DESIGN AND ANALYSIS OF LEAF SPRING FOR SOLAR VEHICLE

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Abstract- Leaf springs are widely used as automotive suspension to absorb shock loads. Suspension system in an automobile determines the riding comfort of passengers and the amount of damage to the vehicle. The main function of leaf spring assembly as suspension element is not only to support vertical load, but also to isolate road-induced vibrations. This paper is the work performed towards the optimization of the leaf spring for solar vehicle with constraints of maximum bending stress, von-Mises stress, deflection and natural frequency of leaf spring under safety load condition. Chromium steel AISI 5150 is used for front and rear leaf spring material. In this paper, front and rear leaf spring are analysed by changing various thickness. The thickness and width of the front leaf springs for optimum design are 8 mm and 50 mm. Thickness and width of the rear leaf spring design are 5 mm and 45 mm. The von-Mises stress of front leaf spring is 755.44 MN/m^2 and rear leaf spring is 662.50 MN/m^2. Working frequency of front and rear leaf spring are 1.466 Hz and 1.815 Hz respectively. Working frequency do not match with natural frequencies of the front and rear leaf spring at six mode shapes. Therefore, the designed leaf spring is safe for modal analysis. SolidWorks software is used for modelling of leaf spring designs and ANSYS software is used for structural and modal analysis of leaf springs.

Keywords- Automobile, Bending stress, Deflection, Leaf spring, Modal analysis, Structural analysis.

I. INTRODUCTION

A solar vehicle is an electric vehicle powered completely or significantly by direct solar energy. Usually, photovoltaic (PV) cells contained in solar panels convert the sun's energy directly into electric energy. The term "solar vehicle" usually implies that solar energy is used to power all or part of a vehicle's propulsion [8]. There are many components in a solar car such as solar panel, chassis frame, steering system, transmission system, suspension system, brake system, axle, wheel, motor, etc. a solar car works as the following principle. Firstly, solar panel converts light energy from the sun into the electrical power. Solar controller converts the energy collected from the solar array to the proper system voltage, so that the batteries and motor can use it. Then, motor controller adjusts the amount of energy that flows to the motor. Finally, the motor uses that energy to drive the transmission system. In the present work, the objective of this paper is to select the optimum thickness design of front and rear leaf spring for light weight solar vehicle.

The vehicle body or frame supports the weight of the engine, the power train, and the passengers. The body and frame are supported by the springs on each wheel. The weight of the frame, body, and attached components applies an initial compression to the springs. The springs compress further as the wheels of the vehicle hit bumps or expand, such as when the wheels drop into a hole in the road. The springs cannot do the complete job of absorbing road shocks. [6]. The many type of suspension springs are coil spring, leaf spring, torsion bar and air spring. A leaf spring is a simple type of suspension spring commonly used in vehicle. The most commonly used leaf spring is the semi-elliptic type. Leaf springs were used first on horse-drawn and later on railway rolling stock. It consists of a number of flat steel springs, of varying lengths, bolted together into a single unit. The spring is fastened to the front or rear axle by means of U-bolts. The ends of the spring are shackled to the frame. The semi-elliptical leaf spring is shown in Figure 1.

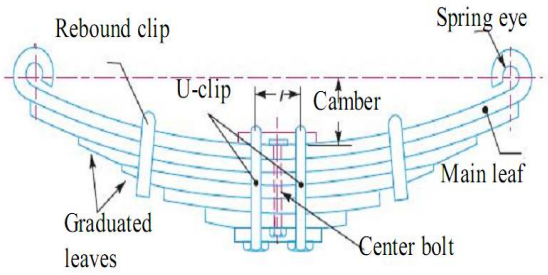


Fig.1. Typical Semi-Elliptical Leaf Spring [5]

The longest leaf known as main leaf or master leaf has its ends formed in the shape of an eye through which the bolts are passed to secure the spring to its supports. The other leaves of spring are known as graduated leaves. Rebound clips are located at intermediate positions in the length of the spring, so that the graduated leaves also share the stresses induced in the full length leaves when the spring rebounds [5].

In this work, semi-elliptical leaf spring design is used for suspension system. The number of leaves for front leaf spring is two leaves and rear leaf spring has three leaves. Leaf spring designs are modelled with SolidWorks software. Five different thickness are considered for structural analysis of front and rear leaf spring design by using ANSYS software. Mode frequencies for the spring are also determined using ANSYS software.

II. DESIGN PROCEDURE OF THE LEAF SPRING

In design procedure of leaf springs, firstly, the weight of vehicle is calculated. Then, thickness, width, length and stiffness of springs are also calculated depending on the specification data.
Table 1 shows the specification and technical data of a solar vehicle

Table1: Specification of Solar Vehicle

Technical Category	Dimensions	units
Vehicle gross weight	490	kg
Weight of solar panel	46	kg
Weight of motor	24	kg
Weight of batteries	168	kg
Seating capacity	2	-
Weight of person	180	kg

Table 2 shows the specifications for front and rear leaf spring.

Table 2: Specification of Leaf Spring

Parameters	Front leaf spring	Rear leaf spring
Length of leaf spring, $2L_1$	530 mm	680 mm
Number of leaves, n	2	3
Number of full length leaves, n_F	1	1
Number of graduated leaves, n_G	1	1
U-bolt length, l	65 mm	60 mm
Camber of spring, δ_{max}	120 mm	80 mm

The design procedure of leaf spring involves the following steps.

1. Calculation of the unsprung weight

In today's standard size automobile, the weight of unsprung components is normally in the range of 13 to15 percent of the vehicle net weight.

$$\text{unsprung weight} = 0.15 \times \text{vehicle net weight} \quad (1)$$

2. Calculation of the sprung weight

Gross vehicle weight is the sum of unsprung weight and sprung weight. Sprung weight can be calculated as

$$\text{sprung weight} = \text{gross weight} - \text{unsprung weight} \quad (2)$$

3. Calculation of vehicle weight on suspension

The vehicle weight on suspension can be calculated as

$$\text{Vehicle weight} = \text{sprung weight} + \text{solar weight} \quad (3)$$

4 Calculation of load on each suspension spring

By using quarter car model approach, load on each suspension is one fourth of the vehicle weight on suspension.

$$\text{load on each spring} = \frac{1}{4} \times \text{vehicle weight} \quad (4)$$

Chromium steel AISI 5150 is used for material of leaf spring. Mechanical properties of AISI 5150 is shown in Table 3.

Table 3: Material Properties of Leaf Spring

Parameters	Values	Units
Density	7850	kg/m^3
Tensile stress	1620	MN/m^2
Yield stress	1520	MN/m^2
Modulus of elasticity	210	GN/m^2
Passion ratio	0.3	-

Allowable stress of material can be calculated as;

$$\text{Allowable stress} = \frac{\text{Yield stress}}{\text{Safety factor}} \quad (5)$$

Safety factor of front and rear leaf spring is 1.65 and 2 respectively.

5 Length of leaf spring leaves

The length of leaf spring leaves may be obtained as following equations.

When band is used, the effective length of spring is

$$\text{Effective length} = 2L_1 - l \quad (6)$$

When U-bolts are used, the effective length of spring is

$$\text{Effective length} = 2L_1 - \frac{2}{3}l \quad (7)$$

when there is only one full length leaf, the number of leaves to be cut will be n and when there are two full length leaves (including one master leaf), then the number of leaves to be cut will be (n-1).

Length of smallest leaf can be calculated as;

$$L_{smallest} = \frac{\text{Effective length}}{n} + \text{Ineffective length} \quad (8)$$

Length of next leaf can be calculated as;

$$L_{next} = \frac{\text{Effective length}}{n} \times 2 + \text{Ineffective length} \quad (9)$$

Length of $(n-1)^{th}$ leaf can be calculated as;

$$L_{(n-1)} = \frac{\text{Effective length}}{n} \times (n-1) + L_{\text{Ineffective}} \quad (10)$$

Ineffective length is the distance centre of U-bolt.

4. Calculation of thickness and width of leaf spring

The leaf spring may be considered equivalent to two cantilever beams. The bending stress can be calculated as;

$$\sigma = \frac{6WL}{nbt^2} \quad (11)$$

The maximum deflection of leaf spring can be calculated as;

$$\delta = \frac{6WL^3}{nEbt^3} \qquad (12)$$

Two unknown equations for calculation of thickness and width are derived from bending stress and deflection equation and these two equations are expressed as follows;

$$bt^2 = \frac{6WL}{n\sigma} \qquad (13)$$

$$bt^3 = \frac{6WL^3}{nE\delta} \qquad (14)$$

By solving equation (13) and (14), thickness and width of leaf spring can be calculated.

5. Calculation of principal stresses, $\sigma_{1,2}$

The principal stresses can be calculated by using

$$\sigma_{1,2} = \frac{1}{2}(\sigma_y + \sigma_x) \pm \frac{1}{2}\left[(\sigma_y - \sigma_x)^2 + 4\tau^2\right]^{\frac{1}{2}} \qquad (15)$$

6. Calculation of von-Mises stress, $\bar{\sigma}$

The von-Mises stress can be calculated by using

$$\bar{\sigma} = \sqrt{\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2\right]} \qquad (16)$$

7. Calculation of stiffness of spring

The stiffness of spring can be calculated as;

$$k = \frac{\text{Total load on the spring}}{\text{Maximum deflection}} \qquad (17)$$

8. Calculation of equivalent stiffness of spring

Any automobile has two elastic elements: spring of the suspension and tyre of the wheel. Two springs are combined in series as shown in Fig.2.

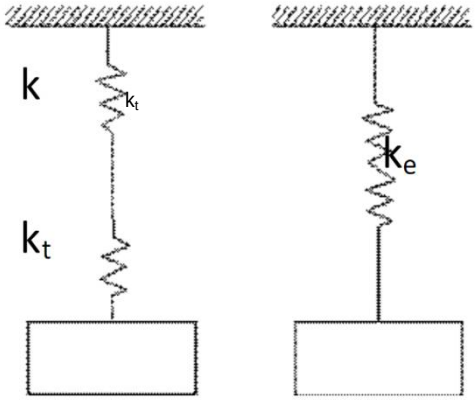


Fig.2. Equivalent spring in series

The equivalent stiffness can be calculated as follow;

$$k_e = \frac{k \times k_t}{k + k_t} \qquad (18)$$

k_t is the range from 180000 N/m to 200000N/m [1]

9. **Calculation of natural frequency**

The natural frequency of anybody or a system depends upon the geometrical parameters and mass properties of the body. The natural frequency can be calculated as;

$$\omega_n = \sqrt{\frac{k_e}{m_s}} \qquad (19)$$

Thomas Gillespie states that suspension system natural frequencies less than 1 Hz will cause motion sickness in a vehicle's passengers, and suspension system natural frequencies greater than 2.5 Hz will provide a 'harsh' ride. [2].

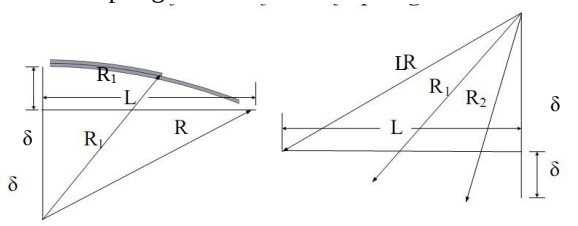
10. Calculation of leaf spring weight

Weight of leaf spring can be calculated by using

$$W = \text{Density} \times \text{Volume} \times \text{Acce : due to gravity} \qquad (20)$$

11. Calculation of radius for leaf spring

(a) Radius for front leaf spring (b) Radius for rear leaf spring



(a) Radius for front leaf spring (b) Radius for rear leaf spring

Fig.3. Radius curvature of leaf spring

Radius curvatures of front and rear leaf spring are shown in Figure 3 (a) and (b) respectively. R is radius to which the leaves should be initially bent and δ is the camber of spring. Radius for master leaf R is calculated as;

$$R^2 = L^2 + (R - \delta)^2 \qquad (21)$$

$$R = \frac{\left(\frac{L^2}{\delta} + \delta\right)}{2} \qquad (22)$$

Radius for first leaf can be calculated as

$$R_1 = R + \text{Thickness of leaf} \qquad (23)$$

Radius for second leaf can be calculated as

$$R_2 = R_1 + \text{Thickness of leaf} \qquad (24)$$

Table 4: Design Result Data of Leaf Spring

Parameters	Front leaf	Rear leaf
Thickness, t	8 mm	5 mm
Width, b	50 mm	45 mm
Allowable stress, σ_{all}	921.212 MN/m^2	760 MN/m^2
Bending stress, σ	821.177 MN/m^2	649.465 MN/m^2
Deflection, δ	105.689 mm	63.338 mm
Stiffness of spring, k	17.822 N/mm	36.049 N/mm
Equivalent stiffness, k_e	16.294 N/mm	30.300 N/mm
Natural frequency, ω_n	1.466 Hz	1.815 Hz
Length of master leaf	530 mm	680 mm
Length of second leaf	-	467 mm
Length of smallest leaf	297.500 mm	360 mm
Radius of master leaf, R	1382 mm	944 mm

Radius of second leaf, R_2	-	949 mm
Radius of smallest leaf, R_1	1390 mm	954 mm
Weight of leaf spring	25.489 N	26.104 N

Table 4 shows the result data of front leaf spring

III. NUMERICAL SIMULATION OF LEAF SPRING

A finite element structural analysis of the front and rear leaf spring models under the Y- direction load was analysed with various thickness by using ANSYS software. The input geometry was drawn in SolidWorks with result parameters.

3.1 Structural Analysis of Front Leaf Spring

The front leaf spring is loaded by forces from the vehicle weight at the contact region of car body and leaf spring.

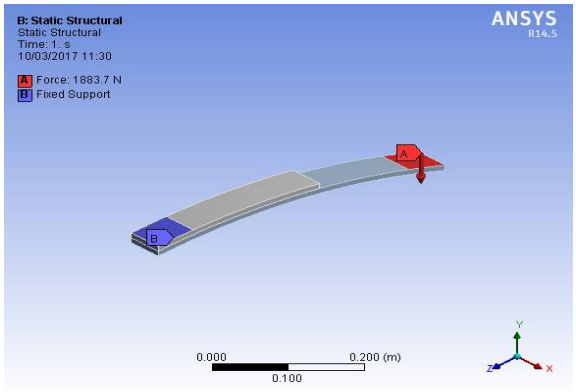


Fig.4. Loading condition and fixed position of front leaf spring

The value of vehicle weight on each of front suspension spring is 1883.704 N. Fixed support is provided at the ineffective length of front leaf spring. The loading condition and fixed position of front leaf spring are as shown in Fig.4.

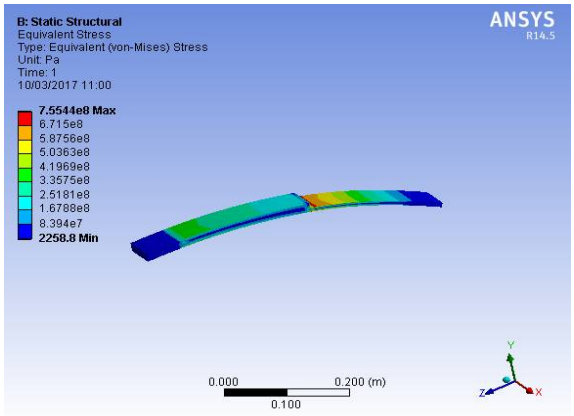


Fig .5. von-Mises stress in front leaf spring using thickness 8 mm

The equivalent (von-Mises) stress of front leaf spring with 8 mm thickness is shown in Fig.5. The maximum von-Mises stress 755.44 MN/m^2 which occur at the end of the smallest leaf.

Table 5: Comparison of von-Mises Stress and Allowable Stress for Front Leaf Spring

Thickness (mm)	von-Mises stress (MN/m^2)	Allowable stress (MN/m^2)
6	1622.2	921.2
7	993.3	
8	755.4	
9	606.1	
10	493.7	

Table 5 shows the numerical result of von-Mises stress for front leaf spring with different thickness. In Table 5, the von-Mises for thickness 6 mm and 7 mm are greater than allowable stress of material. Starting from thickness 8 mm, the von-Mises stress value is below the allowable stress of material. The greater the thickness value, the more satisfy the leaf spring design. But, light weight is the main objective for this research. Therefore, thickness 8 mm is chosen for front leaf spring design to safe light weight and economic.

3.2. Structural Analysis of Rear Leaf Spring

The rear leaf spring is loaded by forces from the vehicle weight at the spring eye of leaf spring. The value of vehicle weight on each of rear suspension spring is 1141.639 N.

Fixed support is provided at the ineffective length of rear leaf spring. The boundary condition and fixed position of rear leaf spring are as shown in Fig.6.

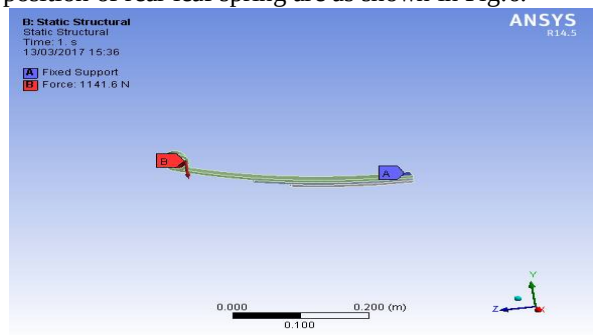


Fig.6. Loading condition and fixed position of rear leaf spring

The equivalent (von-Mises) stress of rear leaf spring with 5 mm thickness is shown in Fig.7. The maximum von-Mises stress 662.5 MN/m^2 which occur at the end of the second leaf.

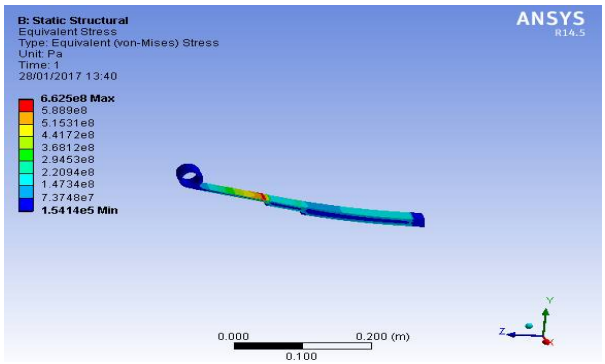


Fig .7. von-Mises stress in rear leaf spring using thickness 5 mm

Table 6: Comparison of von-Mises Stress and Allowable Stress for Rear Leaf Spring

Thickness (mm)	von-Mises stress (MN/m^2)	Allowable stress (MN/m^2)
3	1332.5	760
4	1027.6	
5	662.5	
6	442.7	
7	326	

Table 6 shows the numerical result of von-Mises stress for rear leaf spring with different thickness.
In Table 6, the von-Mises for thickness 3 mm and 4 mm are greater than allowable stress of material. Starting from thickness 5 mm, the von-Mises stress value is below the allowable stress of material. The greater the thickness value, the more satisfy the leaf spring design. But, light weight is the main objective for this research. Therefore, thickness 5 mm is chosen for rear leaf spring design to safe light weight and economic.

3.3. Modal analysis of front and rear leaf spring

A modal analysis is typically used to determine the vibration characteristics (natural frequencies and mode shapes) of a structure or a machine component while it is being design. It can also serve as a starting point for another, more detailed, dynamic analysis, such as harmonic response or full transient dynamic analysis [7].
In modal analysis of front leaf spring, only fixed support is provided at the contact region of car body and leaf spring.

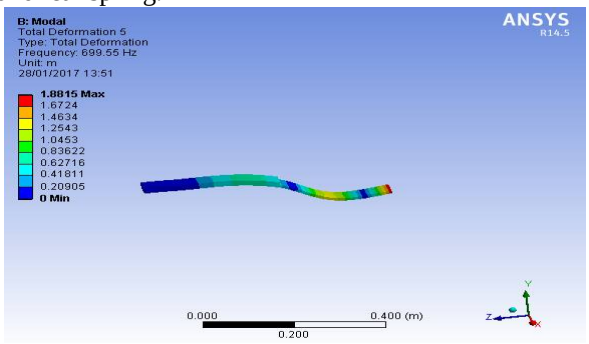


Fig.8. Fourth mode shape of front leaf spring

The fourth mode shape of front leaf spring is shown in Fig.8. Total deformation of fourth mode shape is 1.881 m at frequency 699.55 Hz.

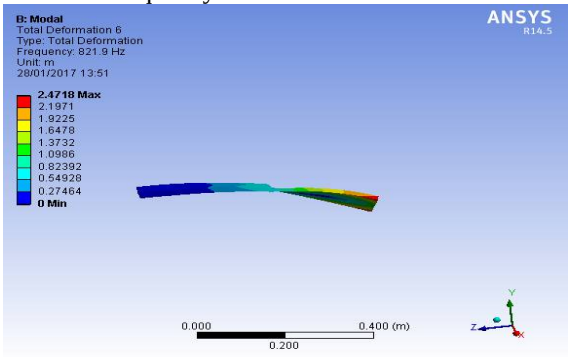


Fig.9. Fixth mode shape of front leaf spring

The Fixth mode shape of front leaf spring is shown in Fig.9. Total deformation of fixth mode shape is 2.471 m at frequency 1115.3 Hz.

Table 7: Natural Frequencies at Six Mode Shapes for Front Leaf Spring

Mode	1	2	3	4	5	6
Frequencies, Hz	67.3	227.3	240.3	699.5	821.9	1115.3

Table 7 shows the natural frequencies at six mode shapes for front leaf spring.

In modal analysis of rear leaf spring, fixed support is provided at the ineffective length of the spring. Only own weight of spring is considered for the modal analysis.
The total deformation of third mode shape of rear leaf spring is 2.587 m at frequency 324.25 Hz as shown in Fig.10.

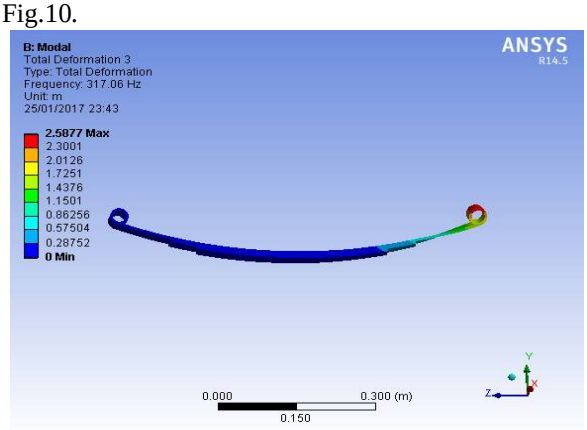


Fig.10. Third mode shape of rear leaf spring

The total deformation of fifth mode shape of rear leaf spring is 176.06 mm at frequency 317.06 Hz as shown in Fig.11.

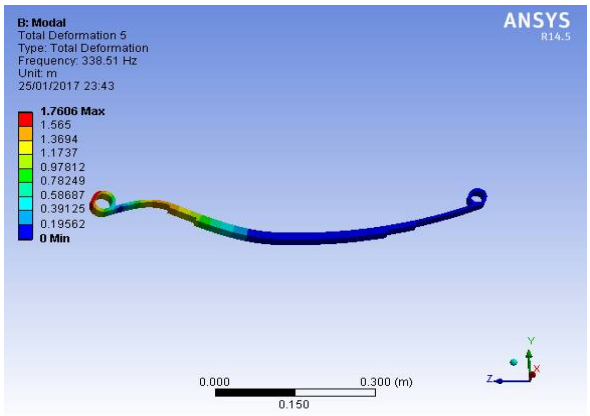


Fig.11. Fifth mode shape of rear leaf spring

Table 8: Natural Frequencies at Six Mode Shapes for Rear Leaf Spring

Mode	1	2	3	4	5	6
Frequencies, Hz	90.62	106.24	317.06	324.25	338.51	349.36

Table 8 shows the natural frequencies at six mode shapes for rear leaf spring.

CONCLUSIONS

In the present work, front and rear leaf spring design are considered cantilever beam design. Chromium steel AISI 5150 is used for material of leaf spring. Front and rear leaf spring for solar vehicle was modeled by using SolidWorks software and analyzed for various thickness by using ANSYS software. From the result, it is observed that the bending stresses of front and rear leaf spring are below the allowable stress of material. Moreover, the deflection of front and rear leaf spring are smaller than the maximum camber height of spring. Therefore, design of front and rear leaf spring are satisfied. In this research, the optimum design dimensions of front leaf spring are thickness 8 mm and width 50 mm. Thickness and width of rear leaf spring are 5 mm and 45 mm respectively. The von-Mises stress of front leaf spring is 755.440 MN/m^2 and rear leaf spring is 662.500 MN/m^2. Mode frequencies for the front and rear leaf spring are also determined using ANSYS software. Working frequency of front and rear leaf spring are 1.466 Hz and 1.815 Hz respectively. Maximum deformation of front leaf spring is 2.471 m that occurs at natural frequency 829.1 Hz of fifth mode shape. Maximum deformation of rear leaf spring is 2.587 m that occurs at natural frequency 317.06 Hz of third mode shape. Working frequency do not match with natural frequencies of the front and rear leaf spring at six mode shapes. Therefore, the designs of front and rear leaf spring are safe for modal analysis.

ACKNOWLEDGMENTS

A special thanks is offered to Dr. Tin San, Professor and Head of Department of Mechanical Engineering, Mandalay Technological University, for his encouragement, constructive guidance and kindly advice throughout the preparation of this paper.
The author especially grateful to Supervisor, Dr. Htay Htay Win, Professor, Department of Mechanical Engineering, Mandalay Technological University for her encouragement, patient guidance, invaluable supervision, kindly permission and suggestions throughout the paper.

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