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BORANG PENGESAHAN STATUS TESIS♦

JUDUL: **MODELING, SIMULATION AND EXPERIMENTAL VERIFICATION OF VARIABLE PARAMETER OF SUSPENSION SPRING**

SESI PENGAJIAN: 2012/2013

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WAN AHMAD SYAFIQ BIN WAN GHAFAR

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MODELING, SIMULATION AND EXPERIMENTAL VERIFICATION OF VARIABLE PARAMETER OF SUSPENSION SPRING

WAN AHMAD SYAFIQ BIN WAN GHAFAR

Report submitted in partial fulfillment of the requirements
for the award of Bachelor of Mechatronics Engineering

Faculty of Manufacturing Engineering
UNIVERSITI MALAYSIA PAHANG

JUNE 2013

SUPERVISOR'S DECLARATION

We hereby declare that we have checked this project report and in our opinion this project is satisfactory in terms of scope and quality for the award of the degree of Bachelor of Mechatronic Engineering with Manufacturing.

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STUDENT'S DECLARATION

I hereby declare that the work in this report entitled "Modelling, Simulation and Experimental Varification of Variable Parameter of Susupension Spring" is the results of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted for award of other degree.

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Dedicated to my beloved father, Wan Ghafar bin Wan Mahmud,
mother, Fatimah binti Omar, brothers and sisters,
and my supervisor, Assoc. Prof. Dr. Wan Azhar bin Wan Yusoff.

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ABSTRACT

Helical spring plays an important role in many applications such as machines, and vehicles. When a helical spring is under a static load, it is important to know their static displacement characteristic. The common static model for helical spring is the Wahl's factor equation, which assumes all design parameters such as spring radius, wire diameter, helix radius and pitch angle are constant. In this research, several mathematical models are used to the static displacement characteristic of automotive suspension helical spring with design parameters. These design parameters include pitch angle, wire diameter and helix radius. Finite element analysis and experimental simulation by Autodesk Simulation Multiphysics (Algor) were performed to verify and support the accuracy of the formulated model with the actual test of the helical spring results.

ABSTRAK

Spring heliks memainkan peranan penting dalam banyak aplikasi seperti mesin, dan kenderaan. Apabila spring heliks dikenakan beban yang statik, perkara penting yang perlu dikenalpasti adalah untuk mengetahui ciri-ciri statik spring tersebut. Persamaan yang biasa digunakan untuk model statik ini adalah persamaan faktor Wahl's, yang menganggap semua parameter seperti diameter luar, diameter gegelung, jarak/sudut antara gegelung adalah sama. Dalam kajian ini, beberapa persamaan matematik digunakan untuk spring statik yang mempunyai parameter yang pelbagai. Parameter reka bentuk termasuk diameter luar, diameter gegelung, jarak/sudut antara gegelung. "Finite Element Analysis" dan simulasi eksperimen oleh Autodesk Simulasion Multiphysics (Algor) telah dijalankan untuk mengesahkan dan menyokong ketepatan model yang dirumuskan dengan ujian sebenar keputusan spring heliks.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

d	Wire diameter
Di	Internal diameter
De	External diameter
Ls	Solid length
Lf	Free length
α	Pitch angle
Ds	Spring diameter
c	Spring index
R	Coil radius
P	Applied load
φ	Torsion
G	Modulus of rigidity
δ	Deflection
k	Spring rate
τ	Shear stress
τ_{max}	Maximum shear stress
τ_{min}	Minimum shear stress
K_w	Wahl's factor

LIST OF ABBREVIATIONS

FEA	Finite Element Analysis
FEM	Finite Element Method
CATIA	Computer Aided Three-dimensional Iterative Application
MES	Mechanical Event Simulation

CHAPTER 1

INTRODUCTION

1.1 Project Background

Suspension system is one of the most important and basic systems in a vehicle. The major purpose of any vehicle suspension system is to maximize the friction between the road surface and the tires to provide the stability steering and good handling of the vehicle. To achieve the stability and rides comfort, there were three important principles must be resolved which is road isolation, road handling and cornering. Numerous studies have been conducted in other to achieve stability and rides comfort.

Vehicle suspension system consists of 3 elements which are wishbones, spring and the shock absorber [1]. These 3 elements are to filter and transmit forces exerted between the vehicle body and the road. The spring is important as it carries the body mass and isolates the vehicle form uneven road surface. This contributes to drive comfort. Furthermore, damper system also contributes to safety as it absorbs the damping of the body and wheel oscillations.

1.2 Problem Statement

Most of the spring fail is due to the fatigue, in other word, they have sustained much compression-extension cycle, which causes the metal to become brittle and then breaks. If the amplitude of these cycles is large, the fatiguing process is accelerated [2]. Springs tend to be highly stressed because they are designed to fit into small spaces with the least possible weight and lowest material cost. At the same time they are required to deliver the required force over a long period of time. The reliability of a spring is therefore related to its material strength, design characteristics, and the operating environment [3]. The same goes for the car suspension spring whereby after some period of time, the car spring will have irregular and unstable stiffness. To overcome this problem, this research investigates the different parameters of an automotive suspension spring that affect the static characteristic (displacement)

1.3 Project Objectives

- To investigate a static mathematical model for helical spring with variable design parameters.
- To create a finite element analysis (FEA) model of the spring and simulate the model using variable design parameters.
- Fabricate and setup an experimental apparatus to collect the spring static displacement-force data, and to verify the actual experimental test with simulation results.

1.4 Project Scope

This project is focused on study the different parameter of the spring that will effect on the static characteristic of the linear spring. The purpose of the project is to compare the result from simulation software (Autodesk) with the actual result from the spring tester machine. The FEM analysis is perform in Autodesk software to define the characteristic of the spring.

1.5 Organization of Report

This thesis consists of five chapters. Chapter 2 presents the literature review while Chapter 3 discusses the methodology for the investigation. Chapter 4 presents the results from the experiment and the discussions regarding the results. Finally, Chapter 5 summarizes the study and provides recommendations for the study.

CHAPTER 2

LITERATURE REVIEW

2.1 Background of Spring

According to Wahl, [4]: “A mechanical spring may be defined as an elastic body whose primary function is to deflect or distort under load (or to absorb energy) and which recovers its original shape when released after being distorted”. Then he goes on detail to the functions of the spring where normally people do not thing of this general definition of the spring which is: to support a body or structure, to apply force, to absorb shock, or to provide load control. With these definitions of the spring, the aircraft wings, the body chassis of the car and even the shoes that we wear also will be considered as a spring. The same concept happen to this entire item which is all will depress under load and revert back to its original shape after load is released. A shoe sole will absorb the impress of the foot fall and the bending of arc of the foot and return to its normal state when the foot is removed. The aircraft wings must take the loading and unloading on take-off and landing of the plane in other to encounters the air turbulence.

2.2 Spring Geometry

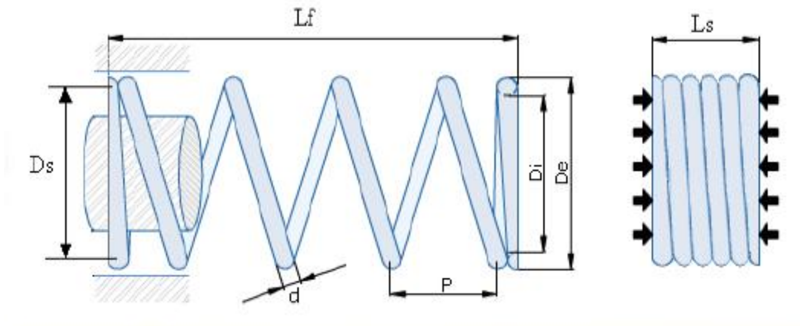


Figure 2.1: Spring geometry [5].

- $\boldsymbol{d}$ (wire diameter): This parameter describes the diameter of wire used as material for spring.
- $\boldsymbol{Di}$ (internal diameter): Internal diameter of a spring can be calculated by subtracting the doubled wire diameter from the external diameter of a spring.
- $\boldsymbol{De}$ (external diameter): External diameter of a spring can be calculated by adding the doubled wire diameter to the internal diameter of a spring.
- $\boldsymbol{Ls}$ (Solid length): Maximal length of a spring after total blocking. This parameter is shown in the picture on right.
- $\boldsymbol{Lf}$ (free length): Free length of compression springs is measured in its uncompressed state.
- $\boldsymbol{P}$ (pitch): Average distance between two subsequent active coils of a spring.
- $\boldsymbol{Ds}$ (Spring diameter): Spring diameter is mean diameter of spring. That is calculated by subtracting wire diameter d from external diameter $\boldsymbol{De}$ [5].

2.3 Shear Stress of Spring

The following notations are typically used: P: Applied load, α: Pitch angle, τ: Shear stress, R: Coil radius, and d: Wire diameter. The torsion is then calculated as $PR\, cos\, \alpha$, the bending moment as $PR\, sin\, \alpha$. The shear force as $P\, cos\, \alpha$, and the compression force as $P\, sin\, \alpha$. Traditionally, when the pitch angle is less than $10°$, both the bending stresses and the compression stresses are neglected.

Assuming that the shear stress distribution is linear across the wire cross section, and $PR\, cos\, \alpha = PR$ the following should be valid [6]:

$$\tau = \frac{16PR}{\pi \cdot d^3} \tag{1}$$

The shear stress here is usually called uncorrected shear stress. The total length l is $2\pi Rn$, where n is the number of active coils. Using the fact that $\gamma = {}^{\gamma}/_{G}$, it can be rewritten as $16PR/(\pi \cdot d^3 G)$, and the total angular Torsion φ becomes [6]:

$$\varphi = \int_0^{2\pi Rn} \frac{2\gamma}{d} dx = \frac{32PR}{\pi d^4 G} dx = \frac{64PR^2 n}{Gd^4}, \tag{2}$$

where G is the modulus of rigidity. The total deflection caused by the angular torsion is [6]:

$$\delta = R\varphi = \frac{64PR^3 n}{Gd^4} = \frac{8PD^3}{Gd^4} \tag{3}$$

The spring rate therefore becomes [6]:

$$k = \frac{P}{\delta} = \frac{Gd^4}{8nD^3} \tag{4}$$

Eq. (4) [6] is still commonly used to estimate the spring rate by suspension designers. As opposed to the uncorrected shear stress in Eq. (1), Wahl [4] proposed corrected shear stress. The uncorrected shear stress neglects a great many factors which modify the stress distribution in actual helical springs. The corrected shear stress, τ_a, is obtained by multiplying the uncorrected stress with a correction factor K, which depends upon the spring index D/d. Fig. 2.2 shows the typical corrected shear stress distribution.

Furthermore, by taking x as the distance from the cross point where the shears stress is zero, Wahl proved that the following equation holds:

$$\tau_a = \frac{32xPR^2}{\pi \cdot d^4(R - d^2/\,16R - x)} \quad (5)$$

With the introduction of the spring index $c = D/d$, the maximum shear stress at the inner side of the coil, where $x = d/2 - d^2/16R$, becomes:

$$\tau_{a1} = \frac{16PR}{\pi \cdot d^3}\frac{4c - 1}{4c - 4} \quad (6)$$

Additional shear stress caused by the neutral surface of a cantilever of circular cross section loaded by force P, the term $4.92P/pd^2$ should be added to obtain maximum shear stress:

$$\tau_{max} = \frac{16PR}{\pi \cdot d^3}\left[\frac{4c - 1}{4c - 4} + \frac{0.615}{c}\right] \quad (7)$$

And minimum shear stress:

$$\tau_{min} = \frac{16PR}{\pi \cdot d^3}\left[\frac{4c + 1}{4c + 4} - \frac{0.615}{c}\right] \quad (8)$$

Equations (7) and (8) are usually used by the design engineer for coil springs when neglecting the curvature. Also, since the equations were derived by over simplification, the larger the Pitch angle, the more error that will result. In reality, coil spring makers today use equations that are generally confidential, and therefore will not be discussed here. The equations require the design engineer to input the coil diameter, design height, design load, spring rate, etc. The equation will calculate the optimum possible shape and dimension of the coil. After this step, for more accurate stress distribution, it is usually too cumbersome not to use FEM to design.

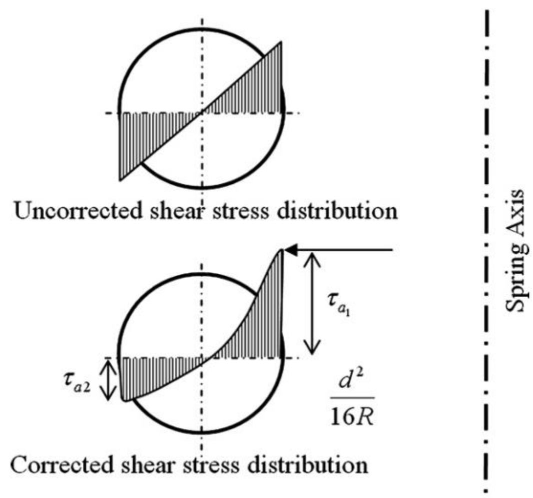


Figure 2.2: Uncorrected shear stress vs. corrected shear stress distribution [6].

2.4 Design Parameter of Coil Spring

The development of metal spring has continued during the past years and the focused is on reducing the operating weight of spring. The specific stresses on spring are continuously increasing which leads to smaller mounting space. Thus, the most care is to be taken for careful manufacturing of spring, focused on the surface layer, hot pre-setting and shot peening. The surface quality plays important part for operational durability of springs than material properties.

Following are the different design parameters which affect the design of mechanical coil spring.

2.4.1 Operating Mode

Spring is design to adapt many situations such as compression, extension, torsion, power and constant force. Depending on its function, a spring may be in static, cyclic or dynamic operating mode. The static condition for any spring is considered if change are happen in deflection or load occur only a few time, for example 10,000 cycle during expected life of cycle during the life of spring [3]. This condition is remaining loaded for a very long of time for a static spring. Spring relaxation, set and creep are the failure mode interest for this static spring.

Cyclic are spring expected to have higher failure rate due to fatigue compare to the constant spring as it is flexed repeatedly. Cyclic spring also can be operated in unidirectional mode or a reversed stress mode. In some cases, the stress is always applied in the same direction, while for the others, stress is applied first in one direction then in the opposite direction [3]. For the same maximum stress and deflection between a unidirectional and reversed stress spring, the shorter fatigue life would be expected since the stress range for the reversed stress spring is twice that of unidirectional spring.

Dynamic loading is referring to intermittent occurrences of a load surge such as a shock absorber inducing higher than normal stresses on the spring. Dynamic loading divided into three main categories: shock, resonance of the spring itself, and resonance of the spring /mass system. Skewis [3] asserted that shock loading is occur when the load is applied with sufficient speed as the first coil of the spring take up more of the load than would be calculated in static and cyclic spring situation. This loading condition occurs due to the inertia of the spring coil. When the operating speed is the same as the natural frequency of the spring or a harmonic of the natural frequency, the spring resonance is appears. Resonance can effect on greatly elevated stresses and possible coil clash resulting in premature failure.

2.4.2 Imperfection on Inside Diameter of Spring

Helical compression springs respond to external compressive force with torsional stress caused by torsion of the active spring coil which, in a first approximation, may be estimated analogous to a straight torsion bar. Since the shear angle is greater on the inner surface than on outer surface, the peripheral torsional stress on the inner coil surface is higher than on the outer surface. This circumstance is described by using a correction factor of k which is dependent on the curvature of the wire. The curvature can be characterized by the quotient from the mean spring diameter and the wire diameter, the so-called coil ratio [6]. This means:

- The maximum stress of coil spring occurs on the inner coil surface.
- Accordingly, fatigue fractures of coil springs generally originate from this area.
- Therefore, the spring coil's inner surface has to be shot peened with particular care, which depending on the spring geometry, constitutes a highly fastidious task [6].

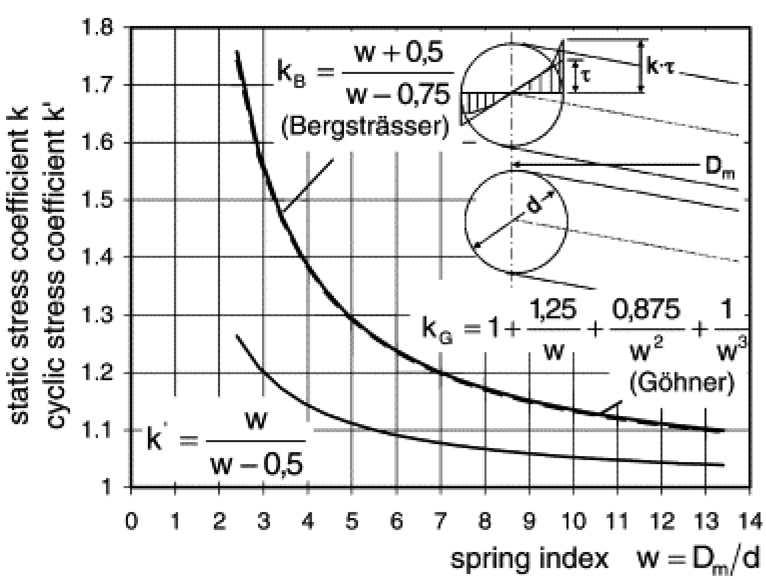


Figure 2.3: Coil ratio vs. stress concentration [5].

Fig. 2.3 shows the correction factor of k to describe the static stress concentration on the inner coil surface of coil spring in dependence on the coil ratio w, factor k_0 represent the effect of the stress concentration in the case of cyclic load.

2.4.3 Stress Peening

Shot peening is a standard technological procedure. Peening is the interaction between a particle (with the necessary hardness) and the surface of a working piece. If the particles are in round shape, it is called shot peening. In the surface layer (up to a depth 0.5mm), compressive residual stresses are induced. At a lower hardness of the working piece, an additional hardening is achieved. In order to obtain better results through the peening process, the so-called stress peening is used.

2.4.4 Operating Temperature

Compression springs are subjected to high temperature requires special attention to spring material selection and spring design. In elevated temperature service, advanced super alloys are required to give stable spring load characteristic. Increase in temperature will affect the elastic modulus and the elastic limit of most spring materials. The decreasing elastic modulus of spring alloys as temperature is increased is shown in Fig. 2.4. This change is completely reversible.

In addition, the rate of the spring will be changed in proportion to the modulus. The change in yield strength for several spring materials is shown in Fig. 2.5. The decrease in strength is not reversible. To avoid this, the designer needs to use a design with lower stresses when the spring is to work in an elevated temperature environment.

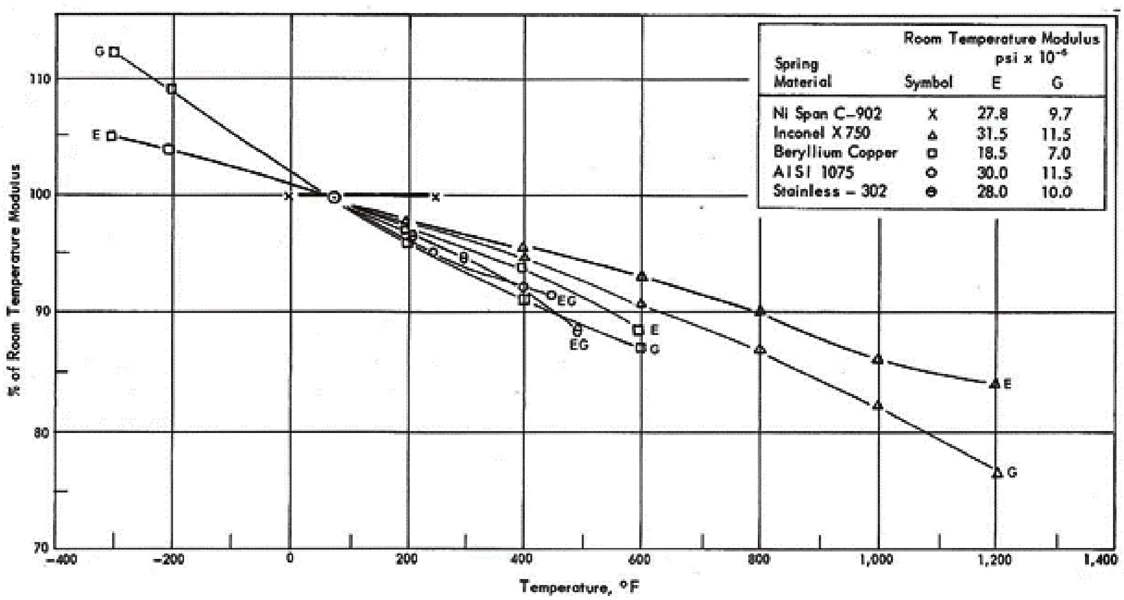


Figure 2.4: Change in modulus with temperature [5].

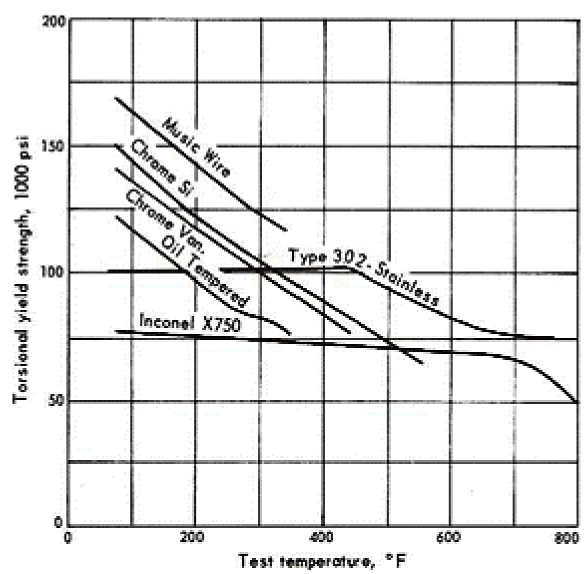


Figure 2.5: Torsional yield strength of spring wire at elevated temperature [5].

Maximum usable temperatures for spring material are simply the temperature at which metallurgical change begins. When a sustained stress is applied at an elevated temperature, the time dependent changes in spring occur. If the stress is sufficiently high, these changes will occur at room temperature. Increasing the temperature will proportionally increase the rate of change. Commonly, the change occurs as a reduction in coil spring length under load or a reduction in spring load at fixed length. This relaxation occurs gradually at first and then at a decreasing rate over time [5]. There is no apparent end point.

2.5 Failure Modes of Mechanical Spring

All type of spring are expected to undergo and operate for over long time without substantially any change in dimension, displacement or spring rate, often under changing loads. Concerning these requirements, potential failure modes include corrosion fatigue, fretting fatigue, relaxation, thermal buckling, yielding, fatigue, creep, and force-induced elastic deformation. The operating life of the mechanical spring arrangement is depending on the tendency of materials to corrosion and stress levels (static, cyclic or dynamic). Moreover, the most common failure mode for this mechanical spring is upon fatigue and excessive loss of load due to stress relaxation. By definition, the object that are loaded under purely oscillatory loads ($\sigma_{mean} = 0$) fail when their stress reach the material's fatigue limit, $\sigma_{fatigue}$. Otherwise, the load that purely static load ($\sigma_{alt} = 0$) fail when their stresses reach the material yield limit, σ_{yield}. The Soderberg Criterion provides s way to calculate a failure unit for spring that have a mixture of σ_{mean} and σ_{alt} stresses. Mean stress is plotted on one axis and alternating stress on the other. Figure 2.6 shows a typical Soderberg plot [3].

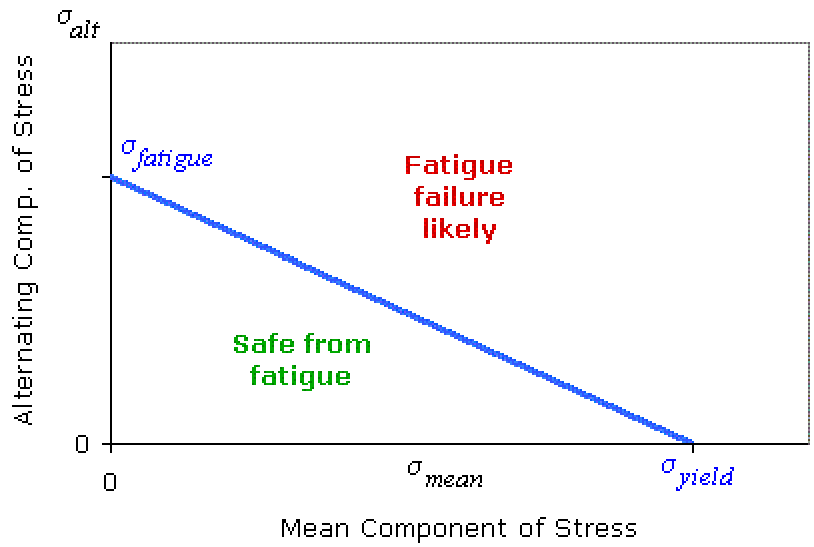


Figure 2.6: Soderberg plot [3].

2.5.1 Fatigue Stress

Spring of all type has finite fatigue limits depending on their fatigue life and the degree of fluctuating loads. Das et.al [6] state that, commonly spring fail due to its high cycle fatigue where the applied stress remains below the yield strength level and the loading cycle is more that 10^5 cycle per second. The four most common fatigue stresses include constant load, constant deflection, unidirectional stress and reversed stress. An example of a constant deflection is a spring inside a valve assembly where the spring is cycled through a specific deflection range. The used of vibration spring under a dead weight is an example of constant load spring where the load applied to the spring does not change the operation but the deflection will. The actuator that used in the return spring are the example of unidirectional spring where the spring always applied in one direction. But for the reversed stress, the stress is applied first in one direction then in the opposite direction such as used in regulator valve. The three stages to a fatigue failure include crack initiation, crack propagation and fracture of the spring material as mention by Skewis [3].

2.5.2 Spring Relaxation

Most of the spring is subjected to some amount of spring relaxation during their life span even under benign condition. The amount of spring relaxation is a function of the spring material and the amount of time the spring is exposed to the higher stresses or temperatures. Compression and extension is subjected to elevated temperature at high stresses in much application which can cause relaxation or loss of load. This condition is called as “set”. The set can be predicted and allowances can be made in spring design after the operating conditions. When no set is allowed in the application, the spring manufacture may be able to pre-set the spring at temperatures and stresses higher than those to be encountered in the operating environment.

A highly stressed spring will set the first several times it is pressed. According to Skewis [3], relaxation is a function of a fairly high stress (but usually lower than that required to cause set) over a period of time. Creep in the spring may conduct to unacceptable dimensional changes even under static loading (set). Spring is actually relax more in a given time when it held at a certain stress compared to a spring cycled between that stress and a lower stress because it spend more time in higher stress. The amount of spring relaxation for certain time is determine first by estimating the operating temperature, the maximum amount of stress spring observed and how long the spring will exposed to the maximum stress and elevated temperature over its lifetime.

2.6 Finite Element Method (FEM)

Finite element method (FEM) consists of a computer model of a material or design that stressed and analysed for a specific result. It is used for many applications such as for a new product design or refinement of existing product. Modifying the existing product is implementing to qualify the product or structure for a new service condition. Finite element analysis may be used to determine the design modification to meet the new condition.

Stress analysis of finite element method conduct by first divide the elastic body into discrete connected part, which are the finite elements. The points where the element is connected are called nodes. The process dividing the domain into elements is called discretisation and the pattern of elements is the mesh [8]. This mesh is programmed to contain the material and structural properties which are define how the structures will react to a certain loading conditions. Nodes are assigned at a certain density throughout the material depending on the anticipated stress level of particular area. Regions which will receive large amount of stress usually have a higher node density than those which experience little or no stress [9]. Point of interest may consist of: fracture point of previously tested material, fillet, corner, complex detail, and high stress areas. The mesh act like spider web in that from each node, there extends a mesh element to each of the adjacent nodes. This web of vectors is what carries the material properties to the object, creating many elements.

2.7 Automotive Coil Spring Materials

In 1879, the first car was made in Australia. Even though the history of gasoline powered for automobile was traced in that year, the mass production of car did not start until about early 1990s for both in Germany and US. A model-T (Ford) was the first car model that used automotive coil spring in 1910 where the suspension is made up by the combination of coil spring integrates with the leaf spring [6]. At this stage, the material for this coil spring is approximately had 500Mpa design stress level. The achievement for development of the material for the coil spring nowadays has reached the point where it is common to have a coil spring with a design stress around 1200Mpa. The timelines of this achievement are shown in Fig. 2.7.

Figure 2.7 shows the approximate timeline vs. the design stress level (Mpa). Design stress levels have increased significantly over the last couple decades. This increase is expected to continue as weight-reduction trends also continue. However, having a higher stress level increases the sensitivity of defects. A small defect will consequently result in a more significant effect.

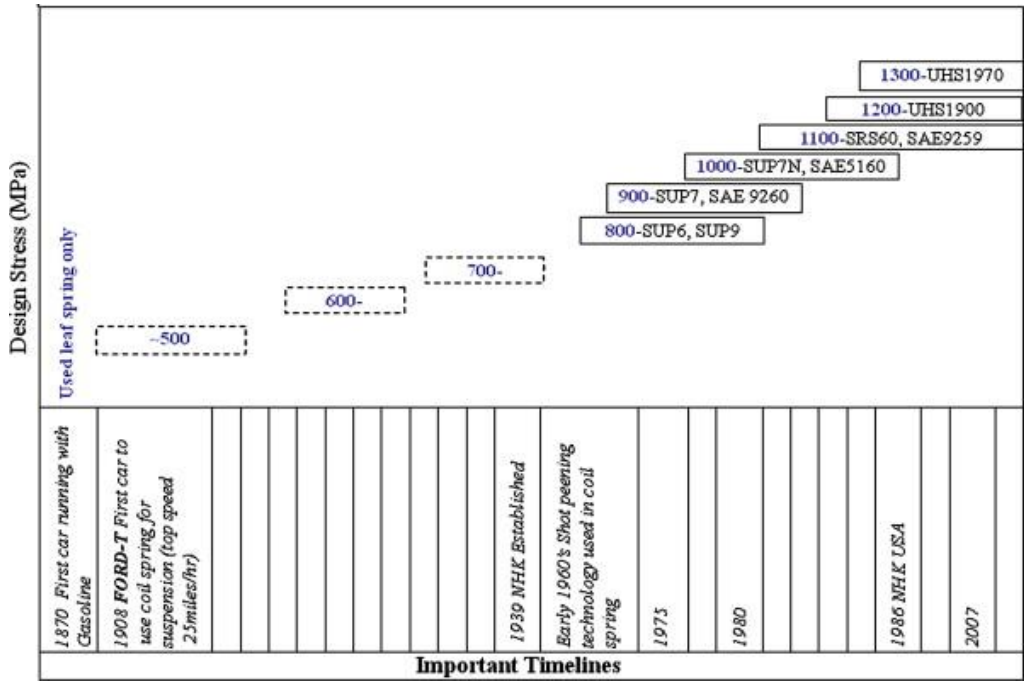


Figure 2.7: Materials used for coil springs [4].

CHAPTER 3

METHODOLOGY

3.1 Introduction

The main objective for this project is to develop dynamic model for suspension spring with variable helix radius. This section will presents about the experiment methodology and the analysis to fulfil the objective of the project.

Methodology is a guideline for a developer to structure, plan and control the process of development a system. This chapter will be constant to discuss the process and method for the project development and developmental issues that are need for implementation and development. For this project, the experiment are cunducted by finding sheer stress of the spring by using Wahl's equation. Finite Element Method or FEM by using Autodesk Simulation 2013 software also implement in this project before manufacturing process is done. The summary of research methodology is shown in figure 3.1.

3.2 Methodology Flow Chart

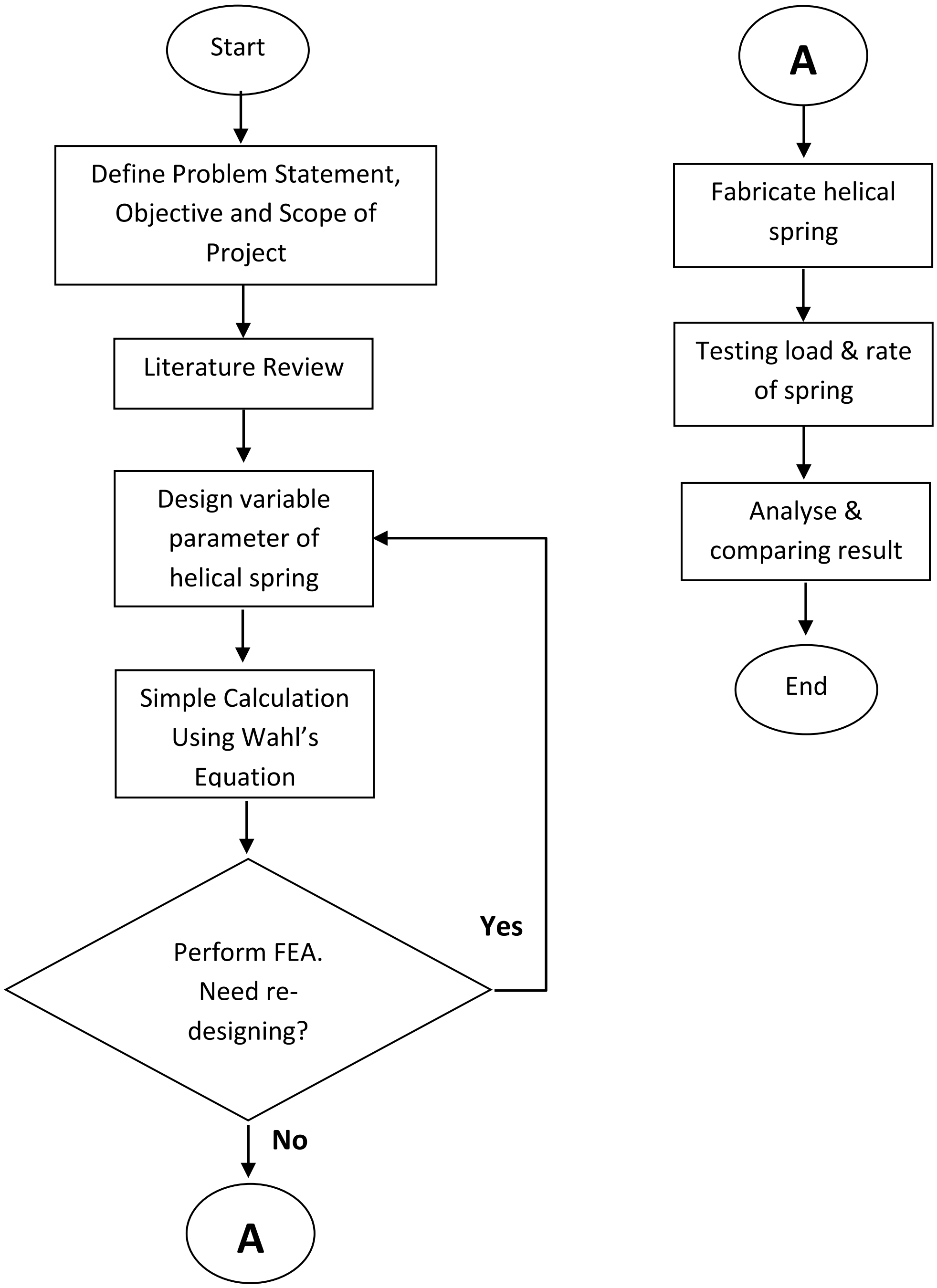


Figure 3.1: Summary of research methodology.

3.3 Build 3D Spring Model using Catia V5R16.

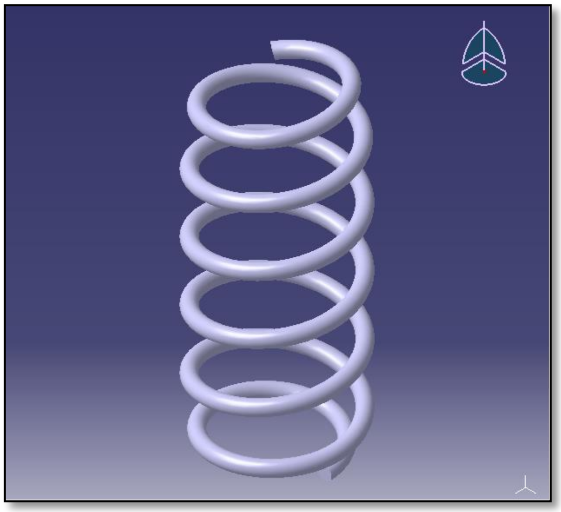
Catia V5 or Computer Aided Three-dimensional Iterative Application have their advantage in designing complex 3D drawing. This software are used to draw a variable parameter of 3D spring model since it is convenient to integrate with the Autodesk Simulation (Algor) software. Helix command in the Wireframe and Surface Design platform in Catia V5 software are used for creating a complex part such as the helical suspension spring, which assume to have rotational cylinder feature and variable cross section. In this research, helix command is used to create the three three-dimensional spring models which will be used for the input to Autodesk Simulation (Algor) for static stress analysis.

The following text describes the sequential procedures for building these model: from Catia V5 side menu, go to start, Mechanical design, and Wireframe and Surface design, then select the point feature, insert the radius of the spring at Y-axis, then click ok. After that, click on the helix icon, and insert the desire parameter of the suspension spring. The steps above have completed one section of the sketch. For this current sample spring modeling, different section for every turn of coil of the spring are assigned. When applying the rib or rotational blend, it should be mentioned that the most confusing step is how to positioned the coordinate system for each section. Each section is defined by a set of different parameter of helix radius. All three model of suspension spring are specified in Table 3.1.

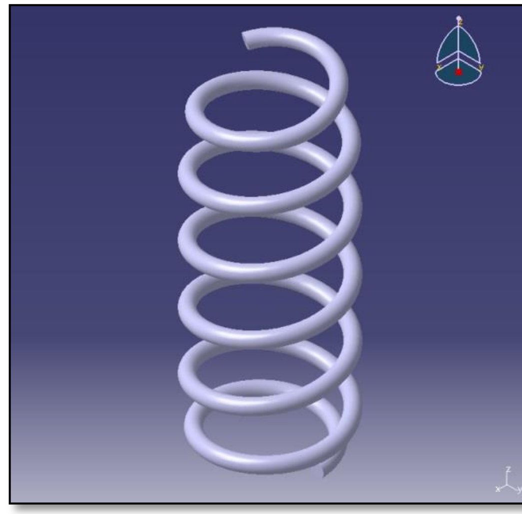
Table 3.1: Geometry parameter for building 3D models.

Turn No.	Wire Diameter (mm)	Heigth-Pitch (mm)	Outer diameter (mm)		
			Model 1	Model 2	Model 3
0	12.0	11.0	96.0	95.5	95.0
1	12.0	40.0	120.0	115.0	100.0
2	12.0	40.0	120.0	115.0	100.0
3	12.0	40.0	120.0	115.0	100.0
4	12.0	40.0	120.0	115.0	100.0
5	12.0	40.0	120.0	115.0	100.0
6	12.0	20.0	105.0	100.0	95.0

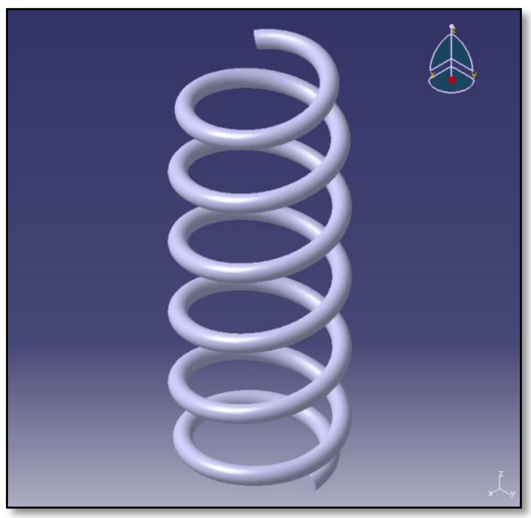
Table 3.1 show the geometry parameter of the suspension spring use in this project. As mentioned before, the variable parameter is only on the outer diameter of the suspension spring, while the wire diameter and pitch and angle are constant since the focus of the study only on the variable of helix radius. Three model of suspension spring are build in the Catia V5 software following the dimension given in table above.



Model 1



Model 2



Model 3

Figure 3.2: 3D spring model in isometric view.

The image in **Figure 3.2** show three finished 3D spring models on an isometric view design in catia V5 software. The model with finite element meshed will be show in next subtopic in this chapter. These model include of all 3 different outer diameter model with constant parameter of wire diameter and heigth-pitch.

3.4 Simple Calculation Using Wahl's Factor Equation.

Then traditional engineering equation used for calculating spring rate is shown in Eq. 4,

$$k = \frac{Gd^4}{8nD^3} \tag{4}$$

where:

d = Wire diameter,

G = Modulus of rigidity,

D = Coil diameter, and

N = Number of turns of coil.

Using the value for this spring, the spring rate is calculated and comparison percentage is made with the actual spring rate. The spring index is defined by $C = D/d$ [6]. Due to the fact that a coil spring is based on a twisted torsion bar, a value known as the Wahl's factor is calculated to determine a multiplier for the shear stress on the inside of the coils. The equation for the Wahl's factor is given in Eq. 9,

$$K_w = \left[\frac{4c-1}{4c-4} + \frac{0.615}{c}\right] \tag{9}$$

Once Wahl's factor is determined, the shear stress inside the coil of spring is calculated from Eq. 10,

$$\tau_{max} = \frac{16PR}{\pi \cdot d^3}\left[\frac{4c-1}{4c-4} + \frac{0.615}{c}\right] \tag{10}$$

Or, after simplification, Eq. 11 also can be used.

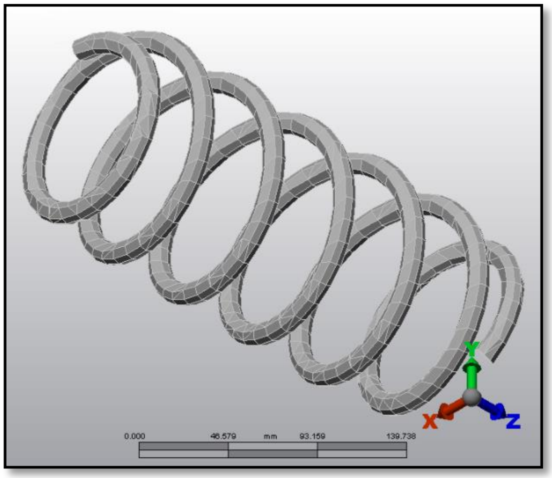
$$\tau = \frac{8FDK_w}{\pi d^3} \tag{11}$$

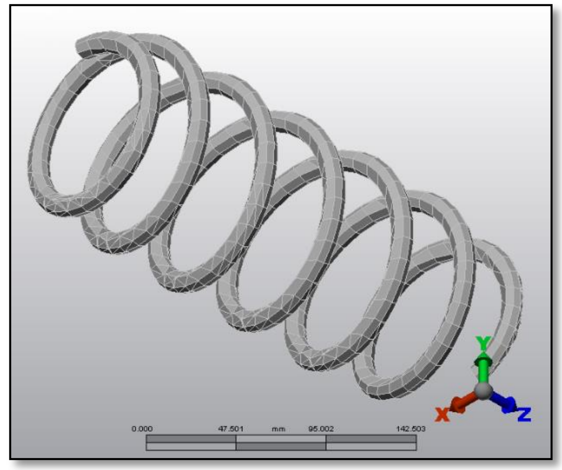
3.5 Finite Element Analysis (FEA) Approach.

Reduced the error caused by the simplification of equation are the reason why FEM are used in coil design. A based design of FEM are begins with the selection of element type which are how the coil spring model are constructed, how accurate the result should be, and how fast the model of coil spring should be run.The accurate result of the FEM are obtained by creating the 3D part of a coil spring and its seats, followed by meshing the part with a 3D solid element. The most accurate result can be produced by finer meshing with the higher order elements in general.

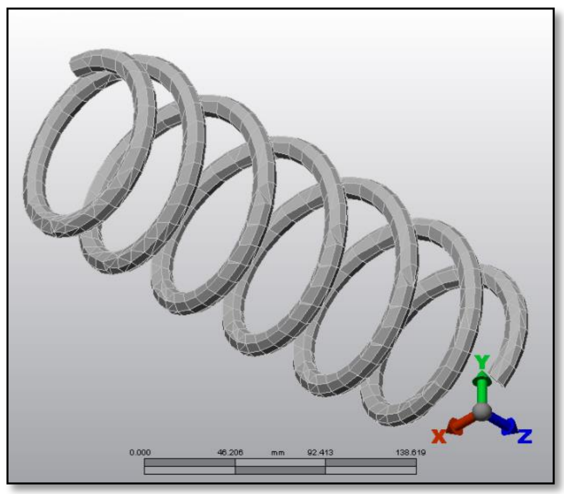
The FEM model may not generate accurate rate analysis results due to model simplifacation and assumption, but will generate the approximate result and significantly reduce the amout of design time. The important issue is to determine whether the coil design using FEM is good enough or not. The determination is made by comparison with past analysis results or with actual experimental result. FEM is also used in evualation of the actual product and re-designing in case of a testing failure.

The finite element modeling of a coil spring is performed after a simple calculation using Wahl's equation and confirmation after both manufacturing and testing, as shown in Figure 3.1 in research methodology flow chart. In this paper, the FEM modeling is also used to simulate how various defect affect local stress distributions. **Figure 3.3** shows three finished model in isometric view with finite element meshed. These model include of three model with constant variable of wire diameter and pitch angle and variable outer diameter or helix radius.





Model 1 | Model 2



Model 3

Figure 3.3: 3D model of spring with finite element meshed.

3.6 Linear Static Stress Analysis.

Autodesk Simulation (Algor) is compatible to most 3D solid models, such as the parts and assemblies created in Catia V5. More over, Autodesk Simulation (Algor) is simple and convenient to run both linear static stress analysis and mechanical event simulation(MES). In this section, the created 3D models are input into Autodesk Simulation (Algor) for linear static stress analysis.The static stresses from the linear stress analysis are to be compared with that from the Wahl’s factor calculation (completed in section 3.4). The MES analysis will be discussed in the next section. The same conslusion is expected that the result from simulation are same as the result from the Wahl’s factor calculation.

3.6.1 Input to the Analysis.

The input to the linear static stress analysis are as follows;

1. Input each of the spring 3D models into Autodesk Simulation (Algor).
2. Create the finite element mesh(mesh fine rate is selected to be 100 percent).
3. Switch to FEA editor.
4. Assigned spring material to be Carbon Steel, SAE 9254, which is the same as that used for actual spring provided by Sapura Industrial Berhad.
5. Specify spring boundry constraint; spring bottom end is fixed in all degrees, spring top is applying force of 1600N normal to the surface.
6. Run the simulation, observed and record the stress data.

3.7 Spring Static Displacement-force Analysis.

In order to observe spring static displacement-force analysis, the same software interface and environment are used and spring static displacement-force can be monitored and plotted during or after the simulation. In this analysis, the assembly is designed as the the impact between the spring model and force that being exert on the spring. Therefore, there are 3 assemblies between each of the three model and the object that called seat.

3.7.1 Specify Static Displacement-force Analysis

The general procedure of displacement-force analysis are as follow;

1. Input each of the spring 3D models into Autodesk Simulation (Algor).
2. Create the finite element mesh(mesh fine rate is selected to be 100 percent).
3. Switch to FEA editor.
4. Assigned spring material to be Carbon Steel, SAE 9254, which is the same as that used for actual spring provided by Sapura Industrial Berhad.
5. Specify spring boundry constraint; spring bottom end is fixed in all degrees, spring top is applying force of 500N normal to the surface.
6. Run the simulation and observed the displacement of the spring.
7. Repeat the simulation with the different value of force by increasing to 1000N until 7000N.

Figure 3.4 show the example of Model 1 after all the input (as mentioned in section 3.7.1) inserted into the FEA editor. The force at the top of the spring are applied normal to the surface of the seat that design specifically to make sure that the force applied are located at the center of the spring.

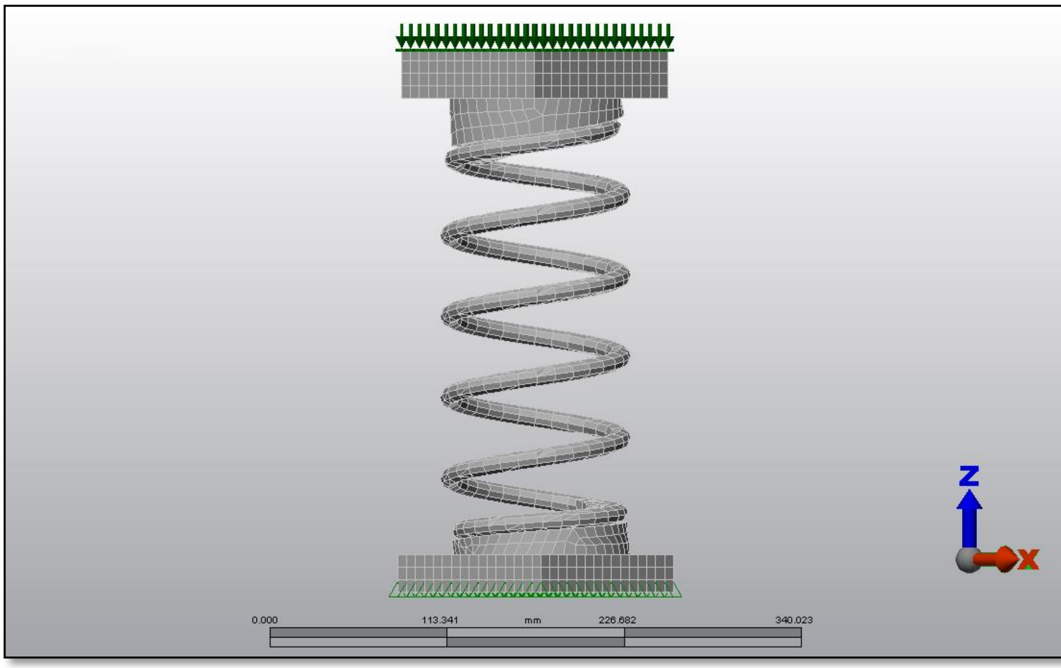


Figure 3.4; Example of Model 1 with force applied at the top and fixed position at the bottom.

3.8 Material Used in Coil Spring

Raw material selecetion are the most important element in acquiring the best quality of any product, including coil spring. Car spring are made using a new material to provide excellent structural performance while reducing weight and the cost of manufacturing. In other to fulfill this requirements, a carbon steel, SAE 9245 have been used in this experiment since this type of the material are used by the Sapura Industrial for thier suspension spring. The table 3.2 show the properties of the carbon steel, SAE 9245 that used in this experiment.

Table 3.2: The properties of carbon steel (SAE9254)

Physical Properties	Thermal Expension:	$10e^{-6}k^{-1}$
	Thermal Conductivity:	25 W/m.K
	Specific Heat:	460 J/kg.K
	Melting Temperature:	1450 -1510 °C
	Density:	7700 kg/m^3
	Resistivity:	0.55 $ohm.mm^2/m$
Mechanical Properties	Young's Modulus:	200000 Mpa
	Tensile Strength:	650 – 880 Mpa
	Elongation:	8 – 25%
	Fatigue:	275 Mpa
	Yield Strength:	350 – 550 Mpa
Hardened and tempered (+QT), tempering temperature 375-500°C		
Annealing	✓	
Quenching	✓	
Tempering	✓	
Normalizing	✓	

Source: Tradekey.com/Hengtian-Steel-Piping (2010)

3.9 Manufacturing Process of Coil Spring

3.9.1 Machine

In this experiment, cold coil machine are used for manufacturing process of coil spring. These spring are produced by cold forming of a strain hardened wires. The spring forming machine is shown in Fig. 3.5. The figure shows a view from the front of a mechanical coiler. The four large roller on the front of the machine work in pairs and force the wire through the wire guide towards the coiling points. There are two grooved coiling points, one verticle and one horizontal from the right hand side of the machine which are positioned round a half round mandrel. The four large wire feeders force the wire through the coiling points which in turn force the wire round the mandrel thus giving you the required spring coil. The number of coil can be adjusted by the amount of wire feed and the pitch spacing and the free length of the spring is governed by the spacing tool just visible on the right hand picture at the twenty past position. When the spring is finished being coiled it is cut off by the cutting tool.

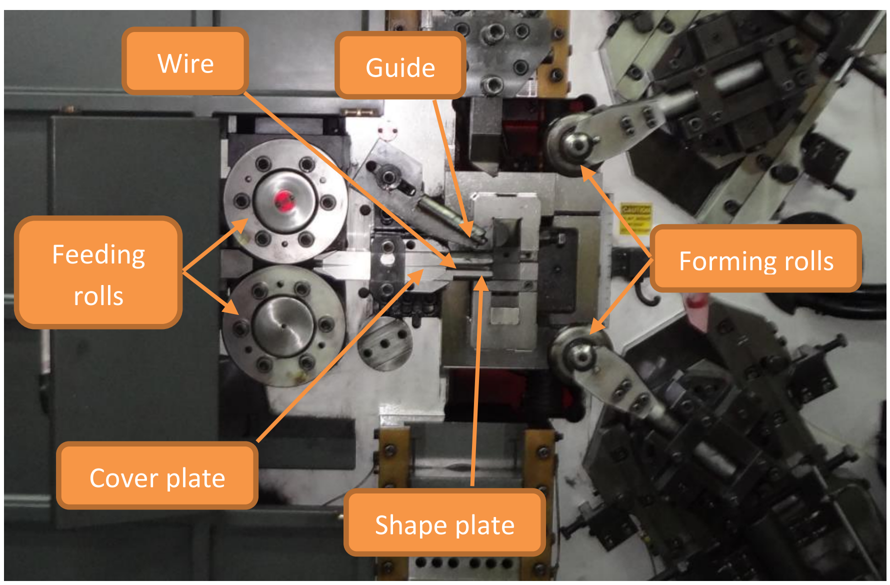


Figure 3.5: The cold coiling machine.

3.9.2 Fabrication of Coil Spring

Spring is made of carbon steel (SAE 9245). As shown in Figure 3.6, the wire to be form is obtained by cold drawing operation. After drawing, the wire is subjected to heat treatment of hardening and tempering. During heat treatment, oxidation of the surface is permitted; the resulting oxide on the wire surface will act as a lubricant during subsequently coiling operation.

Requirement of lubricant for spring are more severe than for most other metalworking operations. A special lubricant may required if the high pressure may be reached to prevent gailling, seizure, or fracture of the wire as well as excessive tool wear. Improper lubricating oils or compound interfere with close-tolerance work and cause variations in the finished parts. The most usual lubricant is that one that comes on the oil-tempered grade of spring wire.

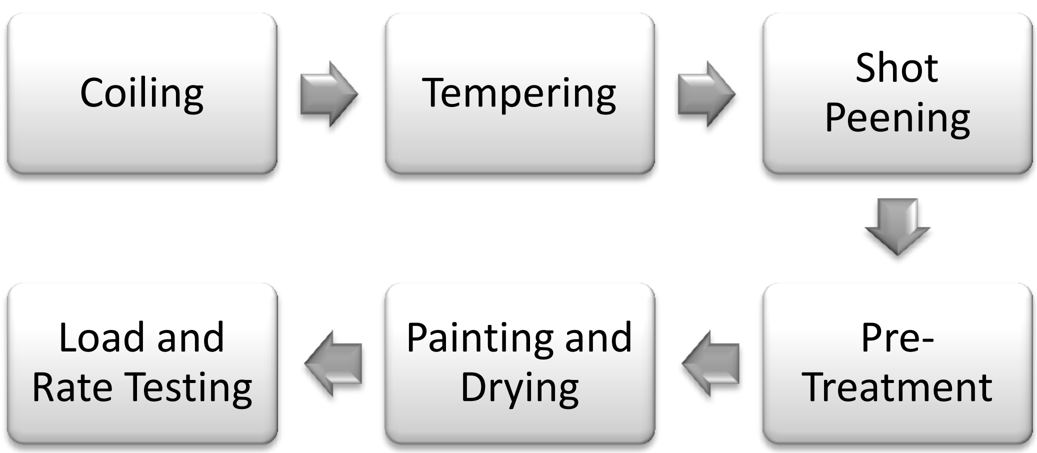


Figure 3.6; Fabrication process of suspension spring

During heat treatment, oxidation of the surface is permitted under carefully controlled conditions. The oxide layer thus formed acts as a lubricant during coiling. Its characteristics must be carefully controlled with respect to thickness, adherence and flakiness. Considering the coiling machine, low lubrication is required in order to allow that the feeding rolls perform the wire's feed. On the other hand, high friction in the forming zone leads to high forming forces and therefore to high normal and tangential loads on the forming tools. For this reason, idle rolls are adopted as forming tools; this kind of tools leads to rolling friction condition. The final geometry of the spring depends on the geometry and on the configuration of the forming rolls and therefore can not be considered a variable in the optimization of the forming process. Figure 3.7 show three model of suspension spring after finishing process.

Figure 3.7; Three model of suspesnion used in this experiment.

3.10 Testing the Model

The coil spring that being analyze is an actual coil spring that been used in car suspension system. Before investigation is is made, the spring mean coil diameter, wire diameter, free length (measure in mm unit) and number of active coil turns is determined first. The spring is manufactured by Sapura Industrial Sdn. Bhd. The exact properties of the Sapure coil spring are not known, but they can be closely estimated from commercial uses of of similar forms of carben steel, SAE 9254. For this analysis,the modulus of rigidity, Poisson’s ratio, and leads to a modulus of rigidity is assumed to a specific value as tabulate in Table 3.2.

Figure 3.8: Spring load and rate tester machine.

For a comfort of the passenger car purpose, the coil spring is test in a spring load and rate tester machine as shown in Figure 3.8. This machine consist of a hydraulic ram, load cell and linear potentiometer. The spring is loaded with the ram, and the load form the spring is measured as a function of displacement. This load is then divided by the displacement to give a spring rate for the spring. Then, a spring rate returned by this test are recorded in the next chapter (Chapter 4).

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter shows all the result obtained from this study. Table of results, graph, and figures are included. Detailed explanation of graphs and figures are also provided. The data is collected starting from the calculation of the Wahl's equation to calculate the rate and maximum static stress of the spring. Then, it follows by the result from the finite element analysis by Autodesk Simulation (Algor). And lastly, the actual result including the actual parameter of the suspension spring after being fabricate and the result from load and rate tester spring machine. The percentage error also obtained and will be discussed in this chapter after some comparison are being made.

4.2 Calculation by using Wahl's Factor Equation.

Then traditional engineering equation used for calculating spring rate is shown in Eq. 4,

$$k = \frac{Gd^4}{8nD^3} \tag{4}$$

Where:
d = Wire diameter,
G = Modulus of rigidity,
D = Coil diameter, and
N = Number of turns of coil.

Using the value for this spring, the spring rate for Model 1, Model 2 and Model 3 is calculated to be 31.33 N/mm, 37.98 N/mm and 40.13 N/mm respectively. The spring index is defined by $C = D/d$ [6]. Due to the fact that a coil spring is based on a twisted torsion bar, a value known as the Wahl's factor is calculated to determine a multiplier for the shear stress on the inside of the coils. The equation for the Wahl's factor is given in Eq. 9,

$$K_w = \left[\frac{4c-1}{4c-4} + \frac{0.615}{c}\right] \tag{9}$$

The Wahl factor for Model 1, Model 2 and Model 3 are tabulate in Table 4.1.

Once Wahl's factor is determined, the shear stress inside the coil of spring is calculated from Eq. 10,

$$\tau_{max} = \frac{16PR}{\pi \cdot d^3}\left[\frac{4c-1}{4c-4} + \frac{0.615}{c}\right] \tag{10}$$

Or, after simplification, Eq. 11 also can be used.

$$\tau = \frac{8FDK_w}{\pi d^3} \tag{11}$$

For this analysis, a force of 1600N is applied to the spring. This is one of the effort that be taken to involve the spring model in real application. For example, the body weight (exclude the weight of chassis) of an automobile may be around 6400N [11]. Using this force, along with the Wahl's factor and dimension of the spring, the maximum shear stress inside the coils is calculated and the result is recorded in **Table 4.1.**

Table 4.1; Stress and spring rate comparison of three model.

Model No.	**Spring Rate, k**	**Wahl's factor**	**Maximum Stress(Mpa)**
Model 1	31.33 N/mm	1.1448	323.91
Model 2	37.98 N/mm	1.1516	312.26
Model 3	40.13 N/mm	1.1589	300.58

4.3 Finite Element Analysis (FEA) Result and Comparison.

With the input to Autodesk Simulation (Algor) as mention in section 3.6, the linear static stress analysis is executed. Spring static displacement and the spring static stress spectrum is obtained. It should be noted that the whole spring was divided into several thousand nodes and elements. Thus, it will be impossible to make any stress or displacement comparison between over 1000 nodes spring model.

In order to solve this problem, only the maximum value of the spring static stress is chosen to be included in the comparison. From this comparison, we could find whether and how well both methods agree with each other. Another discussion is to analyse the effects of the spring variable parameters to spring stress.

The comparison of maximum value of spring static stress is listed in Table 4.2. The first column in table are the calculation from simple Wahl’s factor equation which is copied from section 4.2, and the second column is the Autodesk Simulation (Algor) solution. It is worth noting that the same setting are assigned are assigned for the three approaches. From the table, it is apparent that the maximum value of spring static stresses is agree with each other well. For the spring rate also give some acceptable result as it agreed with each other even there were some error or tolerance of 1 or 2 mm. This comparison strongly demonstrated the correctness and accuracy of the formulated these three model.

Table 4.2: Static stress comparison among two approaches.

Model No.	**Wahl’s Factor Calculation (Mpa)***	**Finite Element Analysis Output (Mpa)**
Model 1	323.91	320.515
Model 2	312.26	310.499
Model 3	300.58	298.48

In other to illustrate the effects of the spring variable parameter of helix radius from the viewpoint of, finite element analysis, spring static stress layouts for the three different models are plotted in Figure 4.1 to Figure 4.3. Since the number of nodes generated by Autodesk Simulation (Algor) is over a few thousand along the spring helix, only qualitative demonstrations could be shown on these plots.

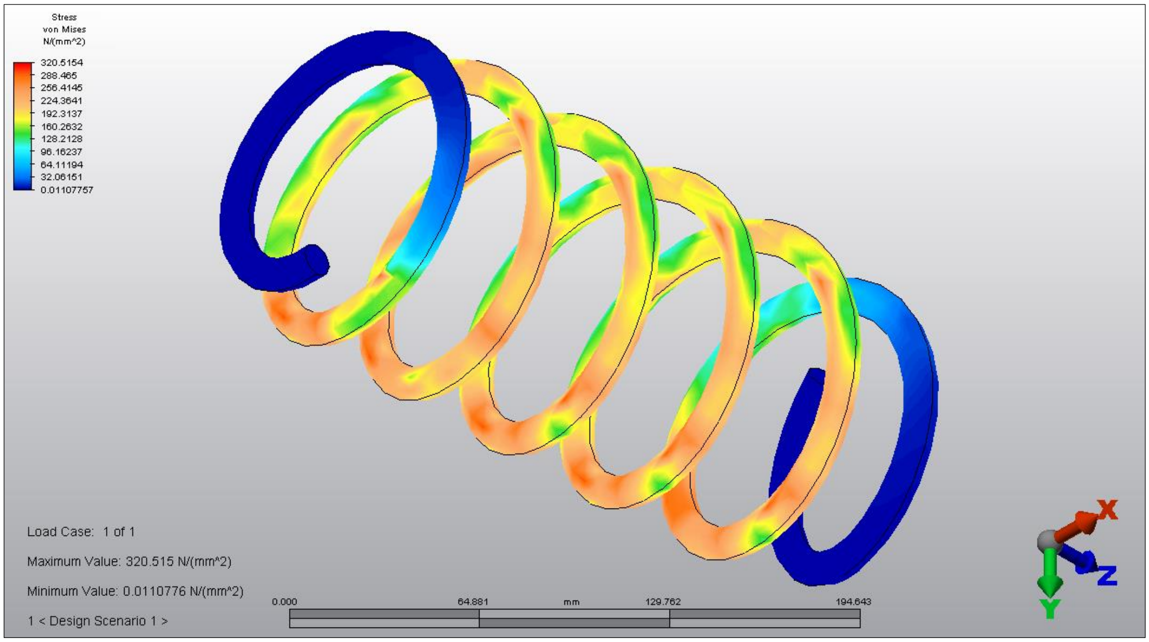


Figure 4.1: Static stress layout of Model 1

Figure 4.1, 4.2 and 4.3 plot the static stress layout spectrum from the Model 1, Model 2 and Model 3 respectively. The result shows that the maximum stress of this Model 1 is 320.515 MPa, for Model 2 is 310.499 MPa, and for Model 3 is 298.48 MPa. As mention in Chapter 1, the suspension spring for these three models is embodied with smaller pitch and helix radius at both ends of the spring and constant wire diameter. It can been be seen that the stress decrease at both ends because of the reduce helix radius and pitch angle.

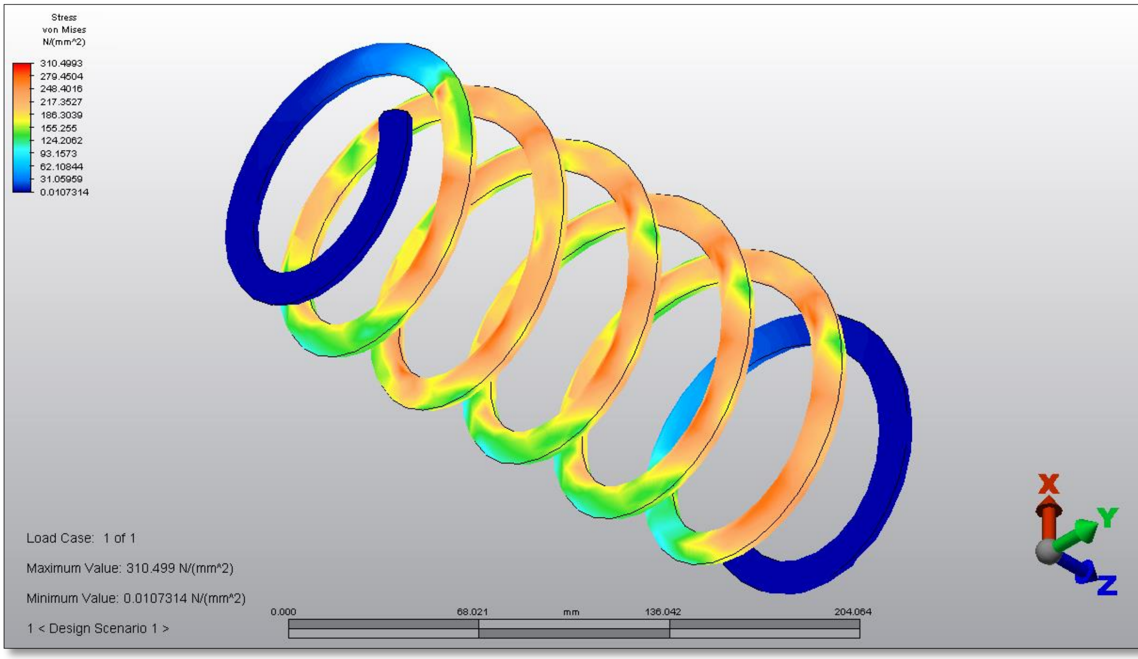


Figure 4.2: Static stress layout of Model 2.

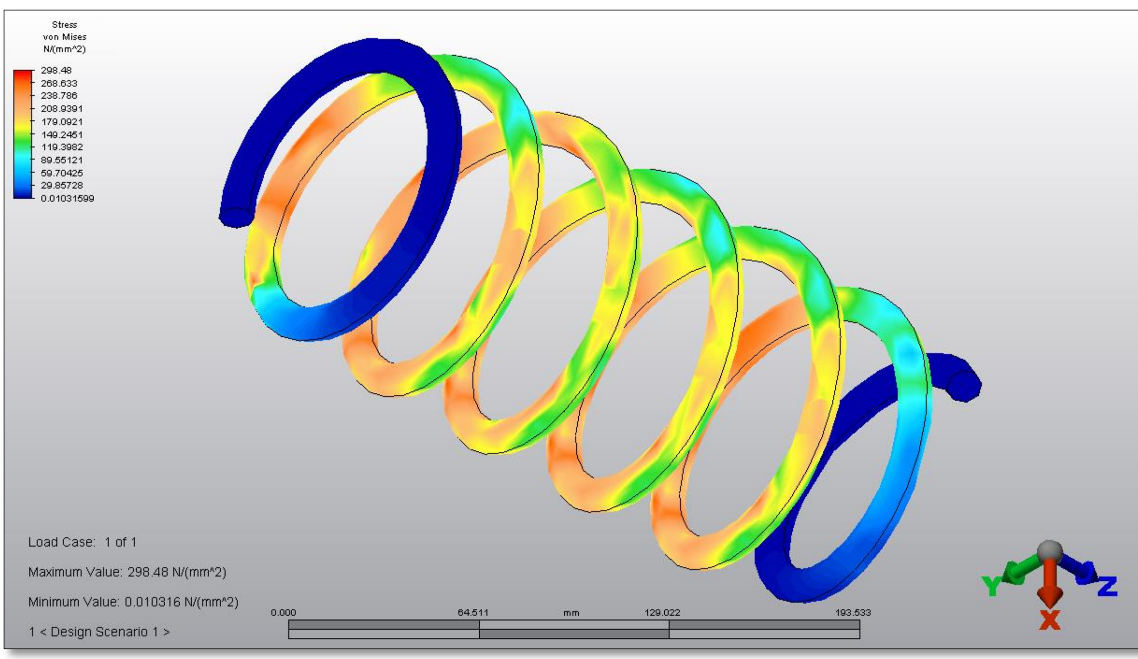


Figure 4.3: Static stress layout of Model 3.

4.4 Displacement-force Analysis Result and Comparison.

After completing this analysis. Several static result such as displacement-force can be obtained. Since static stress has already been discussed in the last section, we will limit our discussion on displacement-force analysis in this section. Table 4.3 show the result of the displacement-force analysis in this experiment.

Table 4.3: Displacement-force data of three model.

FORCE (N)	Displacement (mm)		
	Model 1	**Model 2**	**Model 3**
500	6.727	5.5401	6.06947
1000	23.4541	15.0802	17.0389
1500	38.3811	27.6203	28.0584
2000	53.3082	40.1604	39.0479
2500	68.152	52.2005	50.0474
3000	83.0622	64.2406	61.0368
3500	97.9584	77.7807	72.0263
4000	112.8516	90.3208	83.0158
4500	127.6613	102.8609	94.0252
5000	142.4518	114.401	105.0147
5500	157.597	127.5411	115.9642
6000	172.524	139.4812	126.9836
6500	187.452	152.0212	137.9731

Figure 4.4 show the plotted static displacement-force graph of three model of suspension spring. The data are taken from the Table 4.3 and plotted in order to observe and comparing the result between these three model. From, the graph, we can see that the Model 3 shows the highest slope followed by Model 2 and the lowest slope for the Model 1. These slope are represent the rate of the spring. Then, the rate of the spring is calculate by the gradient of the graph. The calculated rate of spring by the gradient of the graph then summarize into Table 4.4.

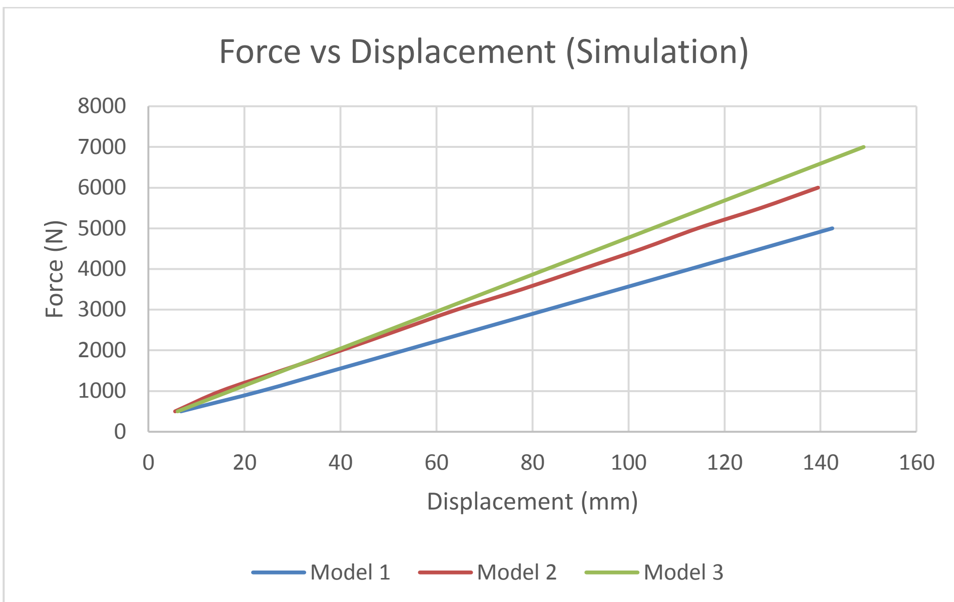


Figure 4.4: Force-displacement of three model.

Table 4.4 show the comparison that we made between the result from calculation of Wahl's Factor, finite element analysis and experimental (actual) result. The first column in the table is the result calculated from simple Wahl's factor equation which also copied from section 4.2, the second column is the Autodesk Simulation (Algor) solution, and the third column is the experimental result, which will be detailed in the next section in this chapter. The calculated rate of the spring of three model by these two method are acceptable and strongly demonstrate the correctness of the Wahl's factor equation since it follow the rule of equation which is the higher the helix radius or outer diameter, *D*, of the spring, the lower the rate of spring constant, *k*. The different result between these two method are observed because the equation of Wahl's factor are assumed to be used for constant parameter of the spring between helix radius, wire diameter and pitch angle, but for this experiment, we have used variable parameter of the spring. The error are acceptable and assumed to be in range of tolerance and could be ignored.

Table 4.4: Spring rate comparison among three approaches.

Model No.	**Wahl's Factor Calculation***	**Finite Element Analysis**	**Experiment Results****
Model 1	31.33 N/mm	33.65 N/mm	n/a
Model 2	37.98 N/mm	40.41 N/mm	n/a
Model 3	40.13 N/mm	42.48 N/mm	n/a

* Copied from Table 4.1.

** Experimental spring rate will be discussed in detail in next section in this chapter.

4.5 Load and Rate Experimental Result.

Two different sort of measurements are carried out during the experiment; actual parameter of the spring after fabrication and pre-set and the rate of the spring. Before load and rate testing are being done, the spring is measure again to get their actual parameter of helix radius and height of pitch. The actual parameter of these three model of suspension spring are summarize in Table 4.5. The full specification of the suspension spring are attached in the Appendix. The tolerance of the parameter of the suspension spring are assumed to be 2mm.

Table 4.5: Actual parameter of three model of suspension spring.

No	Item	Model 1	Model 2	Model 3
1	Outer Diameter A (mm)	96.32	95.55	95.10
2	Outer Diameter B (mm)	107.21	101.68	98.40
3	Outer Diameter (Middle) (mm)	121.78	116.31	111.2
4	Free Length (mm)	295	295	294
5	Number of Turn	6.40	6.45	6.4

In order to obtain accurate data of force-displacement of these three model, all three model are pre-set to 155mm. Another effort for getting more precise measurement is to repeat the experiment and collecting data until the precise and satisfied result are obtained. Selecting the seat that fixed with the top and bottom end of the spring also will effect on the accuracy result of spring rate. The result of load and rate testing of all three model are tabulate in Table 4.6.

Table 4.6: Displacement-force data of actual experimental test.

LENGTH (mm)	**FORCE (N)**		
	Model 1	Model 2	Model 3
5	200	126	149
15	480	373	462
25	790	741	870
35	1092	1113	1284
45	1395	1476	1695
55	1695	1850	2104
65	1995	2217	2514
75	2295	2582	2920
85	2595	2946	3324
95	2891	3306	3728
105	3188	3670	4130
115	3484	4030	4532
125	3780	4388	4934
135	4076	4747	5335
145	4370	5104	5735
155	4666	5463	6135
165	4960	5823	6524
175	5255	6183	6880

Table 4.6 show the result form the experiment of displacement-force by load and rate tester machine. The experiment is start by pre-set the spring to 155mm. then the load arm return to its initial position and starting the experiment by compressing the spring to 5mm. then the force of the load arm are recorded before the load arm are continue compressing to 15mm until its pre-set positioned. For every 10 mm, the force of the load arm are recorded as in Table 4.6.

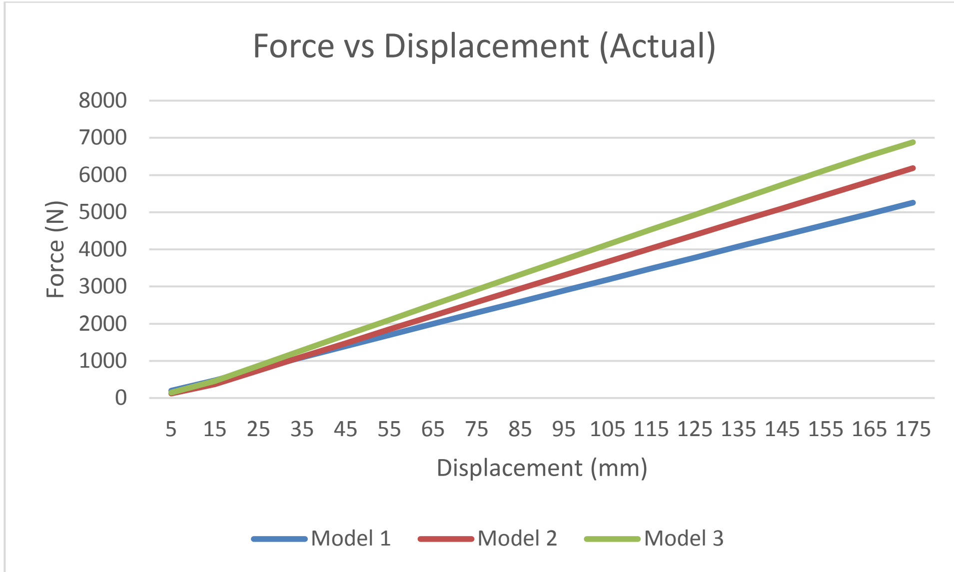


Figure 4.5: Force-displacement graph result of three model.

After all reading are recorded, a force-displacement graph are plotted as shown in Figure 4.5. From this graph, the same conclusion can be made to the simulation result by finite element analysis which is the higher the outer diameter of the spring, the lower the spring rate. To see whether the result form the simulation of finite element analysis is same with the actual result, we plotted another graph to compare within these three model of suspension spring as shown in Figure 4.6 to Figure 4.8.

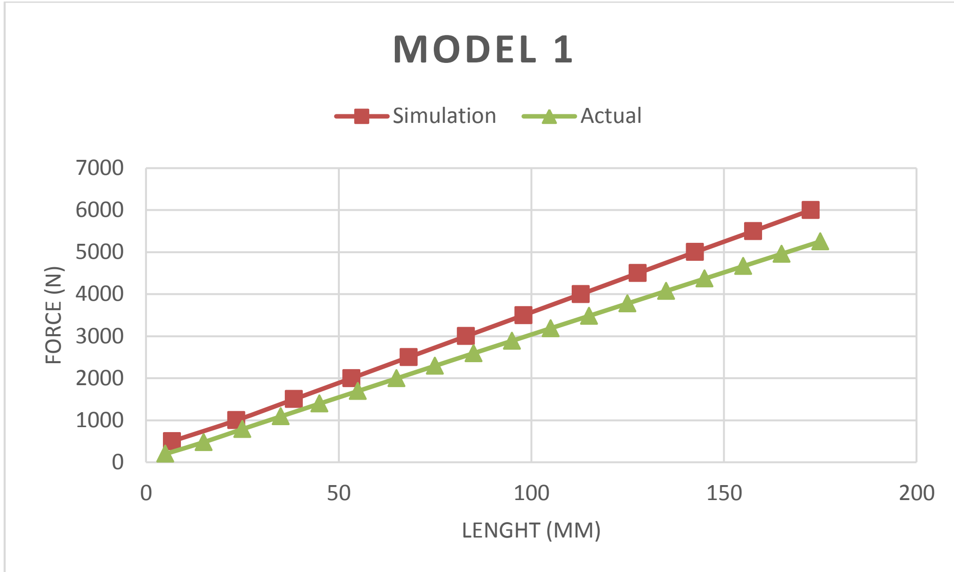


Figure 4.6: Comparison between actual and simulation result of Model 1.

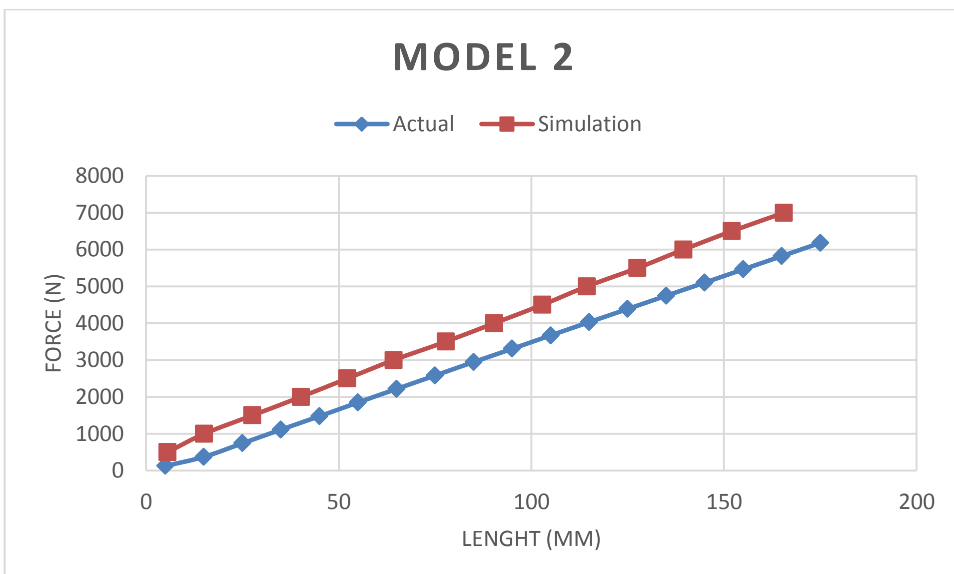


Figure 4.7: Comparison between actual and simulation result of Model 2.

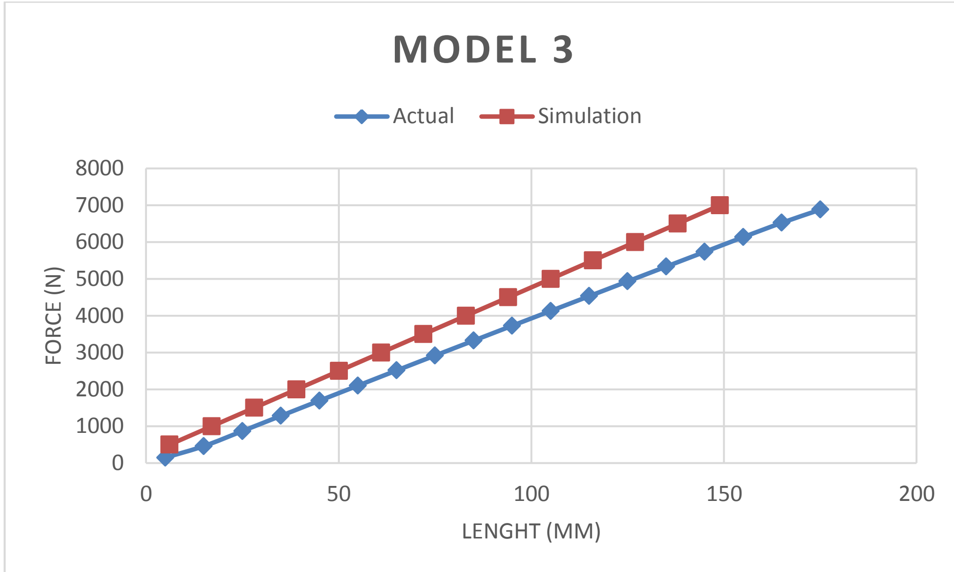


Figure 4.8: Comparison between actual and simulation result of Model 3.

Figure 4.6 show that the comparison of Model 1 result between simulation of finite element analysis and actual. We can see that there were some error between this two methods. From this graph, the rate of spring that found by simulation are 33.65N/mm and it is 11.4% larger than the result from the actual test which is 29.79N/mm. For the result from Model 2 as shown in Figure 4.7, the rate of the spring from simulation by finite element analysis were 40.41N/mm, 10.27% larger than the actual experimental result which is 36.26N/mm. The last comparison is between the Model 3 of suspension spring where it shows that the simulation result from finite element analysis is 42.48N/mm where only 4.83% higher than actual result that show it spring rate of 40.43N/mm. These result are summarize in Table 4.7.

Table 4.7: Comparison result between actual and simulation of three model.

Simulation (Autodesk)			
Model No.	**Model 1**	**Model 2**	**Model 3**
Spring Rate, *k* (N/mm)	33.65	40.41	42.48
Actual (Spring Load Tester)			
Model No.	**Model 1**	**Model 2**	**Model 3**
Spring Rate, *k* (N/mm)	29.79	36.26	40.43
Error(%)	11.47%	10.27%	4.83%

The error result between simulation by finite element analysis and actual result as shown in Table 4.7 must be avoid in order to get the desired characteristic of the spring after the fabrication process. This error are found in this experiment because of some limitation for example the type of material that used in actual and simulation by Autodesk Simulation (Algor). The material that used for the actual suspension spring are Carbon Steel, SAE 9254, but this type of material are not applicable in the software that being used in this study. So, Steel, AISI 1005 are selected and applied for the spring material in the simulation since it has quite similar properties with the material that have been used for the actual suspension spring. Second limitation in this project is the desire parameter of the suspension spring cannot be fabricate since it has some tolerance between the actual and design that we have drawn in Catia V5. This also will effect on the result of the study that will cause an error between the simulation by finite element analysis and actual spring test by load and rate tester machine.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion.

As a conclusion, the objective of this study has been achieved which is to develope a dynamic model of suspension spring with variable parameter of helix radius, run finite element analysis (FEA), fabricate and setup an experimental apparatus to collect spring static displacement-force data and to verify the correctness and accuracy of the actual experimental test with simulation result by software.

The analysis of 3D model developed in Catia V5 software have been solve by using the finite element analysis. The result have been compared and agreed wirh those obtained from the actual analysis by load and rate tester machine that have been done at Sapura Industrial Sdn. Bhd. The result from these three approaches agree well one another. The summarize result are shown in Table 5.1.

Table 5.1: Spring rate result among three approaches.

Model No.	**Wahl's Factor Calculation***	**Finite Element Analysis**	**Experiment Results****
Model 1	31.33 N/mm	33.65 N/mm	29.79N/mm
Model 2	37.98 N/mm	40.41 N/mm	36.26 N/mm
Model 3	40.13 N/mm	42.48 N/mm	40.43 N/mm

5.2 Recommendation.

From the result that been obtained in the previous chapter, the following future works can be recommended are;

1. To get the more accurate result on the static characteristic of the spring, the analysis also must be taken on all parameter including pitch angle and wire diameter of the spring.
2. More time must be consume on fabrication process of coil spring in order to get the exact parameter of the suspension spring with small tolerance. The result will be more accurate and precise when comparing with the simulation by finite element analysis.
3. The software that been used in this project is Autodesk Simulation Multiphysics since they offered a free version for education purpose. But, for this type of analysis, we recommended to used Autodesk Simulation Mechanical since they have Mechanical Event Simulation (MES) interface that easier, less consuming time and more accurate result can we get by using this software interface. This software have no free version and must be purchase at Autodesk website.

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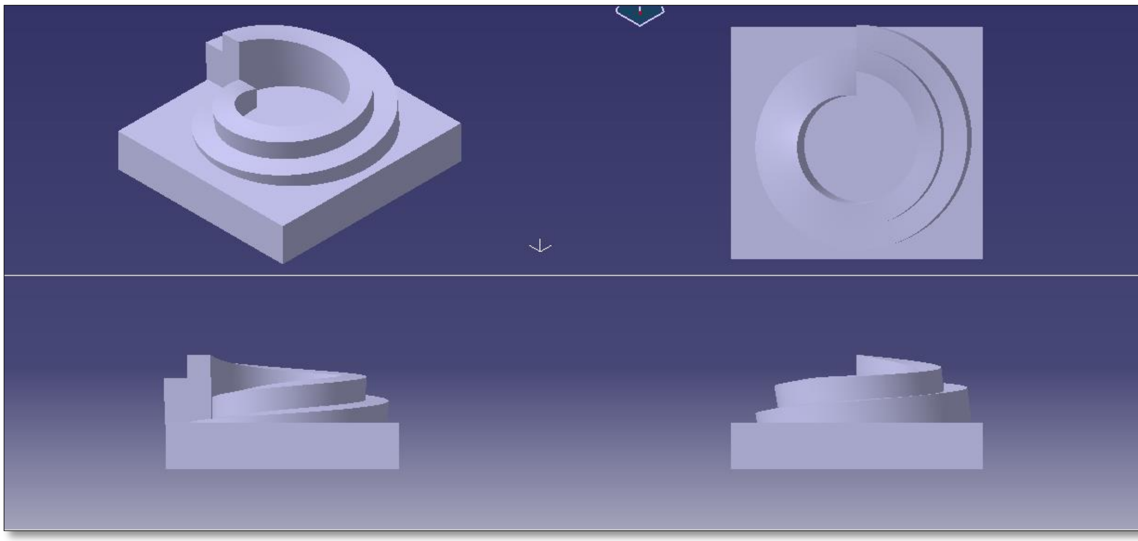
APPENDIX A

PLAN OF WORK

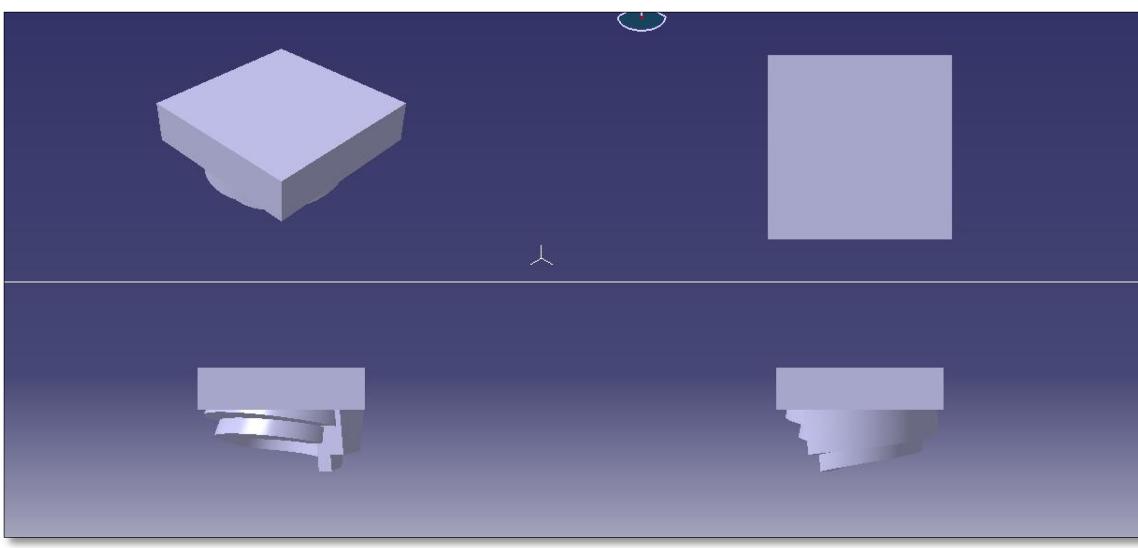
No	Subject/Month	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
1	Title Confirmation										
2	Set Objective and Scope										
3	Problem Statement										
4	Literature Review										
5	Research Methodology										
6	PSM 1 Report										
7	PSM 1 Presentation										
8	Tools Preparation										
9	Experiment Process										
10	Data Collection										
11	Data Analysis										
12	PSM 2 Report										
13	PSM 2 Presentation										

APPENDIX B

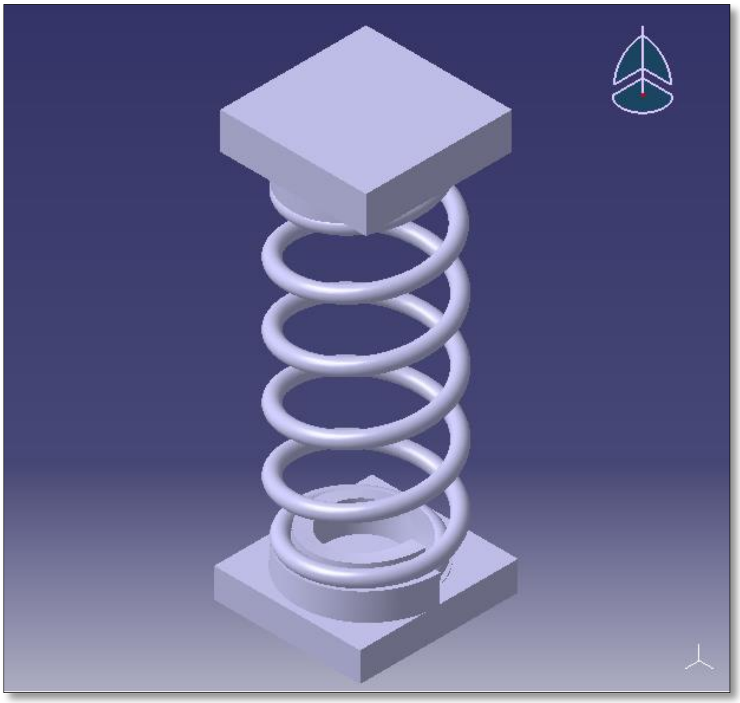
SUSPENSION SPRING MODEL



3D model of bottom seat



3D model of top seat



3D model of spring with seat

Suspension spring after cold coiling process.

Suspension spring after tempering and shot peening process

3 model of suspension spring after painting and drying process.

APPENDIX C

ACTUAL SPRING PARAMETER

***Customer sample data of suspension spring are attached in this appendix.**