can know the riskiest fault. It is believed that different faults will have different frequency response function, FRF. In this study, the amplitude of FRF used will be deformation of a single tooth. The analysis of gear faults will be carried out using finite element method through ANSYS software.

CHAPTER 3
METHODOLOGY

3.1 PROJECT METHODOLOGY

At the end of this project, a comparison between each failure mode will be established. The comparison is about the effects of failure modes to the frequency response function. There are two types of gear fault that will be considered, wear, and tooth crack. It is believed that they will give different results. A modal analysis will be used to obtain the frequency response function of the gear mechanism.

First of all, some knowledge on the gear faults area is needed in order to conduct the modal analysis smoothly. By reviewing some of the topics like the factors and effects of failure modes in gears, a brief methodology has be established to assist the author in conducting the modal analysis.

The project will start by selecting an experiment for validation purpose. For this modal analysis, an experiment set up was taken from previous study on gear wear analysis by Muniyappa Amarnath *et al.* [1]. Only one gear meshing of the gear mechanism will be modelled (the set up is shown in Figure 3.1). This will save time since smaller system require less time to simulate due to small number of nodes and elements. All gear mesh characteristics will follow the properties shown in Table 3.1. After the model is developed, the result of FEM will be compared with the experimental finding. The main reason is to make sure the modelling is correct. The main focus here is to make sure FEM model will have the same frequency response with experiment for the healthy gear condition. The results of the experiment are shown in Table 3.2.

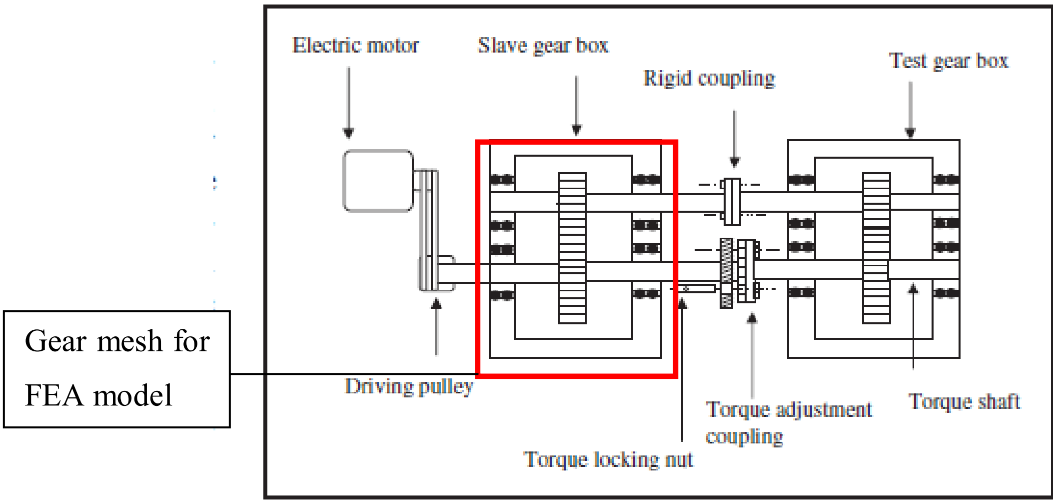

Figure 3.1.Schematic of back to back gearbox

Table 3.1.Dimensions and specifications of the test gears

	Pinion	Gear
Center distance (mm)	150	
Pitch diameter	100	200
Module (mm)	4	
Number of teeth	25	50
Face width (mm)	25	
Pressure angle	20°	
BHN	130	
Material properties of gears		
Young's modulus	2×10^5 N/mm^2	
Poisson's ratio	0.3	
Material (steel)	En 19, 0.22 % Carbon	
Shear modulus	$G = 0.8 \times 10^5$ N/mm^2	
Test conditions		
Pinion speed	n = 2100 rpm	
Static load	W = 0–600 N	
Lever arm	L = 0.6	
Torque on gear wheel shaft	0–413 Nm	

Table 3.2. Measured translational modal and estimated reduction in stiffness

Accelerated Test 1, N = 2100, T = 360 Nm					
Operating hours	Measured frequency (Hz)			Averaged frequency (Hz)	% stiffness reduction
0 hours (Healthy)	4002	3992	3990	3996	0.0
18 hours	3988	3982	3990	3984	1.0
36 hours	3968	3976	3970	3974	1.4
54 hours	3954	3961	3966	3962	1.7
72 hours	3948	3940	3938	3948	2.2
90 hours	3928	3936	3934	3932	3.2
108 hours	3906	3914	3918	3912	3.8

The gear mesh configuration for FEA is shown in Figure 3.2. The model consisted of two gears, the pinion and the driven gear.

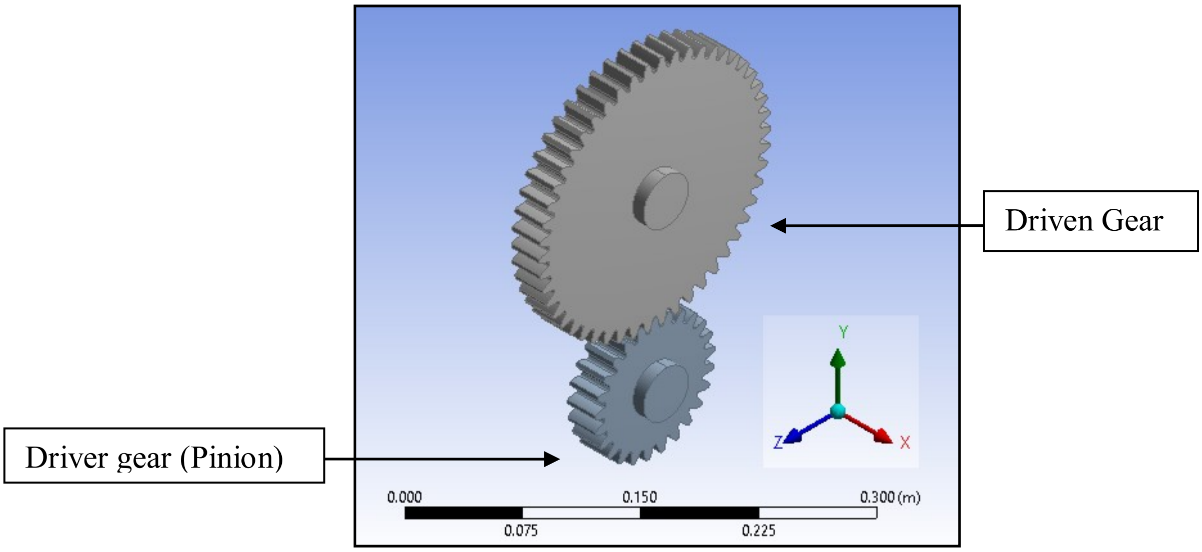

Figure 3.2. Gear mesh configuration

Gear meshing between these two gears is shown in Figure 3.3. A Triangle surface mesher was used for meshing of the gears. The contact areas between the gears are shown in Figure 3.4. At one time, only four surfaces will be in contact. The model contained 51481 nodes and 29481 elements. The element used was SOLID87.

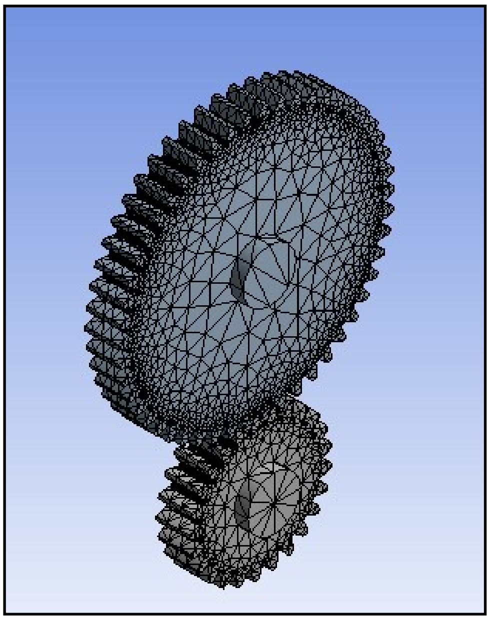

Figure 3.3. Gear Meshing

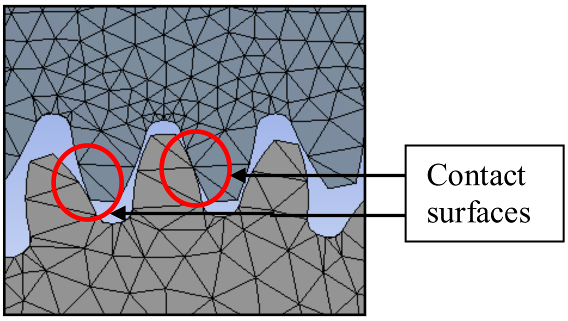

Figure 3.4. The contact surfaces area

The material used was steel. The pinion will be applied a torque of 360 Nm and the driven gear will rotate accordingly. A remote displacement support was applied at the center of both gears so that it only allowed rotational motion in X axis. X,Y,Z displacement will be fixed for both gears since there is no translational movement involved (one degree of freedom). Applied boundary conditions can be seen in Figure 3.5. The model will be simulated in harmonic responses analysis. From this analysis, frequency response function can be obtained.

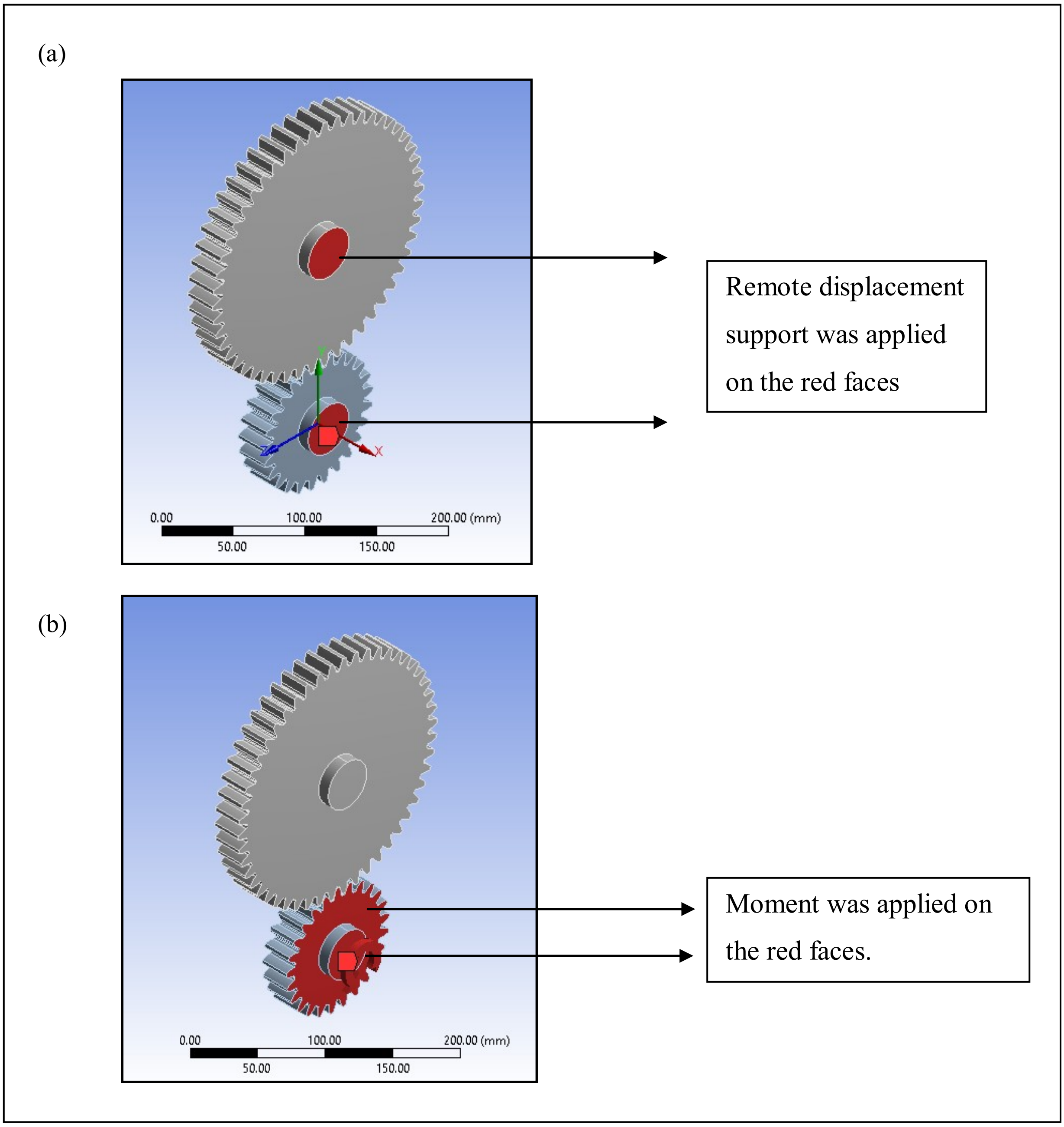

Figure 3.5: Applied boundary conditions to the gears -
a) Remote displacement supports b) Moment to the pinion

Supports and moment are applied to the both side of pinion and gear. There are a total of 4 faces of support and 4 faces of moment.

After the model is validated which means that the FEA frequency result at maximum amplitude is around 3996 Hz, fault design can be applied to the gear. The fault will be designed for the wear first followed by tooth crack.

3.1.1 Designing failure modes

There will be three designs in the gear mechanism, the healthy gear design, wear design and crack design. The failures will be designed on a certain teeth of the pinion. The affected teeth location is shown in Figure 3.6.

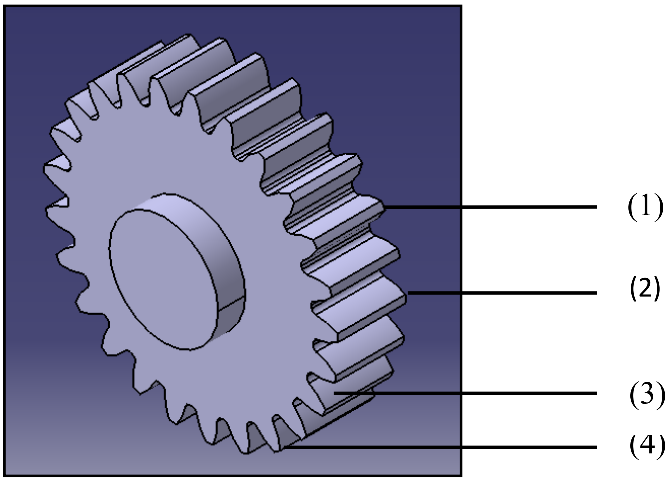

Figure 3.6. Location of the 4 teeth where the fault will be introduced

Wear design

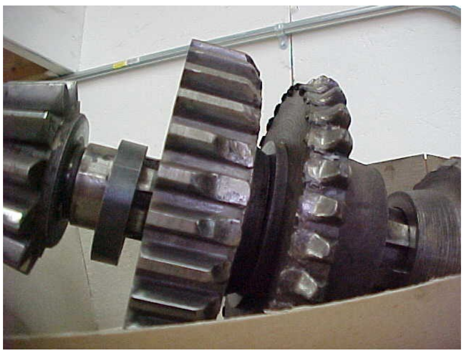

Figure 3.7. Gears undergoing wear failure

Wear is related to the interactions between surfaces and more specifically the removal and deformation of material on a surface as a result of mechanical action of the opposite surface. Wear in gear is shown in Figure 3.7.

In designing wear, two designs will be considered. For the first one, the teeth width was decreased by percentage. Table 3.3 shows the width reduction values. The face width reductions were made by removing parts from one side of the teeth, as shown in Figure. 3.8.

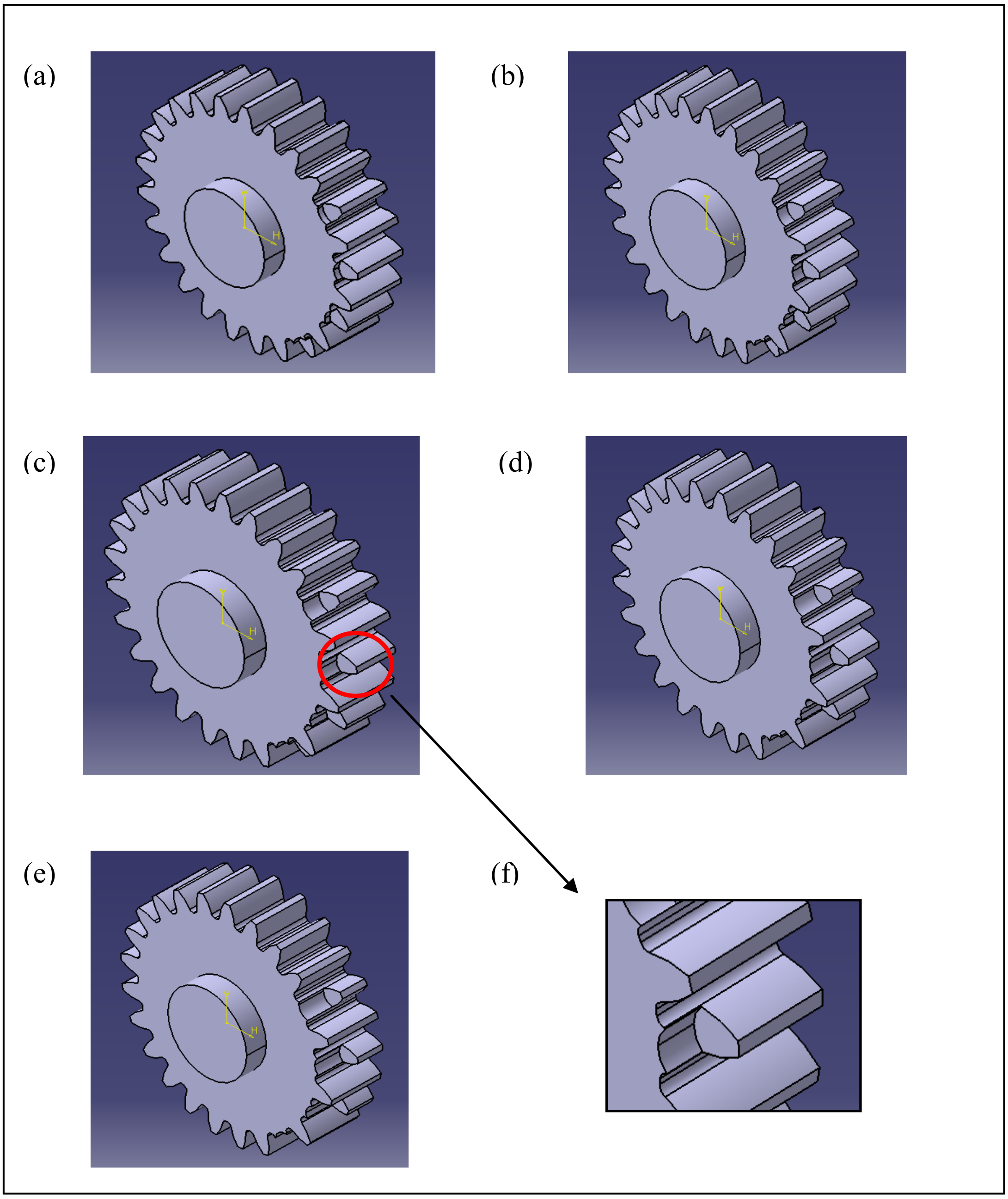

Figure 3.8. Width reduction of wear by percentage - a) 10%, b) 20%, c) 30%, d) 40%, e) 50% f) Zoomed figure of the wear

Table 3.3.Width reduction of wear

Width reduction, %	Width reduction, mm
10	2.5
20	5
30	7.5
40	10
50	12.5

For the second wear, some parts were removed by increasing the area removal, as shown in Figure. 3.9. The value for area removal is shown in Table 3.4.

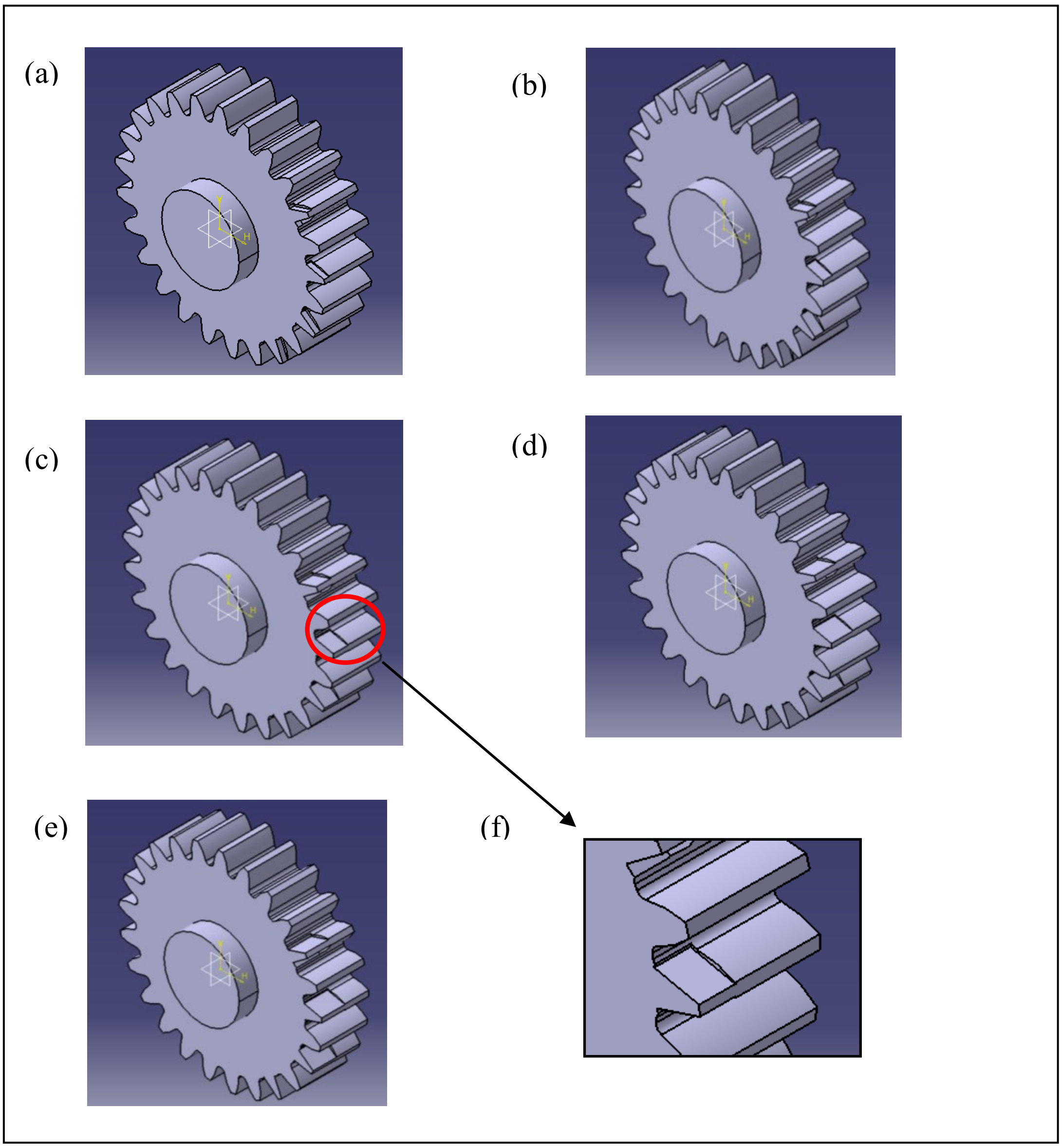

Figure 3.9. Area removal by percentage - a) 10%, b) 20%, c) 30%, d) 40%, e) 50% f) Zoomed figure of the wear

Table 3.4. Area removal of wear

Area removal, %	Width reduction, mm
10	2.5
20	5
30	7.5
40	10
50	12.5

After the simulation, frequency response function can be retrieved in the form of maximum deformation of a single tooth versus frequency. The deformation will determine the risk level of the fault.

Tooth cracks

Figure 3.10. Gear tooth experiencing crack

Crack is a partial separation of parts, with or without a perceptible opening. A smooth crack grows perpendicular to the maximum tensile stress. When the crack grows large enough, it can cause sudden fracture. Crack can be seen in Figure 3.10.

Tooth cracks were designed by increasing the crack length on the upper part of the teeth. The crack length will be increased by percentage of tooth width as shown in Table 3.5. The depth and width will be kept constant at 2.5 mm and 1 mm, respectively. The crack growsfrom one side to the other side as illustrated in Figure 3.11.

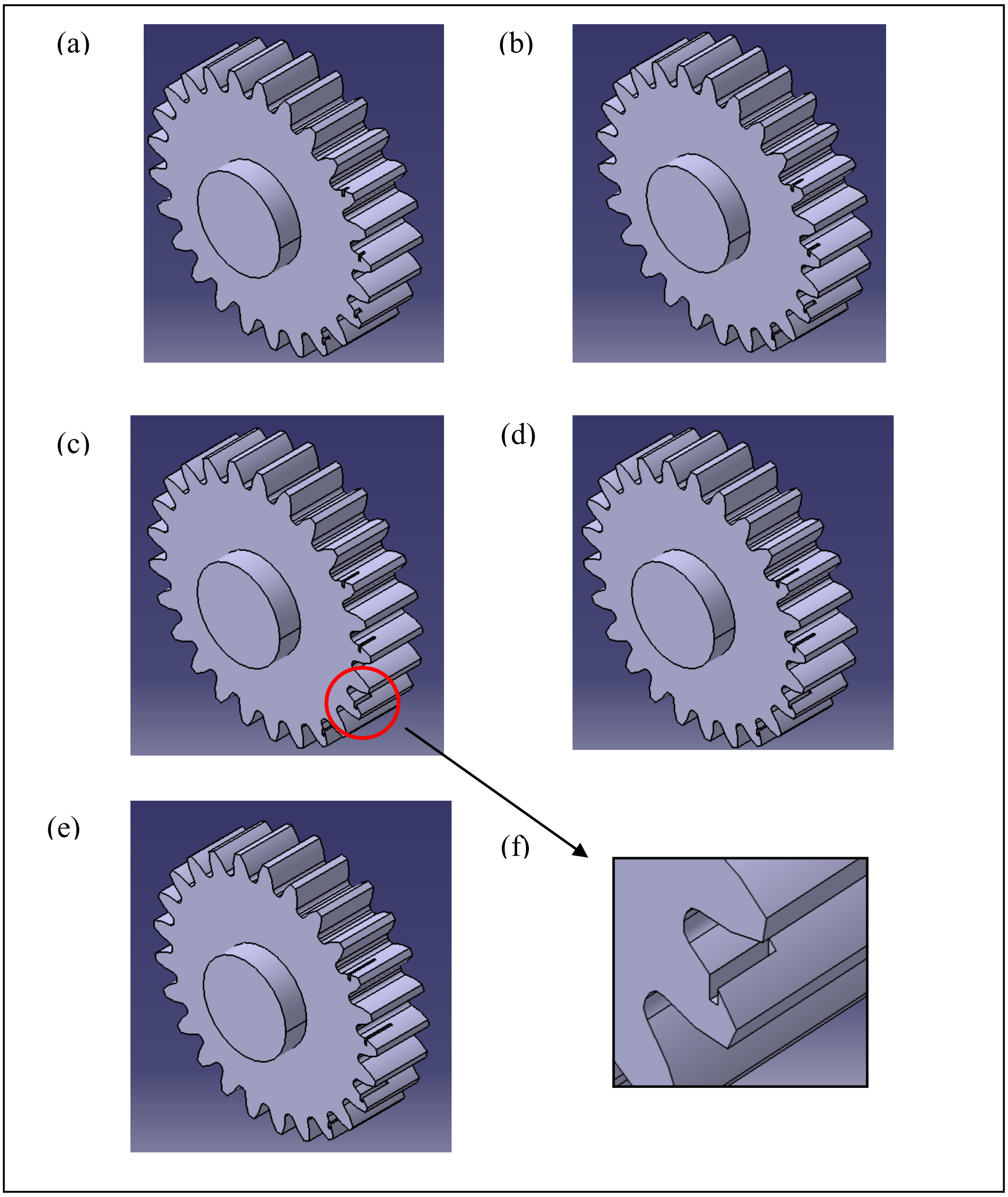

Figure 3.11. Length increment of crack by percentage - a) 10%, b) 20%, c) 30%, d) 40%, e) 50% f) Zoomed figure of the crack

Table 3.5. Crack length increment

Length increment, %	Length increment, mm
10	2.5
20	5
30	7.5
40	10
50	12.5

After the simulation, frequency response function can be retrieved in the form of maximum deformation of a single tooth versus frequency. The deformation will determine the risk level of the fault.

3.1.2 Data Collection and Analysis

For each type of failure, frequency response function was obtained. The frequency and max deformation were recorded for every case. The frequency range was specified from 0 Hz - 5000 Hz. The surface for deformation was selected as illustrated in Figure 3.12.

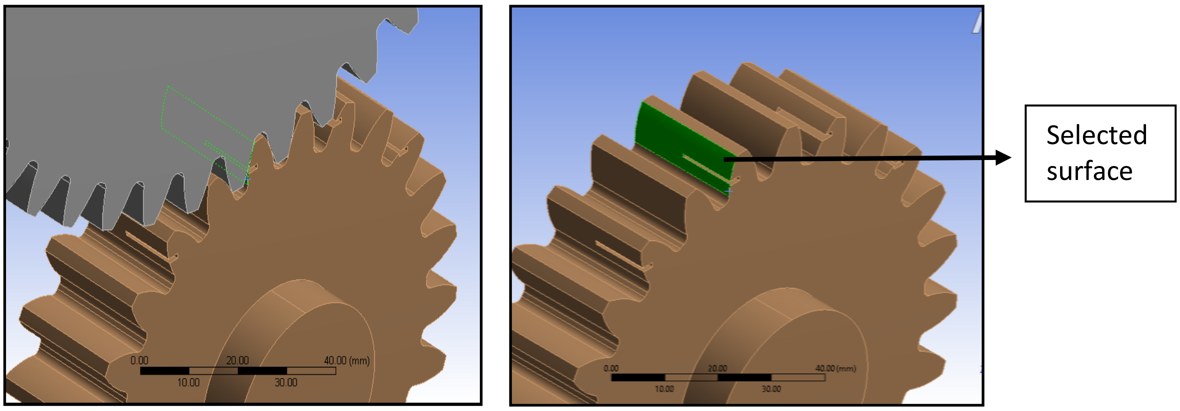

Figure 3.12. Selected surface for analysis

After all the results were collected, they were compared in one line graph. A detailed analysis was carried out on how fault area will affect the frequency and maximum deformation. From the results and analysis, we can conclude which type of failure will give more severe damage to the gear mechanism. An example of data collection can be seen from Table 3.6.

Table 3.6. Data collection for wear and crack cases

Fault area , %	Wear		Crack	
	Frequency, Hz	Deformation, mm	Frequency, Hz	Deformation, mm
10				
20				
30				
40				
50				

3.1.3 Project Flow Chart

Overall steps for conducting the project can be seen in Figure 3.13.

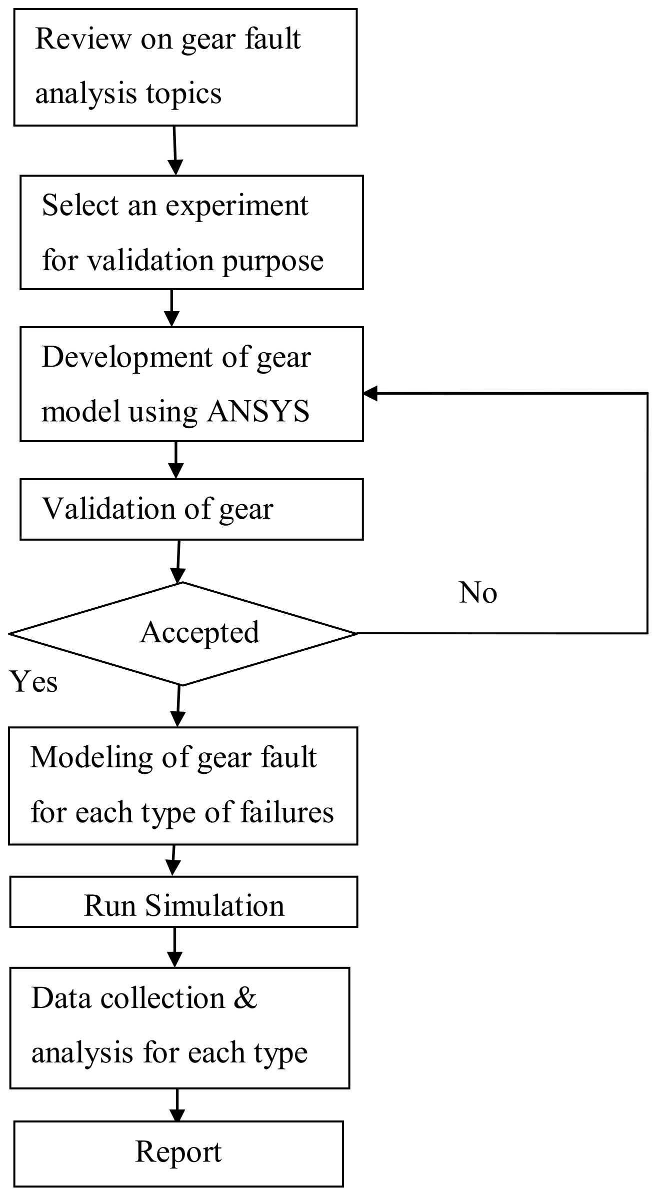

Figure 3.13. Flow chart of project methodology

3.2 KEY MILESTONE

Project key milestone was established in order ensure the project is on track. The project key milestones are shown in Table 3.7 and Table 3.8 for FYP1 and FYP2, respectively.

Table 3.7. FYP1 key milestone

Event	Period (Week)	Responsibility
Project title selection	1-2	Choose a project title to work on from a list of title provided.
Project title approval	2-3	Submission of project title. Resubmit if the title is disapproved. The title is gear fault analysis using finite element method.
Submission of Extended Proposal	3-6	Prepare an extended proposal and submit to the coordinator and
Proposal defence	6-8	Conduct presentation, verbally report the progress of the project to the supervisor and examiner.
Submission of interim report first draft	12-13	Show supervisor first draft of interim report.
Submission of interim report	14	Complete the interim report and submit to the supervisor.

Table 3.8. FYP2 key milestone

Event	Period (Week)	Responsibility
Progress report submission	8	Complete progress report and submit to the coordinator. Coordinator will submit to the supervisor.
Pre SEDEX poster and presentation	11	Poster presentation to the external examiner.
Submission of dissertation draft	12	Show supervisor first draft of dissertation.
Submission of dissertation (soft bound)	13	Submit dissertation in soft copy to supervisor.
Submission of technical paper	13	Submit technical report in soft copy to supervisor.
Oral Presentation	14	Conduct presentation, verbally report the finding of the project to the supervisor and examiner.
Submission of dissertation (hard bound)	15	Submit final dissertation to supervisor.

3.3 GANTT CHART

A proper project plan has been developed to ensure it can be completed within 28 week time. The project Gantt charts are shown in Table 3.9 and Table 3.10 for FYP1 and FYP2, respectively.

Table 3.9. FYP1 Gantt chart

Activities	Week No													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Title selection (Gear fault analysis)	■	■												
Approval of project title		■	■											
Literature review			■	■										
Decide scope of study, objectives and problem statement					■									
Decide on failure modes to study						■								
Construct project planning						■								
Establish steps for validation							■							
Project proposal						■	■	■						
Understanding wear								■	■					
Understanding tooth crack									■					
Establish methodology for designing the faults										■				
ANSYS simulation trial											■			
Improvement on methodology												■		
Draft on data tabulation and analysis													■	
Set up project future work														■
Interim report												■	■	■

Table 3.10. FYP2 Gantt chart

Activities	Week No													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Design healthy gears in CATIA	■	■												
Import design into ANSYS			■											
Set up boundary condition				■										
Simulation of FEA Model					■	■								
Validation with experimental result					■	■								
Design wear on the gear							■							
Design crack on the gear								■						
Simulate the results									■					
Compare all the data gathered										■	■			
Brief analysis on the data collected											■	■		
Final documentation													■	■

CHAPTER 4
RESULTS AND DISCUSSION

4.1 HEALTHY GEAR CONDITION (VALIDATION PURPOSE)

For FEA analysis, the deformation amplitude was considered in order to determine the risk level of faults. Figure 4.1 shows the frequency response for experimental analysis while frequency response of FEA model is shown in Figure 4.2. The frequency obtained from FEA model was 3840 Hz. This value is comparable to the experimental result of 3996 Hz. The difference in percentage was calculated based on equation (1), and it gives a difference of 3.9%. Therefore it can be concluded that the FEA model is suitable and can be employed to obtain FRF.

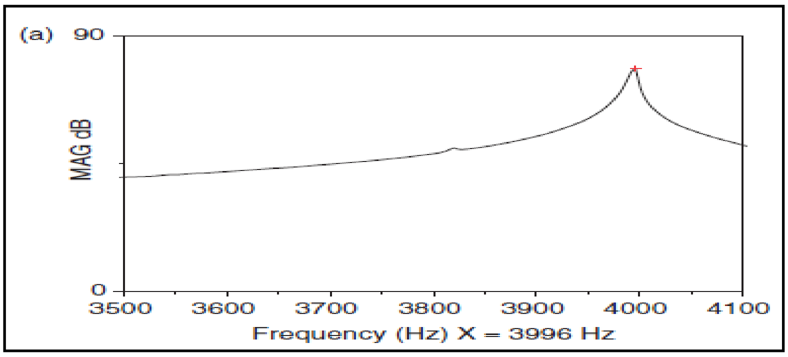

Figure 4.1.Frequency response function (FRF) of experimental test for a healthy gear

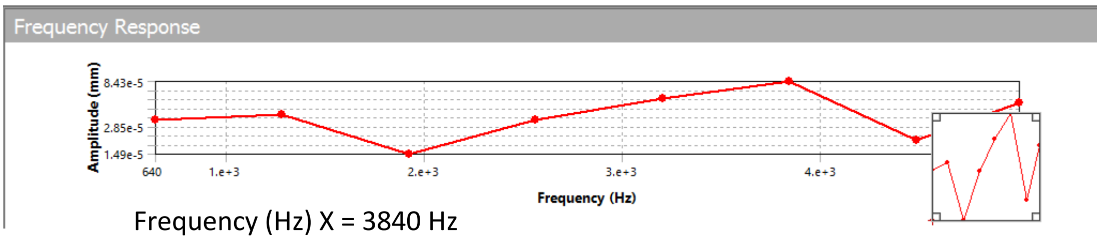

Figure 4.2. Frequency response function (FRF) of FEA model for a healthy gear

$$\text{Percentage of difference} = \frac{\text{Experimental value} - \text{FEM value}}{\text{Experimental value}} \qquad (1)$$

$$= 3.9\%$$

The low percentage of difference showed that the result is almost the same with experimental result. The FEA result may vary with the experimental result due to many factors. Modal analysis will be affected by three factors, mass, stiffness and damping. Any change of these three parameters will lead to the variation of the results.

These are some factors that may affect the results. First of all was the material used.The material used in FEA model was structural steel and not En 19 steel. The difference between these two material density will result in different mass. Alteration of mass will change the frequency. Other than that, the geometry of finite element model was not exactly the same as experimental model. The shape of the teeth was different because of the lack of information provided. Besides, the meshing of these two gears also did not follow the meshing of experimental setup due to lack of information in the experimental setup. Environment factor also may affect the result. Experimental results were possibly affected by many damping factors; example is the movement of air. In FEA, the damping was set as 0. Due to the different damping condition, the result may vary slightly.

Once the model was validated, the next step is to design the faults on the pinion, first will be wear, followed by tooth crack. The fault area was increased and the frequency response for every condition was recorded. The results were compared in order to see the difference in the deformation of a single tooth.

4.2 FREQUENCY RESPONSE FUNCTION

All frequency response functions (FRF) for healthy gear, gear with wear and gear with crack were obtained from the simulation. Figure 4.3 showed FRF for healthy gear condition. The wear approach 1 cases are shown in Figure 4.4 - Figure 4.8, the wear approach 2 cases are shown in Figure 4.9- Figure 4.13 and the crack cases are shown in Figure 4.14 - Figure 4.18. All FRFs are in term of deformation of a single tooth versus frequency. The responses gave the value of deformation at certain frequency, which range from 0 Hz - 5000 Hz. The main focus is to identify the maximum deformation for every cases and its frequency. The frequency taken was the frequency when the maximum deformation occurs.

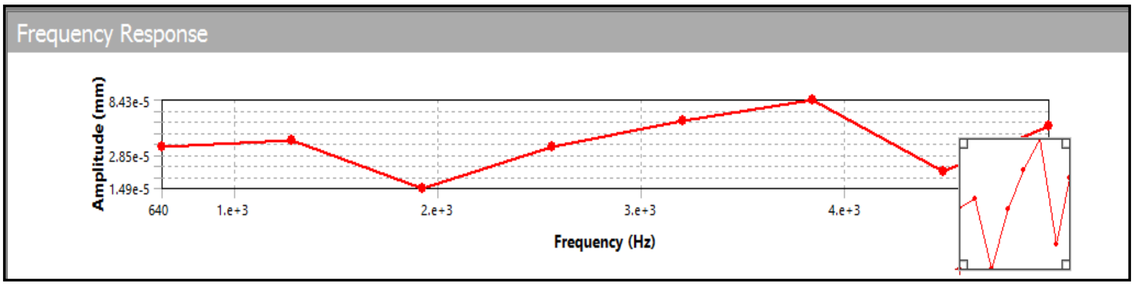

Figure 4.3. FRF of healthy gear condition

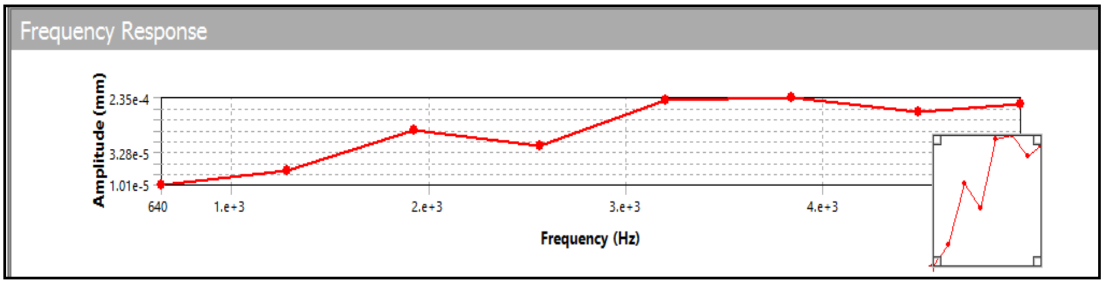

Figure 4.4. FRF for 10% width reduction due to wear

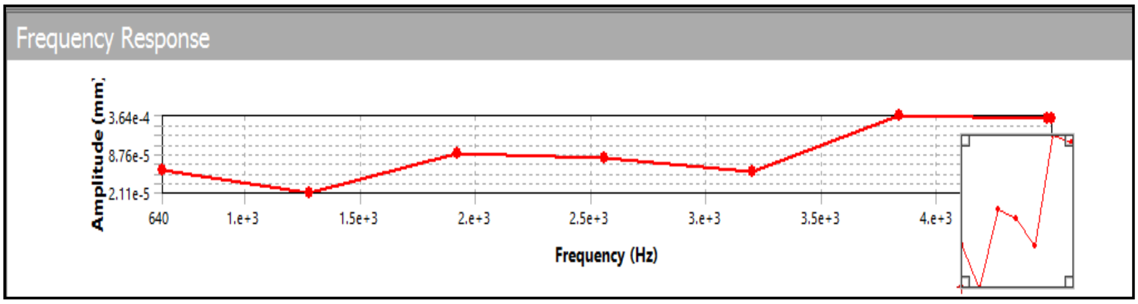

Figure 4.5.FRF for 20% width reduction due to wear

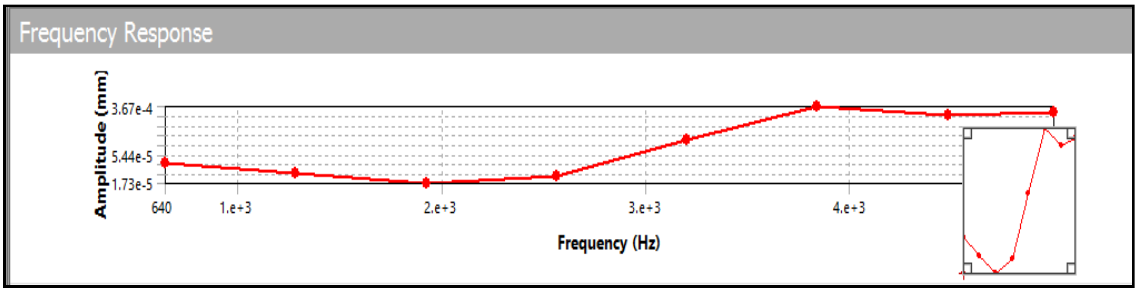

Figure 4.6.FRF for 30% width reduction due to wear

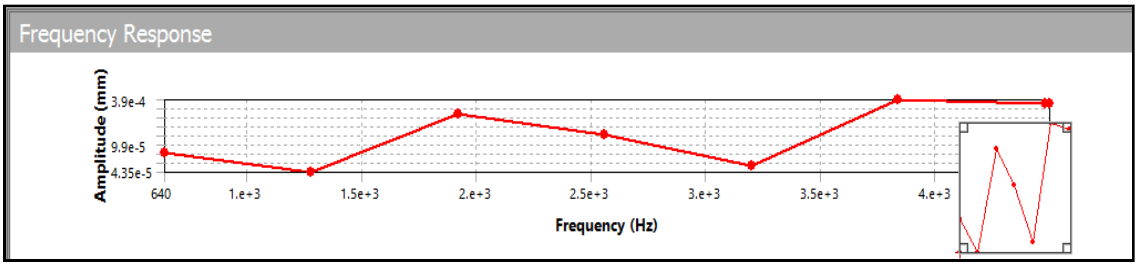

Figure 4.7.FRF for 40% width reduction due to wear

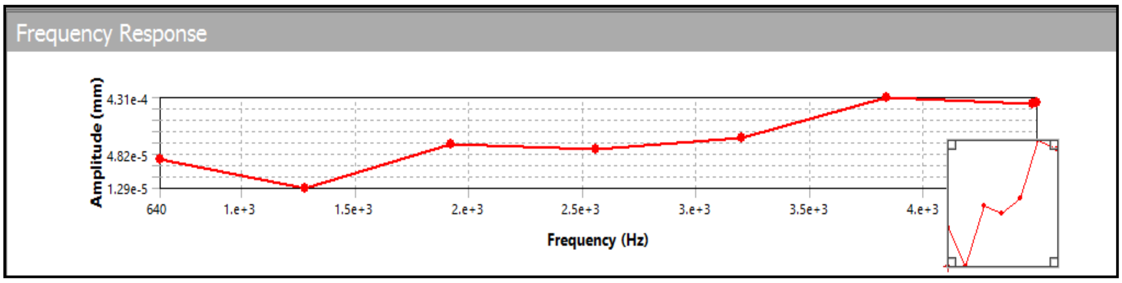

Figure 4.8.FRF for 50% width reduction due to wear

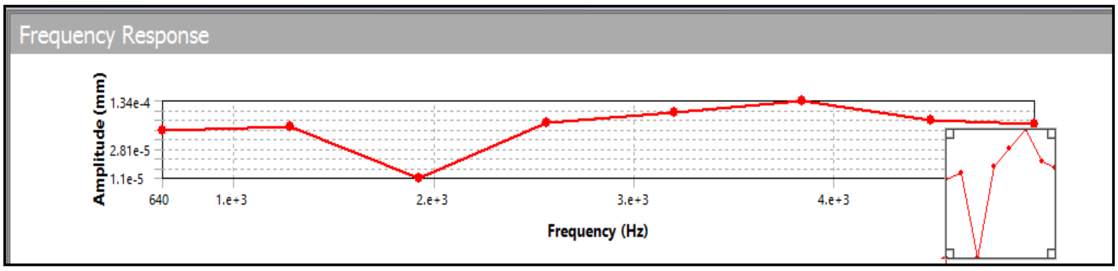

Figure 4.9.FRF for 10% area removal due to wear

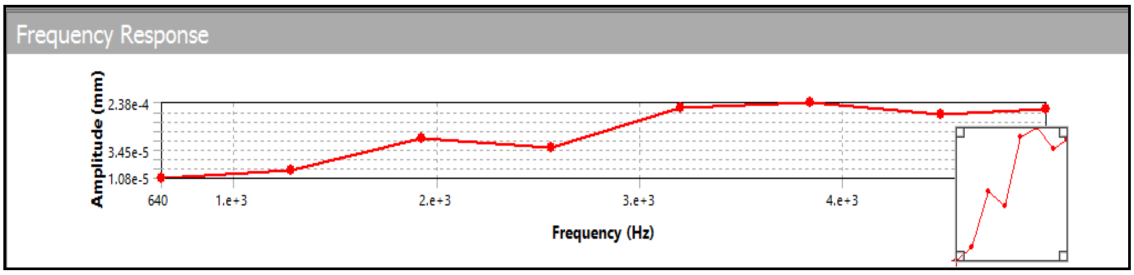

Figure 4.10.FRF for 20% area removal due to wear

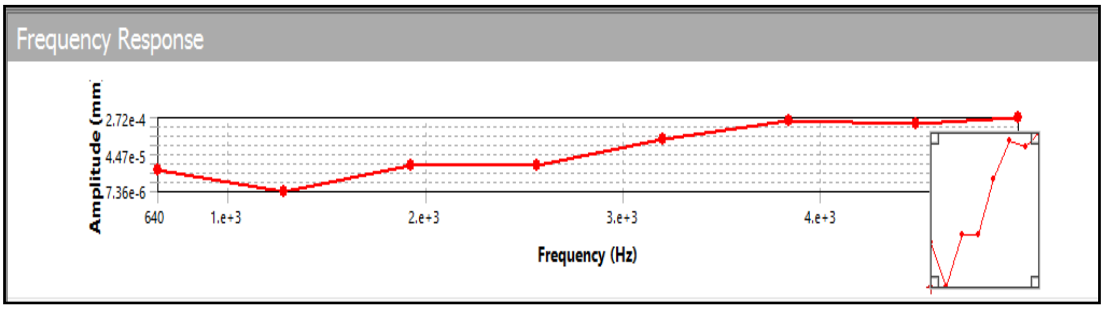

Figure 4.11.FRF for 30% area removal due to wear

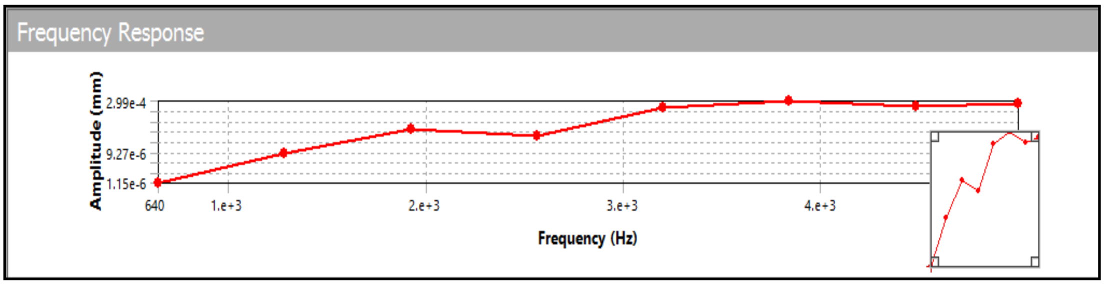

Figure 4.12.FRF for 40% area removal due to wear

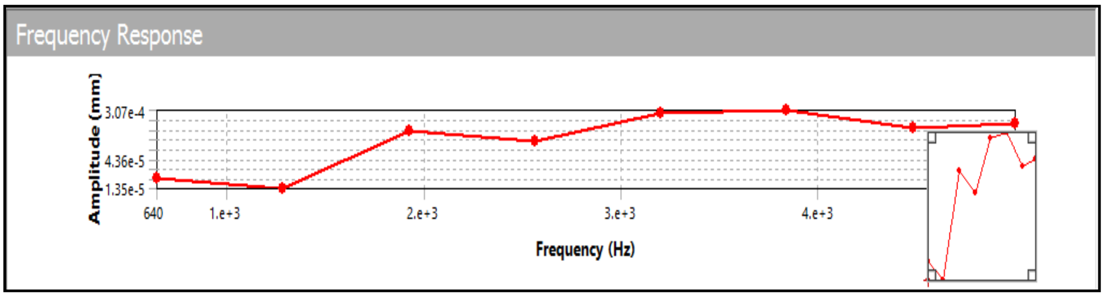

Figure 4.13.FRF for 50% area removal due to wear

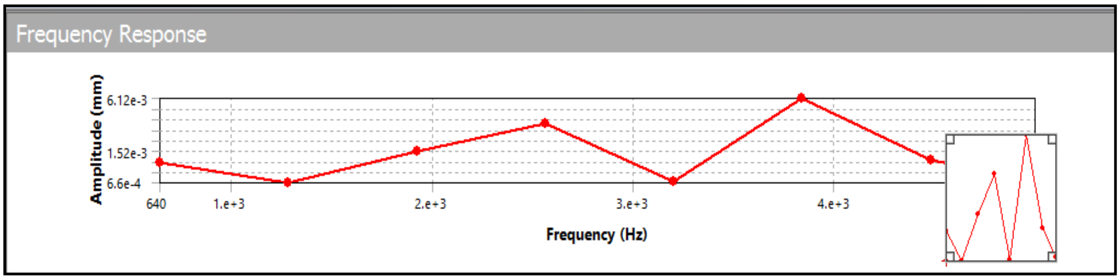

Figure 4.14. FRF for 10% crack length increment

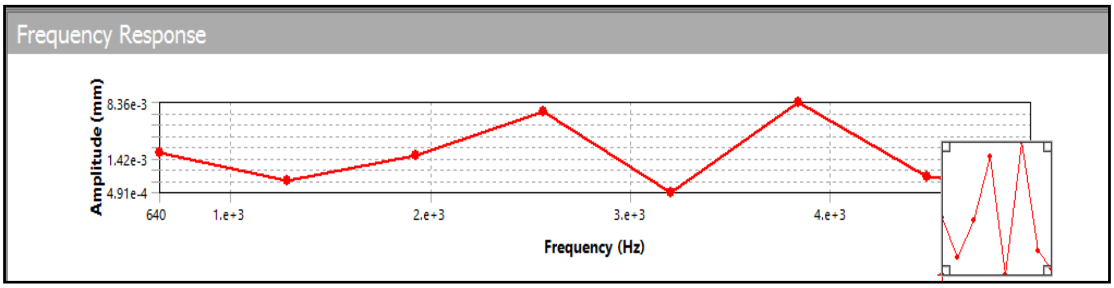

Figure 4.15. FRF for 20% crack length increment

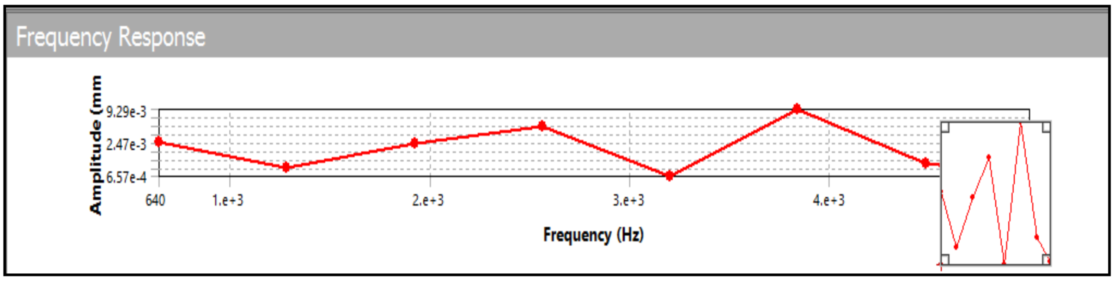

Figure 4.16. FRF for 30% crack length increment

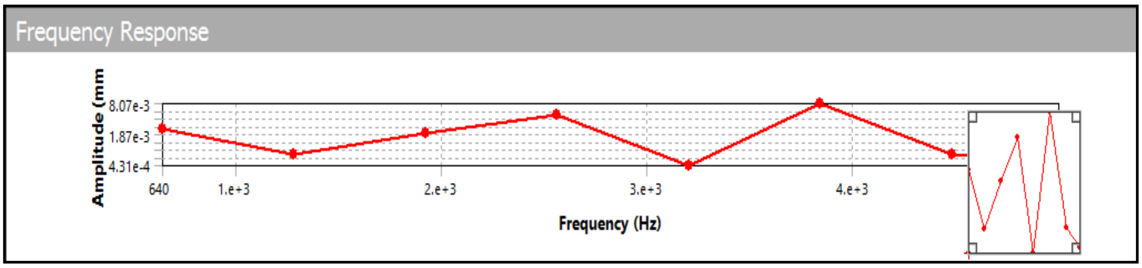

Figure 4.17.FRF for 40% crack length increment

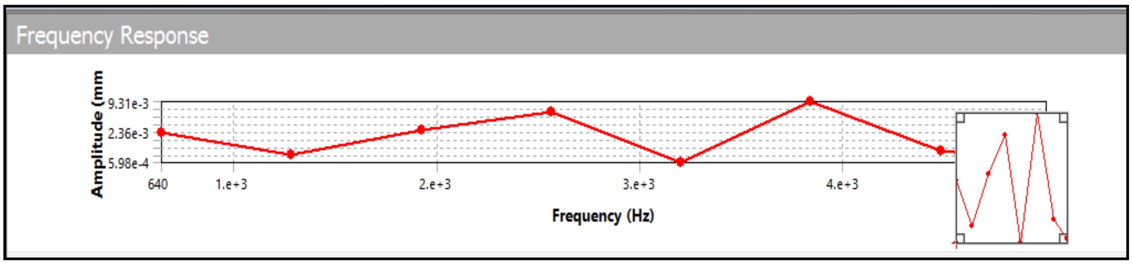

Figure 4.18.FRF for 50% crack length increment

Table 4.1. Result of frequency and maximum deformation for gear with wear (approach 1)

Condition	Wear (approach 1)	
	Frequency,Hz	Maximum deformation,mm
Healthy gear	3840	8.43E-05
10% width reduction	3840	2.35E-04
20% width reduction	3840	3.64E-04
30% width reduction	3840	3.67E-04
40% width reduction	3840	3.90E-04
50% width reduction	3840	4.31E-04

Table 4.2. Result of frequency and maximum deformation for gear with wear (approach 2)

Condition	Wear (approach 2)	
	Frequency, Hz	Maximum deformation, mm
Healthy gear	3840	8.43E-05
10% area removal	3840	1.34E-04
20% area removal	3840	2.38E-04
30% area removal	3840	2.72E-04
40% area removal	3840	2.99E-04
50% area removal	3840	3.07E-04

Table 4.3. Result of frequency and maximum deformation for gear with crack

Condition	Crack	
	Frequency, Hz	Maximum deformation, mm
Healthy gear	3840	8.43E-05
10% crack length	3840	6.12E-03
20% crack length	3840	8.07E-03
30% crack length	3840	8.36E-03
40% crack length	3840	9.31E-03
50% crack length	3840	9.29E-03

The summary of the FRF for gear with wear and crack are shown in Table 4.1, Table 4.2 and Table 4.3, respectively. The table show the changes in frequency and maximum deformation when the fault area increased. These two parameters will be able to tell which failure mode is riskier to the gear mechanism. Lower frequency is more dangerous to the system since the mechanism tend to achieve maximum deformation at low frequency. In the case of deformation, gear teeth will undergo fracture if the deformation is too large. From Figure 4.19, it can be seen there was no change in frequency at maximum deformation for all the cases. All maximum deformation occurred at 3840 Hz. Theoretically, the frequency should be decreasing when the wear and crack area increased. The frequency does not change because of some factors which affect the system vibration. First of all, it was due to the mass factor. The amount of material removal does not change the mass so much. The reduction of mass is shown in Table 4.4 and Figure 4.20. This small mass reduction gave little effect to the system vibration.

The second reason is due to the low stiffness reduction. Stiffness of a material varied when the area moment of inertia was changed. The area moment of inertia changed when the shape changed. However, wear and crack on gears do notalter the stiffness excessively. There was only a small change in stiffness which will not affect the system vibration.

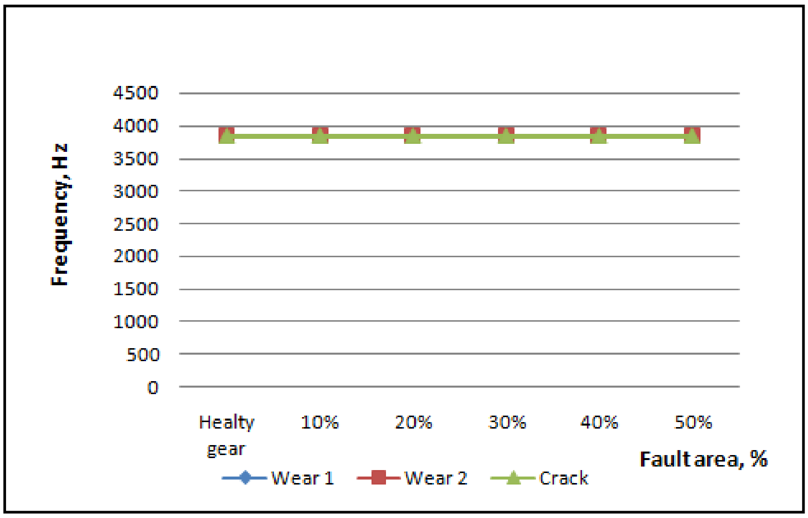

Figure 4.19. Frequency comparison between wear and crack

Table 4.4. Mass change for wear and crack

Condition	Mass, kg		
	Wear (approach 1)	Wear (approach 2)	Crack
Healthy gear	8.0487	8.0487	8.0487
10% affected area	8.0445	8.0472	8.0485
20% affected area	8.0403	8.0458	8.0483
30% affected area	8.0362	8.0444	8.0481
40% affected area	8.0320	8.0424	8.0479
50% affected area	8.0278	8.0415	8.0478

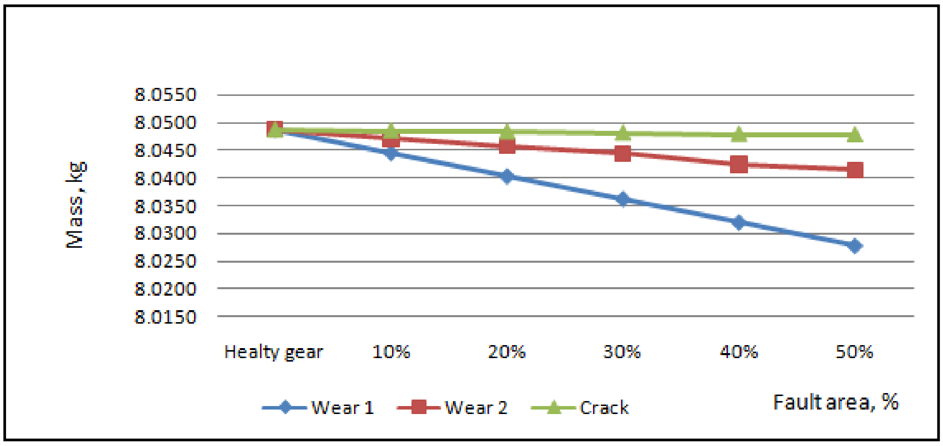

Figure 4.20. Mass change for wear and crack

The deformation of a single tooth increased as the fault area is increased, as shown in Figure 4.21 and Figure 4.22. The increment of deformation is affected by the stiffness and the force applied. As the wear and crack area increased, there are some losses of materials. This will lead to reduction in stiffness, thus the increase in deformation. The relationship between stiffness and deformation can be seen in the equation (2). k is the stiffness of material, F is the force applied to the surface and δ is the deformation of the material.

$$k = \frac{F}{\delta} \quad (2)$$

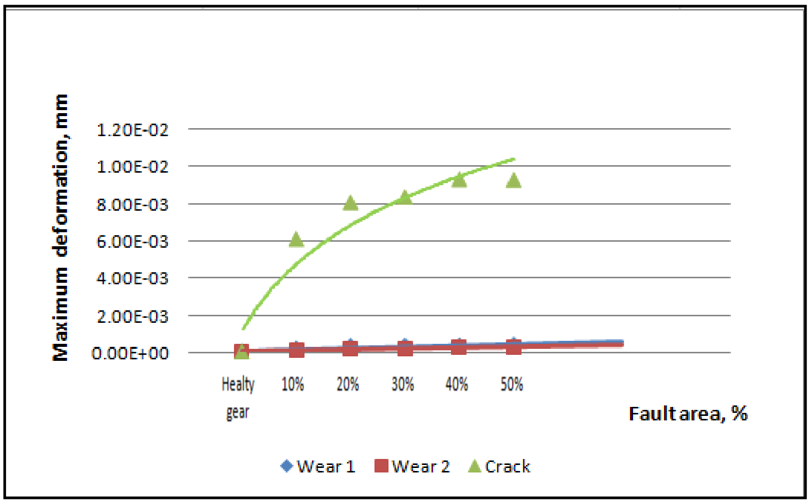

Figure 4.21. Deformation comparison between wear (approach 1), wear (approach 2) and crack

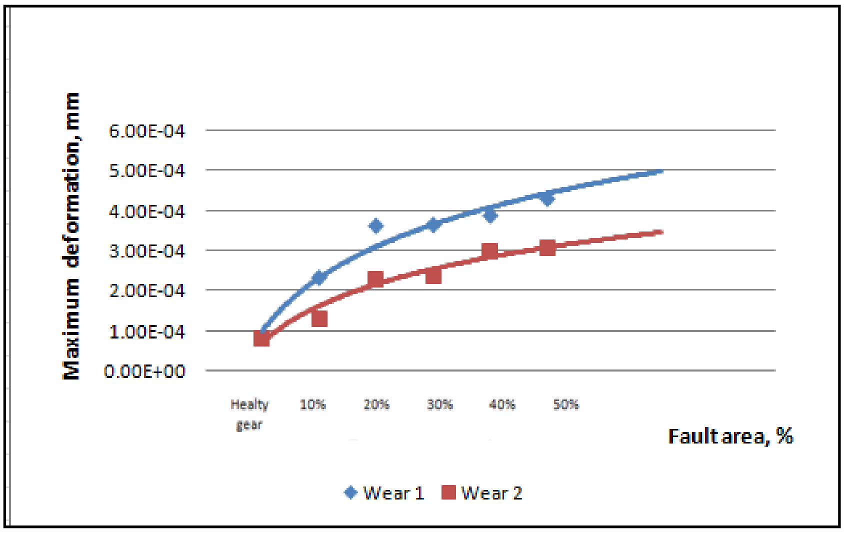

Figure 4.22. Deformation comparison between wear (approach 1) and wear (approach 2)

From Figure 4.21, it was determined that crack experiences more deformation compared to wear. In other word, the probability of cracked tooth to fracture was higher than worn out tooth. The comparison between wear approach 1 and wear approach 2 are shown in Figure 4.22. They were slightly vary in deformation due to difference in stiffness. Gear with wear approach 2 is more stiffer than gear with wear approach 1. The area that experienced deformation is shown in Figure 4.23.

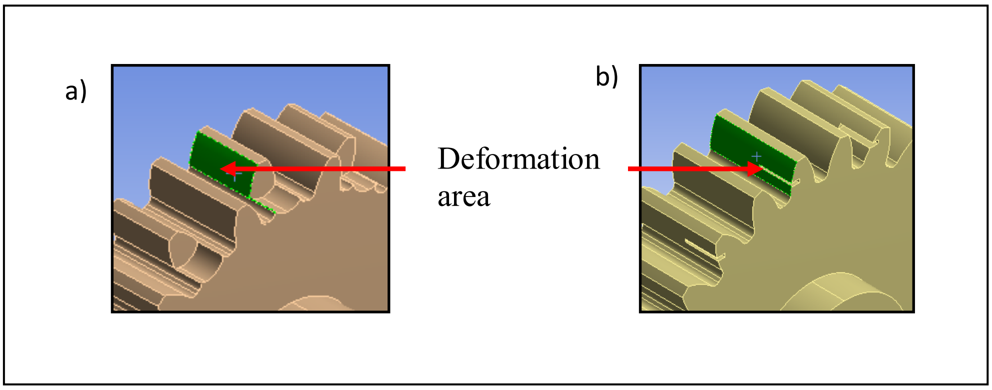

Figure 4.23. Area of deformation a) wear b) crack

The force applied on the surface is the same for both cases. In wear, the removal of material for wear does not change the stiffness excessively. This is because there is no reduction in the thickness of the tooth. For crack, the tooth thickness is decreased slightly. The stiffness equation is shown in equation (3). k is the stiffness, E is the modulus of elasticity, I is the area moment of inertia which can be calculated using equation (4) and L is the tooth height. For calculation of I, it involved F, tooth width and t, the tooth thickness. Overall relationship between stiffness and thickness is shown in equation (5).

$$k = \frac{3EI}{L^3} \tag{3}$$

$$I = \frac{Ft^3}{12} \tag{4}$$

$$k = \frac{EFt^3}{4} \tag{5}$$

From equation (5), it showed that the stiffness is proportional to the tooth thickness. Thus in crack condition, the tooth tend to experience larger deformation.

The second factor was due to the difference in pressure distribution. For wear case, the pressure was distributed uniformly throughout the surface while for the cracked tooth, the pressure distribution was uneven. Upper part of the teeth tend to experience higher pressure than the lower part, due to the reduction of surface area. The pressure distribution is shown in Figure 4.24.

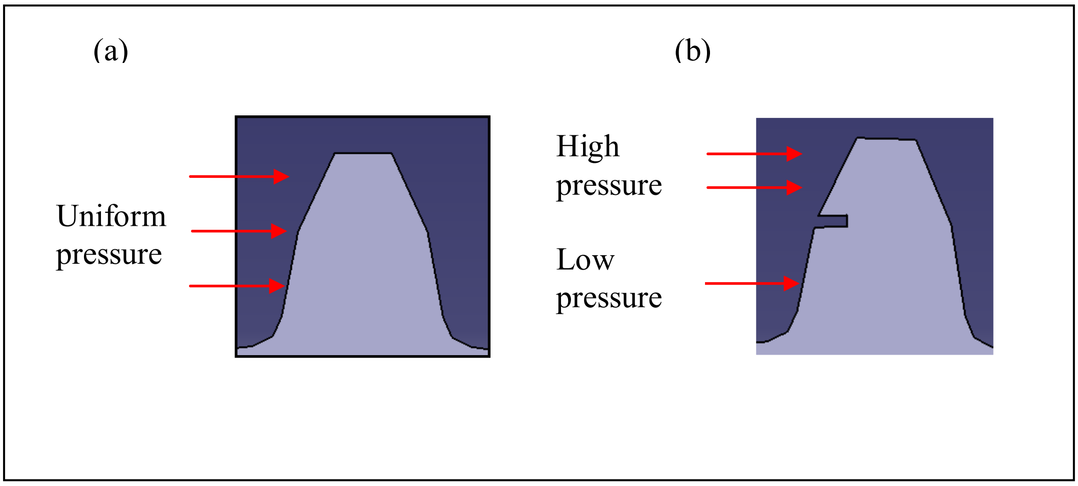

Figure 4.24. Pressure distribution a) wear b) crack

Finite element method had proved that crack failure give riskier condition to the gear mechanism. From this finding, another research on preventing gear failure can be conducted. The priority will be focused on crack problem first than the wear in order to save time and cost.

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

In a nutshell, it is important to investigate the effects of gear failure modes to the gear mechanism. Different faults will affect the gear mechanism in different ways. In the case of this dynamic analysis, it is believed that, every failure mode will give different amount of deformation. By using finite element method, the riskiest failure mode can be determined. In this study, it was concluded that the cracked tooth experienced more deformation compared to worn tooth. From the finding, a new research can be done which is on how to prevent the faults from occurring. The main focus will be on the one that gave the most severe damage to the system, which is the crack. By preventing or slowing the progress of this failure mode, gear mechanism can keep functioning at longer lifespan. Focusing on the major fault will save time and cost.

There are many failure modes beside wear and crack. They are indentation, burrs, spalling, scuffing and erosion. It is recommended for the others to carry out simulation for other types of fault. Variation of failure modes will give better data and contain more information. Besides, by ranking them according to its deformation level, a priority list can be established. This will tell us which of the failure modes need to be taken care first. Other than that, the responding variable can be changed to another parameter like pressure or noise. Pressure will be able to tell which of the failure modes give the most unsafe condition. More pressure acting on the surface means it has higher probability to fracture. The same goes to noise. Low noise is preferable since less disturbance to the environment. By considering other parameters, the analysis result will be more precise, accurate and comprehensive.

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