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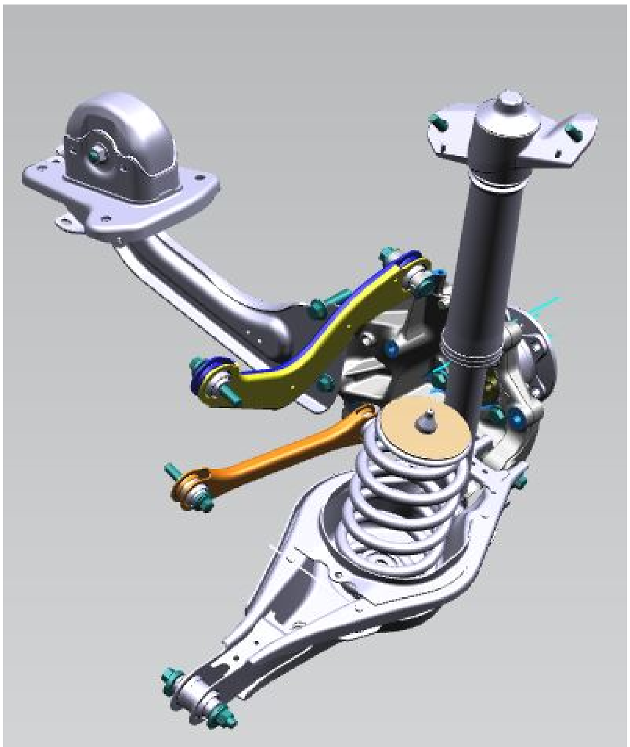

Optimizing Spring Specification

A study on suspension spring design and specification

Master's thesis in Automotive Engineering

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Department of Industrial and Material Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

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Cover: Rear suspension with linkarm of a car.

Chalmers Reproservice
Gothenburg, Sweden 2019

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Abstract

The initial specification for the spring is very crucial for developing a concept design of the suspension system. The spring plays a major role in packaging and performance of the suspension system.

The focus of this master thesis project is to obtain a detailed understanding of the different parameters and the sensitivity of the parameters during the selection of the spring for a suspension system. A detailed understanding is required when specifying the spring component and when selecting the spring dimensions for the suspension concept design.

An analysis tool has been developed using Matlab which begins with calculating spring parameters to meet specific design requirements. The design process is done according to EN 13906-1 [8] standard and then checked if it meets the requirements of the suspension assembly. This data is then stored. The generated data is plotted in a graph based on the required parameters. These graphs are utilized to understand the relation between different parameters and how parameters related. Also, the reason for a not feasible solution is stored to understand more about the parameters.

An optimization tool has been developed to identify the most suitable region for the design of the spring for a given requirement in the suspension concept.

As cars are getting heavier, the packaging of the suspension system is more complex than before and posing new challenges to engineers. It is important to have the right ride and handling of the car by having a good suspension system for a car. Hence it is important to identify the crucial parameters and understand how they interact with each other.

Keywords: Optimization, Spring Specification, Suspension Spring.

Acknowledgements

I would first like to thank my thesis adviser Professor Ingemar Johansson, Senior Adviser Wheel Suspension, CEVT AB who has supported me daily throughout the entire thesis work. Without his assistance and dedicated involvement in every step throughout the process, this thesis would have never been accomplished.

I would like to thank my Examiner and Supervisors at Department of Industrial and Material Science, Professor Magnus Evertsson and Asst. Professor Gauti Asbjörnsson who have guided me through out the project given their invaluable suggestions and feedback. They have steered my thesis in the right direction whenever I needed their support.

I would also like to thank my supervisor at Joel Karlsson at CEVT AB for his guidance and suggestions and making my experience at CEVT AB unforgettable and valuable.

I would like to express my sincere gratitude to all the employees at Wheel Suspension division, CEVT AB for providing me with a better workplace and catering to explore an efficient work-life balance.

Shreyas Ramesh, Gothenburg, June 2019

Nomenclature

γ_a	Shear strain amplitude
ρ	Density
τ	Shear stress
τ_a	Shear stress amplitude
τ_c	Corrected stress
τ_d	Shear stress in spring at design position
τ_F	Shear stress in spring due to force on the spring
τ_j	Shear stress in spring at jounce position
τ_m	Shear stress mean
τ_r	Shear stress in spring at rebound position
τ_T	Shear stress in spring due to torsion
τ_w	Working stress
τ_{max}	Maximum shear stress
τ_{so}	Shear stress in spring at solid position
τ_{total}	Total shear stress in spring
C	Coil clearance
C_e	Buckling parameter
d	Wire diameter
D_m	Mean diameter of spring
D_o	Outer diameter of spring
E	Young's modulus
F	Shear force in spring
f	Eigen frequency of wheel for a passenger car
F_j	Force acting on spring at jounce condition
F_r	Force acting on spring at rebound condition
F_s	Force acting on spring
F_w	Force acting on wheel due to weight of car during design condition
f_{spring}	Eigen frequency of spring

G Rigidity modulus of spring

i_r Installation ratio of spring

k Whal correction factor

L_1 Distance from axis of rotation to axis of spring

L_2 Distance from axis of rotation to wheel centre in a suspension system

L_p Length of spring in preload condition

L_r Length of spring in rebound condition

L_{bu} Length of spring at buckling condition

L_d Length of spring at design condition

L_o Length of spring at free condition

L_{so} Length of spring in solid condition

n Number of active coils in spring

P Pitch

p_{SWT0} Smith-Watson-Topper parameter for shear stress of a material

p_{SWT} Smith-Watson-Topper parameter for shear stress

R Spring rate

S_f Factor for safety

V Volume

W Weight of spring

w Spring index

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1

Introduction

1.1 Background

The design of a coil spring for a wheel suspension system will affect the concept design of a suspension system. The performance of the spring affects the ride height and handling characteristics of a car. The performance of the spring depends on the spring specific design parameters, for example, the wire diameter, mean diameter, the number of coils, spring stiffness and on other parameters like the packaging. The major functions of suspension systems of a vehicle are always to provide ride comfort by absorbing bumps from the road and to provide good handling by keeping the tire in contact with the road. The spring in a suspension system should have the expected load at the defined length to give the correct ride height. Also, the spring rate is crucial for vehicle dynamics and ride comfort performance. The damper, on the other hand, dissipates this energy in the form of heat. The spring in the suspension system thus defines how much force must be absorbed during a bump. The force vs deflection characteristic curve for spring with constant spring rate is as shown below in Figure 1.1.

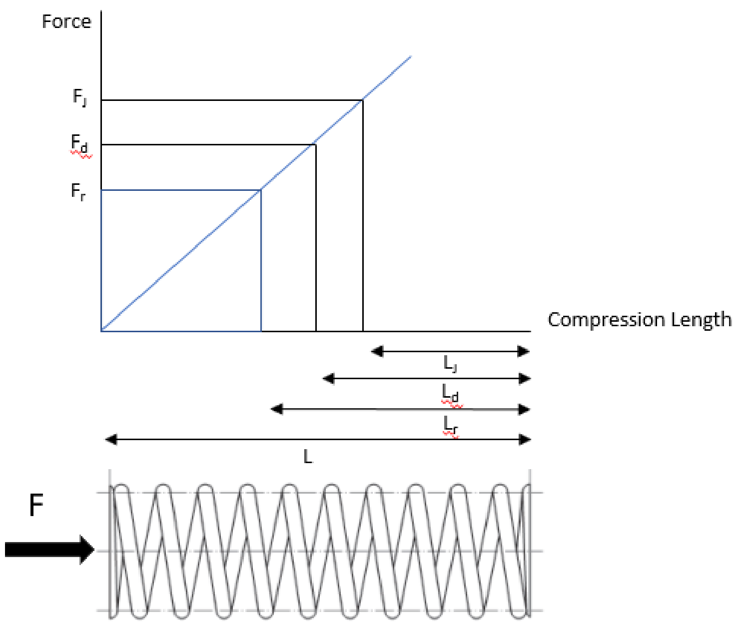

Figure 1.1: Compression of spring

The initial condition for the spring design of a suspension system is the design position. This is used to determine the length of spring at design position and the load on the spring. The spring operates between the jounce/compression and rebound condition based on the wheel travel for which the suspension system is designed. In an automotive suspension system, this wheel movement is considered as dynamic loading condition for the spring and the design of the spring is based on these considerations. The design of the coil spring also affects vehicle dynamics characteristics. The wheel travel rate is the major input received for the design of the spring from vehicle dynamics targets. The vehicle design requirements like the design height are crucial in deciding the optimal spring for the suspension system. The installation ratio defined in section 2.3.2, of the springs also affects the dimensions of the spring.

The spring material is also a parameter that decides the overall dimensions of the springs. As there are a lot of parameters involved which are inter-related in the development of a coil spring for a suspension package there is a need to understand the relation between the design parameters and their influence on the suspension design. The design should be optimized for the suspension design and spring design parameters. Currently, the springs are designed based on the input from the vehicle dynamics targets and the packaging of the suspension system. The initial specification for the spring is created in the concept design phase when the position and installation of the spring is developed. It is crucial to have the prerequisite parameters for the spring in place: load on spring at different positions, stiffness rate and wheel travel when the concept design is developed. The final spring specification is decided based on the vehicle dynamics targets which are also confirmed during tuning by the test engineer. This is later creating certain limitations in the desired outcomes of the suspension systems. Understanding the feasible installation ratio and the dimensions of the springs which can be accommodated during the initial design phase of the suspension system would enable in better understanding of the suspension system concept.

1.2 Aim

The master thesis project aims to obtain a detailed understanding of the different parameters and the sensitivity of the parameters that are required when specifying the spring characteristics and when selecting the spring dimensions for the suspension concept design.

1.3 Deliverable

The project has the following deliverables :

- Literature study.
- Formulas that are required for the analysis of the springs.
- Input and output formats to suit the analysis
- Specification ranges for the selected parameters

- Analysis results for the different specification ranges
- Master Thesis report

1.4 Limitation

The following limitations have been identified for this thesis work.

- The specification of the end coils of the coil springs are not included in the study. Squared end coil is considered for all calculations.
- The durability as a function of detailed material parameters is not included in the project.
- Hot rolled spring steel with Pswt 740MPa, Jounce stress of 1250MPa and solid stress of 1680MPa is chosen as standard during all calculations. However, all the tools are developed such that they permit to modify these values.

1.5 Specification of Issue Under Investigation

The following parameters have been identified to be needed for a valid specification of a spring for a suspension system:

- Spring installation ratio
- Spring diameter
- Wire diameter
- Static spring load
- Spring Stiffness
- Initial compression, full bump and rebound length of spring
- Number of coils
- Buckling

Some of these parameters will affect the suspension concept design and therefore it is important to have a detailed understanding of how the parameters affect the spring specification.

2
Theory

The spring design process mainly involves the mathematical calculation of different parameters using standard design equations. This can be done with simple mathematical tools like MS Excel or similar. The design standards to material-specific requirements should be considered. The spring manufacturer was involved to understand the process and find out the standards and systems they use in the design of springs. The input and output parameters are decided upon to suit the analysis of the spring design. The MS Excel calculation sheet can be made as a practical tool by applying required constraints according to various limiting parameters. A range of parameter values is obtained for the different input parameters. An analysis is performed for different specific ranges of the input parameters. An optimization tool has been used for achieving a required goal and the best solution.

2.1 Stress correction factor

A spring wire section is subjected to torsion and shear when an external force is applied on the spring. The stresses generated in the spring are the primary reason for the failure of springs. The below figure depicts how the shear stress acts on a crosssection of spring when an external compressive force is applied.

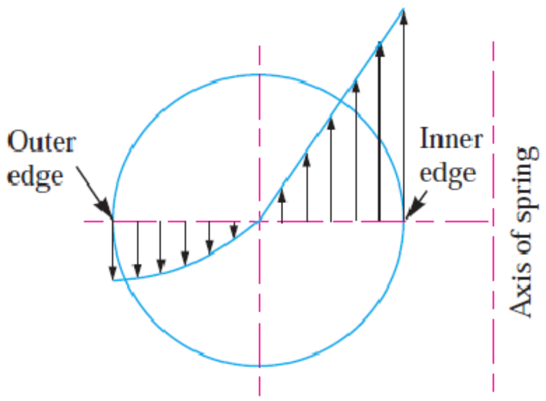

Figure 2.1: Total shear stress in cross section of spring under compressive force

The shear stress arising due to torsion is given by

$$\tau_T = \frac{8F_s D_m}{\pi d^3} \tag{2.1}$$

The shear stress due to force is given by

$$\tau_F = \frac{4F_s}{\pi d^2} \tag{2.2}$$

The total shear stress in the spring is given by

$$\tau_{total} = \frac{8F_sD_m}{\pi d^3} + \frac{4F_s}{\pi d^2} \tag{2.3}$$

This equation can be simplified in terms of spring index

$$\tau_{total} = \frac{8F_sD_m}{\pi d^3}(1 + \frac{1}{2w}) \tag{2.4}$$

where

$$w = \frac{D}{d} \tag{2.5}$$

The distribution of the total shear stress is not uniform in spring, it is depended on the spring curvature. The inside surface of the spring has the higher stresses. The highest shear stress-induced can be determined using the Whal correction factor.

$$k = \frac{4w-1}{4w-4} + \frac{0.615}{w} \tag{2.6}$$

The resulting shear stress formula is given by

$$\tau = \frac{8F_sD_mk}{\pi d^3} \tag{2.7}$$

2.2 Spring Stress Limits

A dynamic application spring has to operate for a minimum number of cycles in a given deflection range, the spring has to be designed such that the material would not fail due to fatigue. The fatigue criterion for a dynamic spring is given by Goodman formula:

$$(\frac{\tau_m + \tau_a}{\tau_w} + \frac{\tau_a}{\tau_e})S_f \leq 1 \tag{2.8}$$

The fatigue calculation of spring is often based on damage characterization defined by the Smith Topper rules. The product of maximum shear stress and total shear strain in the spring. During compression of the spring, the material undergoes torsion and pure shear stress. This theory when applied to shear deformation gives Smith Watson Topper parameter given by the equation

$$p_{SWT} = \sqrt{G\gamma_a\tau_{max}} \tag{2.9}$$

Further the equation can be simplified as

$$p_{SWT} = \sqrt{\tau_a\tau_{max}} \leq p_{SWT0} \tag{2.10}$$

The p_{SWT0} is acquired experimentally and it depends upon the material properties and factor of safety for an application of the spring. The fatigue behaviour of the spring also depends upon the surface treatments like shot peening.
Cold forming of the spring also induces residual stresses in the spring which has to be considered during the fatigue life calculation.

2.3 Packaging Parameters

The packaging parameters for a spring is influenced by the adjacent components of the spring in the suspension system and some of the operating conditions to be fulfilled by the spring. The packaging parameters provide guidelines around which the spring has to be designed. The design of the spring influences the performance of the suspension system. The size and mass of unsprung components, wheel travel, ride stiffness, spring working force range and work according to the requirements.

2.3.1 Design Length of the spring

The design length of spring is the dimension of the spring when the spring is loaded with a curb + 2 persons weight of the car. This length is decided in the very early stage of the vehicle suspension system development.

The design length is a geometric parameter defined by the distance between the lower control arm and the upper fixing point, often the side member in the body structure.

2.3.2 Installation Ratio

The wheel movement rate is an important criterion for wheel suspension design. This is derived from the installation ratio and spring stiffness. The spring stiffness gives the relation between the force applied on the spring vs distance of spring movement. In a car, relationship between the spring movement and the wheel movement is the motion ratio. Installation ratio or also called motion ratio as to it can be measured as the distance between the wheel centre rotation and spring.

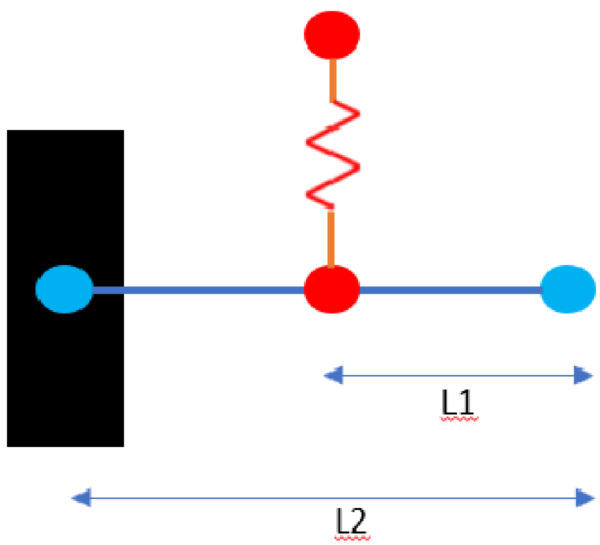

Figure 2.2: Installation Ratio

$$i_r = \frac{L1}{L2} \tag{2.11}$$

2.3.3 Outer Diameter of Spring

The diameter of the spring is restricted by the adjacent and mating parts in the suspension assembly. If the spring outer diameter exceeds the limit value there is a risk of contact between the spring and other parts in the assembly. The design also includes certain clearances to compensate for possible buckling of spring during compression.

2.3.4 Jounce and rebound Length of the spring.

Jounce is the vertical upward movement to a compressed state of the spring when the wheel travels over a bump. Rebound is the vertical movement of spring opposite to jounce when the wheel travels over a trough. The jounce and rebound travel is an important parameter of a suspension system as it influences how the car's driving characteristics will be when driving. A stiffer suspension usually has low jounce and rebound travel whereas a soft suspension would have longer jounce and rebound travel. This also influences how the car's driving characteristics would be under different load, ground clearance during driving. The sum of jounce and rebound length is called wheel travel.

2.4 Optimization

When designing a system which involves complex processes there is a need for making decisions. There can be different alternative options to choose from and the decision is made keeping in mind what is the required outcome. In engineering terms, the different systems can be written in the form of mathematical models which are governed by some constraints. The mathematical model would then have different sets of feasible solutions which are within the limitations. Choosing the best solution can be told as the optimum solution.

The primary elements of a model which are used to define an optimization problem are Variables, Parameters, Constants, Objectives and Constraints. These are used to solve for an optimum solution, however, there might be more than one optimum solution due to varying criteria in the decision-making process. Such problems are called multi-objective or multi-criteria optimization problems.

The Pareto approach is the most common multi-objective optimization technique used. A set of attained solutions can be obtained which fulfil all the design criteria are used to create a subset of optimal points for varying weights for the objectives. A Pareto set is obtained which would contain the optimized solutions for different weights of the objective. There are other approaches such as the Game theory and Goal programming which might be out of scope for this master thesis work. This thesis project also involves identifying the objectives for the optimization problem and then finding possible optimum solutions.

A conclusion must be drawn how different input parameters affect the output parameters during the design of a spring and then to optimize the spring design for a given situation. A certain guideline will be presented for the selection of spring.

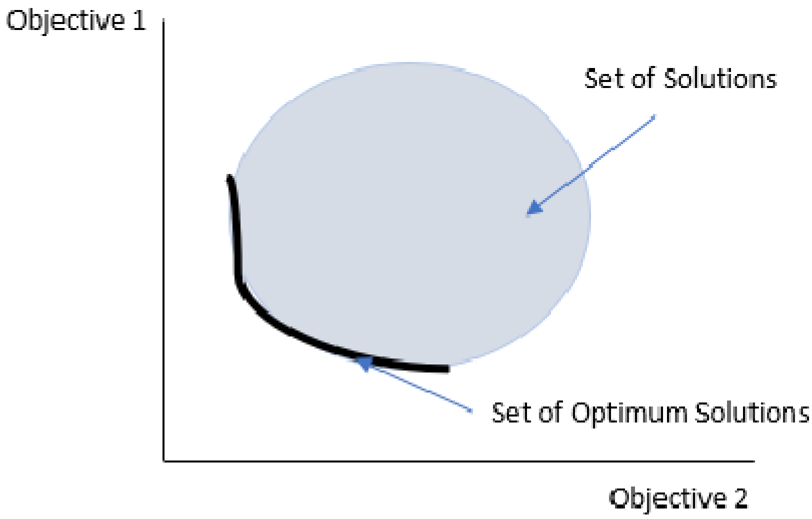

Figure 2.3: Pareto Curve for optimization

3 Methods

The study begins by considering a trailing arm rear suspension of a car. This suspension system allows the designers to choose a suitable location for connecting different components like the spring and damper between the side member and the suspension system. The design parameter of the spring and the installation parameters greatly influence the design and performance of the suspension system. It is important to understand what the influencing parameters are and how are these parameters influencing the design and performance. It is possible to develop a good suspension system which can be tuned for a large load range and required wheel travel if the sensitivity of the parameters can be understood. To understand the sensitivity of different design parameters of a spring certain tools were developed using Excel and Matlab. An optimization tool is also developed using Matlab for Spring specification.

The performance of a spring for a specific application depends on design parameters of the spring and how it is integrated into the system. The spring for trailing arm suspension system is designed to meet the dynamic load conditions on each corner of the car. The spring design parameters include:

- Shear Stresses in the spring allowed
- Load at design position
- Spring Rate
- Wire diameter of the spring
- Mean diameter of the spring
- Number of active coils in the spring
- End condition of the spring
- Free length of the spring
- Pitch of coils

Apart from the design parameters the remaining parameters which affect the performance and the characteristics of the spring are classified as packaging parameters which are mainly determined by the application of the spring. The packaging parameters have a significant influence on the overall concept of the suspension design and its performance. The packaging parameters are as follows:

- Installation ratio/motion ratio
- Force applied on the spring at a given position
- Design Length

- Jounce/Compressed Length
- Rebound Length
- Outer Diameter
- Buckling
- Frequency

The spring design procedure is according to the EN 13906-1 standards which is suitable for a given installation condition.

3.1 Spring Design for the Suspension System

The spring design for a rear suspension of a car is bounded by prerequisites which are developed during the product planning phase. During the planning phase of a car design the wheel travel, kerb weight targets are set. These are used as the initial spring design requirements which have to be fulfilled.

Several other internal standards determined by the spring manufacturer have to be fulfilled for better performance. Some of these standards are the length of spring during rebound condition, coil clearance in Jounce/full bump condition of the spring.

The calculation of the spring design starts by calculating the force acting on the spring. The curb + 2 weight at design position is used along with the installation ratio to determine the force applied to the spring.

$$F_s = \frac{F_w}{i_r} \tag{3.1}$$

The spring index is determined which is given by

$$w = \frac{D}{d} \tag{3.2}$$

The spring index is checked to be within the range of 5-12.
The spring index is used to determine the Wahl correction factor which is given by.

$$k = \frac{4w-1}{4w-4} + \frac{0.615}{w} \tag{3.3}$$

The next step is to determine the stresses in the spring. The design stress is first determined as the force acting on the spring at design condition is available.

$$\tau_d = \frac{8F_s D_m k}{\pi d^3} \tag{3.4}$$

The total length of the spring can be determined using the design load, compressed length for design position and spring rate.

$$L_o = \frac{F_s}{R} + L_d \tag{3.5}$$

The force acting on the spring at jounce condition is determined using the deflection of spring at jounce condition and the stiffness.It is given by:

$$F_j = (L_o - L_j)R \tag{3.6}$$

The shear stress in the jounce condition is given using:

$$\tau_j = \frac{8F_j D_m k}{\pi d^3} \tag{3.7}$$

Similarly, the rebound stress in the spring is calculated.

$$F_r = (L_o - L_r)R \tag{3.8}$$

$$\tau_r = \frac{8F_r D_m k}{\pi d^3} \tag{3.9}$$

$$p_{SWT} = \sqrt{\frac{\tau_j(\tau_j - \tau_r)}{2}} \tag{3.10}$$

To determine the stress in the solid condition of spring. The solid length of spring and the number of turns of the spring have to be determined. The number of active coils is determined by:

$$n = \frac{Gd^4}{8R(D_m)^3} \tag{3.11}$$

The number of active coils should be a minimum of 3 turns for manufacturing reasons. The total number of coils for a squared end condition spring is given by:

$$n_t = n + 2 \tag{3.12}$$

The solid length of spring when compressed completely is determined using the formula:

$$L_{so} = (n_t + 1)d \tag{3.13}$$

In order to find the corresponding shear stress the force at the spring is determined.

$$F_{so} = (L_o - L_{so})R \tag{3.14}$$

$$\tau_{so} = \frac{8F_{so} D_m k}{\pi d^3} \tag{3.15}$$

The obtained stresses have to be within the permissible limits. After the stress conditions are verified, the dimensional parameters are calculated for the spring.

The outer diameter of the spring is determined by

$$D_o = D_m + d \tag{3.16}$$

The initial preload compression length on the spring is determined and it should be minimum 16mm

$$L_p = L_o - L_r \tag{3.17}$$

The clearance between the coils during jounce condition should be minimum 5mm and it is determined by:

$$C = (L_j - L_{so})/n_t \tag{3.18}$$

The weight of the spring is one of the major criteria as it influences on the unsprung mass of the suspension system. The volume of spring is calculated using the formula given below

$$V = \frac{1}{4}\pi^2 D_m d^2 n_t \tag{3.19}$$

Weight of the spring is found by multiplying the volume of the spring with the density of the material.

$$W = V\rho \tag{3.20}$$

Pitch of the spring is determined using

$$P = (L_o - 3d)/n \tag{3.21}$$

The pitch of the spring has to be less than half of the mean diameter of spring to have uniform stiffness behaviour of spring in the working range.
The spring is then checked for buckling as it is one of the possible failure criteria for spring in the suspension system The critical length for buckling is determined using the formula.

$$L_{bu} = \pi D_m \sqrt{\frac{2(E-G)}{(2G+E)Ce}} \tag{3.22}$$

If the free length of the spring is lesser than the critical buckling length the spring design is safe. The stiffness of the spring is verified if it lies in the suitable eigenfrequency range. For a passenger car, the eigenfrequency is given with a range of 1.1-1.7Hz. The spring stiffness range is determined using the formula given by substituting the frequency limits

$$R = \frac{4\pi^2 f^2 * F_w}{i_r^2 g} \tag{3.23}$$

Further, the frequency of the spring determined and ensured is not the same as the tire frequency as the spring might fail due to resonance effects.

$$f_{spring} = 15.8\sqrt{\frac{K}{W}} \tag{3.24}$$

The tire frequency is in the range of 200-250Hz.

3.2 Spring Design Calculator

A spring design calculation tool is developed using an Excel spreadsheet. This tool can calculate the stresses and design parameters of the spring at a fixed point in the suspension system with a fixed design length and wheel travel.

3.2.1 Working of Spreadsheet Tool

The inputs used to the Excel spring calculator tool are:

- Spring Installation Ratio
- Wire Diameter
- Mean Diameter of Spring
- Force on Spring
- Spring Stiffness
- Length of Spring at Design Position
- Jounce travel of Spring
- Rebound Travel of Spring
- Youngs Modulus
- Rigidity Modulus of Material

It is important to ensure these input parameters are realistic. The calculator computes different parameters for spring design and the packaging parameters. These parameters are then compared with the limits set during the development of Spreadsheet based on the material properties and manufacturing requirements for the spring.

A warning is generated by turning the cell into a red colour if the limit value exceeds for the stresses and minimum packaging parameters are not met. The excel sheet is developed such that one parameter in spring design can be varied in each sheet with a standard step size from an initial point. The installation ratio, spring stiffness, mean diameter, wire diameter, number of coils are varied in each calculation sheet and the effect of changing a parameter on the other design parameters, stresses and the dimensions of the spring is determined.

An optimization tool is also developed using the MS Excel for a certain load which determines the best installation ratio and dimensions for the spring to determine the least possible weight. The optimization tool is developed keeping the weight at the objective which has to be minimized. Then the spring stiffness, mean diameter, wire diameter and installation ratio are used as changeable parameter. Upper and lower limits are applied on the changeable parameters, these parameters are usually the manufacturing and packaging limits. Further, the jounce, p_{SWT}, solid stresses and minimum dimensional requirements are limited with the permissible value.

3.2.2 Limitations of Spreadsheet tool

The Excel tool is highly effective in understanding the relationship between different design parameters. However, it has certain limitations as explained below.

- Excel tool limits in computing all the feasible solution in a given range. Excel limits iterative computation. Since there are a high number of parameters and broad range for each parameter, it is difficult to run iterations.

- The Excel tool restricts the use of complex logical decision making commands which can be easily executed in Matlab script.

3.3 Spring Analysis Tool Using Matlab

A Matlab tool is developed to overcome the shortcomings of the spreadsheet tool. It is also used to perform deeper analysis and compare different scenarios in which the spring can be used in the suspension system. The following section explains how the Matlab code is set up and the initial and final values of the parameters within which the computation is performed.

3.3.1 Spring Calculation Tool

The Matlab tool begins with calculating all feasible spring solutions in a given range for parameters. The tool is developed to perform iterations by changing one parameter each time, compute the spring design parameters and the packaging parameters, then check if the solution fulfils the design criteria. The parameter is then incremented with defined step size and the above process is repeated. The selected range for different parameters to analyse the tool is as stated below:

	Parameter	Lower limit	Upper limit
1	Installation Ratio	0.5	1.0
2	Wire Diameter	11.5 mm	15.5 mm
3	Mean Diameter	100 mm	140 mm
4	Force at wheel	3000 N	7000 N
5	Wheel Rate	22 N/mm	40 N/mm

Table 3.1: Parameters used for analysis

Certain parameters are kept fixed as they are decided in the early stages of the car design and also as these parameters would not affect the analysis. The parameters which are kept constant are mentioned below:

- Wheel travel at jounce.
- Wheel travel at rebound.

The major advantage of using this tool is it overcomes the limitations faced in using the Spreadsheet. It also facilitates to develop different analysis tools for our requirement.

3.3.2 Analysis Tools

For a deeper analysis of the parameters in spring design Matlab was further used. A script is developed to count the number of failed iteration when trying to design a spring with certain parameter values. The reason for failed attempts in then summed up and displayed. The picture below shows how the failed attempts are reported.

```
---------------------ERROR REPORT------------------
Number of iterations fails due to Spring index limit: 190650
Number of iterations fails due to no minimum number of coils: 37907124
Number of iterations fails due to Jounce stress exceeding limit: 28671518
Number of iterations fails due to Pswt stress (stress during dynamic condition:
5852969
Number of iterations fails due to Solid length stress exceeds limit: 111643
Number of iterations fails due to insufficient preload: 5426926
Number of iterations fails due to no minimum clearance between coils: 25814878
Number of iterations fails due to excess pitch between coils: 2534227
Number of iterations fails due to buckling failure: 14
Number of iterations fails due to too slender spring: 0
Number of iterations fails due to improper ride frequency: 0
Number of iterations fails due to resonance of spring with tire frequency: 0
Total iterations for spring: 106827550
------------------------------------------------------
```

Figure 3.1: Screenshot of Error Report

Further, several 2D and 3D plots are plotted to understand the relation between different parameters. Also, several solutions at different installation ratio's are plotted. The spring design solutions can also be filtered for a specific range of wheel frequency. This is an important parameter because having several variants of cars with similar wheel frequency would give close to identical ride performance.

3.4 Spring Optimization Tool

It is important to design a spring which fulfils all the design and packaging requirements. Simultaneously it is also possible to choose the best spring to fulfil specific objectives. As a part of the analysis the weight of the spring is taken as the objective. The weight of the spring is the major contributor for the overall cost of a spring. An optimization script is developed to fulfil these objective of having least weight while meeting all the design requirements.

The optimization begins with a master code where the iteration of spring parameter begins. This code is divided into several sections. The first section is to define the variable parameters and a range is defined for these parameters within which they need to be worked upon. These parameters in our code, are wire diameter, mean diameter, installation ratio, spring stiffness and design length of the spring. In the next section of the code the optimization process is started by calling the objective function using *Fmincon* or *Genatic Algorithm*(*GA*). The optimized solution is stored in the variable which is used to compute other parameters of the spring design.

The objective function is an important part of the optimization process. It is important to clearly define what is the objective for which the parameters need to be computed. In this thesis work, weight of the spring is defined as the objective for the optimization process. The objective is achieved if a feasible spring design is available. It is very important to choose the right upper and lower limits for the parameters in the master program. The upper and lower limits for the design length of the spring are chosen based on the analysis results of matalb tool developed in section 3.3.

In the constraint function spring designs are individually checked to meet the design requirements and the packaging requirements. The results are sent to objective function and sorted to identify the spring with least weight. In the constraint function of the code, the crucial stresses and other limiting factors for the spring design is computed.

4
Results

In this section, the results of the spring analysis tool is presented. The analysis is started with the standard design length of spring used in the current model of the car. The design length of the springs are then increased in steps of 20mm and the analysis is performed. This data is merged to also understand the influence of design length on the performance of the spring.

4.1 Fixed Mean Diameter

4.1.1 Analysis

The relation between installation ratio and wheel force is analyzed for spring with mean diameter 110mm and design length 249mm is shown in figure 4.1. The reason for spring design failure is analyzed in different regions of the graph and the results are as follows:

- Region 1: The reason for the failure of spring design is due to multiple criteria. The major contributing factors being 34 percent of failure due to an insufficient number of coils that can be accommodated and 24 percent of failure due to exceeding working stress (p_{SWT}) in the spring.
- Region 2 and 3: The main reason for spring failure in these regions being the jounce stress exceeding the limit contributing close to 41 percent. The second major factor is springs having insufficient preload with a contribution of 20 percent.
- Region 4 and 5: Springs cannot be designed in this region as they are not having the minimum number of coils required for manufacturing.

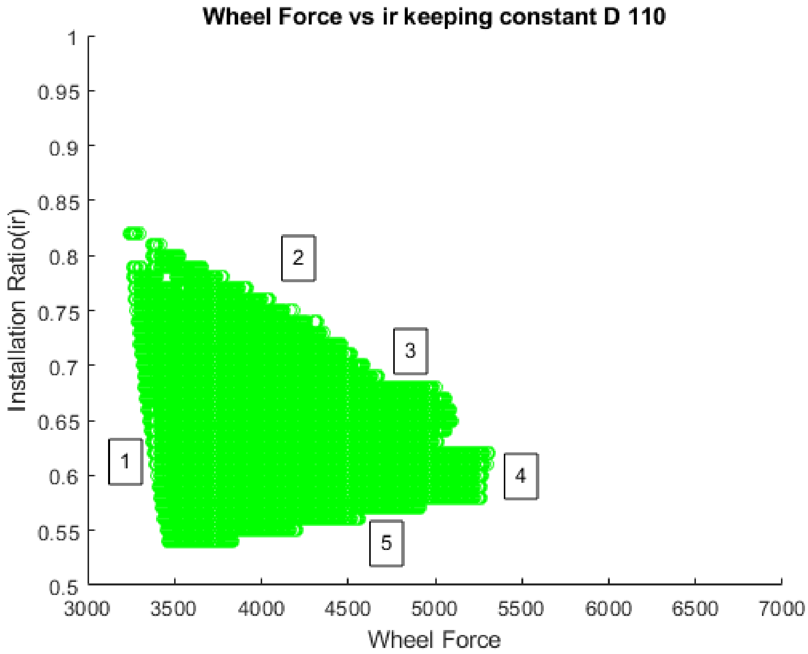

Figure 4.1: Mean Diameter 110mm for design length 249mm

4.1.2 Combined Results

The results obtained by changing the design lengths of the springs are combined and the following plots are derived for a fixed diameter. The design length of the spring is color-coded in the legend.

From the figures 4.2 - 4.4 it can be seen how the feasible solutions shift as the mean diameter of the spring increases. Also, this gives a clear picture of the range in wheel force for which the springs can be tuned if the installation ratio is known.

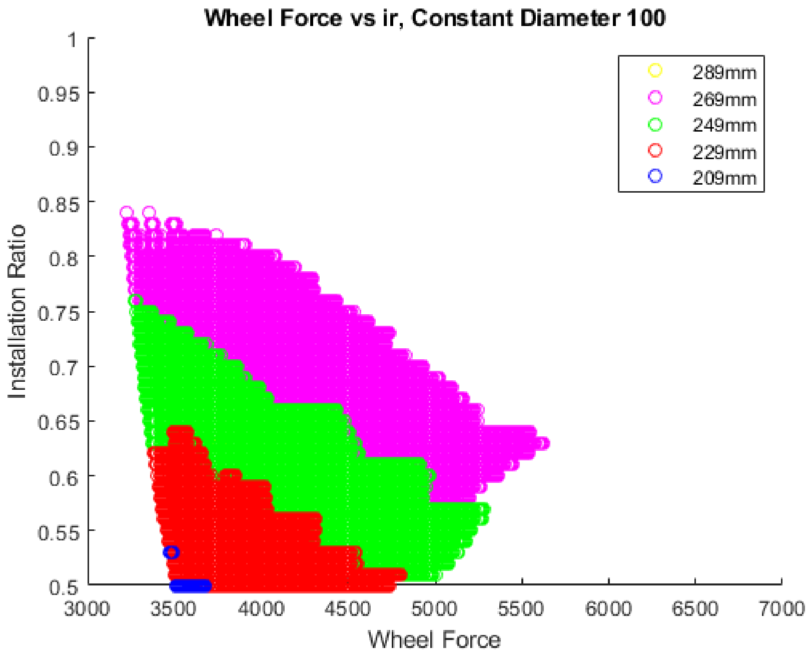

Figure 4.2: Mean Diameter 100mm

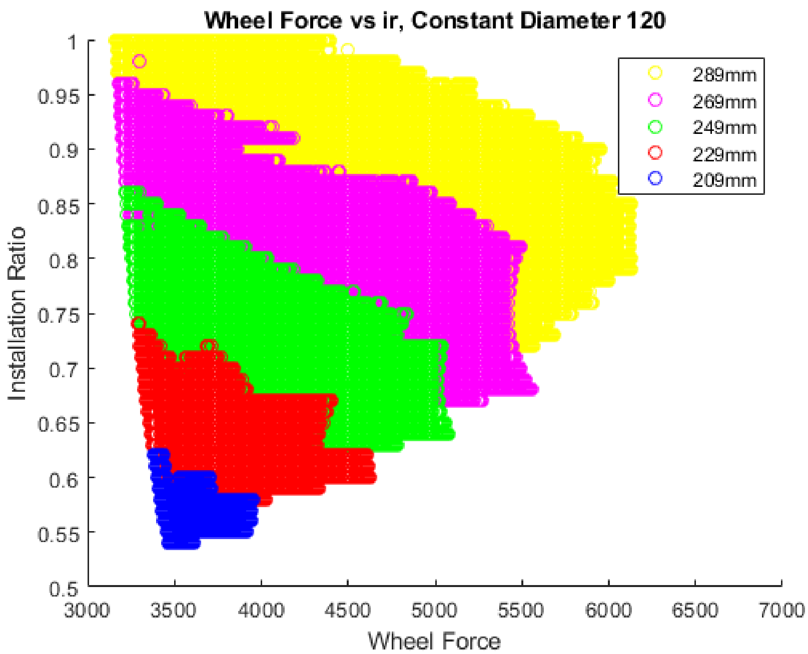

Figure 4.3: Mean Diameter 120mm

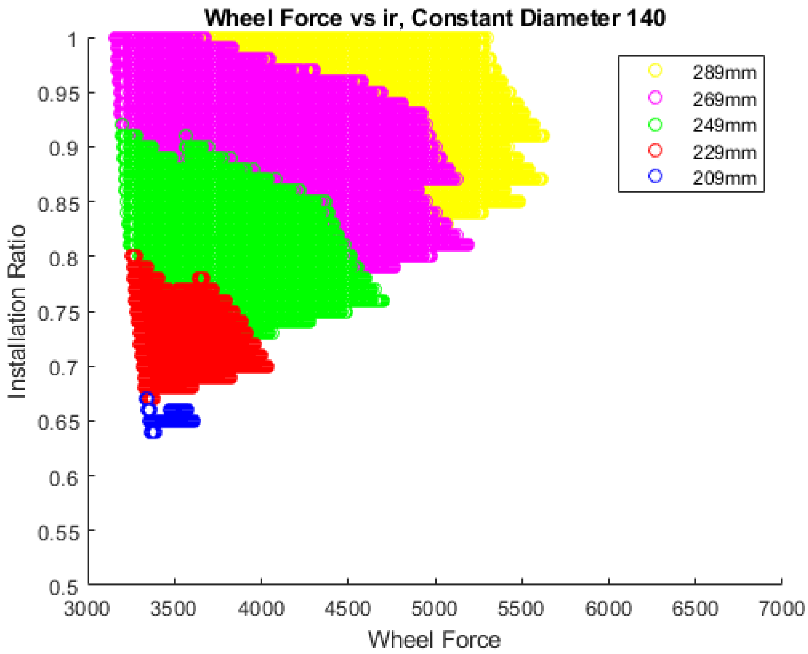

Figure 4.4: Mean Diameter 140mm

4.2 Fixed Installation Ratio

4.2.1 Analysis

The figure 4.5 is obtained by plotting the solutions of feasible spring designs for fixed installation ratio of 0.7 and a design length of 249mm. The reasons for spring design failure at different regions of the plot is as explained below:

- Region 1: The major reason for spring design failure in this region of the graph is the insufficient number of coils that can be accommodated by having sufficient coil clearance during the jounce condition. The contribution of these failure criteria is 54 percent

- Region 2: Similar to region 1 the reason for unfeasible solutions at this region is lack of minimum number of coils with sufficient coil clearance and the contribution of this factor is 82 percent.

- Region 3: In this region, the reason for unfeasible solutions is contributed by multiple factors like jounce stress, working stress reaching the limit and also no minimum number of coils required.

- Region 4: In this region, the stress limits on the spring are the major factor which is restricting for having further solutions. The jounce stress is predominant at 43 percent.

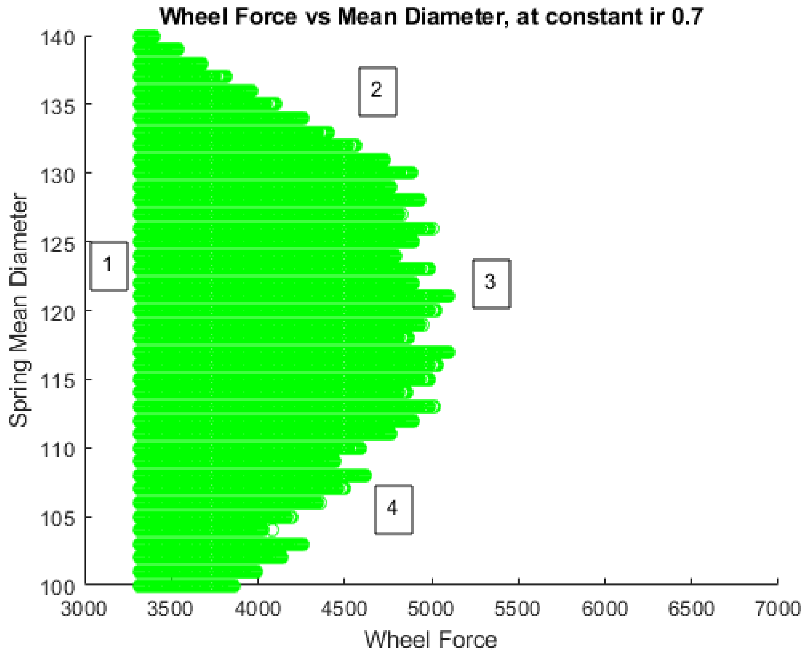

Figure 4.5: Installation Ratio 0.7 for design length 249mm

4.2.2 Combined Results

The plots with fixed installation ratio for different design length of the springs is combined. The results for Installation ratio at 0.5, 0.7 and 1 are discussed.

From figure 4.6 it is seen that at installation ratio 0.5, springs with longer design length cannot be accommodated. Also, the tuning range for wheel force is quite limited. Springs with larger diameter cannot be accommodated as well.

In figure 4.7 it is seen a wide range of tuning option is available for wheel force and also springs can have a wide range of design lengths and diameters.

In figure 4.8 at installation ratio 1, the tuning range for wheel force large but the springs need to have longer design length to achieve required wheel travel.

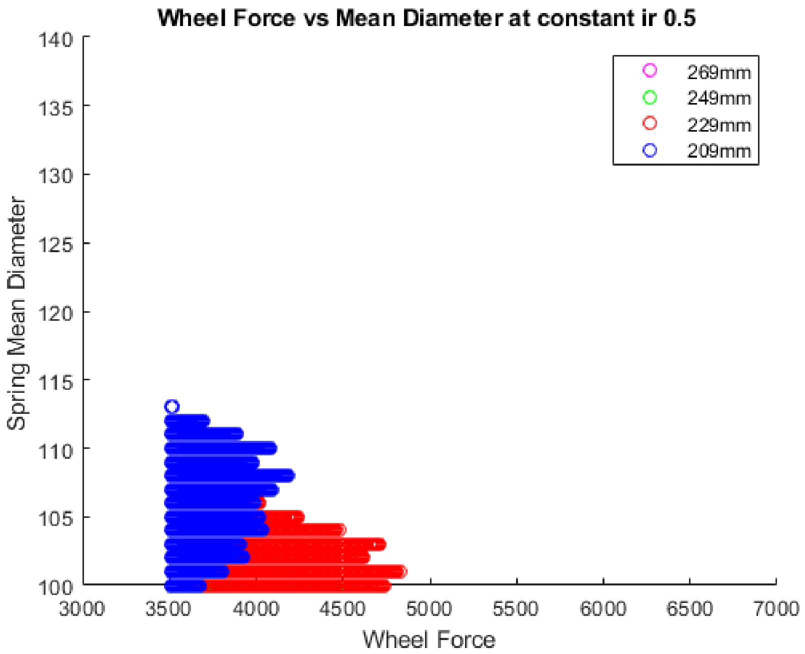

Figure 4.6: Installation Ratio 0.5

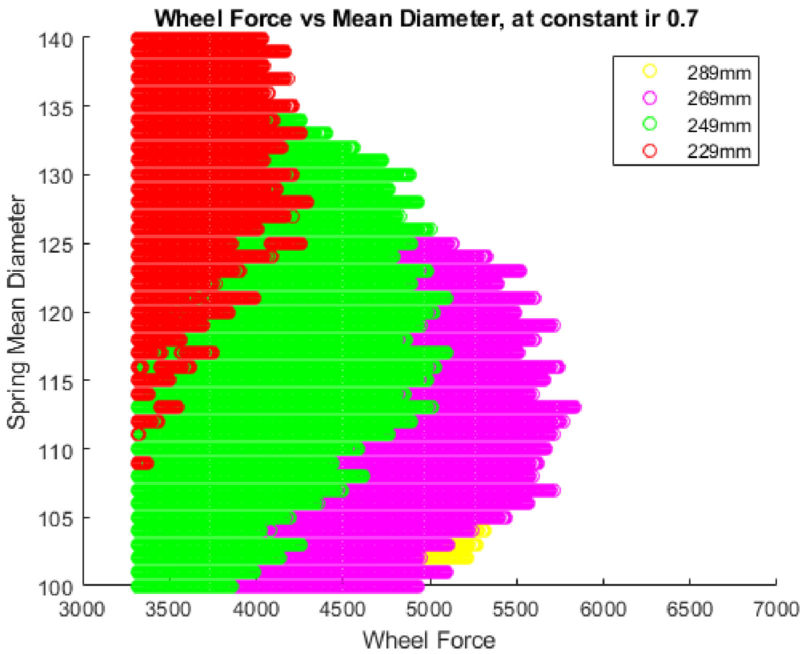

Figure 4.7: Installation Ratio 0.7

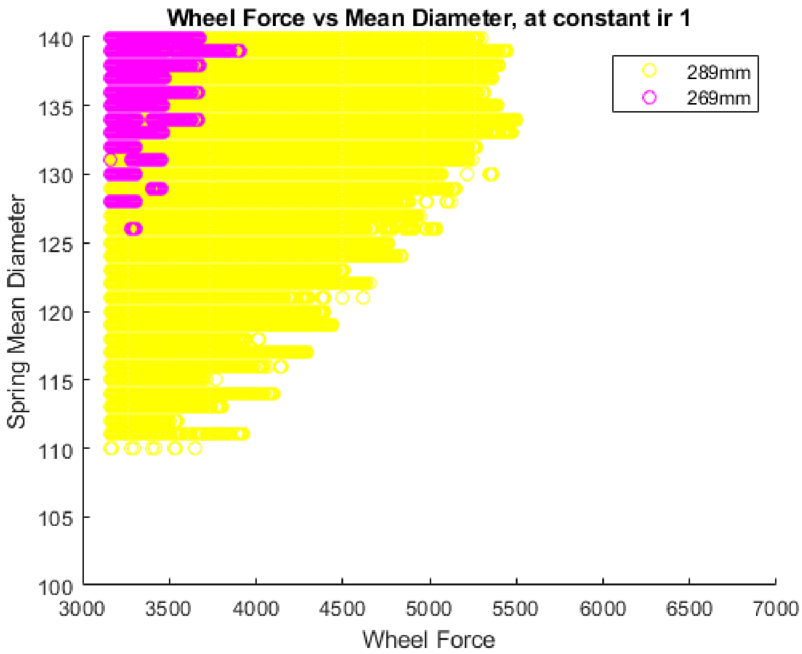

Figure 4.8: Installation Ratio 1.0

4.3 Spring Stiffness Relation

In the following figures, the relation between spring stiffness and wheel force is depicted for different design lengths of the spring. It is also see how the spring stiffness value changes as the installation ratio of the spring changes in the suspension system.

It is clearly seen that springs with design length longer than 249mm cannot be accommodated at the installation ratio 0.5. This is also because as the installation ratio is reduced the force acting on the spring has increased, demanding a spring with higher stiffness. The stiffness of the spring is limited by minimum number of coils and the wire diameter of the springs.

In figure 4.10 it is seen that the spring stiffness is much lower figure 4.9. Also, it is seen as the design length increases the operating window for the force increases, but it is to be noted that this is not endless. For design length of 289mm, there is no major gain in force range of the spring.

In figure 4.11 it is seen that design length of spring 289mm has a higher range for tuning the force, with simulations with much higher design length we can expect to have a much higher range for force tuning.

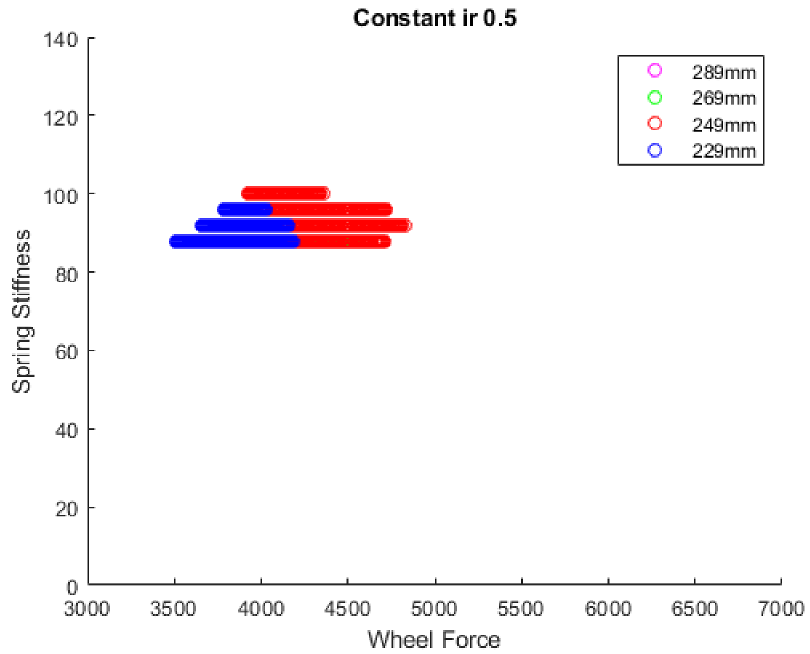

Figure 4.9: Installation Ratio 0.5

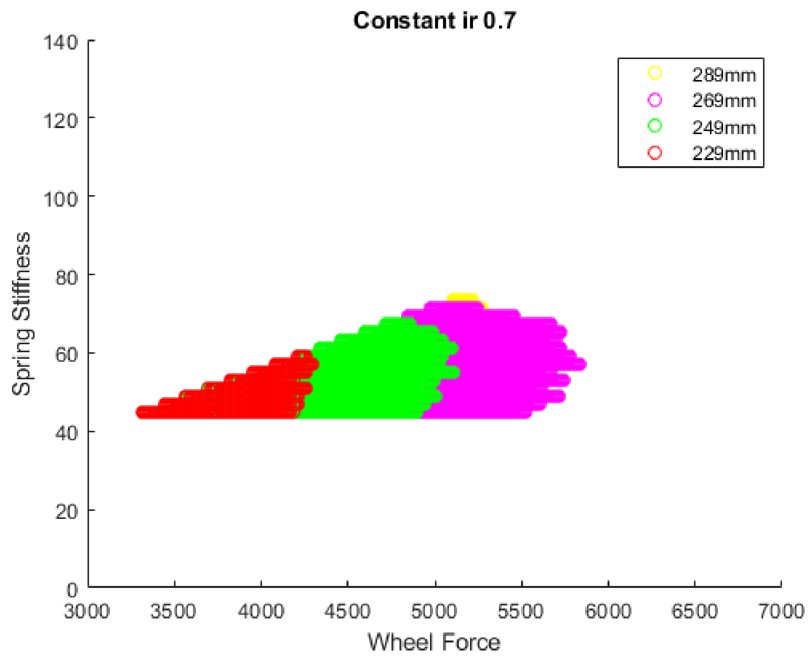

Figure 4.10: Installation Ratio 0.7

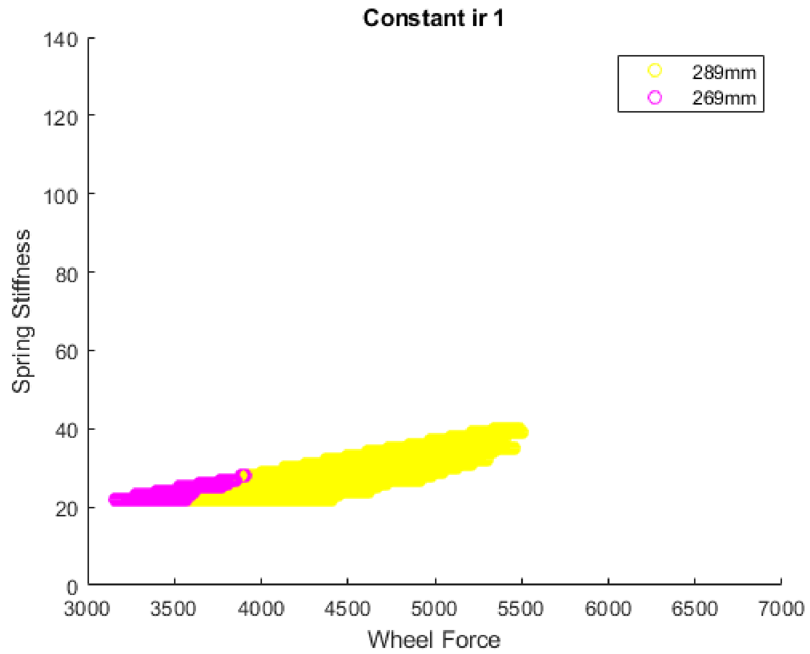

Figure 4.11: Installation Ratio 1.0

4.4 Optimization Result

The results from the optimization tool is as shown in figure 4.12. The jounce and rebound length is constant. The force at wheel during design position is plotted on the X-axis and weight of the spring is along the Y axis. It is seen in figure 4.12 that the weight of the spring increases with increase in wheel force. However the change in weight is not linear.

The lower limit for design length of spring is an important parameter which is chosen for each load. With the help of figure 4.6, figure 4.7 and figure 4.8 the lower limit for the design length of spring is chosen. This is to ensure that the optimized result is a feasible solution.

If the lower limit of the spring is chosen in a non feasible solution region the optimization result would have hit the limit for some of the parameters. So, it is important to check the results have not hit the parameter lower or upper limits after the solution is derived. Table 4.1 shows the values of different parameters derived for respective design load on the spring at design position.

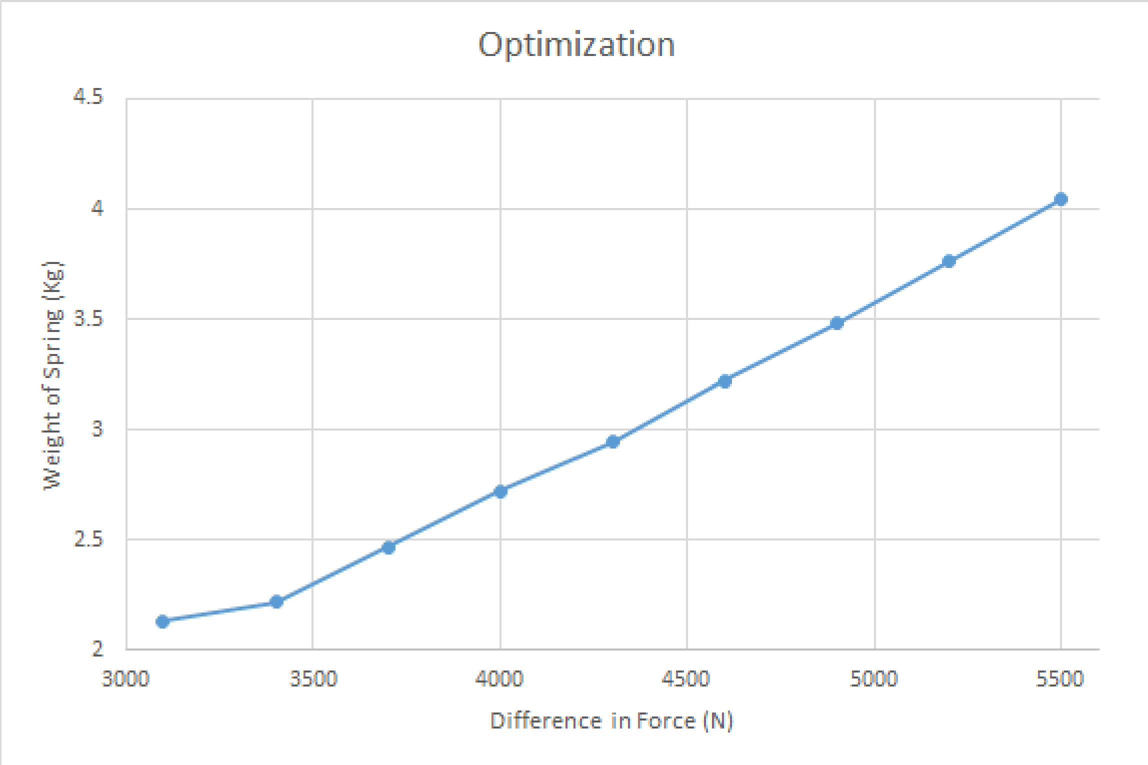

Figure 4.12: Optimization Curve

The results from the optimization process is as follows:

F_w	W	ir	d	D_m	K	L_d	n
3100	2.13	0.97	11.68	101.1	22.14	265	8.38
3400	2.22	0.97	11.68	105.18	22.2	265	8.2
3700	2.47	0.91	12.29	103.19	24.14	265	8.37
4000	2.72	0.87	12.8	101.82	26.18	260.4	8.59
4300	2.944	0.93	12.97	103.16	28.87	261.14	8.93
4600	3.22	0.83	13.76	103.95	30.41	273.76	8.63
4900	3.48	0.81	14.18	102.81	32.5	272.4	8.88
5200	3.76	0.763	14.82	103.01	34.11	278.7	8.77
5500	4.05	0.8337	14.98	107.83	37.04	290	8.79

Table 4.1: Optimized parameter values

5
Conclusion

5.1 Conclusions drawn from fixed mean diameter of spring

In section 4.1 the spring results when mean diameter is fixed are presented. It can be seen in figure 4.1 region 1 is limited by having insufficient number of coils. This means when an attempt is made to design a spring in this region of the plot the spring stiffness required is lower limiting factor for the spring design is the wire diameter which cannot be obtained that is suitable in such a way that it would be thick enough to take the load and satisfy stress limits.

The stress in region 2 and 3 can be overcome by choosing appropriate design length of the spring. The material properties of the spring can also show a different result. Choosing a spring material with better material properties can also be a good way to make the spring work in suitable range.

In region 4 and 5 it is quite evident that the force acting on spring is high. As the installation ratio decreases stiffer springs are required. This can be achieved by changing the wire diameter upto the maximum limit however the number of coils have to be reduced as well to accommodate he high spring stiffness required. This results in lack of minimum number of coils available as the spring length becomes shorter when number of coils are reduced. One might argue that the spring length can be compensated by having higher pitch between the coils. It is to be noted that the pitch cannot exceed half the mean diameter of the spring.

From figure 4.2 it is quite evident that increasing the design length of a spring for fixed wheel travel helps to certain extent. It is also limited for high design length due to stress induced and buckling effects of the spring. Similarly in figure 4.4 we can see that springs with wide mean diameters are not suitable for smaller installation ratio. Also in both the above figures the working range for wheel force is limited with lower installation ratio.

5.2 Conclusions drawn from fixed installation ratio of suspension system

In subsection 4.2.1 the results from the analysis tool is presented. The results from this analysis show that multiple failure criteria have contributed for the design failure in region 1, In region 2 the it is quite clear that minimum number of coils in the spring becomes the important factor for lack of solutions. This is due to the fact that when mean diameter of the spring increases, the wire diameter has to be reduced significantly to maintain required stiffness of the spring but the wire diameter is limited by the industrial standards. This can be solved by having lesser number of coils on the spring which cannot go lesser than 3 coils as it would lead to excessive torsional stress in the spring and result in spring failure.

Some interesting details can be observed in the combined plots. Lower installation ratio 0.5 in figure 4.6 has very limited feasible solutions and even by increasing the design length of the spring feasible spring designs are not available.

In figure 4.7 for installation ratio 0.7 it can be observed that increasing the design length of the spring gives bigger scope for tuning of the spring. However it is also observed it is not endless, the design length of 289mm has very little impact on the force range for the springs.

In figure 4.8 it can be seen that lower design length 209mm to 249mm have no results. The main reason being the spring is compressed and extended beyond the desired working range of the spring. As the installation ratio increases the jounce and rebound length of the spring increases this demands in higher compression and extension lengths of the spring.

It is also interesting to observe that from figures 4.5 to 4.8 that the starting point of wheel force which can be tuned for decreases as the installation ratio of the spring increases.

5.3 Conclusions drawn spring stiffness relation

In the figure 4.9 it is seen that the feasible solution exist for shorted design length of the springs and the stiffness of the springs are higher at installation ratio 0.5. This contradicts to the fact that stiffness of spring decreases as the length of spring increases. So the feasible solution area is quite limited.

In figure 4.10 there is a larger area of feasible solution and spring stiffness are much lower than for installation ratio 0.5. This allows for designing springs with longer design length and more number of coils. It can be seen that solutions of design length 289mm overlap with the other design length solutions suggesting that increasing the design length always would necessarily not increase the force acting at wheel in design position.

From figure 4.11 it can be seen there is room to accommodated spring with longer design length. The spring stiffness are much lower when compared to figure 4.10.

5.4 Conclusions drawn after optimization

In figure 4.12 the relation between the objectives of optimization is seen. This optimization is performed for different design length limits. It can be concluded that the optimized weight of the spring is almost linearly dependent on the force acting at wheel in design position. However, from table 4.1 it can be seen it is not just one parameter that changes in optimized result as the wheel force changes but it is combination of different parameters which is producing this result.

From the analysis and optimization performed it can been seen higher installation ratio for the spring the weight of the spring is lower and the springs can be tuned for larger range for a suspension system. Choosing the right design length of the spring is also an important parameter which will affect the tune-ability of the springs. The mean diameter of the spring is the third most important parameter which will affect the overall performance of the springs. Choosing the right mean diameter also determines the extent to which the springs can be tuned. Further the number of coils and pitch are determined by the spring stiffness. From the optimization tool it can be seen that force acting on the spring influences the overall weight of the spring. The optimization curve will vary when the wheel jounce and rebound length changes for same wheel force.

6
Future Work

One of the limitation of this study is the end coil specification. The spring analysis tool can be developed for different end coil conditions suitable according to the need of the user. This means the design formulas change according to the end coil condition. It will also facilitate in co-relation of the tool result with the spring manufactured. Further, this study can also be performed with different material characteristics to understand how the material properties would influence of other design parameters. Surface treatment factors can be included in the analysis program to have better co-relation of data.

The tool can be further developed to understand how the wheel rate and frequency would affect the overall vehicle dynamics. Other vehicle dynamic parameters could be related to the wheel stiffness and a tool can be developed for selecting a suitable spring for better vehicle dynamics

The optimization tool can be further developed by including various objectives and perform a deeper study on what objective would result in solution desired performance of the springs. There is also future scope for design optimization principles to be used during the concept development phase of the vehicle which and be explored.

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A

Appendices

A.1 Frequency based filtering

For selection of installation ratio, an initial guess can be made using frequency filtering of solutions obtained. In the example shown, this method is applied on the baseline parameters considered. It is found that installation ratio 0.7 would have highest number of feasible spring design solutions when filtered with 1.4 ± 0.03 Hz of wheel frequency. The unfiltered data has a peak at 0.63 which is not feasible as the required wheel frequency cannot be obtained at this installation ratio.

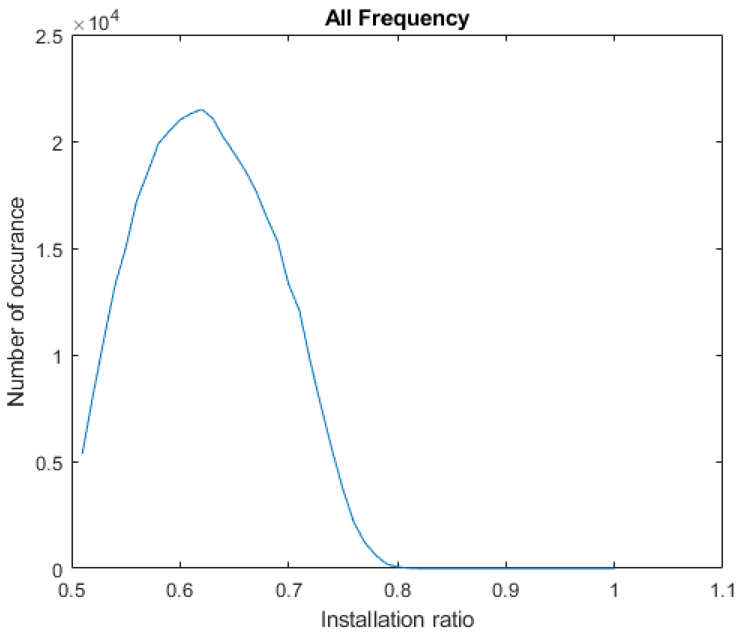

Figure A.1: Data without frequency filtering

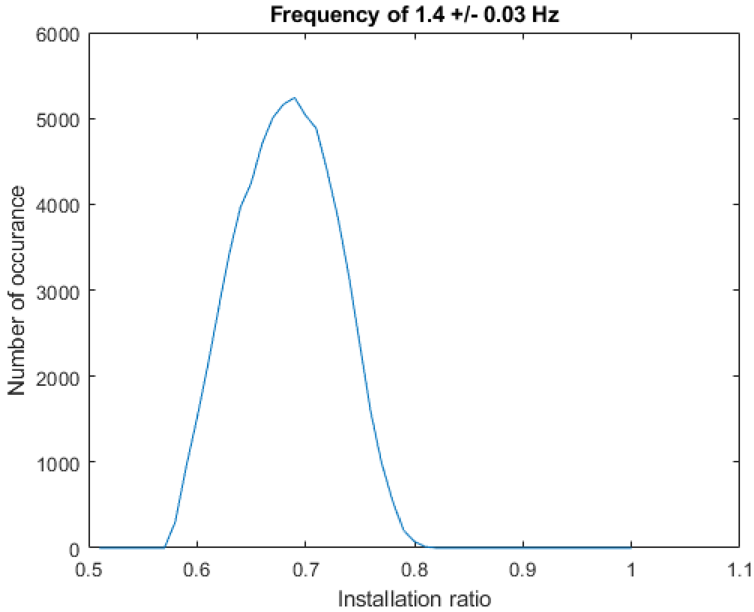

Figure A.2: Data filtered for 1.4 ± 0.03 Hz