International Journal of Computational and Experimental Science and ENgineering
(IJCESEN)
Vol. 11-No.2 (2025) pp. 2856-2871
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Research Article

Optimum Design of Leaf Spring: A case study

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Article Info:

DOI: 10.22399/ijcesen.1552
Received : 20 January 2025
Accepted : 31 March 2025

Keywords

FEA
Von–Mises stress
deformation
strain energy
harmonic response

Abstract:

Leaf spring is a main and an important part of the suspension system. It is widely used in many types of vehicles due to its high capacity to withstand loads and absorb shocks, as well as relatively low manufacturing costs and the ability of maintenance. In this study, a traditional material of alloy steel (Steel 55Si2Mn90) is used, where alternative designs are proposed for the model that used in a medium-load car (TATA ACE). The objective of this study is to obtain an optimal design that is suitable under various loading conditions, where the study focused on the camber parameter as the main variable in the design of the calculations of Von–Mises stress and deformation and strain energy under the static loads, also frequency response and phase response under the harmonic loads.
The numerical results by Ansys v. 16.1 showed that case 3 is the best design that can be used as an alternative model to the original model (case 2).

1. Introduction

A multi-leaf spring consists of a series of flat plates called leaves of the spring, usually of semi-elliptical shape. Leaf springs are commonly used in a wide range of industries, including automotive, railway, and suspension systems. Its function is basic support and stability to withstand loads. Leaf springs play a prominent role in determining performance, efficiency and durability [1:4] In recent years, it has been observed that there is a trend of researchers and designers towards improving the design through careful analysis and modification of design standards and in modern ways, to be more suitable in operational conditions under the influence of loads (static and dynamic). In addition to reducing weight. Optimal design involves a multivariate approach taking into account key factors such as material selection, number of sheets used, geometry, and manufacturing techniques. Advances in CAD-assisted design, simulation tools and analytical models have enabled researchers to explore and evaluate different designs more efficiently and accurately [5:10]. Figure (1) explains an arrangement of leaf springs in the traditional fashion [7].

When choosing the material used in the manufacture of leaf springs, the material must have good resistance to variable loads (tensile and compressive loads). In addition, it must have an appropriate modulus of elasticity that allows it to bend and absorb shocks effectively and appropriately. For the purpose of enhancing the period of use (i.e. its longevity), materials with good corrosion resistance due to their exposure to moisture and various climatic conditions can be used. Weight and cost also play a key role in balancing performance, efficiency and economic considerations. Therefore, it is necessary to focus on several important factors in the selection of materials, which are (hardness and flexibility, fatigue resistance, corrosion resistance, weight and cost). Figure (2) explained to leaf spring characteristics.

Figure 1. *An arrangement of leaf springs in the traditional fashion [7].*

Figure 2. *leaf spring characteristics.*

2. Literature Review

The literature reviews primarily focuses on the optimization theories for achieving the optimum design of leaf springs, with a particular emphasis on the replacement of traditional steel leaf springs with composite leaf springs. The review aims to explore the latest research and advancements in this area, focusing on the techniques and methodologies employed to enhance the design and performance of leaf springs through the use of composite materials. The majority of studies have placed their focus on stresses and deformation as the primary parameters in the design process. To facilitate this analysis, CAD software has been widely utilized for modeling and conducting thorough analyses. Used heterogeneous material is a significantly superior alternative to expensive composite materials and the current steel-only model for leaf springs. By incorporating the heterogeneous material, the stress in the leaf assembly is effectively reduced by an impressive 86 %, leading to a considerable increase in its lifespan [1]. The parabolic leaf spring was modeled using CATIA for CAD design, and the model was then imported into ANSYS Workbench for analysis. The findings revealed that substituting steel with a composite material led to significant deflection, minimal stress variation, and a substantial reduction in weight [2]. Focused to the properties of the selected material before proceeding with manufacturing. Once the verification is complete, appropriate manufacturing methods are employed. Subsequently, design calculations are conducted for both conventional and innovative spring systems. The outcomes of these calculations are then used to compare the deflection and weight of the springs. As a result, the composite spring system emerges as lightweight and offers superior suspension capabilities when compared to its Steel counterpart [3]. Examined the design parameters and their impact, both qualitatively and quantitatively, on the kinematics of the axle and the stress behavior. Among these parameters, the eye lever (e) emerged as the most significant one, influencing the kinematics of the wheel joint and subsequently affecting the steering behavior of the vehicle under vertical loading conditions. Furthermore, the type of eye also played a crucial role in influencing the kinematics of the leaf spring and the steering behavior, particularly during braking. In addition, gained regarding the interplay between the major design parameters of the leaf spring system, their effects on the stress behavior of the leaf spring, and their influence on the vehicle's steering behavior [4]. Developed a Hybrid composite leaf spring that achieves multiple goals: reducing weight, increasing stiffness, decreasing stresses, and enhancing natural frequencies [5]. While [6], interested in the comparison between theoretical and numerical analysis (FIA), where he proved that the stress of Von–Mises is less than the ultimate tensile stress of the material, noting the identical deviation in both methods compared was the theoretical and numerical (FEA) result. Focused to fatigue factor of glass fiber reinforced polymer (E-glass/epoxy) material compared to conventional steel where it proved that the results of the fatigue analysis are much lower than the steel use factor as well as a clear decrease in density (85 % compared to steel). A derived an equation to calculate the rigidity of leaf springs when there is direct contact between the main and auxiliary springs, as well as discuss several parameters that are of high importance in the design, in addition the acceptability of the results obtained by FIA [8]. Interested in studying the effect of weight, hardness and resistance to leaf springs made of conventional steel with compared them to composite materials, where the results showed that composite materials are more effective, less weight, and less cost at the same design specifications [9]. Through experimental and analytical results, it was proved that glass fiber reinforced composite (GFRC) are more efficient than natural-fiber-reinforced (NFRC/JFRC), in addition to achieving low weight and less resistance compared to steel [10]. Focused on modifying the original structure to provide a single leaf spring model using a boron composite material and through analysis it was revealed as a material that can be used in car suspension systems where the material proved to be highly cost-effective [11]. Focused on comparing materials (steel, fiber reinforced plastics (FRP), E-Glass/Epoxy, S-Glass Epoxy, and Kevlar) materials with ASTM standards where it proved that Kevlar is more performant and achieves less weight [12, 13]. Used a composite material (glass carbon) with different reinforcing being varied angles, and results indicated that the composite material used is better than traditional materials in terms of properties and specifications [14]. Design involved analyzing the front and rear leaf springs with various thicknesses. It was observed that the working frequency did not align with the natural frequencies of the leaf springs across six mode shapes. As a result, it can be concluded that the designs of both the front and rear leaf springs are considered safe for modal analysis [15]. Compared against conventional steel, the chosen materials were glass fiber reinforced polymer (E-glass/epoxy), carbon epoxy, and graphite epoxy. The utilization of composite leaf springs resulted in a significant reduction in weight, with E-Glass/Epoxy reducing weight by 81.22 % and Carbon/Epoxy reducing weight by 90.51 % compared to conventional leaf springs [16]. Focused on analyzing the deformations and stresses experienced by the existing leaf spring design when subjected to both static and dynamic loads. Additionally, a proposed experimental approach is suggested for further investigations in future research [17]. The verification process confirmed the suitability of utilizing a parabolic leaf spring in an air suspension system, aiming to reduce material wear and address any inherent deficiencies [18]. Selected is a graphite epoxy composite, which offers comparable mechanical and geometrical properties to steel while being more cost-effective. By utilizing the graphite epoxy composite, the weight of the leaf spring is reduced by 79.88 %. Additionally, a combination of steel and graphite epoxy reduces the weight by 36.51 % compared to a steel leaf spring [19]. An analytical approach was employed to estimate the maximum payload capacity of the vehicle and determine the natural frequencies of the leaf spring for comparison with the excitation frequency, with a focus on safety factor, the study indicated the use of composite materials instead of steel to reduce maintenance requirements and enhance the durability of the car [20]. Reviewed that focuses on composite materials and compare them to traditional leaf springs made (steel alloy) by studying material selection, design procedures and analysis [21]. Interested in comparing the materials used in the leaf springs of the Mahindra pickup and the proposed alternative materials, as the results of the analysis showed that there is a significant decrease in the displacement of steel in contrast to achieving a decrease in weight for alternative materials [22]. Interested in weight reduction, as he proved that there is a slight difference between 55Si2Mn90 compared to 50CrV4 [23]. Used the fused filament fabrication techniques (FFF) in 3D printing to investigate a carbon-epoxy composite that is a suitable alternative to steel leaf spring [24]. Interested of reducing weight while retaining important characteristics and performance of the suspension system by developing an analytical model using Grey Wolf Optimizer (GWO), thus obtaining reduced of production costs and decreases the design time [25]. Studied the deformation prediction of conventional leaf springs and compared them to modified models by non-linear regression analysis using Taguchi's design of experiments [26]. Interested to reducing weight by using hybrid materials and comparing them with (traditional materials, and composite materials) and proving that hybrid materials are effective in the same operating conditions [27]. Focused to place on reducing stresses and displacements used traditional materials and comparing them with other materials [28]. It aims to weight reduce were used fiber-glass reinforced plastic composite material and comparing it with steel, as it has been proven that the composite material has a maximum stress energy compared to steel [29]. Improved stiffness and strength performance was done using numerical analysis and developed by an algorithm to enhance design processes [30]. A Comprehensive review that includes optimization techniques and selection of appropriate materials that match the performance of leaf springs [31].

Focused to estimate of bending stresses of the steel springs, and by comparing the experimental and numerical results, the fatigue life can be predicted [32]. Employed the Takeuchi's theory to design optimize by focusing on the internal and external radii of the leaf springs and obtaining a fitting curvature as well as a significant reduction in weight [33]. A comprehensive review focused on numerical analysis and experimental methods with a study of the effect of materials selected to improve design processes [34]. Used several different materials to make the comparison on the Mahindra Pickup model without changing the geometry of the leaf springs and concluded that chromium vanadium steel is the best alternative material [35]. Improved the design through evaluating the stiffness and damping properties under the influence of loads by dynamic simulation using CAD software, in addition, consideration the experimental design within the proposed constraints [36]. A novel particle swarm optimization algorithm has been utilized to develop an optimized design. The results showed that the fiberglass achieves a reduction in weight while retaining rigidity [37]. Interested to composite materials were used as alternative materials to conventional springs, as the results indicate obtaining lightweight materials and high capabilities [38]. Studied encompasses an evaluation of the static and dynamic properties of two types of parabolic leaf springs: steel 55Si2Mn90 and composite leaf springs made from E glass fiber, carbon fiber, and Kevlar fiber. Among the materials tested, Kevlar fiber emerged as the most suitable choice for constructing lightweight vehicles, surpassing the performance of 55Si2Mn90 [39]. A novel approach is presented, wherein a negative stiffness honeycomb structure (NSHS) is integrated into the design of a leaf spring. The analysis of the proposed design and the conventional leaf spring is carried out using the widely used Finite Element Method (FEM) software Abaqus. The results of this study lead to the conclusion that the NSHS has the potential to serve as a viable leaf spring structure in automobiles. Consequently, the incorporation of NSHS into the leaf spring design offers a promising alternative to the traditional approach [40].

3. Leaf Spring Calculations

3.1. *Bending stress*

Figure (3) shows the flat plate of spring as a simply supported beam, and the maximum bending moment in the center and section modulus can be explained in equations (1 & 2) respectively [38]. While the bending stress (equation 3) it can be obtained by solve equations (1 & 2)

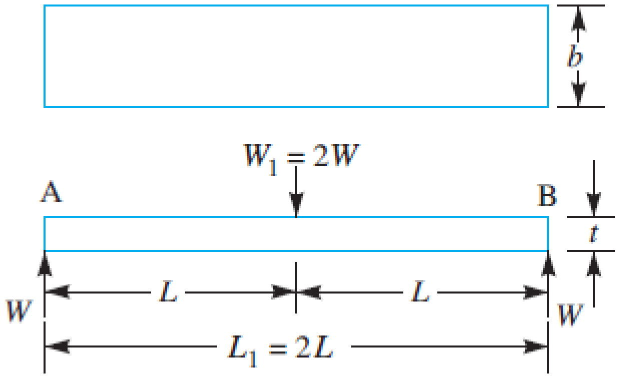


Figure 3. *Simply supported beam (Flat spring) [41].*

$$\text{Maximum bending moment (M)} = W \cdot L \quad \text{Equ. (1)}$$

$$\text{Section Modulus (Z)} = b \cdot t^2/6 \quad \text{Equ. (2)}$$

$$\text{Bending stress } (\sigma) = \frac{M}{Z} = \frac{6 \cdot W \cdot L}{b \cdot t^2} \quad \text{Equ. (3)}$$

Where: W= Load, t = Thickness of plate, b = Width of plate, and L = Length of plate or distance.

When arranging the leaves, a little consideration will appear for the compact as shown in figure (4), which will reduce the space or area occupied by the leaf spring. Therefore, the effect of bending stress cannot be taken alone without providing shear resistance, so it is necessary to have graduated leaves in length as well as suffixes that can be used and reformulate equations.

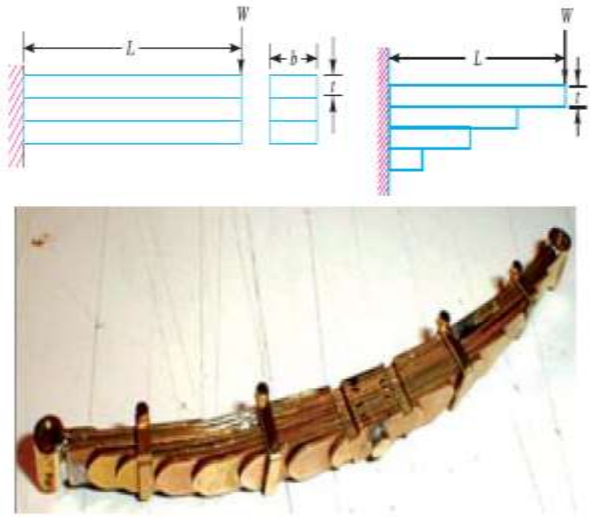


Figure 4. *Form a graduated or laminated leaf spring.*

$$\sigma_F = \frac{3}{2}\,\sigma_G$$
Equ. (4)

$$\frac{6\,W_F\,L}{n_F\,b\,t^2} = \frac{3}{2}\left[\frac{6\,W_G\,L}{n_G\,b\,t^2}\right]$$
Equ. (5)

$$\text{or} \quad \frac{W_F}{n_F} = \frac{3}{2} \times \frac{W_G}{n_G}$$
Equ. (6)

$$\frac{W_F}{W_G} = \frac{3\,n_F}{2\,n_G}$$
Equ. (7)

And resolve eqation (7) we get:

$$W_G = \left(\frac{2\,n_G}{2\,n_G+3n_F}\right) W$$
Equ. (8)

Also,
$$W_F = \left(\frac{3\,n_F}{2\,n_G+3n_F}\right) W$$
Equu. (9)

Where: W = Total load on the spring = WG + WF ,
WG = Load taken up by graduated leaves, anad
WF = Load taken up by full length leaves

Now, Bending Stress for full length leaves equal to:

$$\sigma_F = \frac{6W_F \cdot L}{n_F\,b\,t^2} = \frac{6\,L\,W}{n_F\,b\,t^2}\left(\frac{3n_F}{2n_G+3n_F}\right)$$

$$\therefore \sigma_F = \frac{18\,L\,W}{(2n_G+3n_F)b\,t^2}$$
Equ. (10)

$$\therefore \sigma_G = \frac{12\,L\,W}{(2n_G+3n_F)b\,t^2}$$
Equ. (11)

Von Mises stress (□□) can be calculated according to the equations below:

$$\therefore \sigma_v = \sqrt{(\sigma_{max})^2 + 3(\tau_{max})^2}$$
Equ. (12)

Where: maximum shear stress in the beam can express to ($\tau max = F / A$), A it’s the cross section of the beam, science (factor of safety: f. s = σy / σv) [17].

3.2 Deflection

Equation (12) explained the full length and graduated leaves maximum deflection in leaf spring.

$$\delta = \frac{2\,\sigma_F \cdot L^2}{3\,E \cdot t} = \frac{12\,W \cdot L^3}{E \cdot b \cdot t^3\,(2\,n_G+3\,n_F)}$$
Equ. (13)

Where: W1 = 2 W, and L = 2 L, and $I = \frac{(b.t^3)}{12}$, and n = Number of graduated leaves

4. Computational Modeling and Optimization

Computer-aided design and optimization techniques have played a significant role in the advancement of leaf spring suspension systems. Computational models allow engineers to simulate and analyze the behavior of leaf spring suspensions under different operating conditions. This enhanced to optimum design of leaf springs to achieve the main objectives required such as durability, noise reduction and ride comfort. Tables (1, and 2) are explained to chemical composition and properties of material selected respectively.

Table 1. *chemical composition of Steel 55Si2Mn90 [18, 29, and 42]*

Element	C	Si	Mn	Cr	Mo	P	S
Composition %	0.55	1.74	0.87	0.1	0.02	0.05	0.05

Table 2. *material properties of Steel 55Si2Mn90 [3,10, 27, and 29]*

Parameter	Young’s modulus GPa	Poison’s ratio	Ultimate tensile strength MPa	Yield strength MPa	Density Kg/m3	Spring rate N/mm
Value	210	0.3	1692	1500	7860	31.98

5. Finite element analysis (FEA)

Is a numerical method through CAD programs, where it is used in the design and analysis of engineering structures and is considered one of the most used methods due to the high response, accuracy of results and prediction of failure, which makes engineers and designers in factories develop multi-test studies to evaluate numerical results and compare with experimental results to reach the ideal state. Leaf springs are important component of suspension systems widely used in vehicles, such as automobiles, to provide support and stability through Noise mitigation, vibration dampening, absorption and shock. Table (3) shows geometrical parameters, and the figures (5 and 6) illustrate the 3D modeling of the leaf springs was done using the SolidWorks program v. 2023 and saved as an IGS formula, where the drawing was imported by the Ansys software for the purpose of conducting numerical analysis. While Figure (7) includes mesh generation, the following specifications (Advanced Size Function: Proximity and Curvature, Relevance Center: Medium, Initial Size: Medium, Smoothing: Medium, Transition: Fast, Span Angle Center: Medium, Curvature Normal Angle; Default 45.0 °) were applied to all models used in this study. This study focused on the parameter (Camber), where new designs (4 cases) were proposed and compared with the original design for the purpose of evaluating the strength of the leaf springs used in a suspension system of TATA ACE vehicle. The numerical analysis was performed under the influence of static and dynamic loads in same conditions.

Table 3. *Geometrical parameters of leaf spring (standard type of TATA ACE)*

Parameters	value	
Total length (mm)	930	
Thickness (mm)	8	
Width (mm)	60	
Camber (mm)	Case 1	82
	Case 2	82.77 (standard - Own source)
	Case 3	83.54
	Case 4	84.31
	Case 5	85

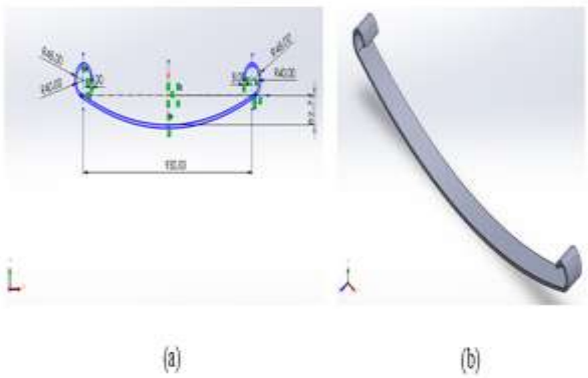


Figure 5. *3D modeling of master leaf springs by SolidWorks*

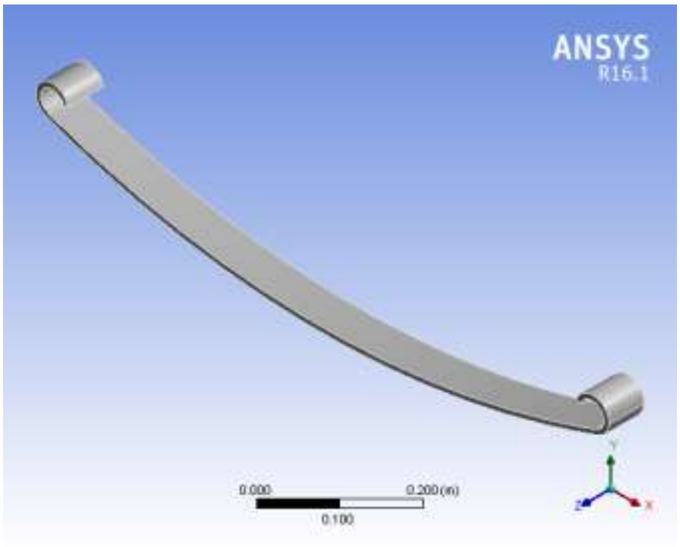


Figure 6. *3D modeling solid imported of master leaf springs*

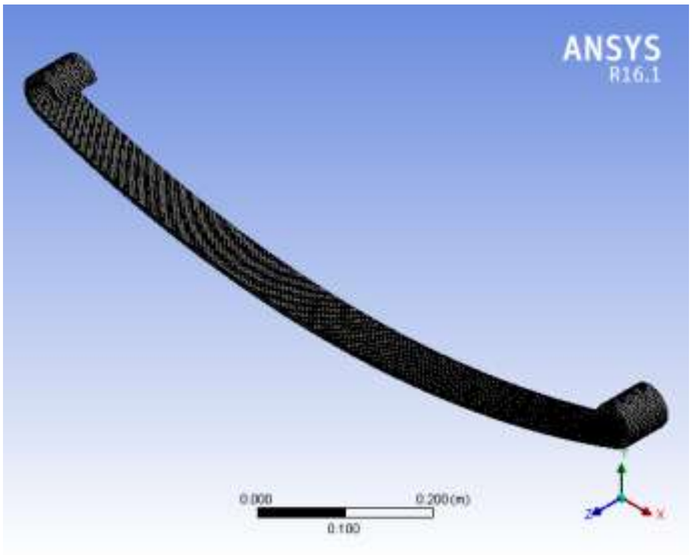
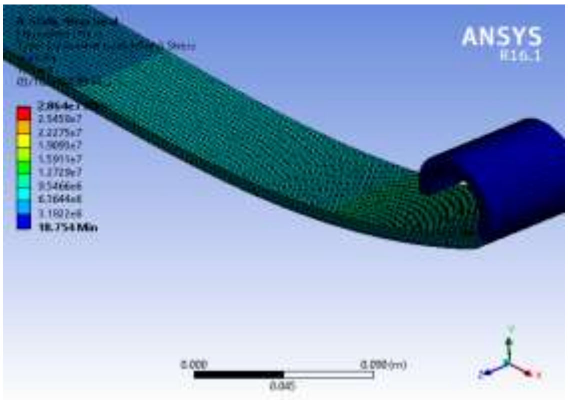


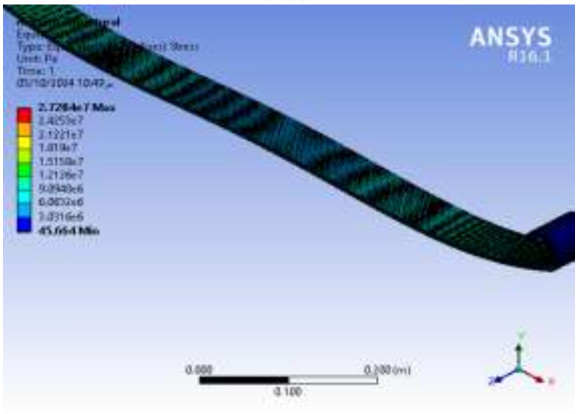
Figure 7. *Mesh generation*

6. Results and discussions

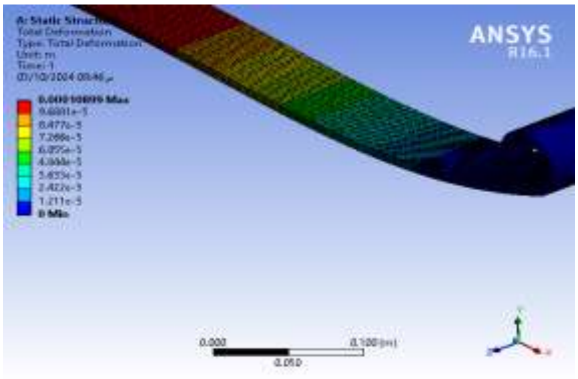
6.1 Static Analysis

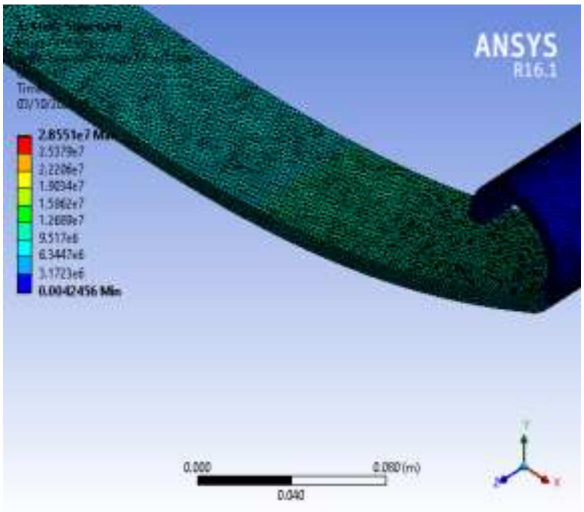
Numerical analysis using Ansys software V. 16.1 is carried out under the influence of linear static load. Figures (8 – 9 – 10) explained finite element analysis to evaluate the strength of leaf springs (Von – Mises Stress, deformation, and strain energy) under applied load (2500 N). Table (4) is a summary of the results of the proposed designs, showing that the maximum equivalent stress (Von – Mises Stress) is (28 64 MPa) in case (1). While the maximum deformation is (1.1802 × 10-4 m) observed in case (3), in addition, the maximum strain energy is (7.5812 × 10-6 J) in case (2).

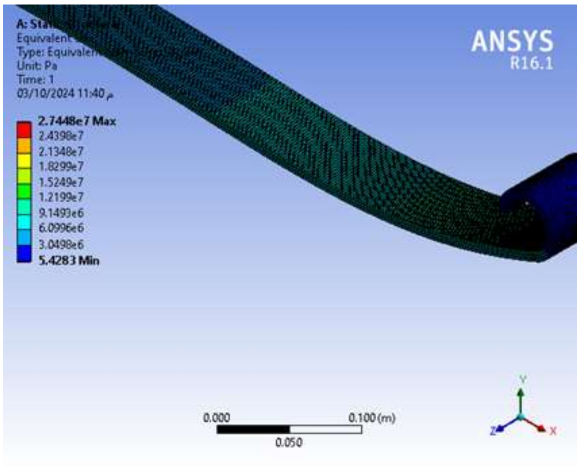




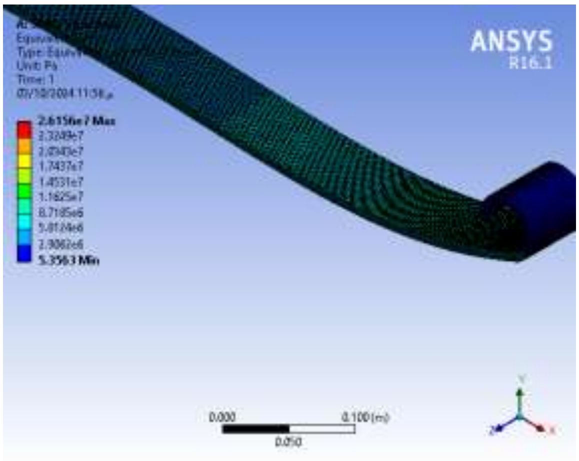
a- Von – Mises Stress (Case 1)
b- Von – Mises Stress (Case 2)





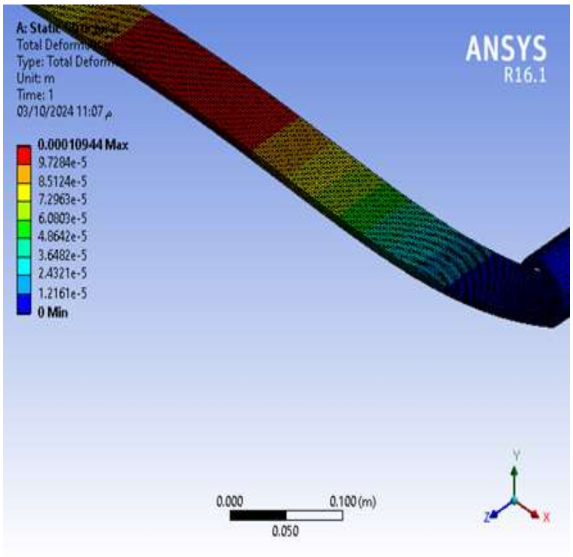


c- Von – Mises Stress (Case 3)
d- Von – Mises Stress (Case 4)

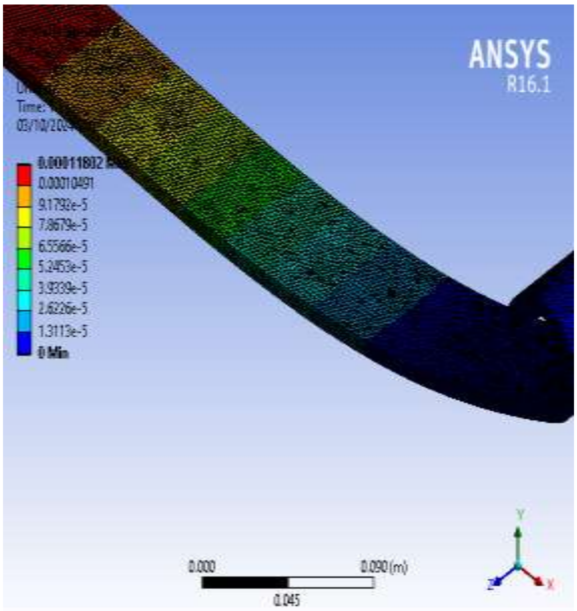


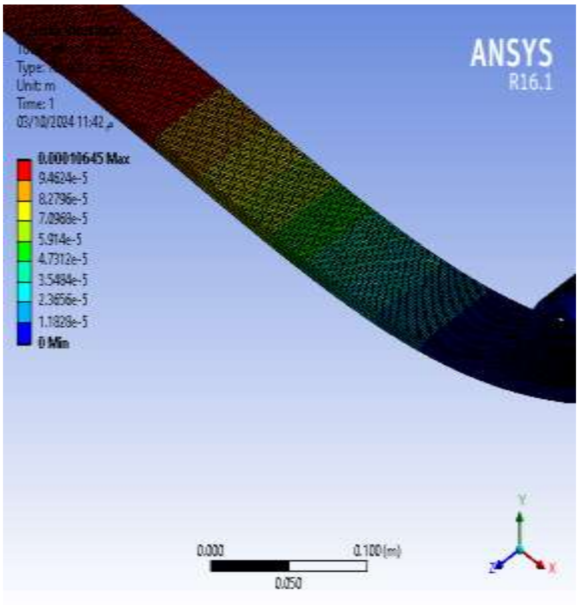
e- Von – Mises Stress (Case 5)

Figure 8. *Von – Mises stress of leaf spring*

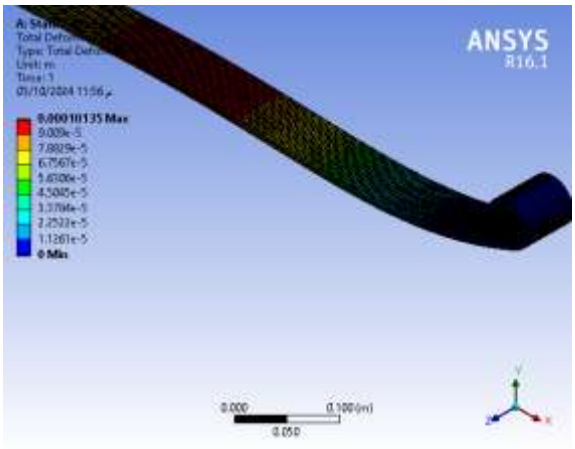


a- deformation (Case 1)
b- deformation (Case 2)



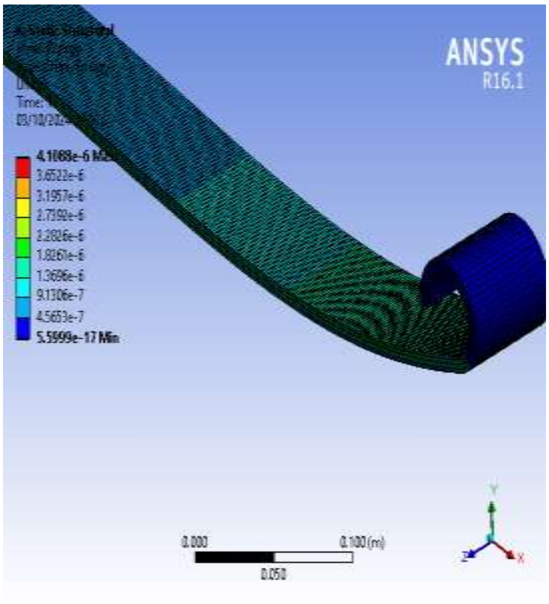


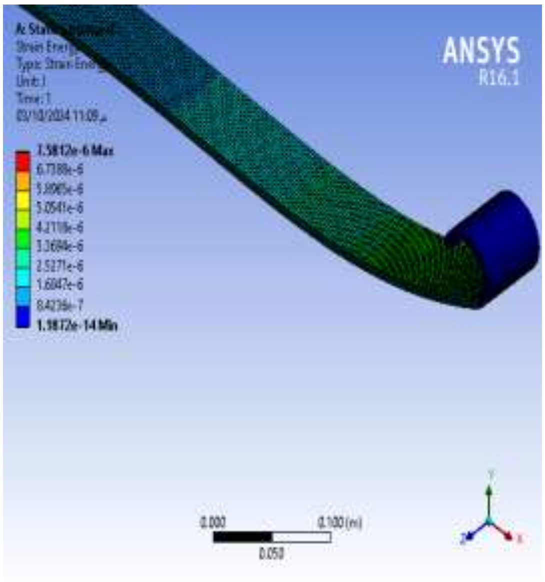
c- deformation (Case 3)
d- deformation (Case 4)



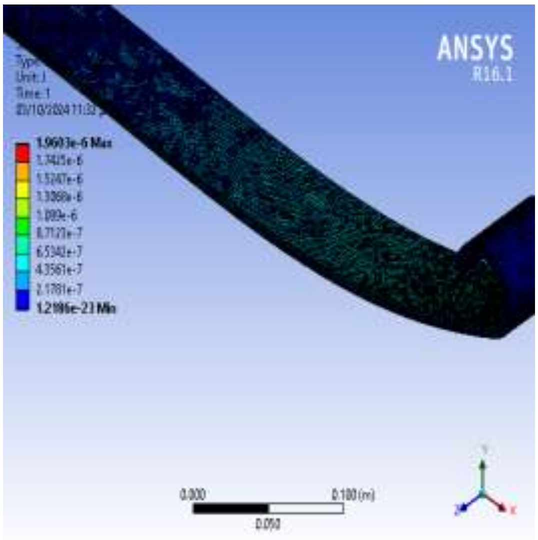
e- deformation (Case 5)

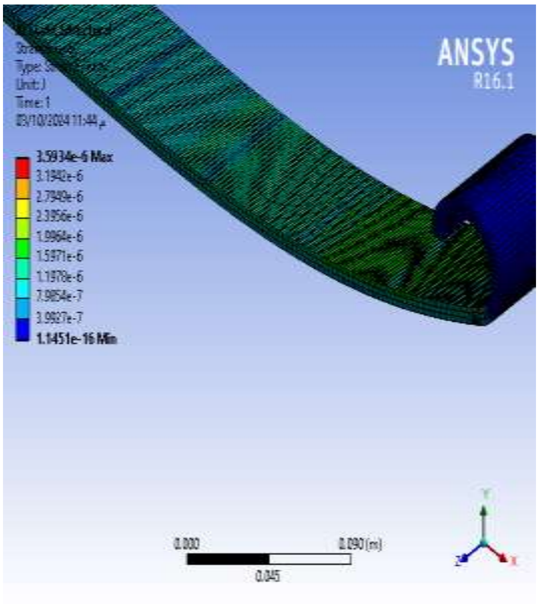
Figure 9. *Deformation of leaf spring*



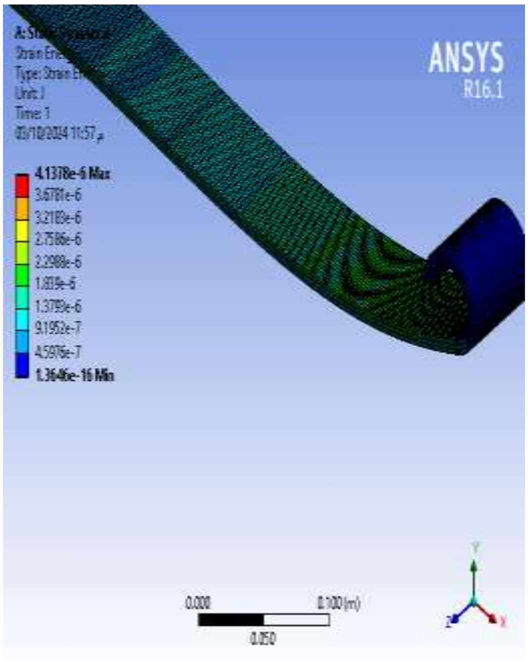


a- Strain Energy (Case 1)
b- Strain Energy (Case 2)





c- Strain Energy (Case 3)
d- Strain Energy (Case 4)



e- Strain Energy (Case 5)

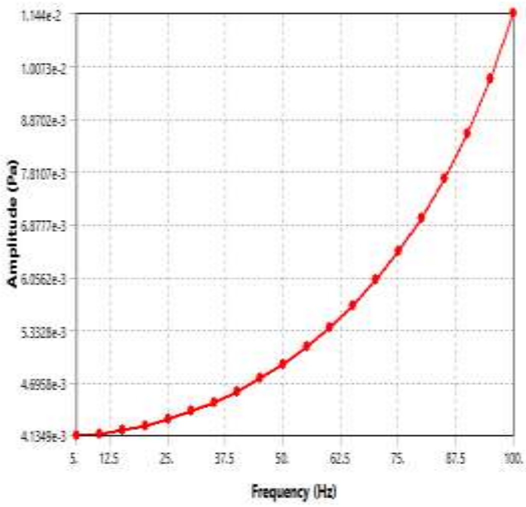
Figure 10. *Strain Energy of leaf spring*

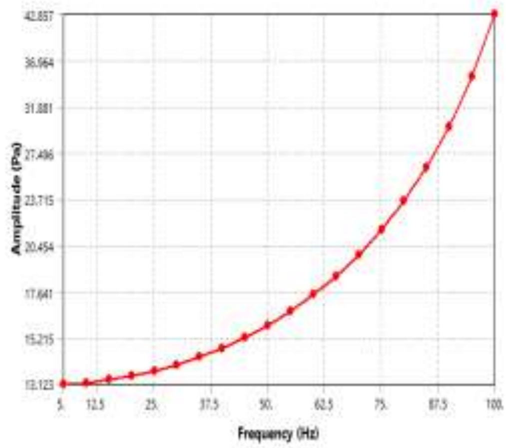
Table 4. *Comparison of proposed design*

Parameter	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Max. Von-Mises stress (*MPa*)	28.64	27.284	28.551	27.448	26.156
Max. Deformation (*m*)	1.0899×10^{-4}	1.0944×10^{-4}	1.1802×10^{-4}	1.0645×10^{-4}	1.0135×10^{-4}
Maximum strain energy (*J*)	4.1088×10^{-6}	7.5812×10^{-6}	1.9603×10^{-6}	3.5934×10^{-6}	4.1378×10^{-6}

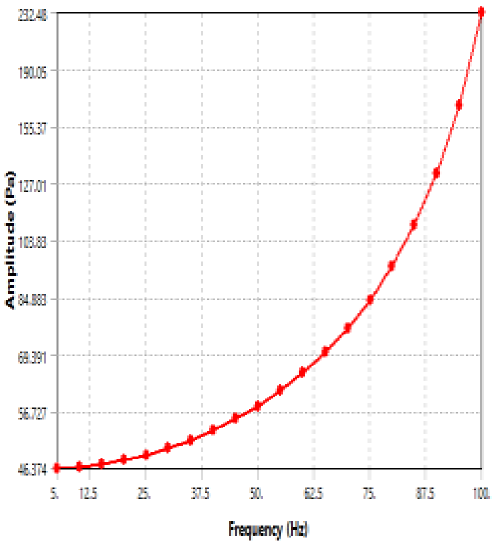
6.2 Dynamic Analysis

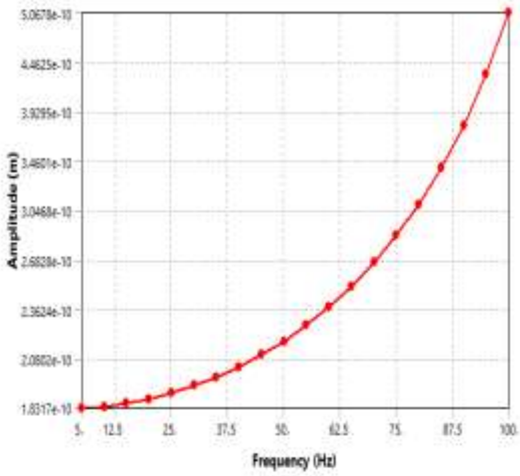
Approximately, (50 – 80 %) of leaf spring failure is due to operating conditions under dynamic loads. Generally, analytical pattern is used in analysis programs to evaluate the vibration characteristics (frequency response, and phase response) of the mechanical part during its design, where the harmonic force of 2500 N and the frequency rate (0 – 100 Hz) were projected at an increment rate of 5 Hz (i.e. Solution Intervals = 20 steps). Figures (11 and 12) shown the results of the frequency response (stress and deformation) of the proposed designs, where the best value of amplitude appears in (stress response = 232 Pa, and deformation response = 1.2796 × 10-6 m). While the figures (13 and 14) shows the results of the phase response at sweeping phase (720o). Figures (15 and 16) explained to comparison of the numerical results of the proposed designs. which are represented by a high response to case 3, and case 5, there is a little variation among models (case 1, case 2, case 4, and case 5).

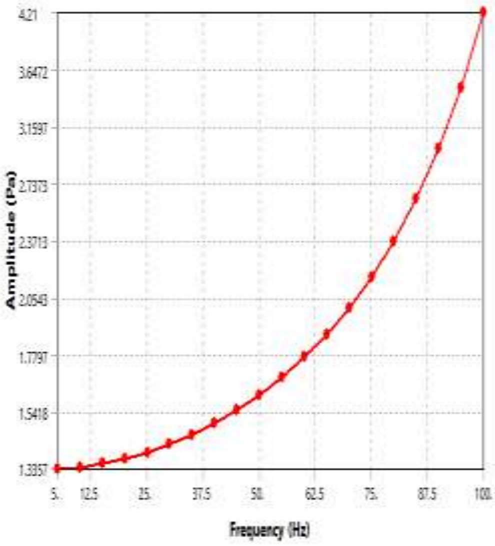


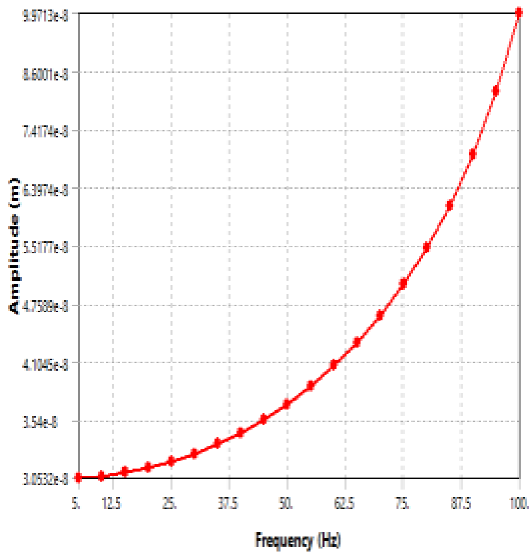


Case (1)   Case (2)



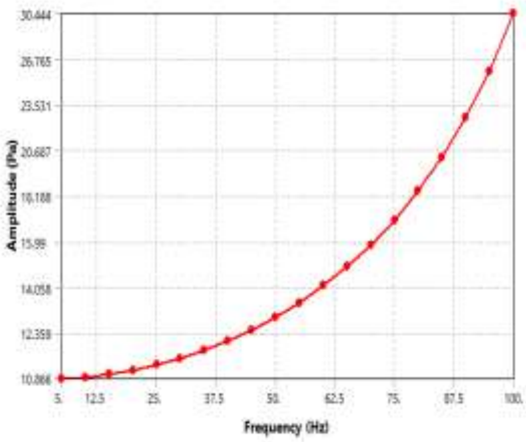


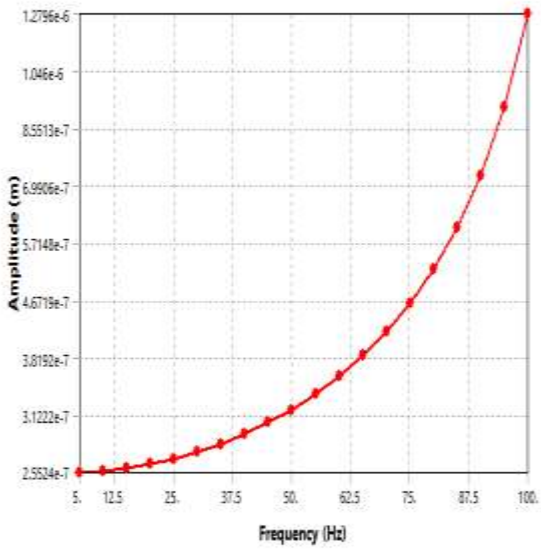




Case (1) Case (2)

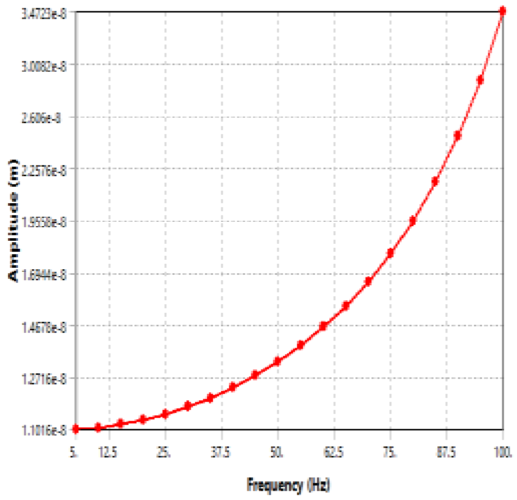
Case (3) Case (4)

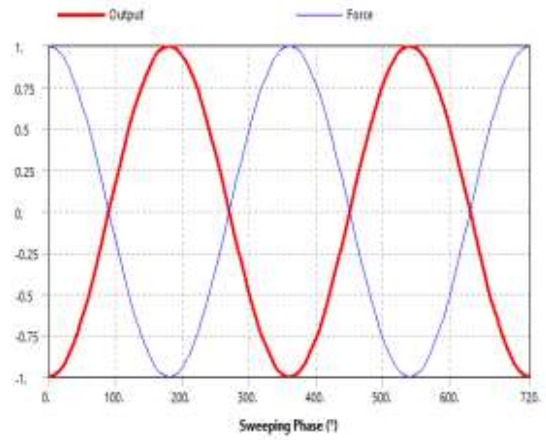




Case (5)

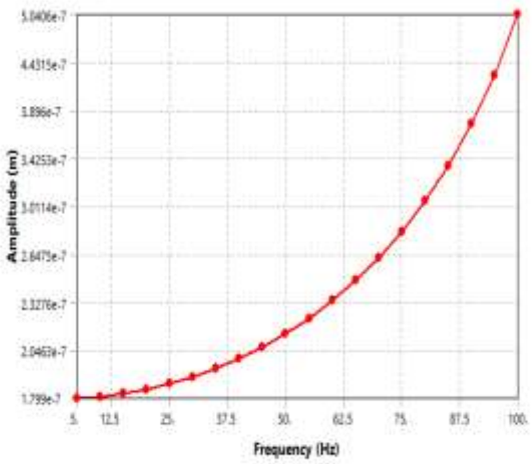
Figure 11. *Frequency response (Stress response) of leaf spring*

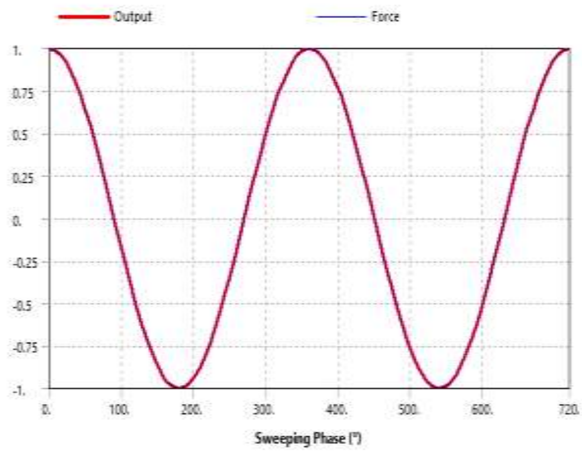




Case (1) Case (2)

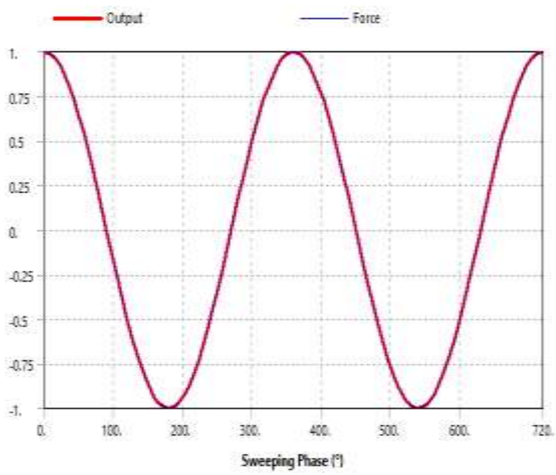
Case (3) Case (4)

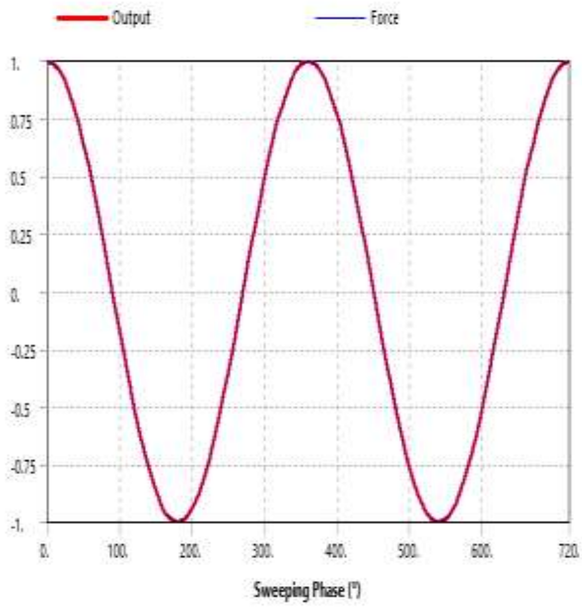




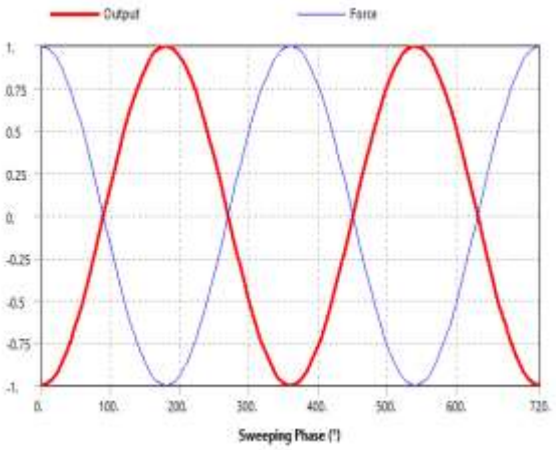
Case (5)

Figure 12. *Frequency response (Deformation response) of leaf spring*



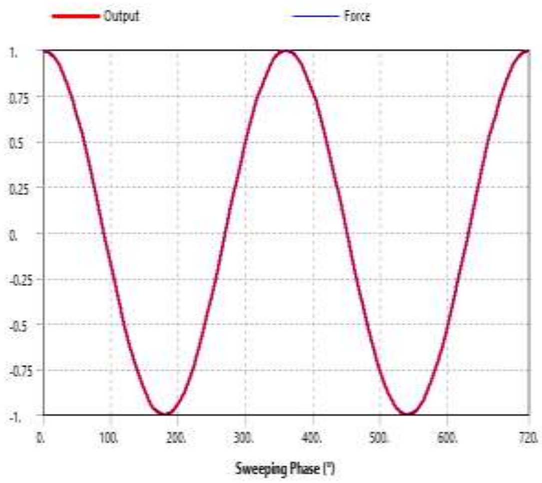


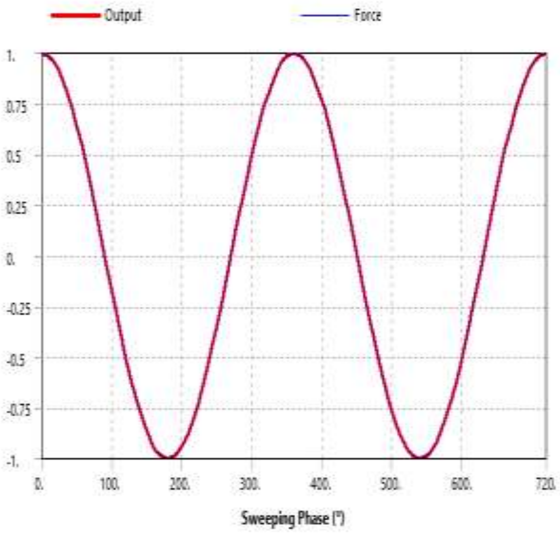
Case (3) Case (4)



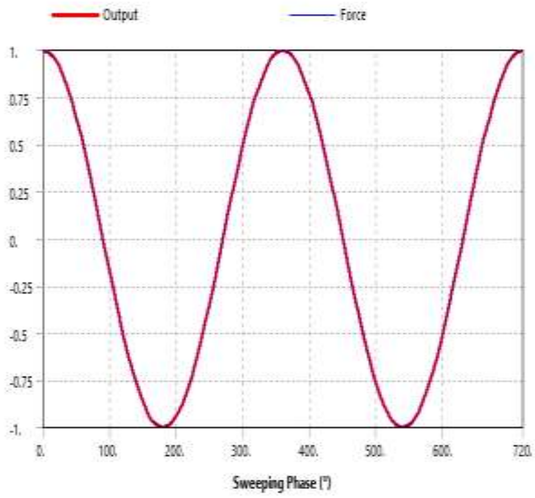
Case (5)

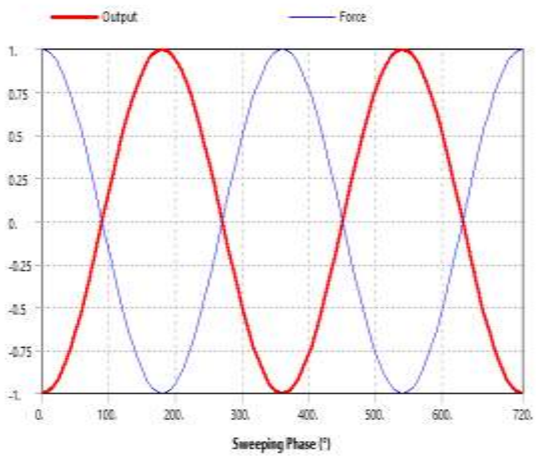
Figure 13. *Phase response (Stress response) of leaf spring*



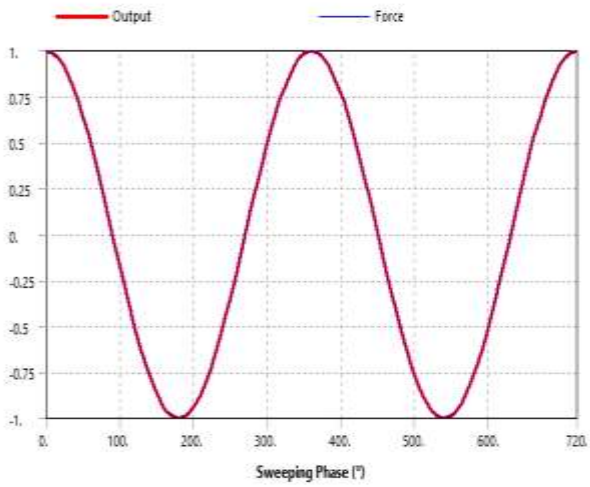


Case (1) Case (2)





Case (3) Case (4)



Case (5)

Figure 14. *Phase response (Deformation response) of leaf spring*

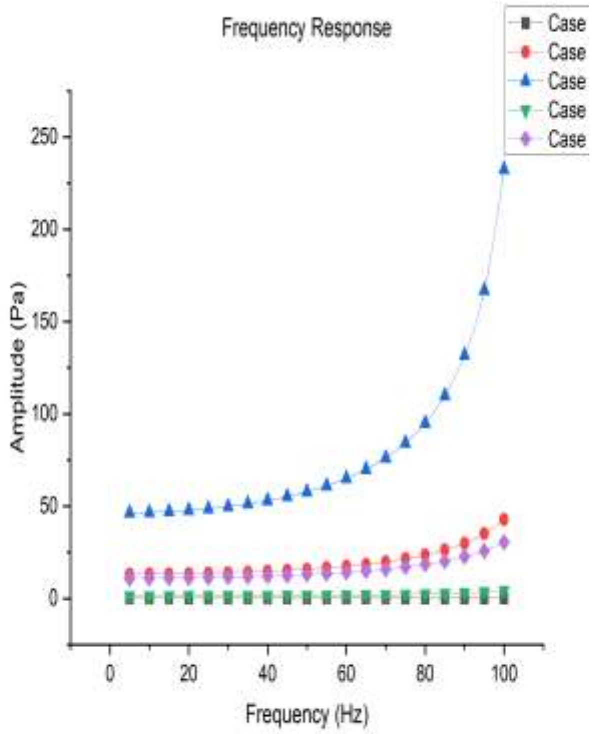


Figure 15. *Frequency Response (Stress comparison)*

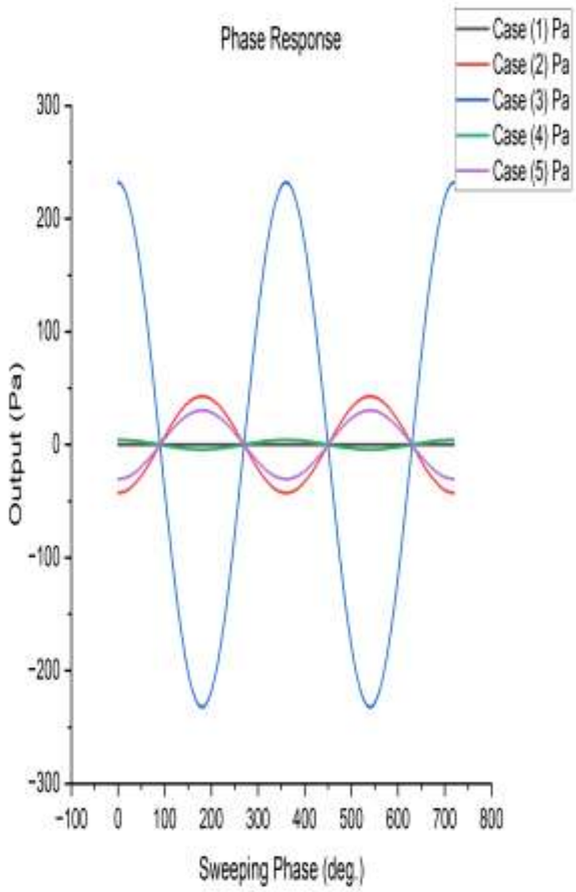


Figure 16b. *Phase response (Stress comparison)*

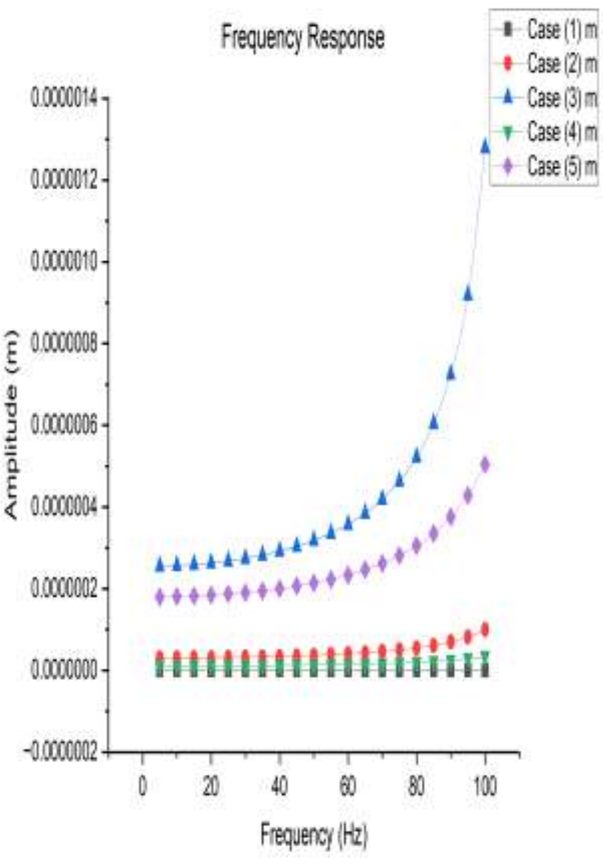


Figure 16a. *Frequency Response (Deformation comparison)*

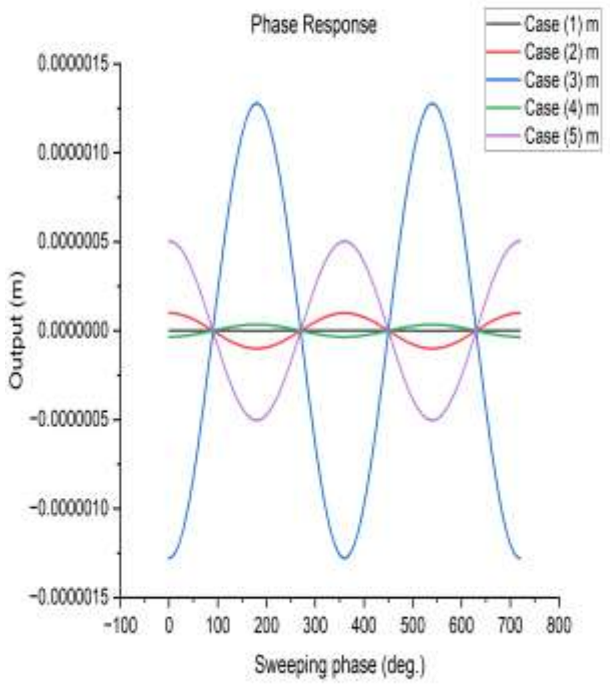


Figure 16c. *Phase response (Deformation comparison)*

7. Conclusion

In this current work, designs for leaf springs under the influence of a static load of 2500 N were proposed, as well as a harmonic load of 2500 N with a frequency (0 to 10 Hz) at an increment rate of 5 Hz was proposed to assess the resistance of leaf springs, determine the best model and obtain an optimal design under the static and dynamic loads. The 3D geometric models by SolidWorks 2023 and the analysis were done using the Ansys v. 16.1 software. And focused on the camber parameter as an essential variable in design. The numerical results were summarized as follows:

- There is a little variation in the values of von Mises stress between the first and third models (case 1 = 28.64 MPa and case 3 = 28.551 MPa).
- A little difference in the deformation was observed between all models, where the highest value was recorded in the case 3 = 1.1802 × 10-4 m and the lowest value was recorded in case 5 = 1.0135 × 10-4 m.
- The lowest value of strain energy is in case 3 = 1.9603 × 10-6 J.
- Frequency responses were the best of amplitude observed in case 3 (stress response = 232 Pa, and deformation response = 1.2796 × 10-6 m).

Finally, this study was verified, and the models were compared, the case 3 is the appropriate design that can be used as a replacement for the main model (case 2) used in the leaf spring of TATA ACE. In addition, analysis software helps designers to shorten the period studying and evaluating of mechanical parts.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.

- **Author contributions:** The authors declare that they have equal right on this paper.

- **Funding information:** The authors declare that there is no funding to be acknowledged.

- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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