Structural Optimization of a Leaf Spring Suspension System with Hangers and U-Bolts for Stability and Vibration Reduction in Six-Wheel Trucks

Parin Jakkum
Department of Mechanical Engineering, Faculty of Engineering, Thammasat School of Engineering, Thammasat University, Pathum Thani, Thailand
Parin.jak@gmail.com

Nattadon Pannucharoenwong
Department of Mechanical Engineering, Faculty of Engineering, Thammasat School of Engineering, Thammasat University, Pathum Thani, Thailand
pnattado@engr.tu.ac.th (corresponding author)

Phanuwat Wongsangnoi
Department of Mechanical and Production Engineering, Faculty of Industrial Technology, Sakon Nakhon Rajabhat University, Muang Sakon Nakon, Thailand
Phanuwat@snru.ac.th

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ABSTRACT

Leaf spring suspension systems are widely used in medium and heavy-duty trucks due to their high load-carrying capacity and durability. However, limited vibration and impact reduction can adversely affect driving comfort and the safety of transported goods. This study focuses on the design and analysis of reinforced leaf spring structures using 51CrV4 spring steel to improve vibration performance. The COMSOL Multiphysics software was employed to analyze the suspension system through eigenfrequency, frequency response, and time-dependent analyses, with material behavior modeled using Hollomon's law. The leaf spring model had dimensions of 1400×70×180 mm, 10 mm thickness, and consisted of four leaves. Reinforcement steel plates with thicknesses of 2.5, 5, 7.5, and 10 mm were investigated under a vertical load of 60 kN. Regarding the 10 mm reinforcement case, the material stiffness coefficient was 1,600 N/m^3 and the strain hardening exponent was 0.083. The results indicate that the resonance frequency was reduced by approximately 57%, shifting from 150 Hz to 65 Hz. Although the frequency response amplitude increased by 532%, the dominant resonance frequency shifted to a lower range, resulting in a more controllable vibration response. The peak time-domain displacement increased five times, and the overshoot reached 9 mm. Among all cases, the 10 mm reinforced leaf spring showed the most effective vibration reduction performance. In comparison with studies focusing on composite leaf springs or static performance, this work emphasizes the combined frequency-domain and time-domain vibration behavior of reinforced steel leaf springs.

Keywords-leaf spring suspension; six-wheel truck; natural frequency; frequency response; time-dependent analysis

I. INTRODUCTION

Vehicle vibration control is a significant aspect of suspension system design, especially for medium to heavy-duty trucks (6-10 wheels) operating under heavy loads and severe road conditions. Among suspension components, the leaf spring supports vertical loads, transmitting impact forces to the chassis, and maintaining vehicle stability. Conventional truck leaf springs, typically composed of stacked steel plates, are designed in accordance with SAE J157 and TIS 948-2533 standards to ensure sufficient strength and durability [1, 2]. However, limited vibration absorption under rough and variable loading conditions can adversely affect ride comfort, cargo safety, and component longevity [3].

To address these limitations, reinforcement of leaf springs using 51CrV4 alloy steel plates are an effective approach to enhance stiffness, vibration resistance, and service life. The Finite Element Method (FEM) analyzes the mechanical behavior of leaf springs under realistic loading conditions, with research focusing on strength improvement, fracture behavior, material selection, vibration characteristics, and suspension performance optimization for heavy-duty vehicles [4-8].

In addition, SAE J157 and TIS 948-2533 further support the importance of accurate numerical modeling. This study investigates the effects of reinforced steel plates with varying thickness applied to truck leaf springs using the COMSOL Multiphysics software. Eigenfrequency, frequency response, and time-dependent analyses are conducted to evaluate vibration behavior and suspension efficiency under dynamic loading conditions. While previous studies have mainly focused on composite leaf springs or static performance, this work emphasizes the dynamic vibration behavior of reinforced steel leaf springs under transient loading conditions. The combined investigation of eigenfrequency, frequency response, and time-dependent behavior provides an understanding of reinforcement effects for six-wheel truck applications.

II. THEORETICAL BACKGROUND

This study focuses on the vibration behavior of a leaf spring system using mechanics of materials and numerical analysis to evaluate its load-carrying capability and dynamic response. Based on [5, 6], eigenfrequency, frequency response, and time-dependent analyses are employed to investigate the vibration characteristics of the reinforced leaf spring.

Eigenfrequency analysis is used to identify natural frequencies and mode shapes, while frequency response analysis evaluates resonance behavior under harmonic excitation. Time-dependent analysis examines the transient vibration response of the system under impact loading conditions using a single-Degree-of-Freedom (1-DOF) mass–spring–damper representation, as illustrated in Figure 1.

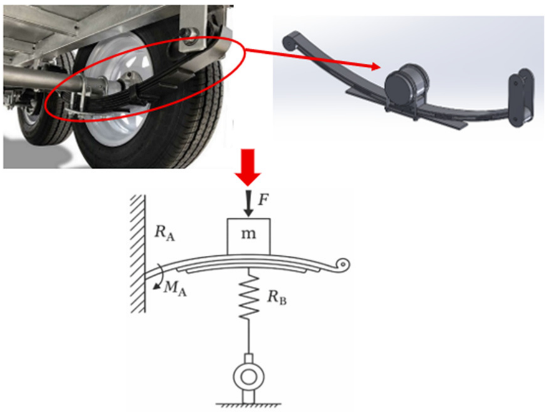


Fig. 1. Free body diagram of the truck leaf spring.

The theoretical formulations, including the 1-DOF vibration model and Hollomon’s law for nonlinear material behavior, are used to provide physical insights into the numerical results. These formulations support the interpretation of the finite element simulations, which incorporate realistic geometry, boundary conditions, and material properties.

Analysis based on Hollomon’s law [9] is used to describe the plastic behavior of metals and to analyze the stress-strain relationship of plates or structural components under loading conditions in finite element analysis, as shown in:

$$\sigma = K\varepsilon^n \tag{1}$$

where σ is the stress, ε is the strain, K is the strength coefficient, and n are the strain hardening exponents.

The equation of motion of the mass-spring-damper-system is used to describe vibration behavior over time and to analyze dynamic response. The governing equation of motion for the 1-DOF system is:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(t) \tag{2}$$

where m is the mass of the system, c is the damping coefficient, k the stiffness, $x(t)$ is the displacement, and $F(t)$ is the external force as a function of time.

Eigenvalue analysis is applied to determine the natural frequencies of the structural system, as expressed in:

$$(K - \omega^2 M)\Phi = 0 \tag{3}$$

where K is the stiffness matrix, M is the mass matrix, ω is the angular frequency, and Φ is the mode shape vector.

III. RESEARCH METHODOLOGY

In this study, numerical simulation using COMSOL Multiphysics software was employed to analyze the vibration behavior of the suspension system. The material properties of 51CrV4 spring steel, as listed in Table I, were adopted for the numerical model [6, 7].

A. *Material Properties*

TABLE I. MATERIAL PROPERTIES OF 51CRV4 SPRING STEEL

Property	Value	Unit
Young’s modulus	206	GPa
Poisson’s ratio	0.3	-
Density	7,850	kg/m^3
K	1,600	N/m^3
n	0.083	-

From Table I, the geometric characteristics and simulation conditions of the leaf spring were defined to represent realistic truck operating conditions, as summarized below:

1. Leaf spring geometry: Dimensions of 1400×70×180 mm with a plate thickness of 10 mm, consisting of four stacked plates. The geometry was defined in accordance with SAE J157 and TIS 948-2533 standards.
2. Reinforcement steel plates: Plate thicknesses of 2.5, 5, 7.5, and 10 mm were considered.

3. Applied loading: Vertical compressive load of 60,000 N applied for a duration of t = 0.1 s.
4. Spring foundation: Foundation stiffness of K = 1600 N/m³.
5. Numerical analyses: Eigenfrequency, mode shape, frequency response, and time-dependent analyses were performed using COMSOL Multiphysics.

TABLE II. CHEMICAL COMPOSITION OF 51CRV4 STEEL

Elements	Content (%)
C	0.57
Si	1.63
Mn	0.63
P	0.006
S	0.003
Cr	1.01
Ni	0.11
Cu	0.016
V	0.17

As presented in Table II, the alloying elements of 51CrV4 steel provide a balanced combination of strength, toughness, and wear resistance [6, 7]. Figure 2 depicts the numerical simulation workflow used to evaluate the effect of reinforcement plate thickness on vibration behavior.

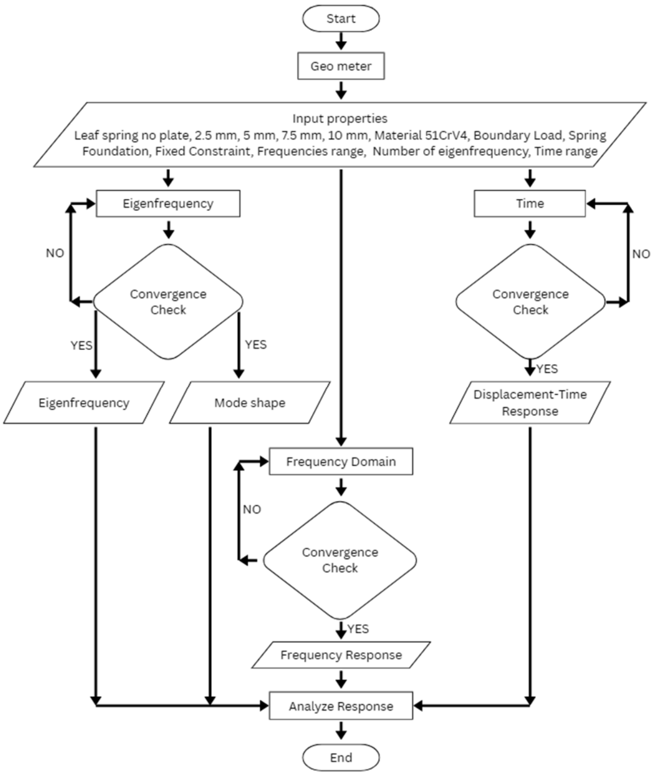


Fig. 2. Research methodology flowchart.

Simulations were conducted for plate thickness ranging from 2.5 to 10 mm with a step of 2.5. The non-reinforced leaf spring exhibits a maximum displacement of approximately −7.5 mm and reaches equilibrium within 1 s. Reinforced configurations show increased overshoot with increasing plate thickness, with the 5 mm and 7.5 mm plates producing the highest overshoot of about +15 mm and stabilizing within 1.5 s, whereas the 10 mm plate reduces the overshoot to approximately +9 mm. Frequency response analysis indicates that reinforcement shifts the dominant frequency range from 100-200 Hz to 60-70 Hz and reduces displacement amplitude, reflecting improved vibration performance.

B. FEM Analysis

After designing the leaf spring geometry using SOLIDWORKS, the three-dimensional model was imported into COMSOL Multiphysics for numerical simulation to analyze the vibration behavior of the suspension system with reinforced steel plates of different thickness values. The simulation investigated the effects of reinforcement plates on natural frequencies and vibration behavior under transient loading conditions representative of uneven road surfaces.

Material properties corresponding to 51CrV4 spring steel were adopted in the model. The material density was set to 7,850 kg/m³, the Young's modulus to 206 GPa, and the Poisson's ratio to 0.3. A vertical compressive load of 60,000 N was applied over a duration of t = 0.1 s, along with a spring foundation stiffness of K = 1600 N/m³. Plastic deformation parameters based on mechanical properties were also incorporated to more accurately represent material behavior.

The initial and boundary conditions were defined as approximate realistic operating conditions, with the applied load distributed over the boundary of the structure. For the time-dependent analysis, the vertical load was applied at t = 0.1 s to simulate impact conditions such as road irregularities. In contrast, no external load was applied in the eigenfrequency analysis, and the natural frequencies were determined solely by the geometry and material properties, as displayed in Figure 3.

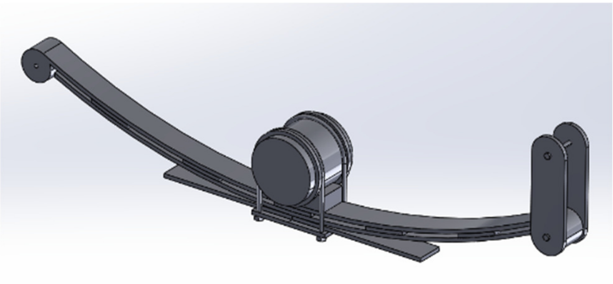


Fig. 3. Leaf spring model.

Based on Figure 3, the leaf spring was modeled using SOLIDWORKS, and its components were defined according to the labeled positions A to E, as follows:

1. A = 10 mm, representing the length of the top steel plate.
2. B = 10 mm, representing the length of the bottom steel plate.
3. C = 10 mm, representing the width of all steel plates.

4. D, representing the thickness of the reinforcement steel plate, with the following test values: 0 mm, 2.5 mm, 5 mm, 7.5 mm, and 10 mm.
5. E = 10 mm.

C. Mesh Generation

In the COMSOL simulations, a triangular mesh was employed to accommodate the curved geometry of the leaf spring, particularly in regions subjected to impact loading. Mesh refinement was applied in critical areas to improve accuracy. The final model consisted of approximately 10,000 elements, providing sufficient resolution while maintaining reasonable computational time. A mesh convergence study confirmed that further refinement did not significantly affect the displacement results.

IV. SIMULATION RESULTS

A. Time-Dependent Analysis Results for Each Case

Based on Figure 4, the time-dependent Y displacement responses of the leaf spring differ significantly among configurations, particularly during the initial 0-0.5 s of the transient phase. The non-reinforced leaf spring shows a limited displacement of approximately -7.5 mm and stabilizes within 1 s, indicating quick stabilization but poor impact absorption. The 2.5 mm reinforcement increases displacement to -25 mm with an overshoot of +6 mm, reflecting higher stiffness but stronger rebound. The 5 mm and 7.5 mm reinforcements exhibit the largest responses, with minimum displacements of -40 mm and -38 mm and a maximum overshoot of +15 mm, indicating excessive oscillations. In contrast, the 10 mm reinforcement indicates a more controlled response, with a minimum displacement of -34 mm and a reduced overshoot of +9 mm, providing the most balanced vibration behavior.

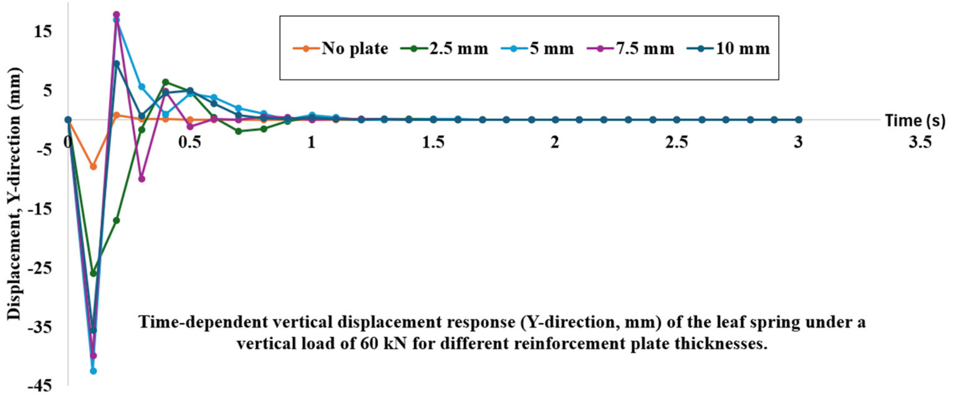
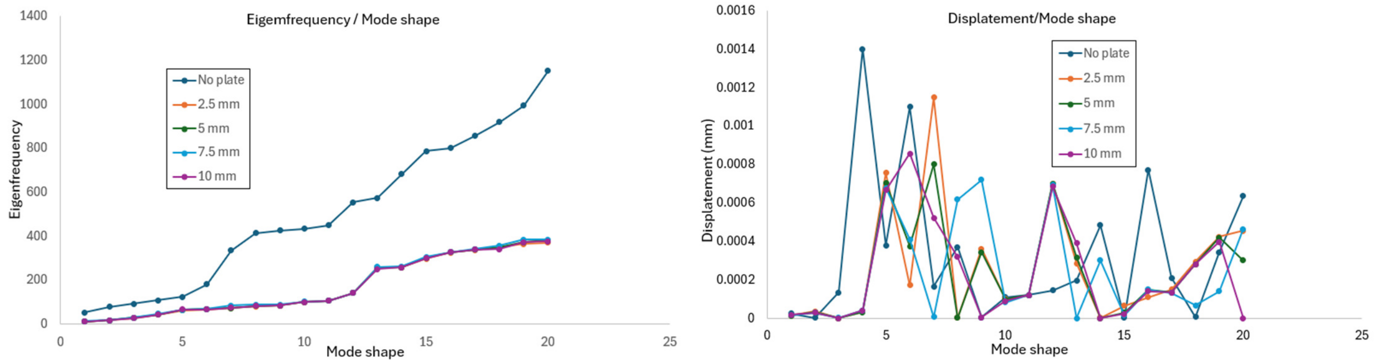


Fig. 4. Vertical displacement response, in Y-direction, of a leaf spring under a 60 kN load for different reinforcement plate thicknesses (No plate, 2.5, 5, 7.5, and 10 mm) over time.

B. Natural Frequency and Mode Shape Displacement Analysis

The results, presented in Figure 5, suggest that the reinforcement of steel plates significantly influences the natural frequencies of the leaf spring, particularly from Mode 6 onward. Reinforced configurations exhibit higher natural frequencies than the non-reinforced case, indicating increased structural stiffness and improved vibration resistance in higher-order modes. In addition, the reinforced leaf springs demonstrate lower displacement amplitudes, especially in Modes 6, 7, and 15, where notable frequency shifts occur. These findings demonstrate that the reinforcement plates enhance vibration control by reducing modal displacement and mitigating resonance risk.



(a) (b)

Fig. 5. Eigenfrequency and displacement results showing the influence of reinforcement thickness on natural frequencies and modal displacement.

V. DISCUSSION

This study demonstrates the improvement of the suspension system of a six-wheel truck through the reinforcement of the original leaf spring with 51CrV4 steel plates. The observed numerical results from COMSOL revealed that the thickness of the reinforcement plate has a direct influence on the dynamic behavior of the system. The case of 10 mm reinforcement plate provides the most favorable overall performance, showing effective vibration reduction and a significant decrease in resonance frequency. These findings suggest that steel plate reinforcement, particularly with an appropriate thickness, can be effectively applied to the design or improvement of truck leaf springs to enhance suspension performance, as summarized in Table III.

TABLE III. COMPARISON OF LEAF SPRING CONFIGURATIONS WITH DIFFERENT REINFORCEMENT THICKNESSES

Plate thickness (mm)	No plate	2.5	5	7.5	10
Max displacement (mm)	-7.5	-25	-40	-38	-35
Overshoot (mm)	-	6	15	15	9
Time (s)	1	1.5	1.5	1.5	1.5
Resonance (Hz)	150	65	65	65	65
Max resonance (mm)	0.72	6.2	5.2	4.9	4.55

The numerical trends observed suggest that changes in reinforcement thickness directly influence stiffness and dynamic response. Moreover, the obtained vibration characteristics align with general engineering expectations for automotive leaf spring applications, supporting the reliability of the numerical results.

Table III highlights that increasing the reinforcement thickness shifts the resonance frequency to a lower range. However, excessive thickness leads to larger displacement and overshoot. Among the investigated configurations, the 10 mm reinforcement provides the most stable vibration response, which is consistent with general performance considerations in SAE J157 and TIS 948-2533 for automotive leaf spring applications. Figure 6 compares the force-displacement behavior of the 2.5 mm plate with the results from [5].

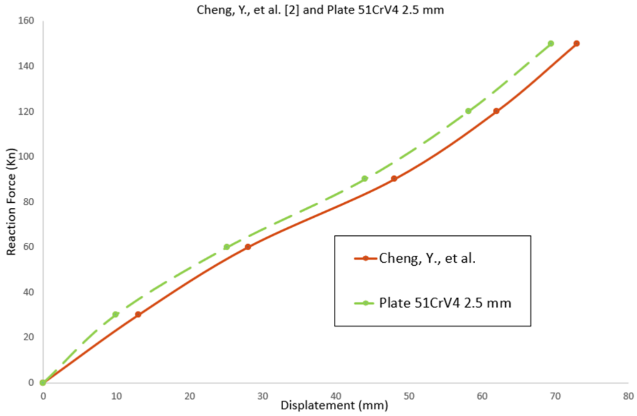


Fig. 6. Comparison of force displacement curves between [5] and the 51CrV4 plate model with 2.5 mm thickness.

To evaluate the accuracy of the developed model, the force displacement relationship was compared with the experimental results of [5], obtained from physical testing of a 51CrV4 steel leaf spring with a decarburized surface layer. The numerical model with a reinforcement thickness of 2.5 mm exhibits slightly lower displacement values at the same force levels. This difference is mainly attributed to the absence of the decarburization layer in the numerical model, whereas surface softening in the experimental specimens leads to higher deformation. Despite this difference, the overall trends show good agreement, indicating that the proposed model can reliably represent the mechanical response of the leaf spring under loading conditions, as illustrated in Figure 6.

VI. CONCLUSIONS

Based on COMSOL simulations, reinforcing a truck leaf spring with 51CrV4 steel plates significantly influences vibration behavior in both the time and frequency domains. Among all configurations considered, the 10 mm reinforcement plate provides the most effective overall performance, reducing the resonance frequency from approximately 150 Hz to 65 Hz and decreasing the frequency response amplitude to 4.55 mm, the lowest among the reinforced configurations. Although increasing reinforcement thickness improves vibration attenuation, it also increases settling time and may introduce excessive overshoot, particularly for 5 and 7.5 mm plates. Therefore, an appropriate balance between vibration reduction and initial dynamic response is required. Overall, the 10 mm plate offers the best compromise, demonstrating strong potential for practical application in compliance with SAE J157 and TIS 948-2533 standards. The findings of this study can serve as a preliminary design guideline for selecting reinforcement thickness in heavy-duty truck leaf springs, as outlined in Table IV.

TABLE IV. COMPARISON BETWEEN THE NO PLATE AND 10 MM REINFORCEMENT CASES

Parameter	**No plate**	**10 mm**	**Output**
Resonance (Hz)	150	65	57% decrease
Frequency response (mm)	0.72	4.55	532% increase
Time response (mm)	-7.5	-35	Increased by 5 times
Overshoot (mm)	-	+9	Increased of 9 mm
Time to normal (s)	1.0	1.5	50% increased

The 10 mm reinforced leaf spring exhibits a substantial reduction in resonance frequency while maintaining a controllable dynamic response compared to the no-plate case. These vibration characteristics support the applicability of the proposed reinforcement design within the scope of SAE J157 and TIS 948-2533 standards for practical truck suspension systems.

DECLARATION OF COMPETING INTERESTS

Not applicable to this work.

ACKNOWLEDGMENT

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DATA AVAILABILITY

All simulated data are described within the paper.

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