A STUDY OF THE STRAIN SIGNALS BEHAVIOUR

NG JUN PIN

Thesis submitted in fulfillment of the requirements
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UNIVERSITI MALAYSIA PAHANG
FACULTY OF MECHANICAL ENGINEERING

I certify that the project entitled “A Study of the Strain Signals Behaviour” is written by Ng Jun Pin. I have examined the final copy of this project and in my opinion, it is fully adequate in terms of language and standard, and report formatting requirement for the award of the degree of Bachelor of Engineering. I was here with recommend that it be accepted in partial fulfillment of the requirements for the degree of Bachelor of Mechanical Engineering.

(DR. GIGIH PRIYANDOKO)

Examiner Signature

SUPERVISOR'S DECLARATION

I hereby declare that have checked this project and in my opinion, this project is adequate in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

Signature :

Name of Supervisor : NURAZIMA BINTI ISMAIL

Position : LECTURER OF MECHANICAL ENGINEERING

Date : 28 JUNE 2013

STUDENT'S DECLARATION

I hereby declare that the work in this project is my own except for quotations and summaries which have been duly acknowledged. The project has not been accepted for any degree and is not concurrently submitted for award of other degree.

Signature :

Name : NG JUN PIN

ID Number : MA09078

Date : 28 JUNE 2013

Dedicated to my father, Mr. Ng Lee Tong, my beloved mother, Mrs. Teoh Soo Peng,

my brothers Ng Wei Guan and Ng Wei Chuan,

my sisters Ng Jun Ying and Ng Chai Wei,

and last but not list to all my beloved friends…

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ABSTRACT

This study presents the study of strain signals behavior. In this study, the strain signal of helical spring at different value of excitations is used to study the signals behavior. When a vehicle was driven on any road surfaces, the significant load is transmitted to the helical spring to absorb loads. The load values were varied according to the type of the road surfaces. The signals were analyzed by statistical analysis and frequency-time domain. Signals are classified based on the value of the statistical parameter. The signals are used to predict fatigue damage of the helical spring. From the result obtained, the unpaved road signals consist of higher peak shocks. It exhibited higher statistical value compared to the signals obtained from university road and highway. These feature increased the fatigue damage potential of the helical spring. The finite element analysis of helical spring was performed by MSC Nastran with Patran software. The finite element model was analysed using the linear elastic stress. Finally, the result obtained and signals are employed to test the fatigue damage of helical spring. Strain-life model which are Coffin-Manson, SWT and Morrow model are used to predict the fatigue damage of helical spring. The obtained result indicated that unpaved road has the highest fatigue damage followed by university road and highway.

ABSTRAK

Kajian ini membentangkan sifat isyarat terikan. Dalam kajian ini, isyarat terikan spring heliks dikaji dengan mengenakan daya yang berbeza. Ketika kenderaan dipandu melalui permukaan jalan yang berbeza, beban kereta akan mengenakan daya pada heliks spring kereta untuk menyerap beban. Permukaan jalan yang berbeza akan menghasilkan isyarat terikan yang berlainan. Isyarat terikan spring heliks yang diperoleh akan dianalisis dengan analisis statistik dan domain frekuensi masa. Oleh itu, isyarat terikan spring akan dikelaskan berdasarkan nilai parameter statistik. Isyarat ini juga digunakan untuk meramalkan kerosakan lesu spring heliks. Daripada keputusan yang diperoleh, isyarat terikan spring heliks jalan tidak berturap terdiri daripada kejutan puncak yang lebih tinggi. Selain itu, ia juga mempunyai nilai statistik yang lebih tinggi berbanding dengan isyarat terikan spring heliks yang diperoleh dari jalan university dan jalan raya. Ciri ini akan meninggikan potensi kerosakan lesu pada spring heliks. Analisis unsur terhingga dijalankan dengan menggunakan MSC Nastran dan Patran. Pendekatan linear elastik digunakan untuk menjalankan analisis tersebut. Keputusan analisis unsur yang diperoleh dan isyarat terikan diperlukan untuk menghasilkan plot kontor kerosakan pada kritikal tempat spring heliks. Model Coffin-Manson, SWT dan Morrow digunakan untuk meramalkan kerosakan lesu pada spring heliks. Dari hasil keputusan didapati bahawa jalan yang tidak berturap menunjukkan kerosakan tertinggi, diikuti dengan jalan university dan akhirnya lebuh raya.

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LIST OF SYMBOLS

σ	Standard deviation value
$\bar{x}$	Mean value
e	Epsilon
π	22/7
f_o	Cyclic frequency
θ_n	Phase angles
∞	Infinity
τ	Time displacement
T	Period
k	Number of sample function
$F(\omega)$	Fourier Transform
$f(t)$	Inverse Fourier transform
ω	Angular frequency
N	Number of sample points
ε_a	Elastic component of the cyclic strain amplitude
σ_a	True cyclic stress amplitude
σ'_f	Fatigue strength coefficient
N_f	Number of cycles to failure
b	Fatigue strength exponent
E	Elastic modulus
ε_p	Plastic component of the cyclic strain amplitude
ε'_f	Strain ductility coefficient
N_f	Number of cycles to failure
c	Regression slope called the fatigue ductility exponent
N_i	Number of cycles to initiation
$\Delta\varepsilon$	Strain range
σ_m	Mean stress
σ_{max}	Maximum fatigue stress
$\mu\varepsilon$	Microstrain
K	Kurtosis
S	Skewness
Pa	Pascal

LIST OF ABBREVIATIONS

FEA	Finite Element Analysis
r.m.s.	Root-mean-square
SD	Standard deviation
DFT	Discrete Fourier Transform
FFT	Fast Fourier Transform
NI	National Instrument
PSD	Power Spectral Density
STFT	Short-Time Fourier Transform
S-N	Stress-life
ε-N	Strain-life
LEFM	Linear Elastic Fracture Mechanics
SWT	Smith-Watson-Topper
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing

CHAPTER 1

INTRODUCTION

1.0 Background of Study

Strain signals are complex, non-linear and non-stationary. Strain signals often interrupted with noise disturbance from surroundings. Strain signals include the information about the characteristic of signal amplitude, duration, frequency, statistical parameters such as mean, root mean square value, standard deviation, Skewness, Kurtosis, etc.

During the driving, the helical spring is subjected to different cases of static and dynamic loads. The helical spring will undergo tension and compression continuously. It will lead to the vibration of the vehicle. The helical spring absorb the load values of the vehicle. It tends to isolate the structure and the occupants from shocks and vibration which generated from the road surface. Helical spring withstands the action of high frequency fluctuating load from the road surface. Hence, its strain signals will be excited at different frequencies.

According to Guler (2006), while the velocity of the car increased, the displacement of the car body is lower than those at the tire. Thus, it indicated that the load value acted on the helical spring is significantly higher. The load will be varied while travelling on the different types of the road surfaces. The factor is taken into account to cause strain on the helical spring. This study is focusing on the behavior of the strain signals at different value of excitations.

As the helical spring is one of the main parts of the suspension system, it becomes necessary to do the stress and strain analysis because the helical spring undergoes the fluctuating loading over the service life.

1.1 Problem Statement

Abdullah *et. al.*, (2010) found that helical spring experienced the significant load which contributing to the mechanical failure due to fatigue. Helical spring, one part of the suspension system which directly experiencing the load when the vehicle was driven on the road. Strain occurred on the helical spring via the action of compression and tension. The strain signals executed were influenced by the varied excitations due to the road unevenness. Once mechanical failure happened, the helical spring will lead to the extreme of vehicle vibration which may cause the discomfort to the driving process. Therefore, study is carried up to determine the behavior of strain signals at different road profiles.

1.2 Objectives

The aim of this study is to study the behavior of the strain signals at different value of excitations.

1.3 Scopes

The first element that needs to be considered is to perform finite element analysis using MSC Nastran with Patran software. MSC Nastran enables the stress analysis to be done on the helical spring. MSC Patran is the widely used pre / post-processing software for Finite Element Analysis (FEA). The software provides solid modeling, meshing, analysis setup and post-processing for multiple solvers which also including MSC Nastran.

The second element is to conduct experimental testing to collect variable loading. The data collected is further processed with statistical analysis and frequency time-domain analysis by using MATLAB and DASYLab software respectively.

The third element is fatigue damage analysis performed by using nCode DesignLife software packages. Initially, the result of static loading is imported from the MSC Nastran with Pastran software. The signals collected from different road profiles also imported to run the analysis. It shows the result of fatigue damage with colour contour for the finite element which displayed. DesignLife software is a powerful data processing system for engineering test data analysis with specific application for fatigue analysis.

The last element is the validation process. This process requires analysis of the signal classification based on the value of the statistical parameter. Behaviour of the strain signals at different values of excitations are determined.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter reviews about literature review of signal, statistical parameter and frequency domain analysis. Furthermore, the fatigue life prediction is also presented in this study.

2.2 Signal

Signal is a series of number that come from measurement as a function of time. (Meyer, 1993) It is being measured by an analogue-to-digital converter to produce a series of signals at regularly spaced interval times as showed in Figure 2.1. The time series provide the information of statistical parameter by manipulating the series of discrete number. In the case of fatigue research, the signals are a form of information of measuring cyclic load, such as force, stress and strain against time.

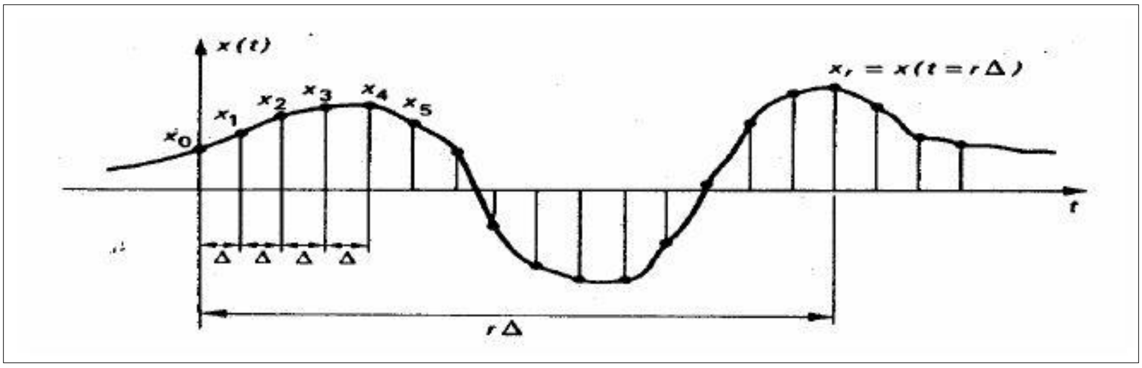

Figure 2.1: Sampling a continuous function of time at regular intervals

Source: Abdullah (2005)

When signals are calculated in term of the probability density function, the variable *x* has a normal or Gaussian probability distribution as illustrated in Figure 2.2. According to Newland (1993), it is a fact that many random vibrations which occurred have the shape of Gaussian distribution. The equation of Gaussian distribution is given by

$$p(x) = \frac{1}{\sqrt{2\pi}(\sigma)} e^{-(x-\bar{x})^2/2(\sigma)^2} \tag{2.1}$$

where: *p(x)* is the probability density function or Gaussian distribution

σ is the standard deviation value

x is the instantaneous value

$\bar{x}$ is the mean value

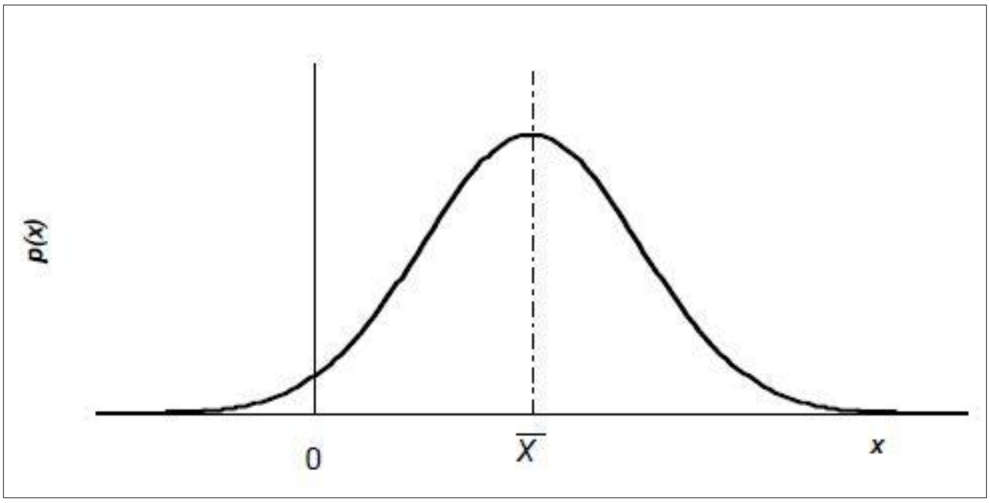

Figure 2.2: The Gaussian distribution

Source: Abdullah (2005)

2.3 Signal Types

Signals can be classified based on their nature and characteristic in time domains. They are divided into two types, deterministic and nondeterministic as shown in Figure 2.3.

Deterministic signals also known as stationary signals. The signals have the constant frequency and level content over a long period of time. It also exhibits statistical properties which remain unchanged with t changes in time. It can further divisible into periodic and nonperiodic signals. Periodic signals have the pattern of wavelets which repeat at equal increment of times. It can be categorized into sinusoidal and complex periodic signals. Nonperiodic signal has the waveform which varies over the duration of time. It is further divided into almost-periodic and transient.

Sinusoidal signal is represented mathematically by

$$x(t) = X \sin 2\pi f_o t \tag{2.2}$$

where: X is the amplitude

f_o is the cyclic frequency

x(t) is the instantaneous value at time t

Complex periodic signal is the sum of the amplitudes of its component signal for each value of the independent variable. These amplitudes are related to the frequency and phase of the signal. The equation is presented by

$$x(t) = \sum_{n=1}^{\infty} X_n \sin(2\pi f_n t + \theta_n) \quad n=1,2,3,\ldots \tag{2.3}$$

where: f_n is the cyclic frequency

θ_n is the phase angles

Almost periodic signal is similar to the complex periodic signal but it contains the sine wave of arbitrary equations which frequency ratios are not rational number. In other words, the frequency of one or more of the higher frequency components of the signal is not an integral multiple frequency of the signal's lowest frequency component. Transient signal is defined as nonperiodic signal with a finite time range. (Bendat and Piersol, 1986) Transient signal includes all other deterministic data which can be described by a suitable function. This signal can be described by a step or ramp function. It occurs at a short period of time and then disappears. Transient signals can be square pulse, triangular pulse and sine pulse which decay to zero.

Nondeterministic signals are also defined as random signals. Most signals in nature exhibit the nondeterministic characteristic. A nondeterministic signal is occurred randomly and the wavelet is irregular. It can further be classified into two categories, stationary and nonstationary. Stationary signal is the relevant statistical parameters remain unchanged for the whole signal length. Stationary signal can be divided into two categories, ergodic and nonergodic. When one sample record of signals is completely representative of the entire process, the process is ergodic. The mean value and the autocorrelation do not differ. The mean value μ_x (k) is mathematically defined as

$$\mu_x\,(k) = \lim(T \to \infty)\frac{1}{T}\int_0^T x_k\,(t)dt \qquad (2.4)$$

and the autocorrelation function is

$$\mathrm{R}_x(\tau, k) = \lim(T \to \infty)\frac{1}{T}\int_0^T x_k\,(t)x_k\,(t+\tau)dt \qquad (2.5)$$

where: τ is the time displacement

T is the period

k is the number of sample function

Nonstationary signal is ones who amplitude and frequency vary with times. It can divided into mildly nonstationary and heavily nonstationary. According to Priestley (1988), mildly nonstationary signal is a random process with stable mean, variance and root mean square value for most of the record, but with short periods of changed signal statistic due to the present of transient behaviour. Heavily nonstationary signal is defined in a similar manner to mildly nonstationary signals but it is characterised by the presence of more transient events. (Giacamin, *et. al.*, 2000)

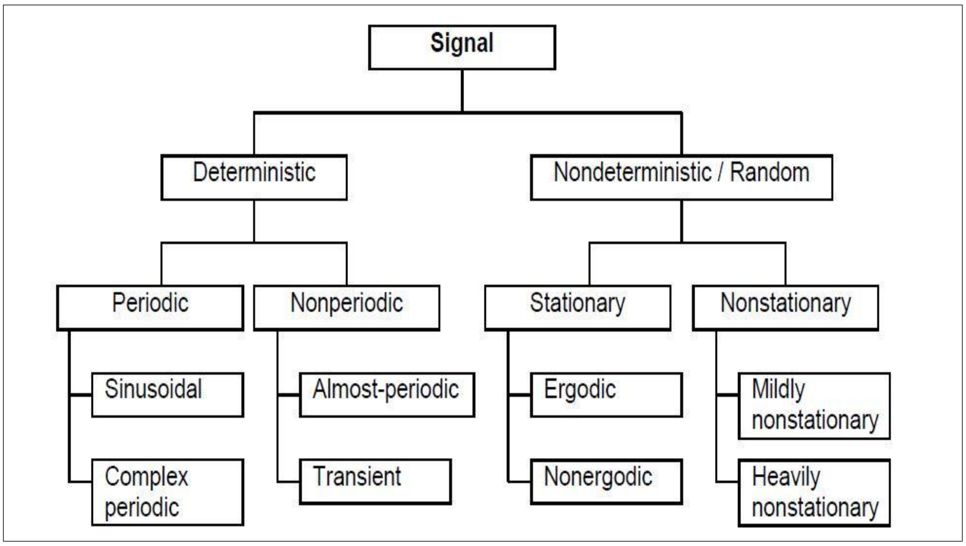

Figure 2.3: Typical signal classification

Source: Abdullah (2005)

2.4 Signal Statistical Parameter

Statistical parameters are used to classify the random signals. The most commonly used are the mean value, the standard deviation value, the root-mean-square (r.m.s.) value, the Kurtosis and the Skewness. The simplest statistic to compute is the mean value. For a signal with a number of *n* data points, the mean value is given by

$$\bar{x} = \frac{1}{n}\sum_{j=1}^{n} x_j \tag{2.6}$$

The standard deviation (SD) value is measuring the spread of data about the mean value. The standard deviation is defined as

$$SD = \{\frac{1}{n}\sum_{j=1}^{n}(x_j - \bar{x})^2\}^{\frac{1}{2}} \tag{2.7}$$

for the samples more than 30. When the samples less than 30, the standard deviation is mathematically defined as

$$SD = \{\frac{1}{n-1}\sum_{j=1}^{n} x_j^2\}^{\frac{1}{2}} \tag{2.8}$$

The root mean square (r.m.s) value is used to quantify the overall energy content of the signal and is defined by the following equation:

$$r.m.s. = \{\frac{1}{n}\sum_{j=1}^{n} x_j^2\}^{\frac{1}{2}} \tag{2.9}$$

Kurtosis is a global signal statistic which is the 4th signal statistical moment. It is highly sensitive to the spikeness of the data. It compares the distribution of the data with a Gaussian type distribution. The Kurtosis equation is defined as :

$$\text{K}= \frac{1}{n(r.m.s)^4}\sum_{j=1}^{n}(x_j - \bar{x})^4 \tag{2.10}$$

The statistic index Kurtosis represents an indicator for the analysis of damage in low speed machineries with no continuous shock. It must be used with the global value rms and time signals. According to Lorenzo and Calabro (2007), signal with Gaussian data distribution, for example the acceleration, has the Kurtosis value = 3, while in presence of impulsive phenomenon, the distribution of data isn't show the Gaussian shape and the Kurtosis value is more than 3 due to high amplitude fatigue cycles. Nopiah et al. (2009) found that, Kurtosis is used for detecting the fault symptons because of the sensitivity to high amplitude events.

The Skewness, which is the signal 3rd statistical moment. It is a measure of the degree of symmetry of the distribution of the data points about the mean value. For a Gaussian random signal, the Skewness is zero value. Positive skewness value is the probability distributions which are skewed to the right whereas the negative skewness value indicates that the probability distributions which are skewed to the left with respect to the mean value. The Skewness of a signal is defined as

$$S = \frac{1}{n(SD)^3}\sum_{j=1}^{n}(x_j - \bar{x})^3 \tag{2.11}$$

2.5 Frequency Domain Analysis

2.5.1 Fourier Transform

Fourier transform is used in signal analysis, quantum mechanics and etc. It is used to identify the frequency components from a continuous waveform. For signal processing, Fourier transform is a tool used to transform a time data series domain into the frequency domain. It is used to convert the non-periodic function of time into a continuous function of frequency. The Fourier transform pair for continuous signals are mathematically defined as followed

$$F(\omega) = \int_{-\infty}^{\infty} f(t)e^{-i\omega t}dt \tag{2.12}$$

$$f(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)e^{i\omega t}d\omega \tag{2.13}$$

where: *F(ω)* is the Fourier Transform of *f(t)*

f(t) is the inverse Fourier transform

ω is the angular frequency

$i = \sqrt{-1}$

2.5.2 Discrete Fourier Transform

Discrete Fourier Transform (DFT) is defined as the signal which digitalized by digital equipment. The signal will become the finite and discrete form of Fourier Transform. It works well under the condition where a sampled time domain signal which is periodic. The signal is periodic and decomposed into the sinusoidal form. The DFT equation is defined as followed

$$X_k = \frac{1}{N}\sum_{t=0}^{N-1} x_j e^{-2\pi ikt/N} \tag{2.14}$$

where: *j*, *k* =0,1,2,3..., (N-1)

N is number of sample points in the DFT data frame.

The inverse of the DFT is defined as

$$x_j = \sum_{k=0}^{N-1} X_k e^{2\pi ijk/N} \tag{2.15}$$

where: *k* = 0,1,2,3,..., (N-1)

Fast Fourier Transform (FFT) is the decomposition of the DFT, which the number of computations needed for N points from $2N^2$ is reduced to 2NlgN. According to Bendat and Piesol (1986), power spectral density (PSD) is a useful representation of random signals. PSD describes the general frequency composition of the data in terms of the spectral density of its mean square values. It has the signal energy which measured within a certain frequency band.

2.5.3 Short-Time Fourier Transform

Short-Time Fourier Transform (STFT) is a method of time-frequency analysis. It produces information which has a localisation in time. STFT is used for analyzing non-stationary signals where the statistic characteristic varies with time. By using

Fourier analysis, it is not possible to get the frequency information at a particular point because the Fourier transform is used for analyze the entire signal. STFT extracts several frames of the signal to be analyzed with a window of signal which moves with time. Each of the frames can be assumed as stationary for the purpose of analyse. As Patsias (2000) pointed out that the Fourier Transform will then be applied to each of the frame using a window function with the condition that it is typically nonzero at the analysed segment whereas zero at the outside. In short, for wide analysis window, it will provide excellent frequency information but poor time resolution. In contrary, for the narrow analysis window will provide good time resolution but poor frequency information.

2.6 Total Fatigue Damage

Fatigue is the process responsible for premature failure and damage of the components which subjected to the repeated loading. (Bannantine *et. al.*, 1990). If the number of load cycles to failure is less than 1000 cycles, the fatigue is considered as low cycle. In contrast, when the number of load cycles to failure is more than 1000 cycles, the fatigue is considered as high cycle. Fatigue life analysis is performed at the early stage of design to reduce the development time and cost. (Rahman *et. al.,* 2007)

Three basic approaches have been used to analyze fatigue damage, such as stress-life approach (*S-N*), strain-life approach (ε -*N*) and linear elastic fracture mechanics (LEFM). *S-N* approach is first formulated in the 1850s to 1870s. It used nominal stress rather than local stress to understand and quantify metal fatigue. The method does not functionally well in low cycle application. As Rahman et al. (2010) points out that most components may appear to be subjected to the nominally cyclic elastic stresses. The stress concentration may present in the component and causes the load cyclic plastic deformation. However, this approach is suitable to predict high cycle fatigue and situations in which only elastic stresses and strains are present.

Linear elastic fractured mechanics (LEFM) is developed in 1920 but the first experimental research is done in 1961. It is an analytical method which relates the stress at the crack tip to the nominal stress field around the crack. LEFM first assumes that the material is isotropic and linear elastic. The stress field near the crack tip is calculated by using the theory of elasticity. When the stress nears the crack tip exceed the material toughness, the crack will grow. LEFM is valid only when the inelastic deformation is small compared to the size of crack. (Paasch and DePiero, 1999)

Strain life (ε-N) is first introduced in the 1960s. The method considers the elastic-plastic local stresses and strains. It is able to account directly for the plastic strain which presented at the stress concentration. Hence, this approach is used to analyze the data of the study.

2.6.1 Strain-Life Based Approach (ε-N)

The strain-life based approach is the observation at critical locations of the material undergoes cyclic loading, such as notches which response to strain rather than the load controlled. It arises from the fact that most components are designed to confine nominal stresses at the elastic region but the stress concentration at notches causes plastic deformation to occur. The material surrounding the plastically deformed zone remains fully elastic. Thus, the deformation at the notch root is determined as strain controlled.

Strain-life based approach is an accurate way of predicting the life cycle in low cycle fatigue regions. According to Beden *et. al.*, (2009), strain-life based approach can be apply for both low cycle and high cycle fatigue. For the low cycle fatigue, the plastic strain component is dominant whereas for high cycle fatigue, the elastic strain component is dominant. At the higher strain, it indicates that the fatigue resistance depends on the ductility but the smaller strains is depending more on the strength.

Fatigue failure is begins to occurs at the local discontinuity. When the stress at this discontinuity exceeds the elastic limit, plastic strain occurs. Strain-life fatigue curve plotted on the log-log scales is showed in Figure 2.4. The total strain amplitude is resolving into elastic and plastic strain components from the steady-state hysteresis loops. Both of the elastic and plastic curves are assumed to be straight line. At the larger strain, plastic strain component is predominant whereas at the lower strain, elastic strain component is predominant.

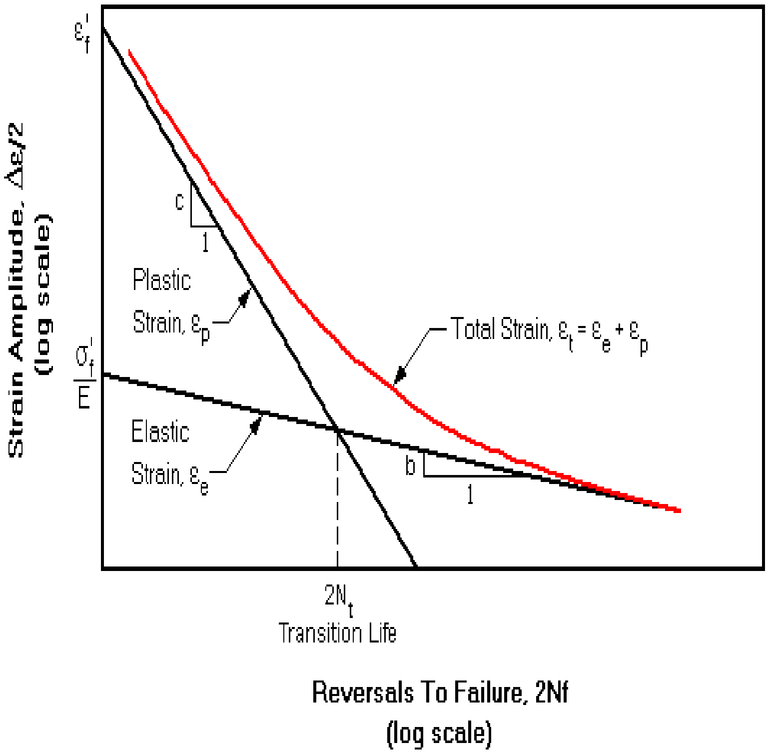

Figure 2.4: Strain-life curve

Source: Radonovich (2007)

Basquin observed that strain-life data may represent by a straight line relationship when plotted using log scales. The relationship which expressed in terms of true elastic strain amplitude as

$$\varepsilon_a = \frac{\sigma_a}{E} = \frac{\sigma'_f}{E}(2N_f)^b \tag{2.16}$$

where: ε_a is the elastic component of the cyclic strain amplitude

σ_a is the true cyclic stress amplitude

σ'_f is the fatigue strength coefficient

N_f is the number of cycles to failure

b is the fatigue strength exponent

E is the elastic modulus

In 1950s, Coffin and Manson proposed the plastic strain component of a fatigue cycle may also be defined as followed:

$$\varepsilon_p = \varepsilon'_f (2N_f)^c \tag{2.17}$$

where: ε_p is the plastic component of the cyclic strain amplitude

ε'_f is the strain ductility coefficient

N_f is the number of cycles to failure

c is the regression slope called the fatigue ductility exponent

The strain-life equation is the combination of the Basquin's equation and the Coffin-Manson's equation.

$$\frac{\Delta\varepsilon_t}{2} = \frac{\sigma'_f}{E}(N_i)^b + \varepsilon'_f (N_i)^c \tag{2.18}$$

Equation 2.14 is defined in terms of cycles (N).

Radonovich's (2007) study found the following, " Cycles may be more precisely specified as cycle to failure (N_f) or cycles to initiation (N_i)". Cycles to failure is the number of cycles which undergo by the specimen until failure occurs. Cycles to initiation is the number of cycles until initiation of a crack is determined by particular amount of load applied during strain-controlled testing. However, the modern practice is to divide fatigue into crack initiation and crack growth after a crack has reached a minimum detectable size. Hence, the strain-life equation is defined in terms of cycles to initiation (N_i).

2.6.2 Mean Stress Effects

In an actual loading application, mean stress have an effect on the metallic fatigue behaviour (Abdullah, *et. al.*, 2010). Strain-controlled cycle with a mean strain will result in a mean stress which may fully or partially relax with continued cycling. The relaxation occurs is due to the presence of plastic deformation. Hence, the rate of amount of relaxation depends greatly upon the magnitude of the plastic strain amplitude. In other words, it implies that more mean stress relaxation is occurred at larger strain amplitude. Tensile mean stresses are known to reduce the fatigue strength of a material whereas the compressive mean stress will increase the fatigue strength of a material. Mean stress effect on fatigue life is smaller on the low cycle fatigue region and larger in the high cycle fatigue region as showed in Figure 2.5.

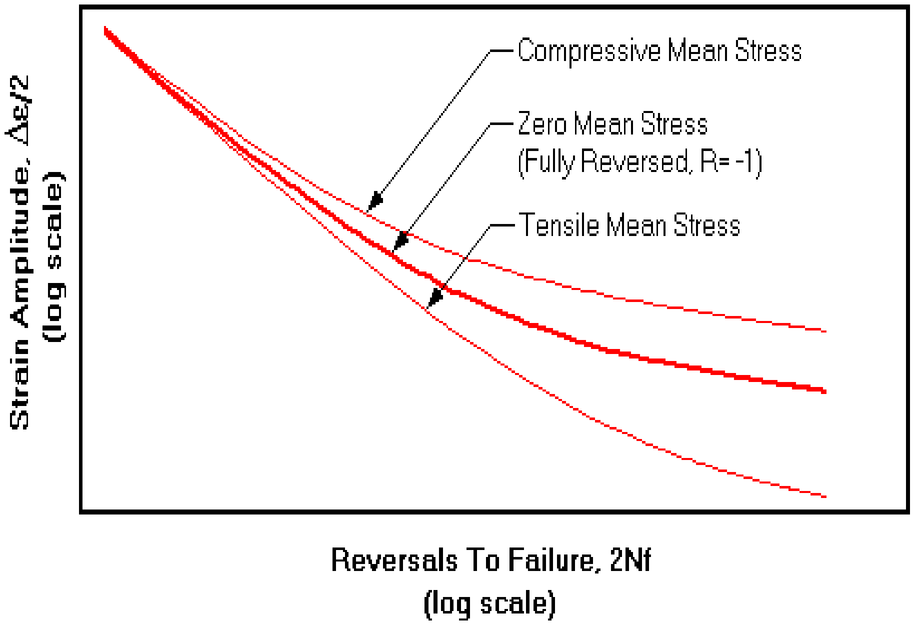

Figure 2.5: Effect of mean stress on Strain-Life curve

Source: Bannantine (1990)

Morrow was the first person who suggested modifying the baseline strain-life curve by employing the true fracture strength as the intercept. Morrow modified the elastic term of the strain life equation for introducing the local mean stress into the strain life equation. The equation is defined as

$$\varepsilon_a = \frac{\Delta\varepsilon}{2} = \frac{\sigma_f^{'} - \sigma_m}{E}(2N_f)^b + \varepsilon_f^{'}(2N_f)^c \qquad (2.19)$$

Figure 2.6 shows the effect of a tensile mean stress in modifying the strain-life curve using the Morrow equation.

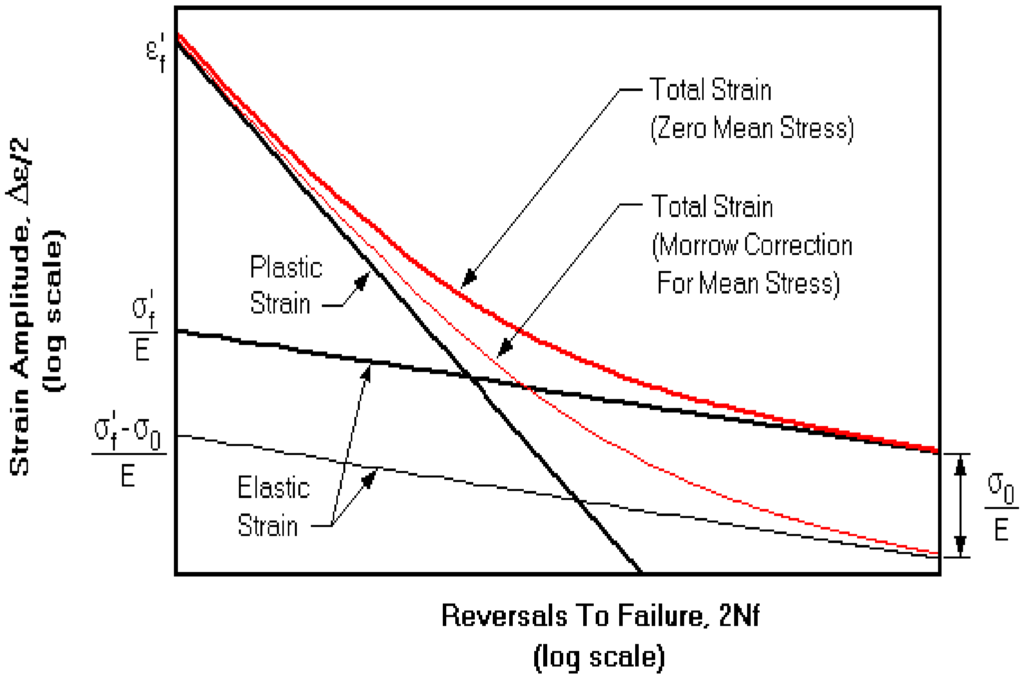

Figure 2.6: Effect of mean stress on strain-life curve (Morrow correction)

Source: J.A. Bannantine (2009)

Another method which takes the account for mean stress was proposed by Smith, Watson and Topper (SWT). SWT strain-life model is defined by:

$$\varepsilon_a \sigma_{max} = \frac{(\sigma_f^{'})}{E}(2N_f)^{2b} + \sigma_f^{'}\varepsilon_f^{'}(2N_f)^{b+c} \qquad (2.20)$$

where: $\Delta\varepsilon$ is the strain range

ε_a is the true strain amplitude

σ'_f is the true fracture strength

σ_m is the mean stress

σ_{max} is the maximum fatigue stress

E is the modulus of elasticity

ε'_f is the fatigue ductility coefficient

N_f is the number of cycles to failure

b is the fatigue strength exponent

c is the fatigue ductility exponent

The SWT strain-life model predicts that no fatigue damage occurs when the maximum stress is zero or negative. This statement is not always true. For loading sequences which are predominantly tensile, SWT approach is more conservative. In contrast, for the loading which are predominantly compressive, the Morrow correction is used. (FEA-Opt Technology, 1998)

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter is discussed the ideas about the method of implementing this research. In this study, there are a few categories in the methodology process. The categories are design of helical spring, finite element analysis, road testing and analysis by using the approach of statistical parameter, FFT and fatigue damage assessment.

Helical spring is modeled by using CATIA V5 software. MSC Nastran with Patran software is used to run the finite element analysis from the solid modeling. Linear elastic stress analysis is performed by subjected the helical spring with the force at the bottom end in accordance with the weight of the vehicle. It is followed by the collecting strain loading data from the road testing. After that, analysis is performed by using the approaches of statistical parameter, FFT and fatigue damage assessment. The signal and FFT are collected by using DASYLab and further processed the statistical parameter by MATLAB. The fatigue damage assessment is done by using DesignLife software. The analysis is done to study the fatigue of helical spring at different value of excitations. Figure 3.1 is an overview about the overall steps during the research.

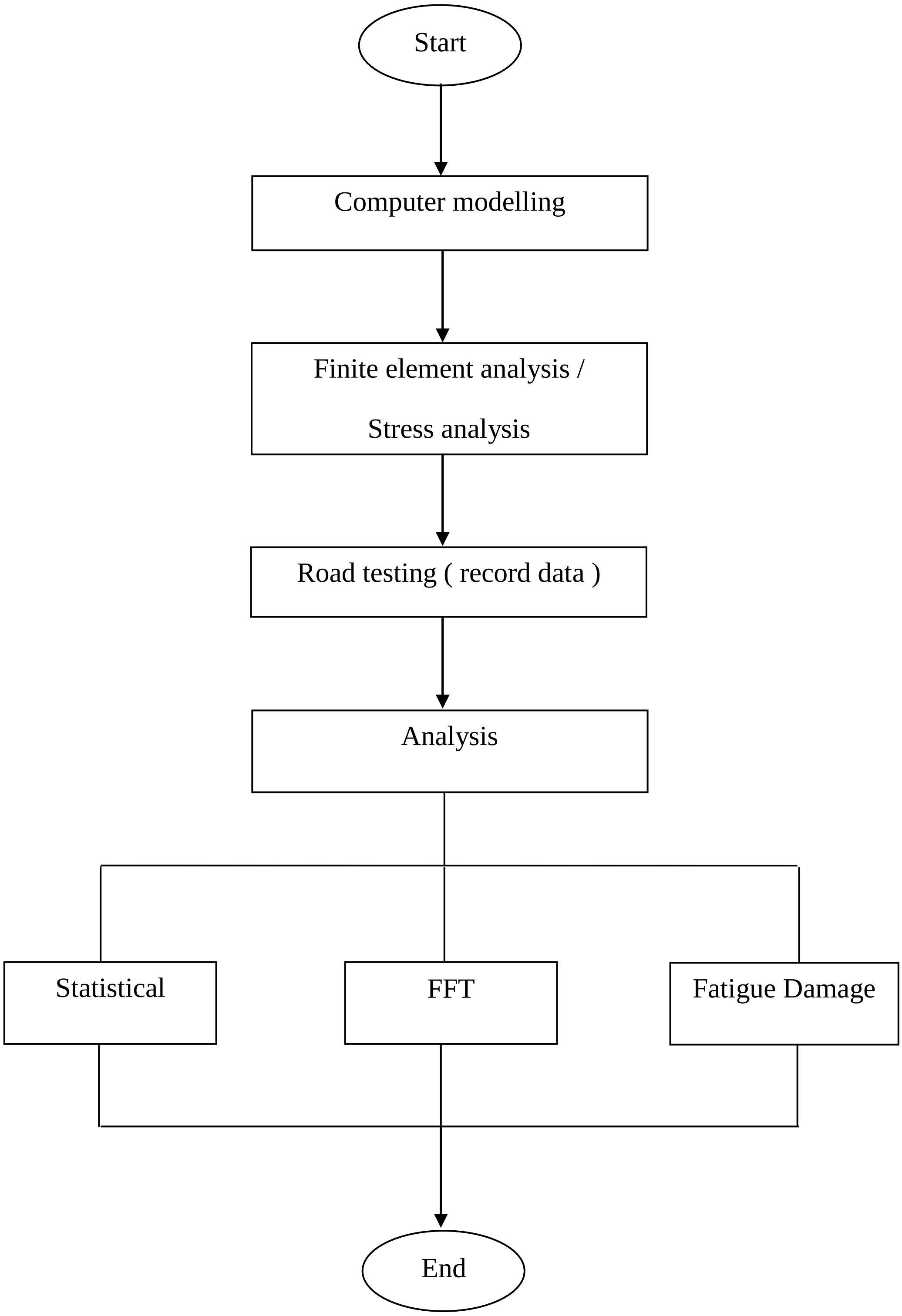

Figure 3.1: Flowchart of Research Methodology

3.2 Solid Modelling Of Helical Spring

In this study, the helical spring of Proton Persona Sedan 1.6 Manual Transmission (MT) Base Line is used to conduct the static loading analysis and cyclic analysis. The specifications of the helical spring are listed in Table 3.1.

Table 3.1: Helical spring specification

Dimension	
Coil diameter	145mm
Wire diameter	13mm
Active loop number	7
Pitch	67mm
Height	440mm

The helical spring geometry is modeled in the CATIA V5 software. CATIA V5 is one of the advanced CAD software leading product development. It integrates a suite of collaborative product design software applications, such as Computer Aided Design (CAD), Computer Aided Engineering (CAE) and Computer Aided Manufacturing (CAM). CATIA V5 is widely used in the industry of automotive, aerospace, electronics, shipbuilding and etc. CATIA V5 supports multiple stages of product development, from conceptualization, design, manufacturing and engineering. CATIA V5 enables the development of a full product, from the stage of design basic product specification until the product in service. CATIA V5 is possible for the creation of 3D parts, from the step of sketching, modifying until validate the complex innovative shapes. Figure 3.2 shows the model of helical spring.

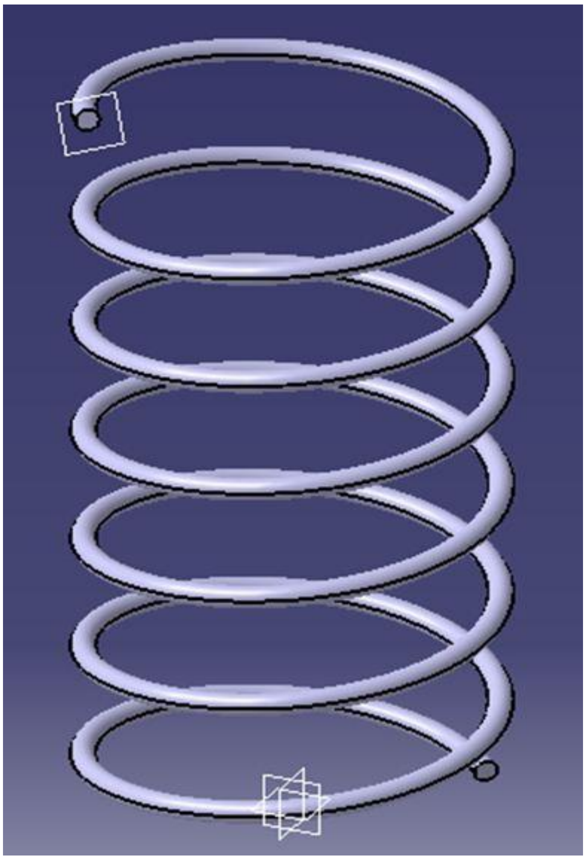

Figure 3.2: Helical spring in CATIA V5 software

3.3 Simulation of Helical Spring

3.3.1 Linear Elastic Stress Analysis

Finite element analysis is used to stimulate the physical behavior and analysis the structural integrity of the design. In this study, finite element method is carried up to analyze the fatigue occurred at the helical spring. Helical spring is made up of typical steel. The material properties are given in the Table 3.2.

Table 3.2: Material properties of spring steel

ASTM A227	
Modulus of Elasticity, E	210GPa
Poisson's Ratio	0.3

The linear static finite element analysis of helical spring is performed by using MSC Nastran with Patran software. The purpose is to determine the stress and strain results from the finite element model. Mesh study is performed on the helical spring to ensure sufficient fined size of element in order to get the accuracy of the result. The element shape selected is tetrahedral due to tetrahedral shape can produce high quality meshing for the boundary solid. The topology selected is TET 10 because TET 10 is able to undergo the higher stress. After the meshing, there are 16829 nodes and 8523 elements produced as showed in Figure 3.3.

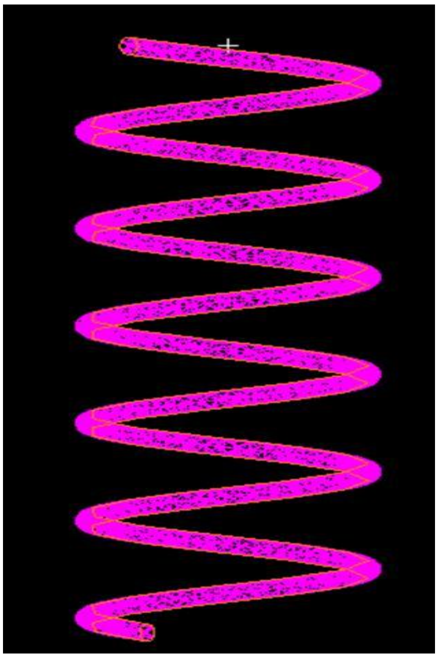

Figure 3.3: Helical spring with 16829 nodes and 8523 elements

As this helical spring is used in the vehicle passenger car, it is indeed to find out the load acting on the helical spring. The force applied is 3000 N. The load is applied in upward direction of one end of the spring and the other is fixed in X, Y and Z directions. The material utilized consists of a linear elastic, isotropic material. The choice of linear elastic material is essentially mandated. The model loading consists of applied mechanical load, which is modeled as the load and displacement control. In Figure 3.4, it shows that the maximum principal shear stress of 3.91 kPa occurred at node 13590. From this observation, the inner side of helical spring is the stress critical zone. Figure 3.5 shows that the maximum displacement of the spring occurred at node 8429 and the value is 12600.00 mm. The upper side of the fixed end of helical spring is zero displacement.

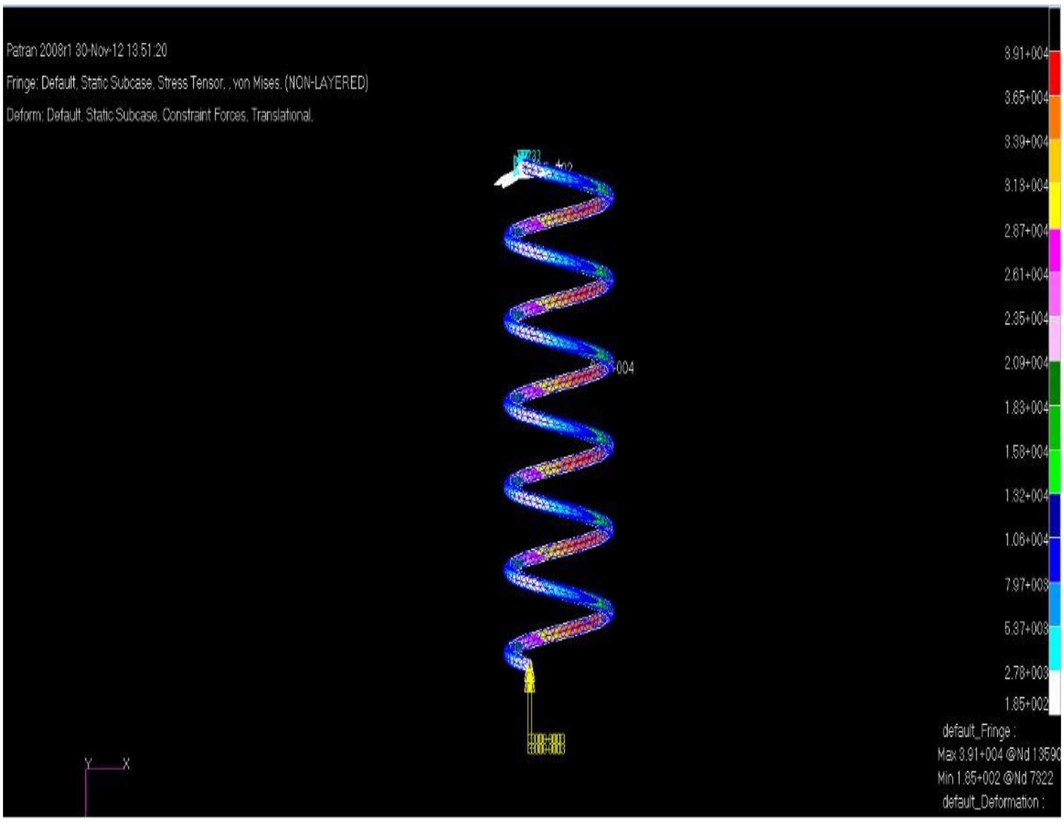

Figure 3.4: Stress distribution for static loading

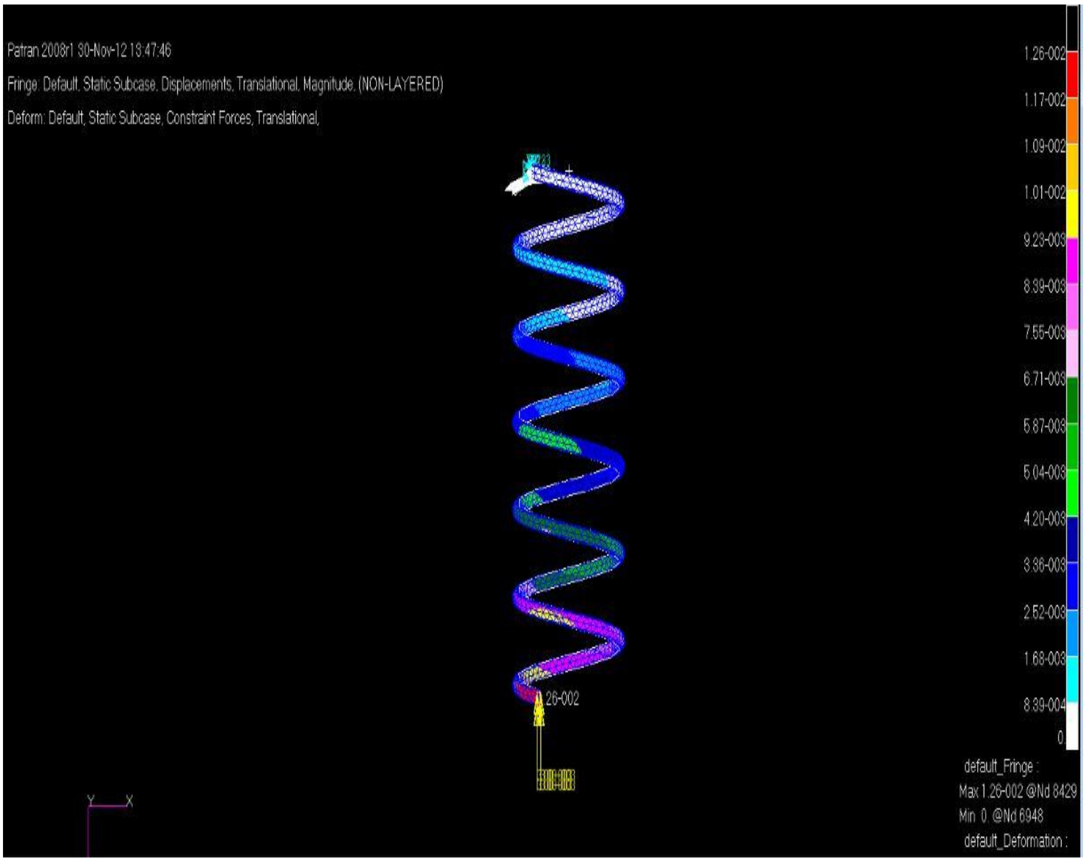

Figure 3.5: Displacement distribution of static loading

3.3.2 Statistical and FFT Analysis

Statistical analysis is used to classify the signal behavior. DASYLab software, analyze the strain signal into the global statistical parameter and Fast Fourier Transform (FFT) as showed in Figure 3.6. The statistical parameter value, such as, mean, root mean square (r.m.s), standard deviation, Skewness and Kurtosis are computed. The result of FFT is presented in graphical form of Power Spectral Density (PSD). The flat top type of window is used because flat top gives broader band shape and maximum amplitude error of 1%.

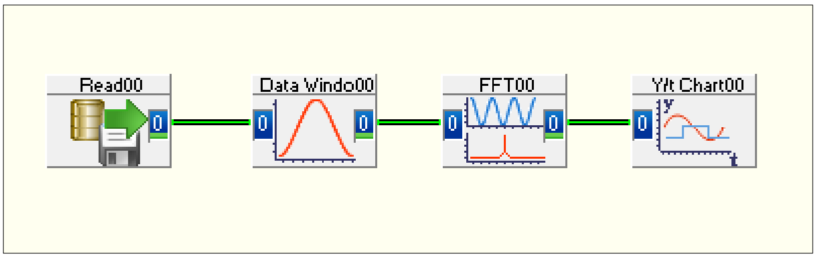

Figure 3.6: FFT analysis using DASYLab

3.3.3 Fatigue Analysis

Fatigue analysis is used to predict the fatigue life as showed in the Figure 3.7. In this study, DesignLife software had been used for the analysis. DesignLife software provides the fatigue life prediction from finite element. DesignLife software is capable for the fatigue analysis which including stress life, strain life and etc. The finite element model in the form of op2 type file at MSC Nastran with Patran is imported to the DesignLife software with variable strain signal to simulate the actual road conditions. Strain signal is captured from three different types of roads profile, which are highway, unpaved road and university road. Each road will excite different strain signal to the helical spring. The last stage is the fatigue assessment which is done by calculating the fatigue damage values using three models of strain-life, which are Coffin-Manson, Morrow and Smith-Watson-Topper (SWT).

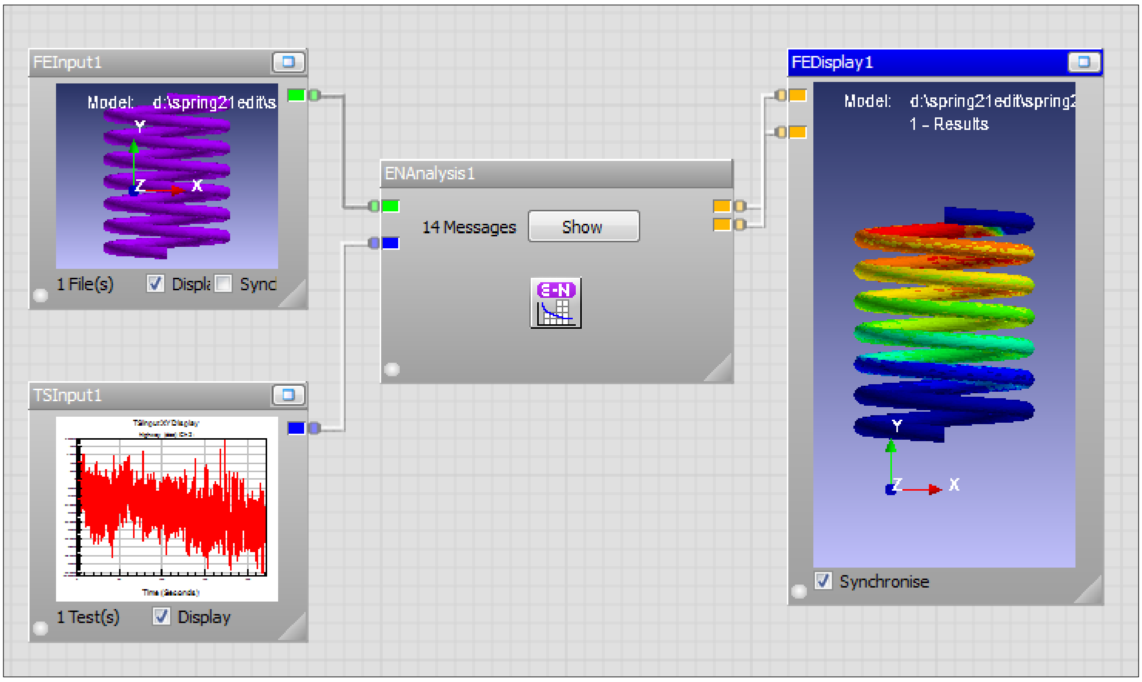

Figure 3.7: Fatigue life assessment using nCode DesignLife

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter shows the result obtained from the study which are strain signal of helical spring from different road profile, statistical parameter analysis, FFT analysis and fatigue finite element analysis of the helical spring. The strain signals data that had been obtained from the experiments were analysed by using the DASYLab, MATLAB and DesignLife software.

4.2 Strain Signal

The strain signals of highway, university road and unpaved road are recorded in DASYLab software. The strain loading data on helical spring was measured by using the strain gauge of 5 mm size. Three road profiles, highway, university road and unpaved road are used for this study. Highway road represents nearly consistent load features. University road represents load features which include speed bump, roundabouts and rough surface structure. Unpaved road represent the mostly inconsistent load feature due to a lot of holes. The velocity of the vehicle is maintained at 40-50 km/hr. Each testing is carried up for duration of 60 s at a sampling rate of 500 Hz. The strain signal of highway, university road and unpaved road in the function of time are showed in Figure 4.1, Figure 4.2 and Figure 4.3, respectively. The strain signal of highway has lower strain signal amplitude background due to the smoothness of road surface. The strain signal of university road contains occasional shocks where there are bumpers. At time, it also exhibits lower strain signal due to slow down in velocity when there are roundabouts. For the unpaved road, it resulted a higher strain amplitude loading data due to lot of occasional shocks.

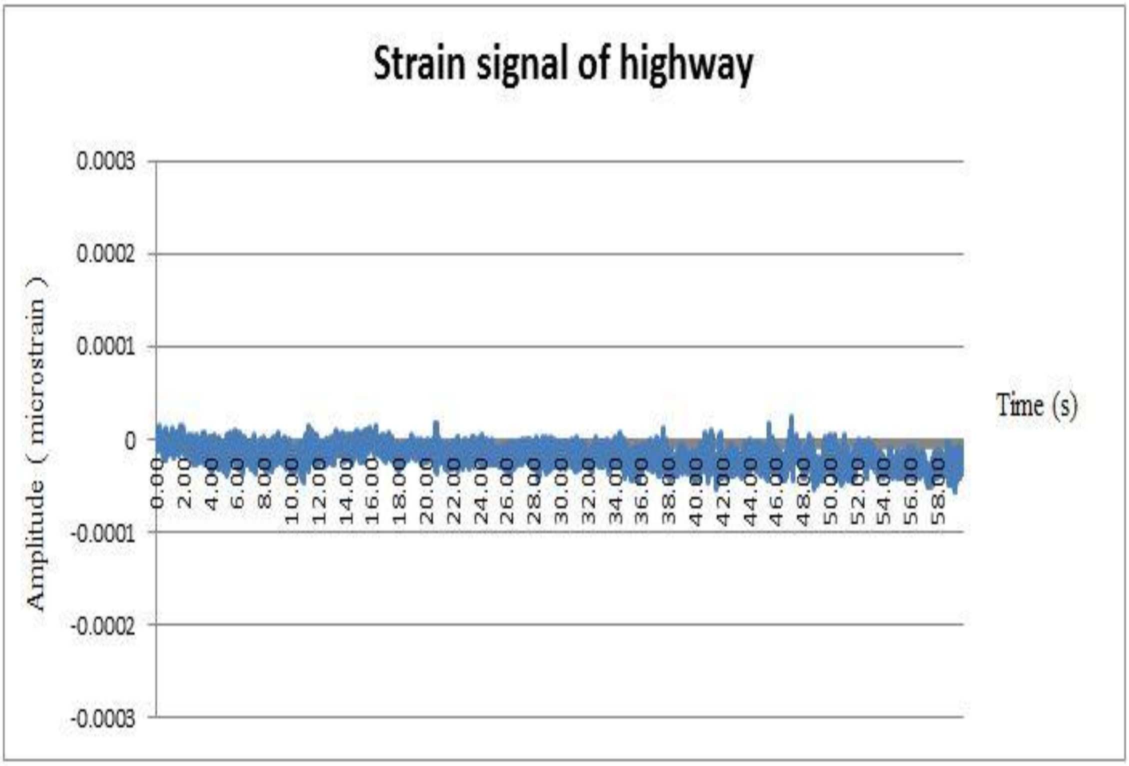

Figure 4.1: Strain signal of highway

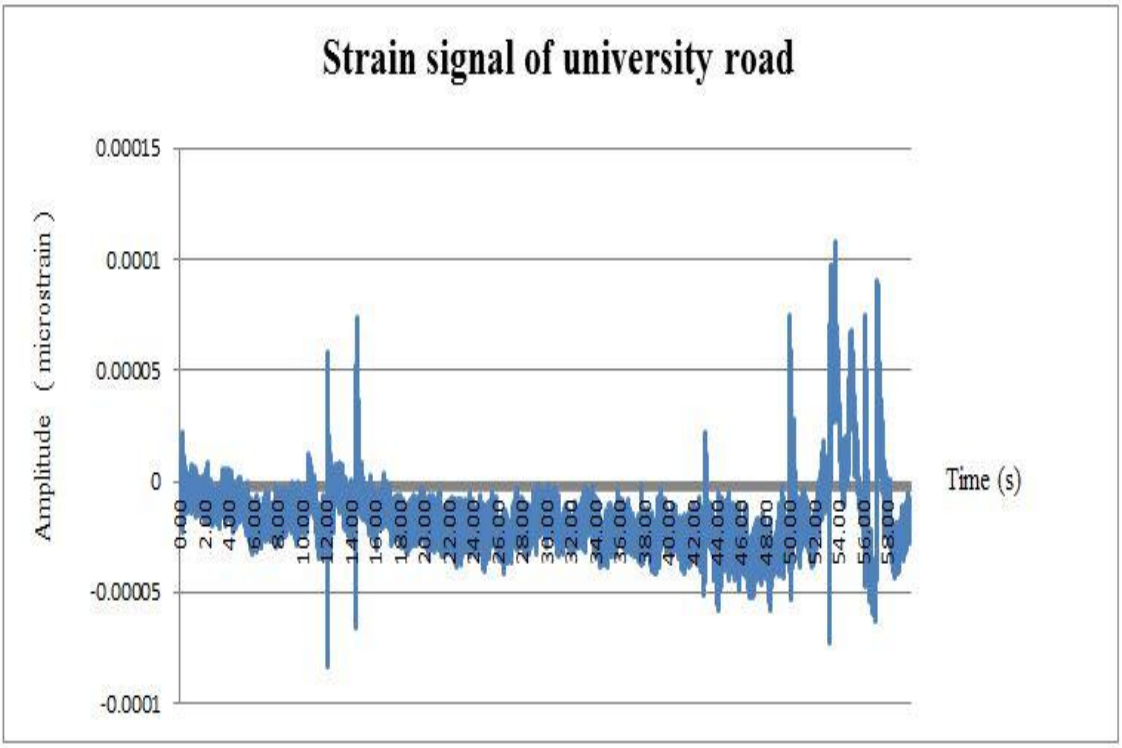

Figure 4.2: Strain signal of university road

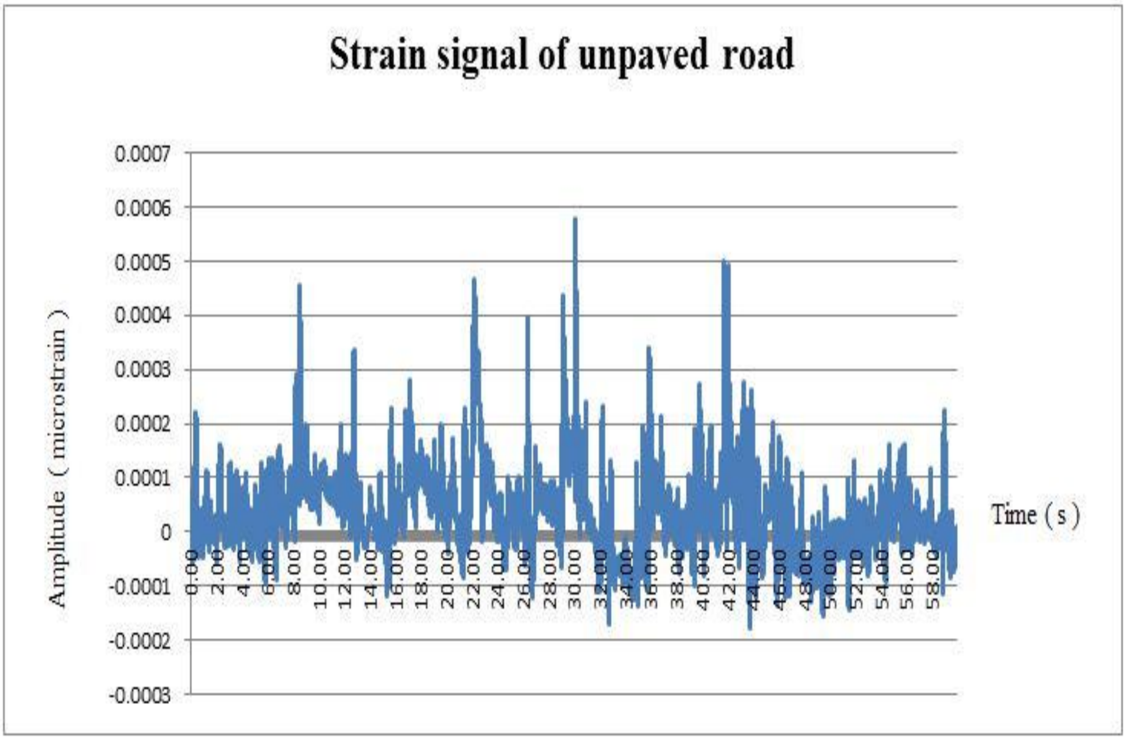

Figure 4.3: Strain signal of unpaved road

4.3 Statistical Parameter Analysis

The strain signals data obtained from DASYLab were then processed using MATLAB to obtain the statistical parameter. The statistical parameters are mean, root mean square, standard deviation, Skewness and Kurtosis. The result obtained is tabulated in Table 4.1. It showed that unpaved road had a highest mean amplitude strain signals which recorded at 31.52 microstrain. Then, it is followed by university road and lastly highway which were -16.34 microstrain and -17.74 microstrain respectively. The mean value is the highest peak in the probability density function. In the three case studies, the mean values were not equal to zero, thus, it showed a non-Gaussian distribution. The higher amplitude signal indicates that there is higher stress applied to the helical spring. Highway had the lowest vibrational energy of the signal which is found from the root mean square value, 20.33 microstrain. The root means square value of university road and unpaved road were 23.11 microstrain and 85.08 microstrain respectively. Unpaved road showed the highest standard deviation value, 79.02 microstrain, i.e the signals were spread over a larger range of value. It is followed by university road and lastly highway, 16.34 microstrain and 9.93 microstrain respectively. The Skewness value of highway and unpaved road is negative value indicated that probability distributions which were skewed to the left, while university road had the positive value of Skewness indicated the probability distribution skewed to the right, with conjunction to the mean value. Thus, these implied that the result obtained from three road profiles are non-Gaussian distribution. Kurtosis value is the measured of the extreme value that occurred in the experiment. In this case, university road has the highest Kurtosis value because there is bumper, roundabout and round surface structure which caused significant varied load exerted on the helical spring. Besides, the peak in the strain signals occurred due to the braking of the vehicle. Based on the result obtained, all the strain signals from highway, university road and unpaved road show the behavior of nondeterministic and nonstationary.

Table 4.1: The statistical values for different road profiles

	Highway	University road	Unpaved road
Mean (με)	-17.74	-16.34	31.52
Root Mean Square (με)	20.33	23.11	85.08
Standard deviation (με)	9.93	16.34	79.02
Skewness	-0.07	2.48	-0.79
Kurtosis	2.83	13.80	4.63

4.4 FFT Analysis

When the vehicle is driving on the road surface, it generates a lot of excitation to the helical spring. Thus, it contains a large number of input frequencies. The input signal was sampled at a 500Hz. In the frequency analysis, the data in the form of time domain was transformed into the frequency domain by using the FFT algorithm. Frequency analysis data is presented in graphical form of Power Spectral Density (PSD). It displayed the frequency composition of the data in terms of the spectral density. It is used to measure the energy of a signal. Each value in the graph showed the amplitude and phase of the particular sinusoidal wave at the particular frequency. In this case, the strain signals obtained from the experiment exhibit non-Gaussian distribution, thus, it is related to the broad band signal. The broad band signal consists of a wide range of frequencies and distinct spikes. From the study, unpaved road has a wider range of frequency as showed in Figure 4.6. It is followed by the university road as showed in Figure 4.5 and lastly highway as showed in Figure 4.6. From the result obtained, it showed that the higher amplitude region is predominantly located at a lower frequency spectrum. In contrast, the lower amplitude signals are located at a higher frequency spectrum. Lower amplitude signals will result the minimized damage to helical spring.

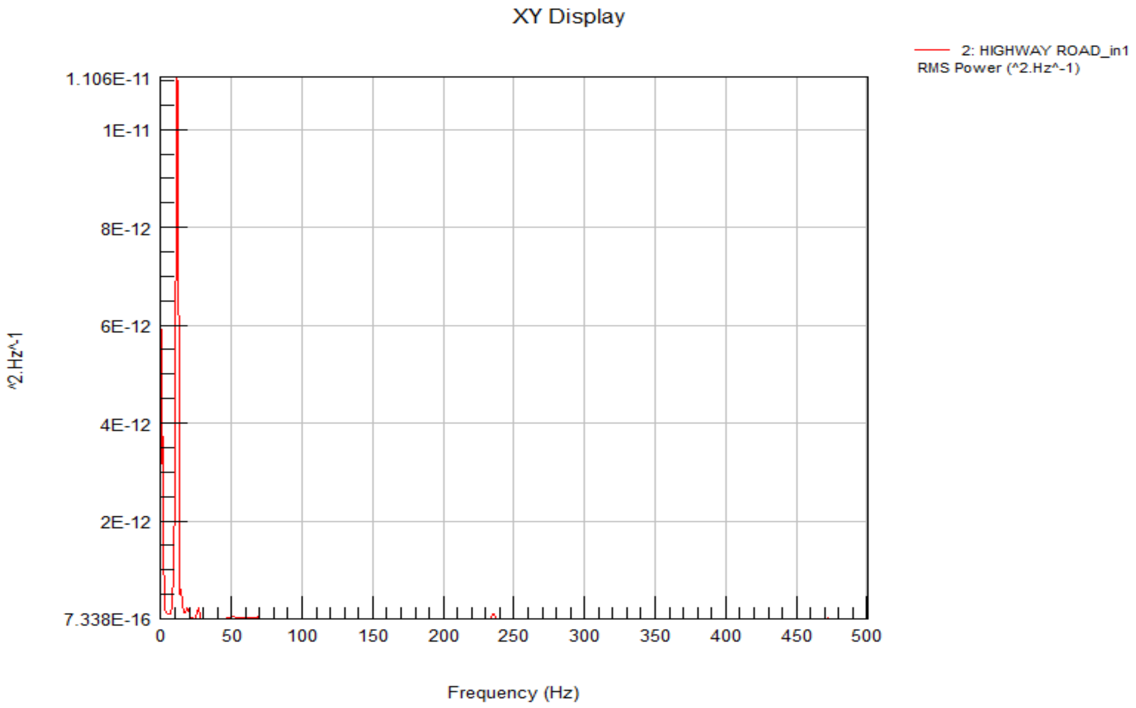

Figure 4.4: FFT of highway

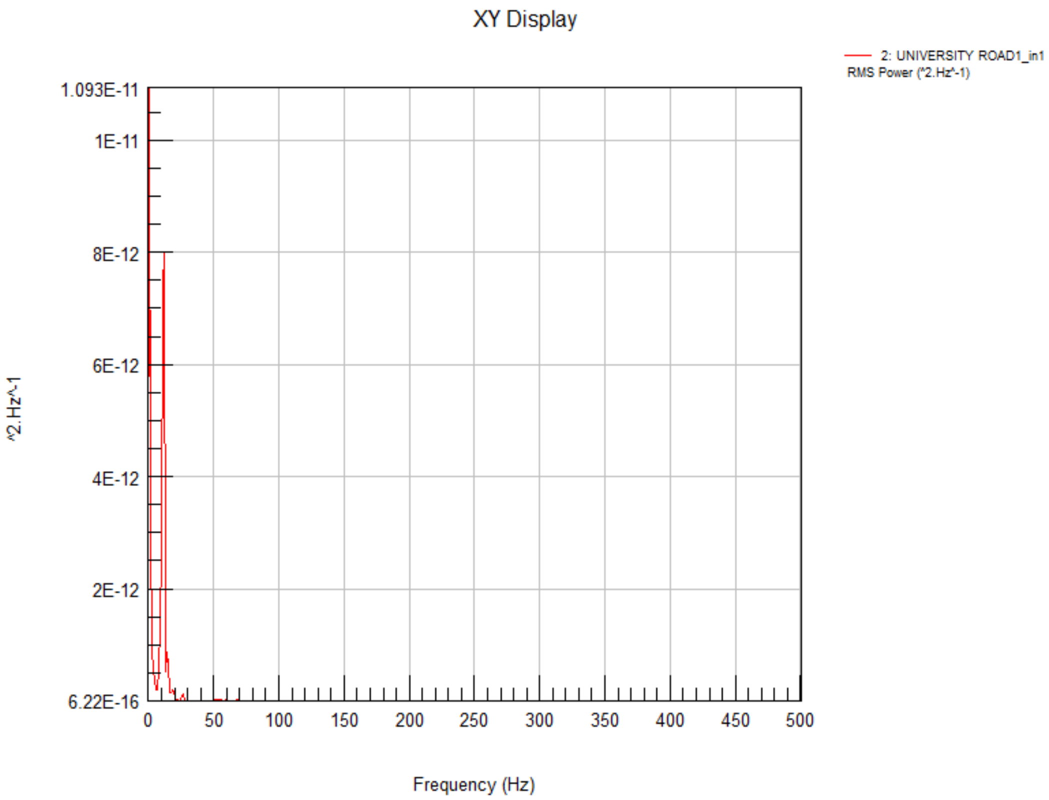

Figure 4.5: FFT of university road

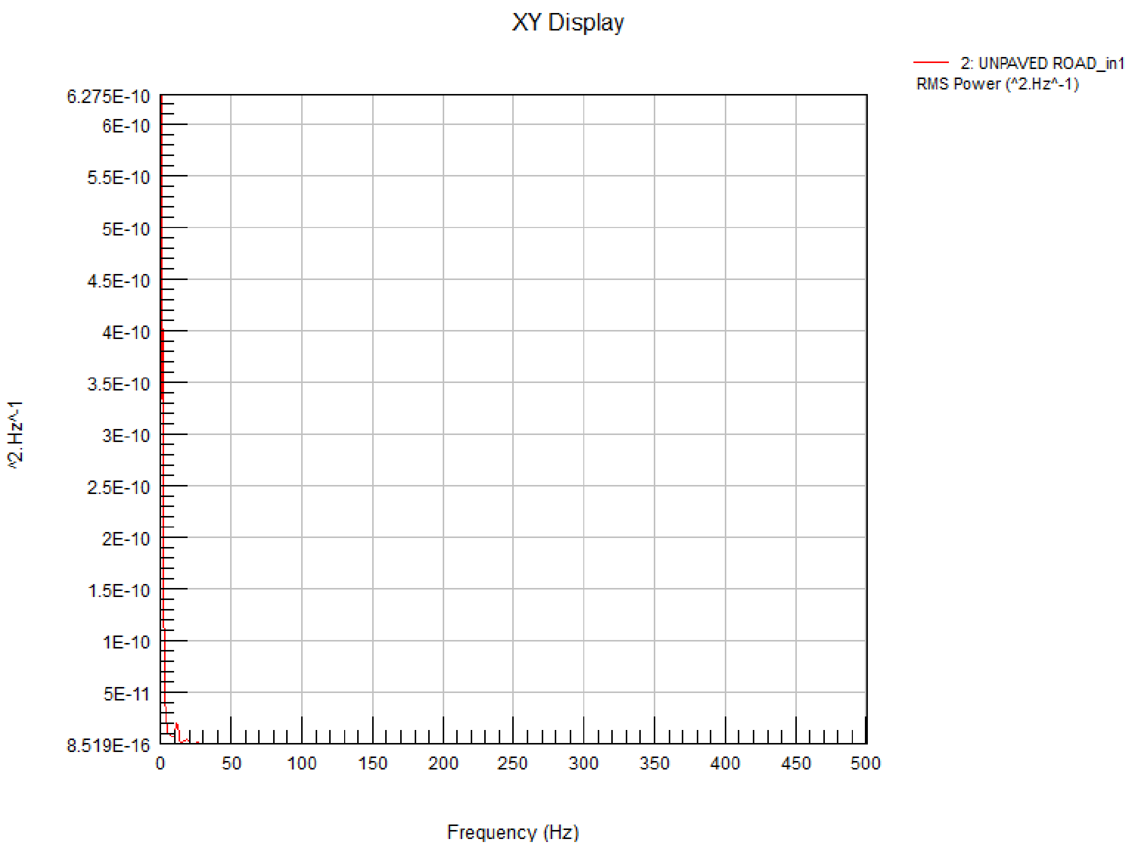

Figure 4.6: FFT of unpaved road

4.5 FATIGUE ANALYSIS

Fatigue analysis is aimed to identify the critical location of helical spring. It is carried up by the finite element method of helical spring with the strain signal on real road test. Strain life model is used for the analysis. Strain-life model includes techniques of converting the loading and geometrical as input to predict the fatigue damage. Helical spring is subjected to fully reversible cyclic loading may result nominal cyclic elastic stress. Local cyclic plastic deformation may occur due to the stress concentrations in the helical spring.

The results of fatigue damage obtained were based on strain-life models of Coffin-Manson, Morrow and Smith-Watson-Topper approaches by using nCode DesignLife software. Unpaved road gave the highest total fatigue damage, followed by university road and lastly highway. The total fatigue damage of unpaved road is 1.85 x 10^{-1}, 3.39 x 10^{-1}, and 3.40 x 10^{-1} for Coffin-Manson, Morrow and Smith-Watson-Topper (SWT) model respectively. For the university road, it showed the fatigue damage value of 3.50 x 10^{-3}, 4.25x10^{-3} and 4.30 x 10^{-3} for Coffin-Manson, Morrow and SWT model respectively. The total fatigue damage occurred on the highway is the lowest, which were 5.08 x 10^{-4}, 5.09 x 10^{-4} and 7.85 x 10^{-4}, for Coffin-Manson, Morrow and SWT model respectively.

From Figures 4.7, 4.8 and 4.9, it showed the colour contour of helical spring on highway road test using Coffin-Manson, Morrow and SWT method. Figures 4.10, 4.11 and 4.12 showed the result of helical spring on university road by the Coffin-Manson, Morrow and SWT method. Figure 4.13, 4.14 and 4.15 showed the result of helical spring on unpaved road using the Coffin-Manson, Morrow and SWT method. From the result, it implies that red colour contour has the highest strain which will result the highest fatigue damage value. It is also the location where the crack growth. In contrast, the blue colour indicated the lowest fatigue damage value. Unpaved road has the highest fatigue damage value for all the strain-life model testing.

SWT method is more conservative compared to Coffin-Manson and Morrow method when subjected to positive mean loading. In contrast, Coffin-Manson model is preferable when subjected to negative mean loading. (Husin *et. al.*, 2010) For the case of highway and university road where the mean loadings were negative, Coffin-Manson model is more conservative. In the case study, unpaved road gave the positive mean loading, SWT model was more conservative.

Table 4.2: Result of fatigue damage

Strain-life model	Coffin-Manson	Morrow	SWT
Highway (x 10^{-4})	5.08	5.09	7.85
University Road (x 10^{-3})	3.50	4.25	4.30
Unpaved Road (x 10^{-1})	3.40	3.39	1.85

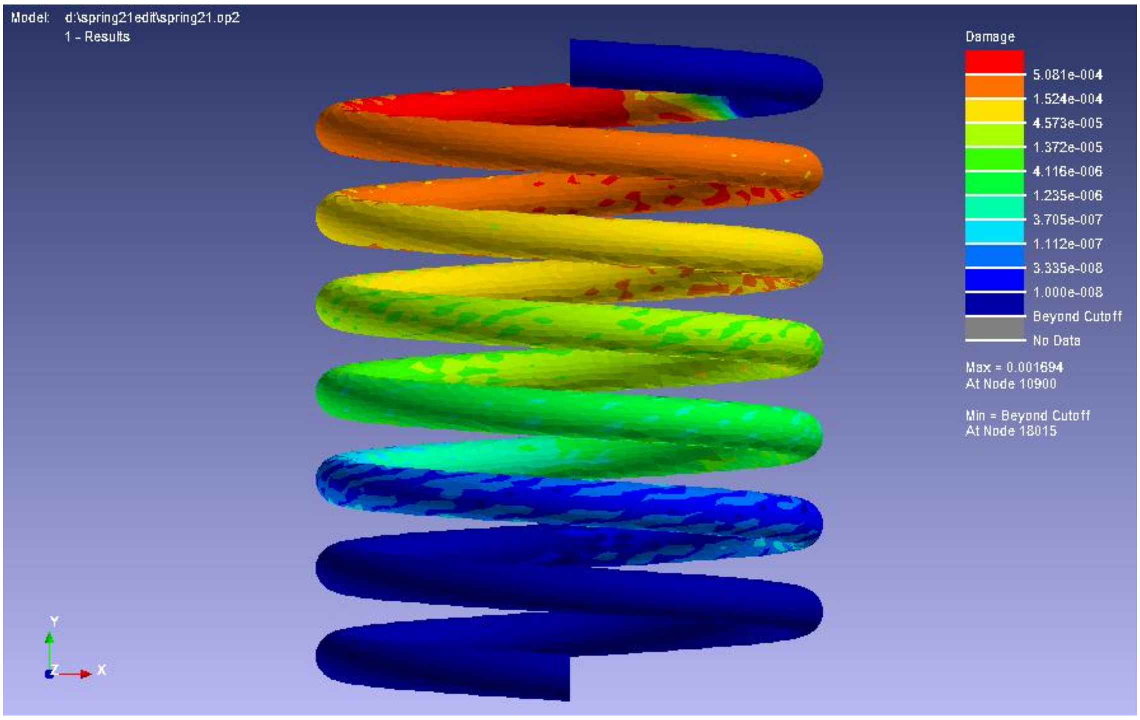

Figure 4.7: Colour contour of the fatigue test using Coffin-Manson method for highway

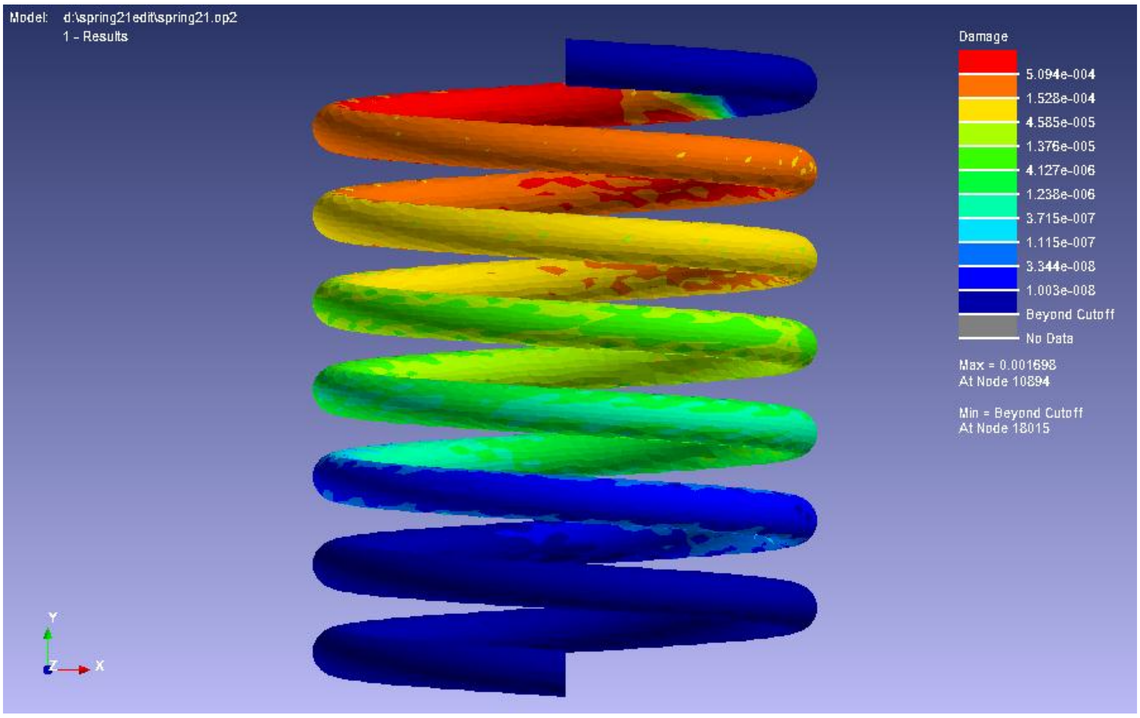

Figure 4.8: Colour contour of the fatigue test using Morrow method for highway

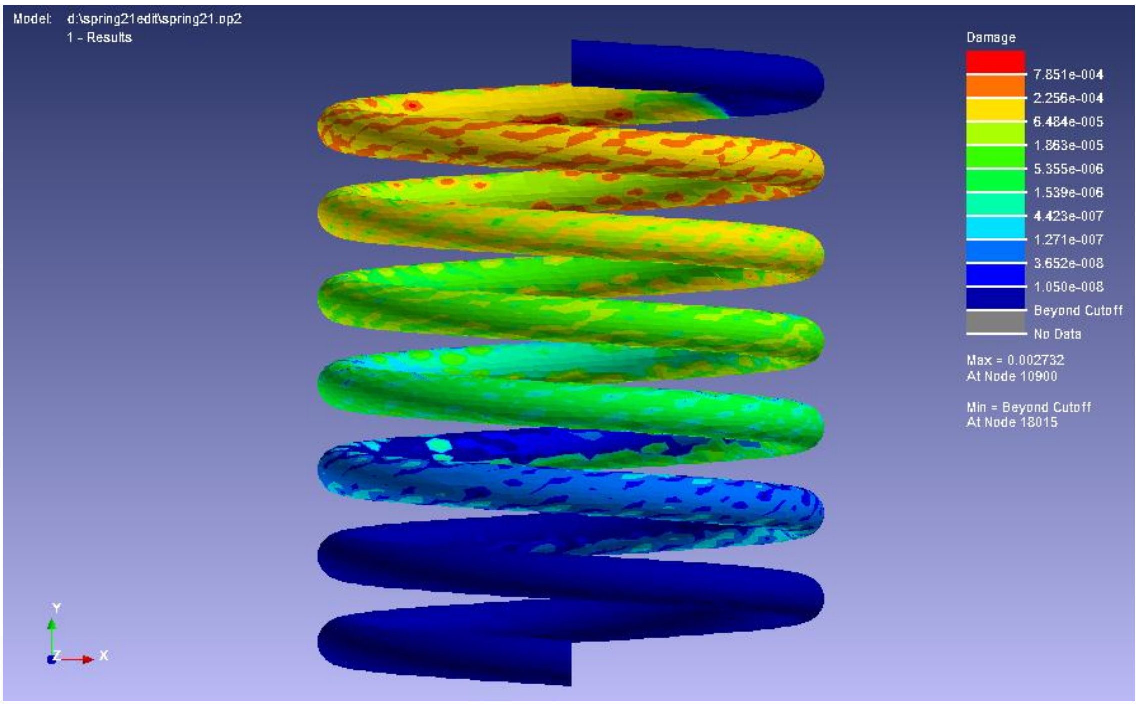

Figure 4.9: Colour contour of the fatigue test using Smith-Watson-Topper method for highway

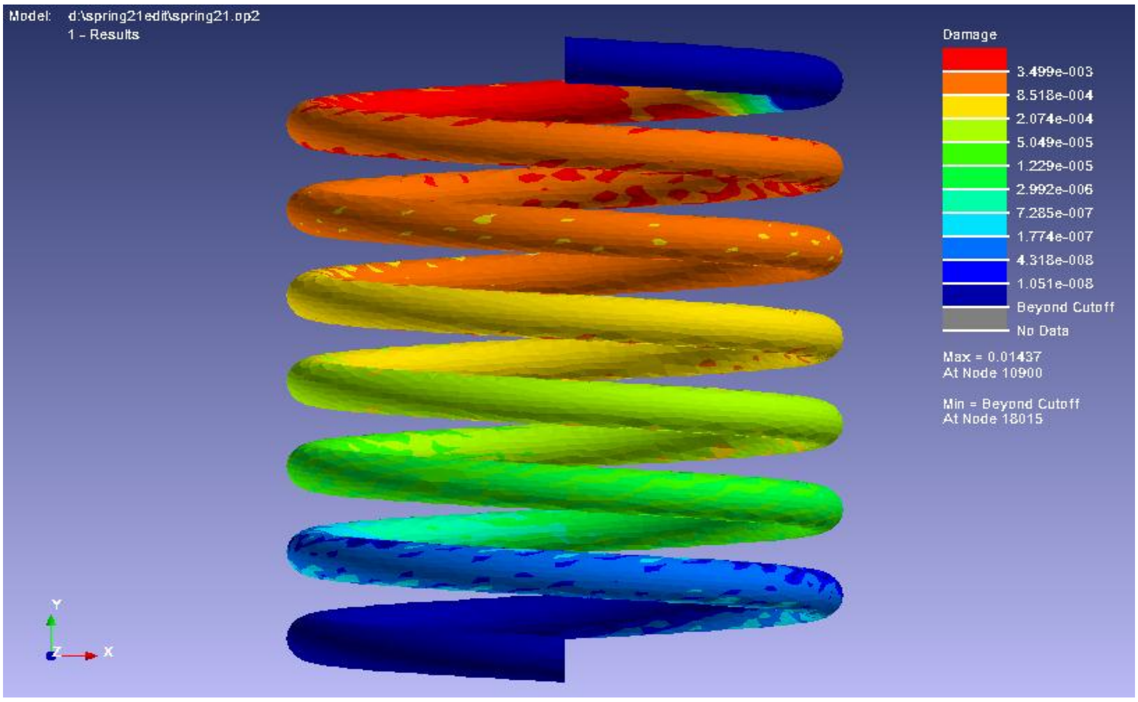

Figure 4.10: Colour contour of the fatigue test using Coffin-Manson method for university road

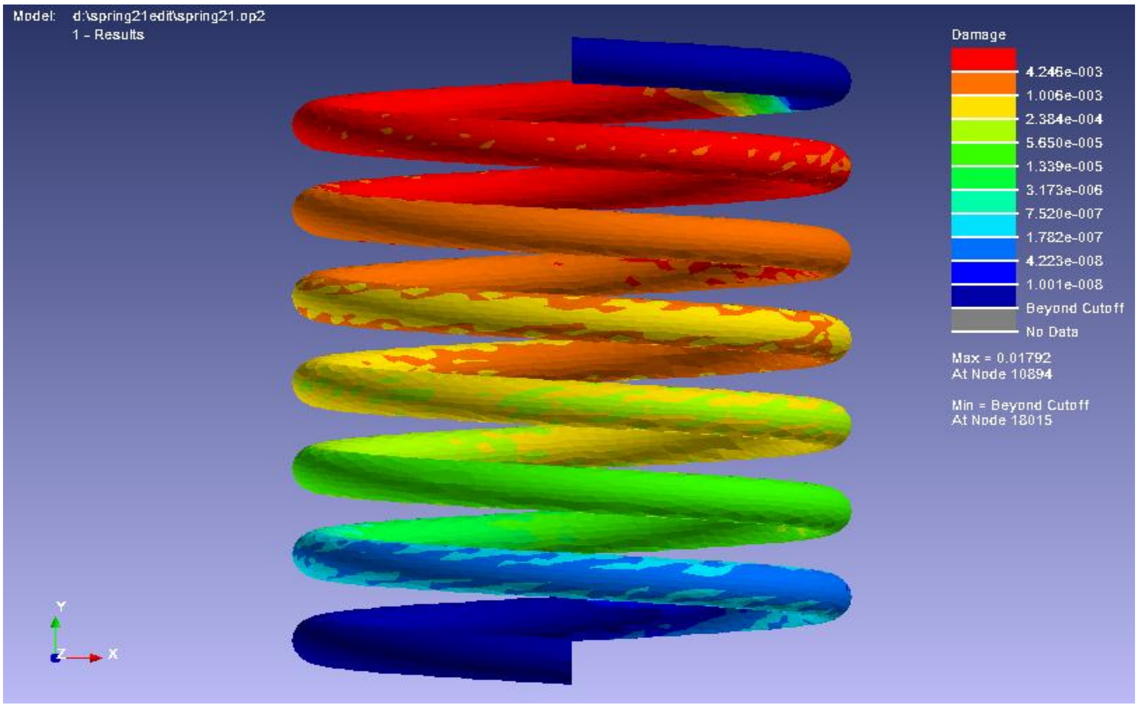

Figure 4.11: Colour contour of the fatigue test using Morrow method for university road

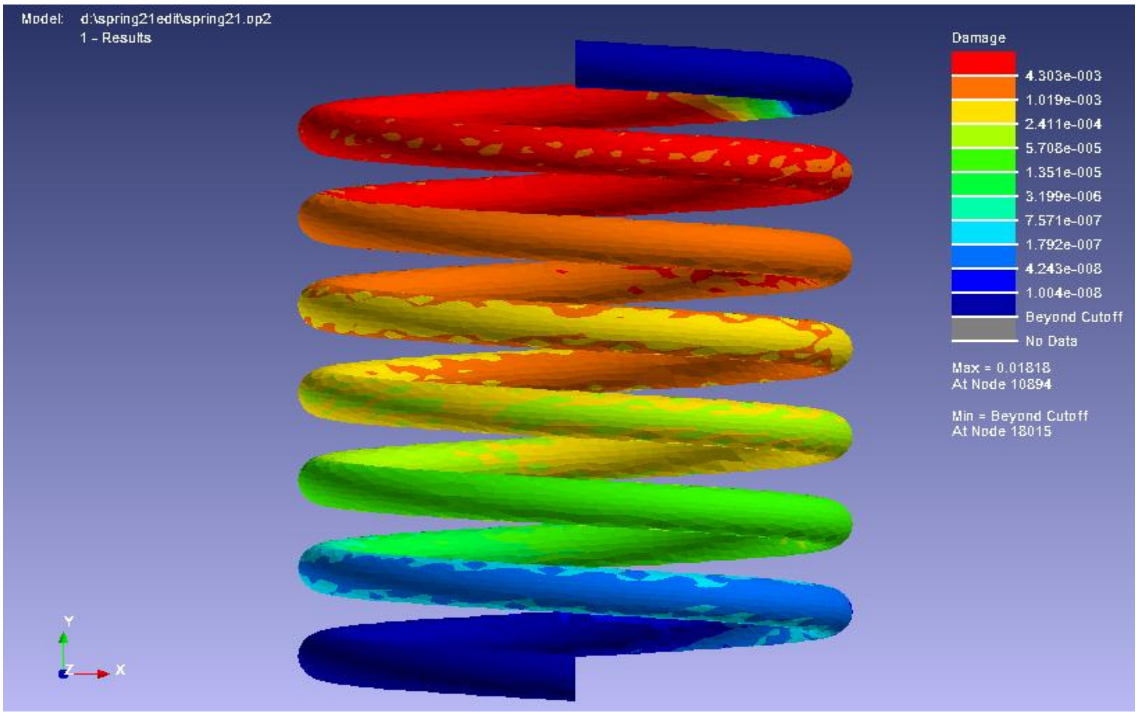

Figure 4.12: Colour contour of the fatigue test using Smith-Watson-Topper method for university road

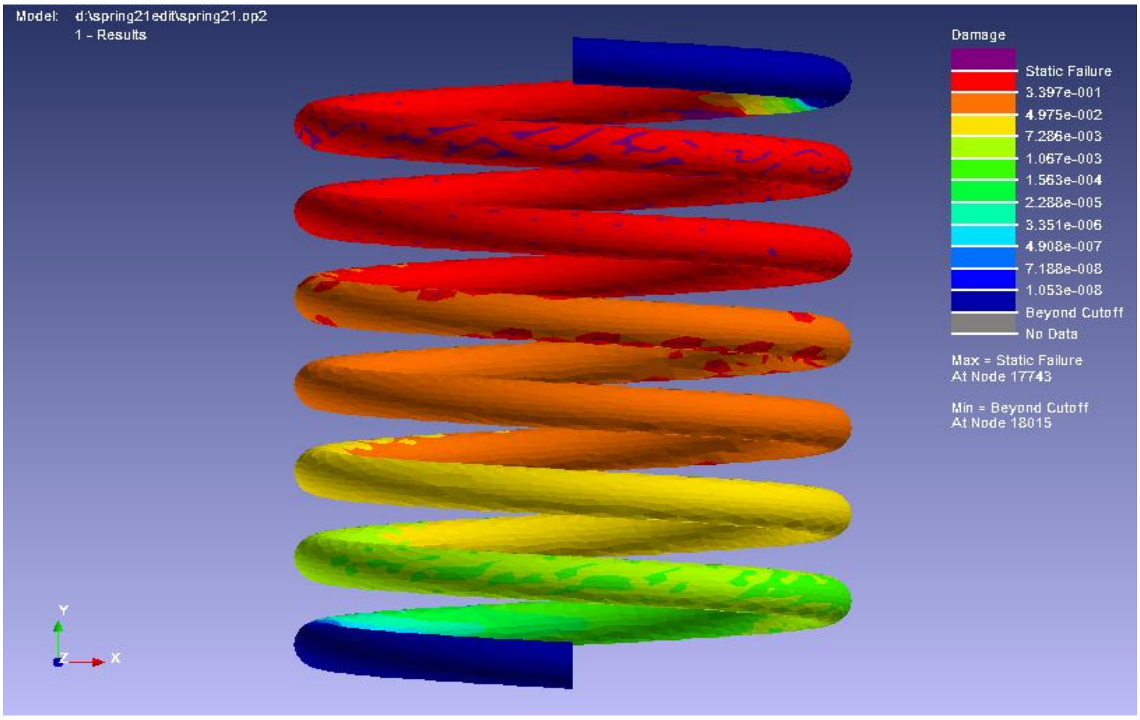

Figure 4.13: Colour contour of the fatigue test using Coffin-Manson method for unpaved road

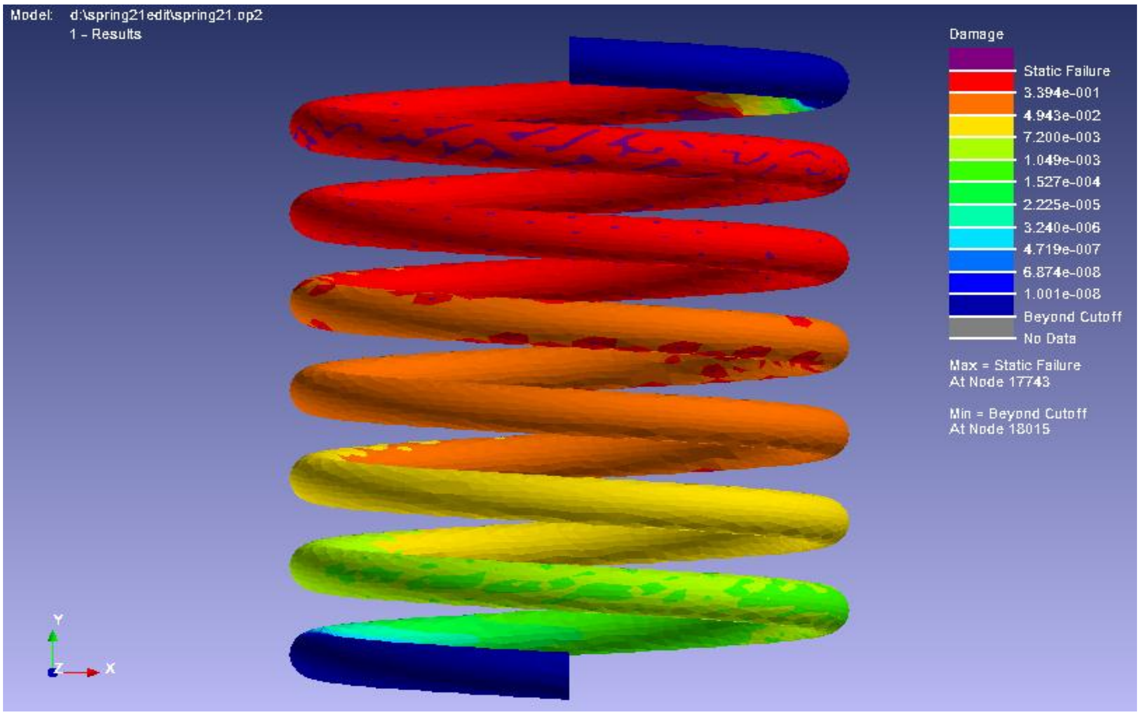

Figure 4.14: Colour contour of the fatigue test using Morrow method for unpaved road

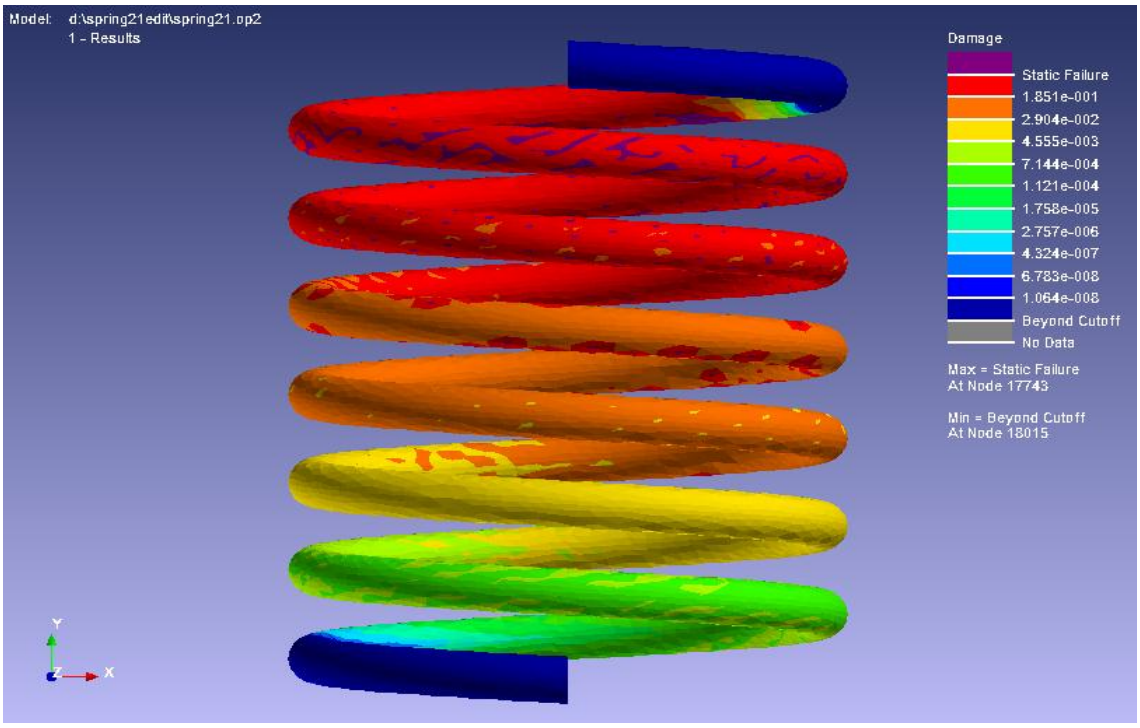

Figure 4.15: Colour contour of the fatigue test using Smith-Watson-Topper method unpaved road

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This study is presented on a study of strain signals behavior. The signals used in this research was obtained from three road profiles, highway, university road and unpaved road. Helical spring of Proton Persona Sedan 1.6 Manual Transmission (MT) Base Line is modeled for static loading and cyclic loading. The signals are analyzed with statistical parameter, FFT and fatigue life. The strain signals analyzed for the statistical parameter were performed using MATLAB software. The strain signals analyzed for the FFT were obtained by DASYLab software. The fatigue life was performed using nCode DesignLife software.

In the presented case study data, the signals obtained from highway, university road and unpaved road exhibit nondeterministic and non-stationary characteristics. Statistical analysis is carried up to classify the signals. Unpaved road has the highest amplitude mean, root mean square and standard deviation. This is because the helical spring undergoes the highest stress, vibrational energy and the strain signals are spread over a wide range of value. Whereas highway has the lower amplitude mean, root mean square and standard deviation value than the university road. The Skewness obtained from the highway and unpaved road are negative value while university road has the positive value with conjunction to the mean value. These indicated that three signals obtained were non-Gaussian distribution. The Kurtosis value from unpaved road is lower than the university road due to less extreme value in the signals. Highway has the lowest Kurtosis value because the load feature of highway is consistent and no occasional shock occurred during the whole experiment. In short, signals of highway are further characterized as mildly non-stationary signal with stable mean, variance, root mean square value but with short period of transient events. Signals of university road and unpaved road are characterized as heavily non-stationary due to present of more transient events.

Based on the frequency analysis, power spectral density (PSD) is performed to analyze the distribution of signal energy across the frequency domain. It showed the mean square amplitude of each sinusoidal wave with respect to the frequency. From the case study, the three signals obtained are related to non-Gaussian distribution. Hence, they have the broad band signals. Broad band signal has a wide range of frequencies and distinct spikes. In the high frequency distribution, there are low amplitude events of the fatigue cycle. In contrast, the signals contain the fatigue damage characteristic at the low frequency distribution.

For the fatigue assessment, it is used to study the critical location and damage value of the helical spring. The strain-life models of Coffin-Manson, Morrow and Smith-Watson-Topper (SWT) are used. SWT model is suited to use as fatigue prediction for tensile cycles whereas the Coffin-Manson model is suited to use for compressive cycles. It is indicated by the means loading obtained from highway and university road were negative, Coffin-Manson model is more conservative and estimates the highest durability of helical spring. For the case study of unpaved road which was positive mean loading, SWT model is more conservative. From the FEA analysis, it also found that inner of the helical spring undergoes the higher strain which will lead to the fatigue growth. This is because at higher strain, it will result the higher stress and lead to failure of helical spring.

5.2 Recommendation

The experimental reported in this thesis has resulted in a better understanding of strain signals behaviour for helical spring in automobile. However, there are still several researches which could be pursued in the future. These researches may include the laboratory test and theoretical development.

In the experiment presented in this thesis, strain signals data is obtained from the real road testing. The strain gauge is glued on the coated surface of helical spring. It decrease the sensitivity of the strain signal executed from the helical spring. Hence, laboratory test is indeed to get the strain signal of helical spring without coated surface. It will increase the accuracy of the strain signal obtained.

Furthermore, the modeling of helical spring by CATIA software is assumed to have constant pitch for each coil due to the limitation. In the real situation, there is variable pitch between each coil. The upper and lower fixed node of the helical spring is hardly determined. Thus, further efforts should be put to develop a testing program which takes into the consideration of variable pitch and exact fixed node location.

Experimental testing can be carried up to develop a new theoretical model parameter to classify the strain signals based on the statistical parameter value more accurately.

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APPENDIX A

Figure 6.1: Strain gauge is glued on helical spring

APPENDIX B

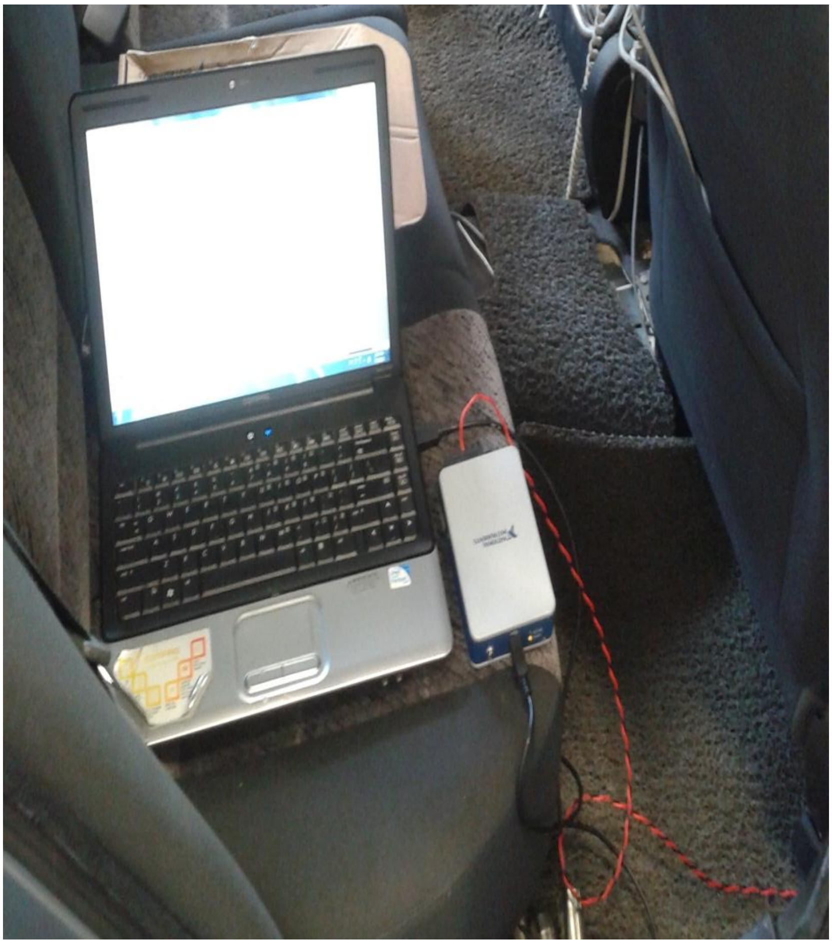

Figure 6.2: National Instrument (NI) is connected from strain gauge to laptop

APPENDIX C

Figure 6.3: Setup of strain signal experiment at test car

APPENDIX D

(a)

(b)

APPENDIX D

(c)

Figure 6.4: Road profile (a) highway, (b) university road, (c) unpaved road

APPENDIX E

GANTT CHART FOR FINAL YEAR PROJECT 1

Project Progress	Week													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Discussion about the title and time with the supervisor														
Find the relevant material that involve strain signal and strain-life approach														
Do the introduction, background of project problem statement, objective, scope														
Research study about strain signal														
Research study about the strain-life approach and other method														
Discussion about project methodology With supervisor														
Study of the helical spring and parameter Involved														
Finite element analysis														
Setup of the experiment and state the overview of the procedure														
Submit draft thesis and log book for Final Year Project 1														
Final Year Project 1 Presentation														

Plan Progress

Actual Progress

APPENDIX F

GANTT CHART FOR FINAL YEAR PROJECT 2

Project Progress	Week													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Discussion about the methodology with Supervisor to proceed with PSM 2														
Collecting strain signal of shock absorber test rig														
Finding statistical parameter and FFT														
Fatigue analysis by using DesignLife														
Analysis the result														
Conclusion of the project study														
Submit thesis and log book for Final Year Project 2														
Final Year Project 2 Presentation														

Plan Progress

Actual Progress