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Modelling and simulation of the vibration and stress state of the vehicle damping system

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Abstract

This study explores the modelling, simulation, and performance evaluation of a vehicle damping system aimed at enhancing ride comfort, structural durability, and vibration absorption efficiency under real-world operating conditions. A quarter-car suspension model was developed and analyzed using Finite Element Analysis (FEA) tools, with the 3D geometry created in Autodesk Inventor and simulations conducted in ANSYS Workbench. The system includes key components such as the spring coil, damper strut housing, pushing rod, hub, and upper spring perch. Static structural analysis was performed to assess stress distribution, strain, and deformation across components under typical loading scenarios. Modal analysis revealed the system's natural frequencies ranging from 0 Hz to 78.48 Hz, with mode shapes indicating areas of high deformation. The maximum stress observed was 5.6×10^7 MPa in the spring coil, remaining within the material's yield strength limits. These results indicate that the vehicle damping system is structurally sound and dynamically stable, making it suitable for use in automotive suspension applications. The simulation framework significantly improves design optimization, enhances vibration isolation performance, and contributes to the development of more efficient and durable damping systems in the automotive industry.

Keywords: Vehicle Suspension; Damping System; Stress and Vibration Simulation; Modal Analysis; Finite Element Analysis

1. Introduction

Since decades, research has been going on regarding how well the suspension systems of different vehicles behave to control the ride comfort, ride stability and passenger safety, as well as the systems of damping which prevent large and unwanted oscillations and maintains the structural integrity. Vehicle damping systems, mechanical or hydraulic, also act by absorbing and dissipating shock impulse caused by road vibrations to improve the overall vehicle performance.

The analysis of damping technologies are well developed in existing literature that classifies damping technologies as passive, semi-active, and active suspension systems. As emphasized in the studies of Kumar and Kumar (2021) and BhanuPrakash and Pratesh (2021), the proper choice of materials is essential to ensuring that shock dampers are optimized for performance, where Finite Element Analysis (FEA) proves useful to evaluate stress and deformation. Modal and structural analyses, in addition to Rogerio et al., (2023) and Yin et al. 2024; 2023a; 2023b) have highlighted vibration isolation, stress distribution, and resonance conditions. However, there are still some limitations that have prevented a good model of the real-world damping behavior of systems operating in nonlinear and dynamic environments in the literature. Key factors such as material wear, environmental degradation, and long-term fatigue effects have yet to be fully integrated into computational models, limiting the predictive accuracy of existing research.

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This study aims to address specific limitations in existing vehicle damping system analyses by developing a finite element-based simulation model that focuses on the structural response and vibration behavior of key damping components under static loading and modal excitation. While prior research has explored material selection and general suspension performance, much of it has not examined in detail the stress distribution and deformation behavior across individual components of a quarter-car damping system using integrated CAD and FEA tools.

The primary objective of this research is to model and simulate the vibration and stress state of a vehicle damping system to identify critical areas of stress concentration, evaluate deformation patterns, and determine the system's natural frequencies and mode shapes. These insights are essential for understanding how damping components respond under typical road-induced forces and for identifying potential zones of failure or material fatigue.

To accomplish this, a quarter-car model was developed in Autodesk Inventor and analyzed using Finite Element Analysis (FEA) in ANSYS. Static structural simulations were conducted to evaluate stress and strain distributions under operational loads, while modal analysis was performed to determine the natural frequencies and associated mode shapes of the system. This dual approach provides valuable data on both the mechanical resilience and dynamic characteristics of the suspension system.

By focusing on these analyses, the study offers a clearer understanding of how structural integrity and vibration behavior interact within a typical damping system. The results help validate the effectiveness of the system design and highlight areas for potential refinement, contributing to the broader goal of improving suspension reliability and comfort without extending beyond the capabilities demonstrated in this research.

The mass-spring-dashpot system is a fundamental model in mechanical dynamics, representing the interaction of mass (vehicle body), spring (suspension stiffness), and dashpot (damping). According to BhanuPrakash and Pratesh (2021), the damper or shock damper serves to dissipate vibrational energy, minimizing the transmission of road irregularities to the vehicle body. When a vehicle encounters bumps or rough terrain, damping mechanisms are vital in controlling vertical oscillations and maintaining traction.

Several types of dampers are used in modern vehicles, this include the hydraulic dampers which is the most common type, using fluid displacement through small orifices to convert kinetic energy into heat, the gas-charged dampers which is an enhanced hydraulic dampers that incorporate nitrogen gas to prevent fluid aeration, improving performance under load, the adjustable dampers, this allow manual or electronic control of damping characteristics, enabling drivers to toggle between comfort and performance settings and magnetorheological dampers.

Vibrations in vehicle systems are typically classified into free and forced vibrations. Free vibration occurs following an initial disturbance without continuous external excitation, whereas forced vibration results from sustained external forces—often leading to resonance if the forcing frequency matches the system's natural frequency. In either case, damping reduces amplitude, controls stress cycles, and prevents material fatigue. The role of damping in minimizing cyclic stress and prolonging component life has been extensively studied. Mehmood et al. (2014) and Lee et al. (2019) emphasize the correlation between inadequate damping and early fatigue failure in suspension systems. Similarly, studies by Daberkow et al. (1999) explored the integration of CAD-based solid modeling with simulation environments, concluding that accurate structural dynamics modeling requires multi-body system representation.

FEA software like ANSYS has become a preferred tool in suspension design. Its ability to simulate complex geometries, boundary conditions, and material behaviors makes it highly effective for modal, static, and transient dynamic analyses. According to Rogerio et al. (2023), ANSYS facilitates real-time prediction of system behavior under varied load and vibration conditions, making it invaluable for engineering design validation.

Moreover, instrumentation supports simulation by providing real-world data for model calibration. It captures key parameters such as displacement, force, and acceleration, ensuring that simulated conditions accurately mirror operational realities. This link between empirical data and computational models enhances simulation precision and informs more reliable design decisions.

In summary, the existing literature establishes a strong foundation for modeling and simulation of vehicle damping systems. However, there remains a gap in integrating all damping modes, environmental factors, and material degradation into a single comprehensive model. This study aims to bridge that gap by developing and simulating a quarter-car damping system in ANSYS, evaluating both its structural and vibration characteristics.

2. Materials and methods

Autodesk Inventor was used to develop a model for a quarter car suspension system. The model was imported into ANSYS Workbench to evaluate the structural and dynamic behavior of the vehicle damping system. The model consisted of major components including the spring coil, damper strut housing, upper spring perch, hub, pushing rod, and tire, mimicking a typical vehicle suspension configuration. The input properties of the system is as shown in Table 1 - 6.

Table 1 Properties of damper Strut Housing of the vehicle damping System

Damper Strut Quantity	**Parameter**
Volume	5.2277e+005 mm^3
Mass	4.1037 kg
Density	7.85e-006 kg mm^-3
Coefficient of Thermal Expansion	1.2e-005 C^-1
Specific Heat	4.34e+005 mJ kg^-1 C^-1
Thermal Conductivity	6.05e-002 W mm^-1 C^-1
Resistivity	1.7e-004-ohm mm
Young's Modulus	200000 Mpa
Poisson's Ratio	0.3
Bulk Modulus	1.67E+05
Shear Modulus	76923 Mpa

Table 2 The Properties of Pushing Rod of the Vehicle Damping System

Pushing Rod Quantity	**Parameter**
Volume	1.6141e+005 mm^3
Mass	0.44711 kg
Density	2.77e-006 kg mm^-3
Coefficient of Thermal Expansion	2.3e-005 C^-1
Specific Heat	8.75e+005 mJ kg^-1 C^-1
Young Modulus	71000 Mpa
Poisson's Ratio	0.33
Bulk Modulus	69608 MPa
Shear Modulus	26692 Mpa
Density	7.954e-006 kg mm^-3
Tensile Yield Strength	743 MPa
Tensile Ultimate Strength	1135 MPa

Table 3 The Properties of Upper Spring Perch of the Vehicle Damping System

Upper Spring Perch	**Parameter**
Volume	1.6141e+005 mm^3
Mass	0.44711 kg
Density	2.77e-006 kg mm^-3
Coefficient of Thermal Expansion	2.3e-005 C^-1
Specific Heat	8.75e+005 mJ kg^-1 C^-1
Young's Modulus	71000 MPa
Poisson's Ratio	0.33
Bulk Modulus	69608 MPa
Shear Modulus	26692 MPa

Table 4 The Properties of Spring Coil of the Vehicle Damping System

Spring Coil	**Parameter**
Volume	72645 mm^3
Mass	0.57026 kg

Table 5 The Properties of Hub of the Vehicle Damping System

Hub	**Material Used- Cast iron, EN GJN HV350**
Appearance Density	7.699e-006 kg mm^-3
Tensile Yield Strength	325.3 MPa
Isotropic Secant Coefficient of Thermal Expansion	1.049e-005 C^-1
Tensile Ultimate Strength	325.3 MPa
Isotropic Thermal Conductivity	2.245e-002 W mm^-1 C^-1
Specific Heat Constant Pressure	5.396e+005 mJ kg^-1 C^-1
Poisson's Ratio	0.275
Shear Modulus	78196 MPa
Bulk Modulus	148000 MPa
Young Modulus	199000 MPa

Table 6 The Properties of Tyre of the Vehicle Damping System

Tyre	Material Used- Rubber, Natural
Density	9.498e-007 kg mm^-3
Tensile Yield Strength	24.25 MPa
Tensile Ultimate Strength	24.25 MPa
Isotropic Secant Coefficient of Thermal Expansion	2.198e-004 C^-1
Isotropic Thermal Conductivity	1.442e-004 W mm^-1 C^-1
Specific Heat Constant Pressure	1.903e+006 mJ kg^-1 C^-1
Isotropic Resistivity	3.162e+016 ohm mm
Isotropic Relative Permittivity	2.538
Isotropic Electric Loss Tangent	6.33E-03

2.1. Static Structural Analysis

The static structural analysis was carried out to evaluate the structural behavior of the system when subjected to static loading situations. The stresses, strains, and displacement within the structure were analyzed. The damping system is defined as shown in Figure 1.

The process typically involves defining the structure's geometry, material properties, loads, and boundary conditions, followed by solving for the structural response using mathematical models or computational tools.

The static structural analysis was carried out to determine the stress distribution and deformation of the damping components under operational loads. Material properties, boundary conditions, and applied forces were defined based on typical road load cases. Each component was meshed using tetrahedral elements, and constraints were applied to simulate realistic loading conditions. Key performance metrics included von-Mises stress, strain, and total deformation.

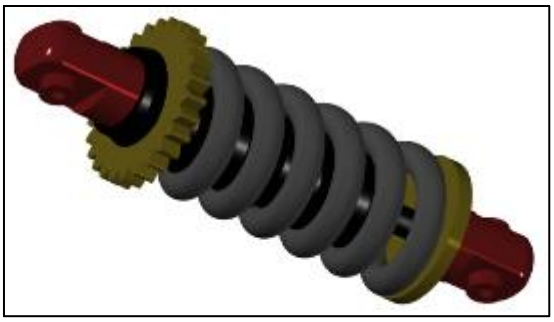


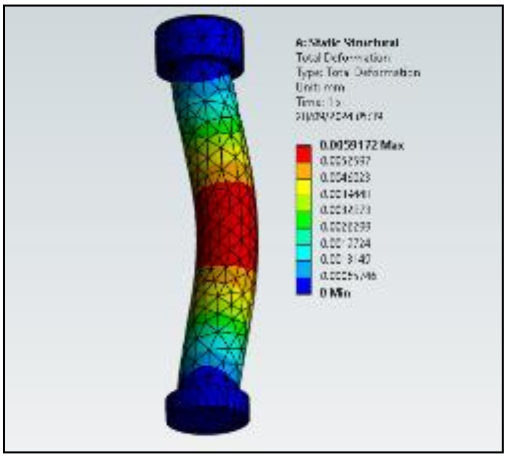
Figure 1 The Damping absorbing system

Modal analysis was conducted to identify the natural frequencies and associated mode shapes of the damping system. The analysis is crucial for evaluating the vibration behavior of the system, especially in relation to resonance frequencies that may compromise ride comfort and structural integrity. Eight mode shapes were extracted, representing deformation patterns at various frequencies from 0 Hz to approximately 78.48 Hz.

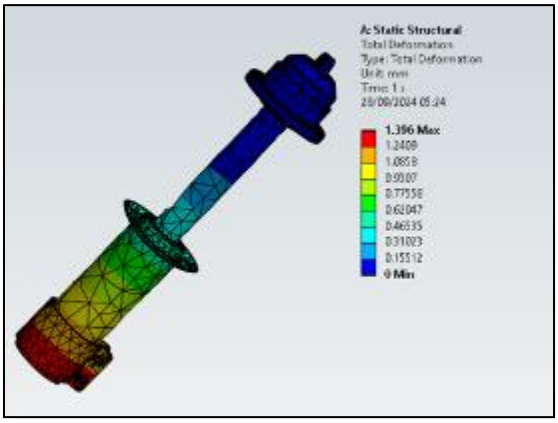
3. Result and Discussion

Figures 2 through 7 illustrate the deformation patterns under static loading conditions. Spring Coil (Figure 6) exhibited the highest deformation, indicating it bears the most load and flexibility in the suspension system.

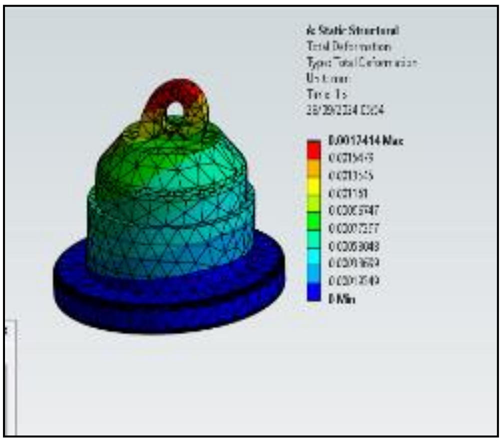
Upper Spring Perch (Figure. 4) showed the least deformation, suggesting its role as a relatively rigid structural support. The results indicate effective load transfer among components, with stress concentrations primarily at the spring coil and pushing rod. Maximum stress recorded was 5.6 $\times 10^7$ MPa, which remains within the material's yield strength, confirming structural safety under the simulated conditions.



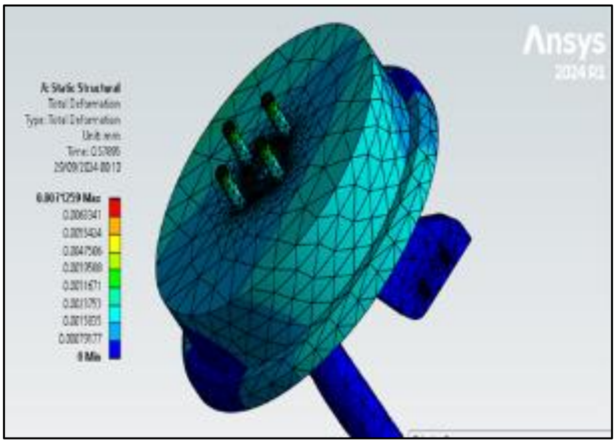
Figurer 2 Pushing Rod Model Deformation



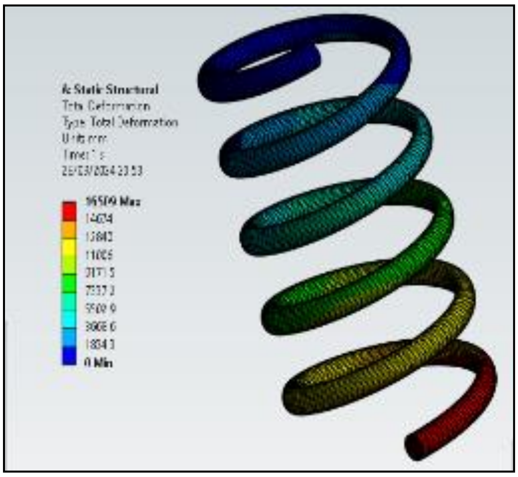
Figurer 3 damper strut Housing Model Deformation



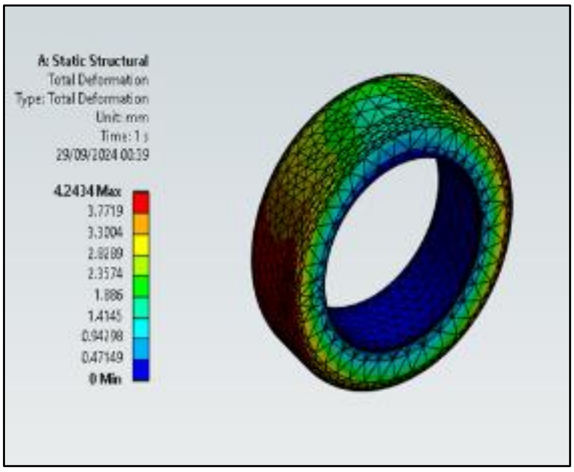
Figurer 4 Upper Spring Perch Model Deformation



Figurer 5 Hub Model Deformation



Figurer 6 Spring coil Model Deformation



Figurer 7 Tire Model Deformation

3.1. Strain Analysis

The Figure 8 through 13 below shows the equivalent (von-Mises) strain of the pushing rod model, damper housing strut model, upper spring perch model, hub model, tire model of the vehicle damping system. Spring Coil and Hub Models experienced the highest strains, reflecting areas of high energy absorption.Minimal strain was observed in the Upper Spring Perch and Tyre Model, validating their design robustness.This highlights the effectiveness of the damping system in distributing strain across flexible components while maintaining rigidity in structural members.

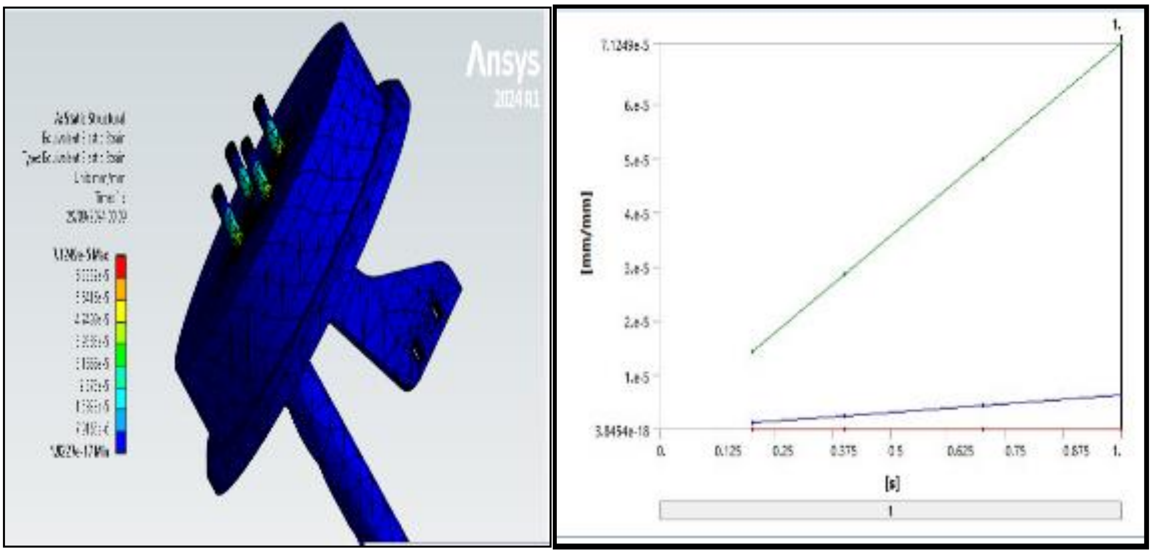


Figure 8 Equivalent (von-Mises) strain of hub model

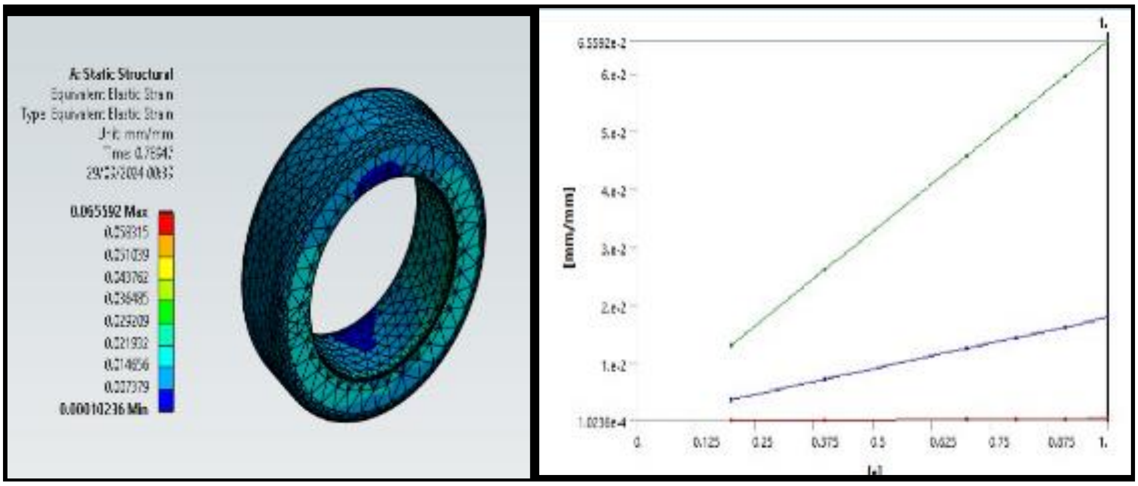


Figure 9 Equivalent (von-Mises) strain of tyre model

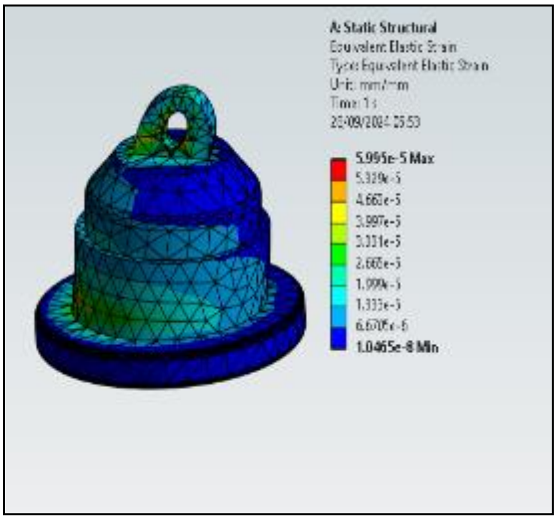


Figure 10 Equivalent (von-Mises) strain of upper spring perch model

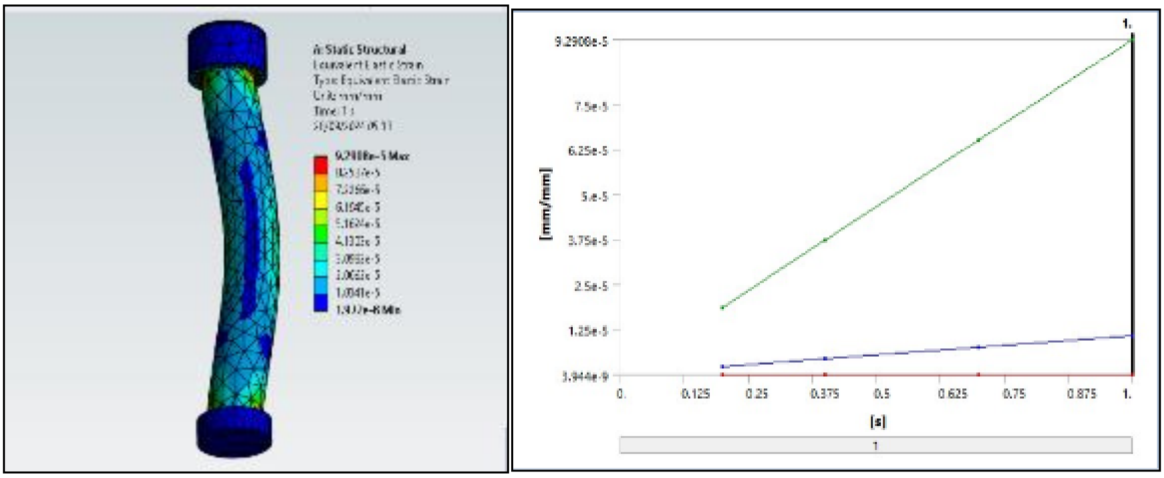


Figure 11 Equivalent (von-Mises) strain of pushing rod model

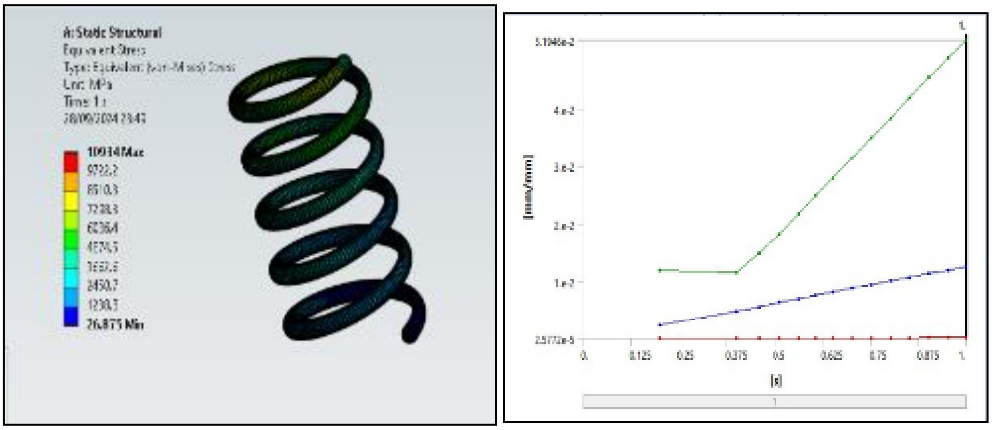


Figure 12 Equivalent (von-Mises) strain of spring coil model

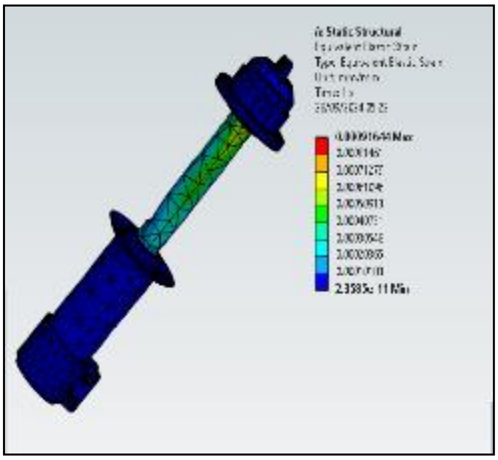


Figure 13 Equivalent (von-Mises) strain of the damper strut housing model

3.2. Stress Analysis

The Figure 14 through 19 below shows the equivalent (von-Mises) stress of the pushing rod model, damper housing strut model, upper spring perch model, hub model, tire model of the vehicle damping system. The Spring Coil (Figure. 14) again emerged as the most stressed component. The Pushing Rod (Figure 19) showed significant stress concentrations near load application points, which could be potential failure initiation zones.:

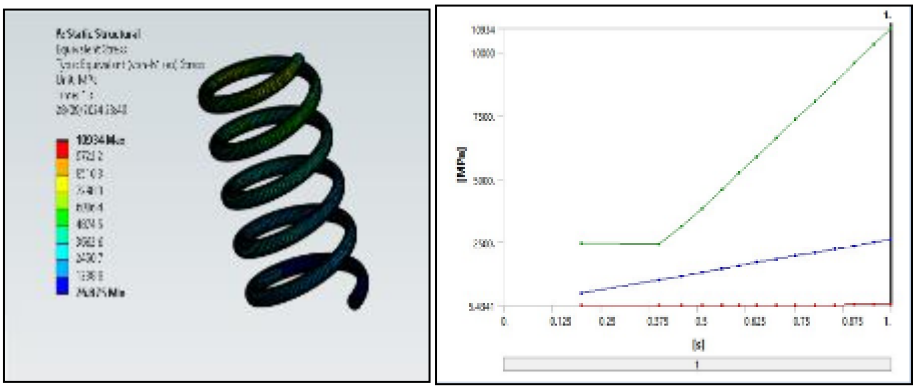


Figure 14 Equivalent (von-Mises) stress of the spring coil Model

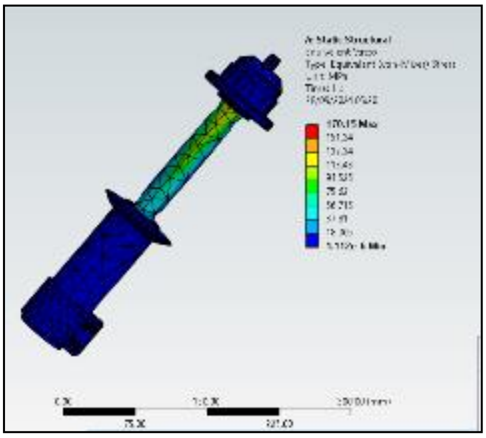


Figure 15 Equivalent (von-Mises) stress of the damper strut housing Model

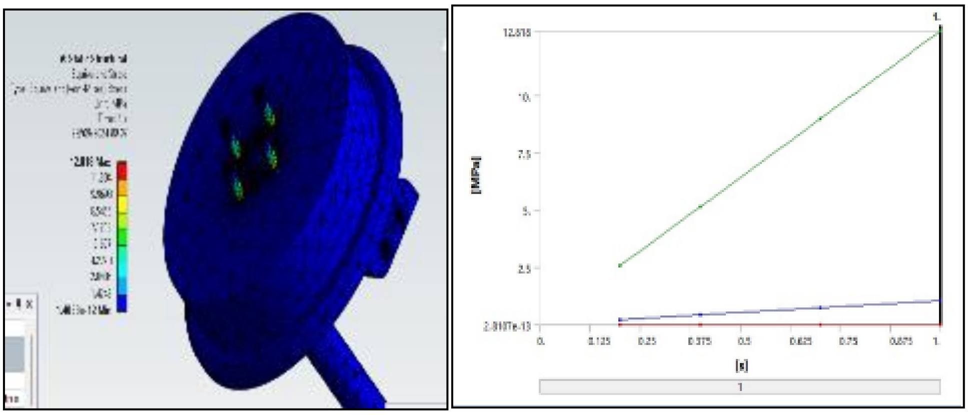


Figure 16 Equivalent (von-Mises) stress of the hub Model

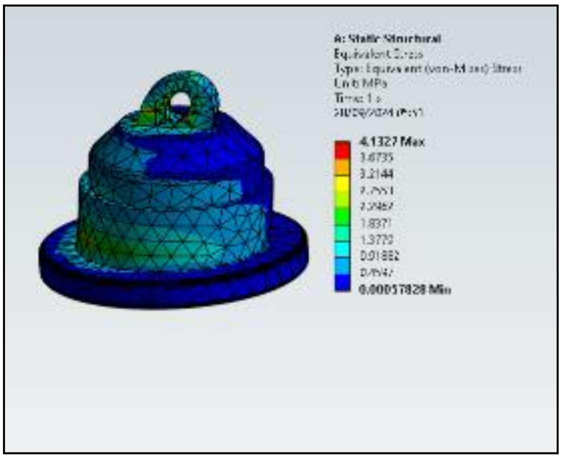


Figure 17 Equivalent (von-Mises) stress of the upper spring perch Model

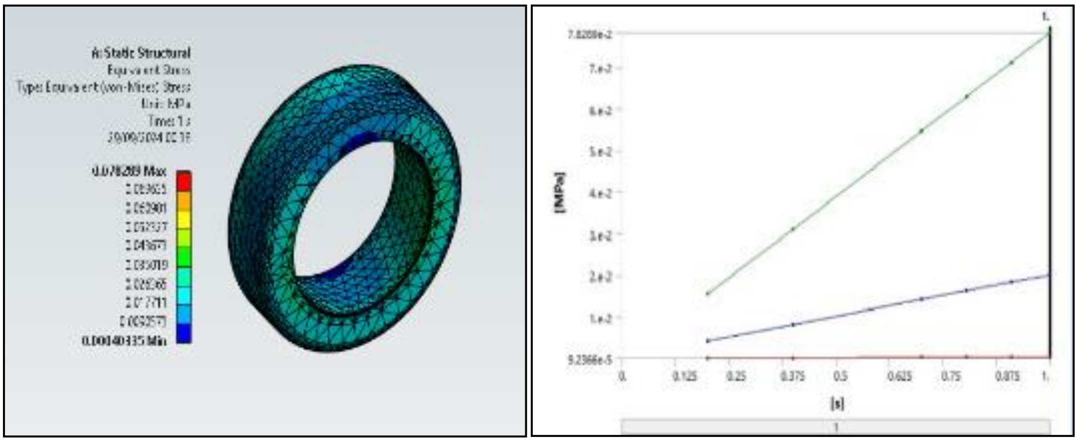


Figure 18 Equivalent (von-Mises) stress of the tyre Model

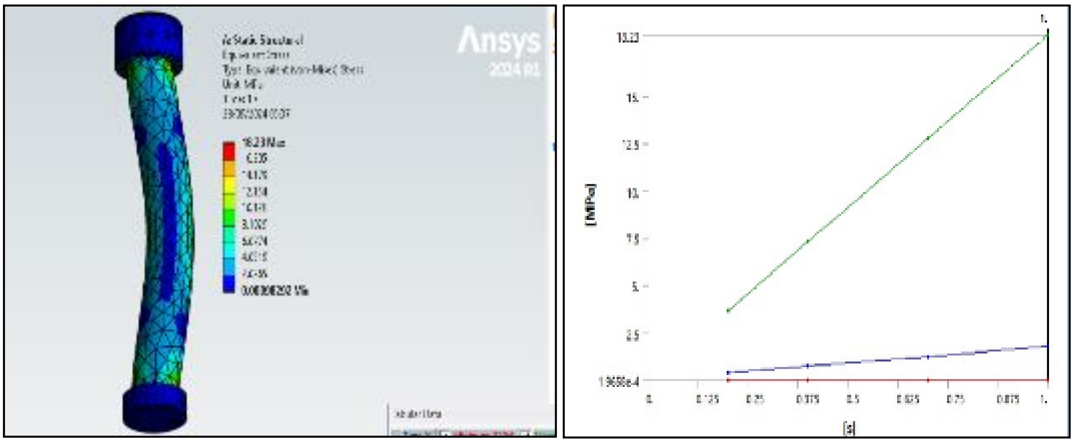


Figure 19 Equivalent (von-Mises) stress of the pushing rod Model

3.3. Modal Analysis

The natural frequencies of the dashpot system are obtained by performing the modal analysis using Finite Element Method (FEM).

The obtained mode shapes of the dashpot system models are hereby presented:

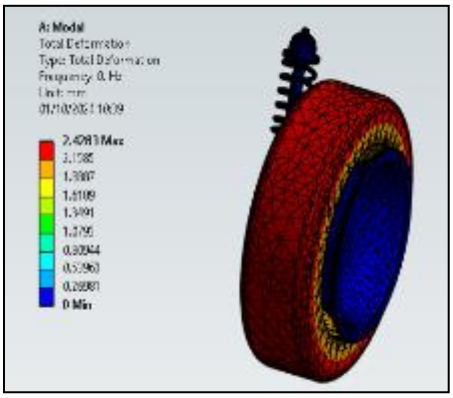


Figure 20 VDS 1st Mode Shape (0Hz)

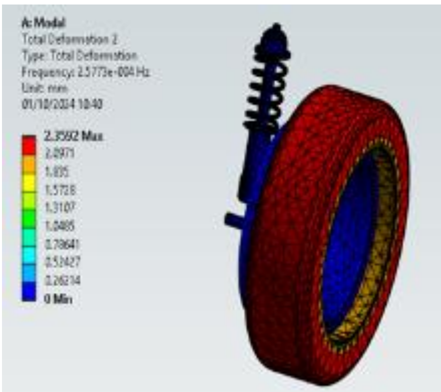


Figure 21 VDS 2nd Mode Shape (25.4mHz)

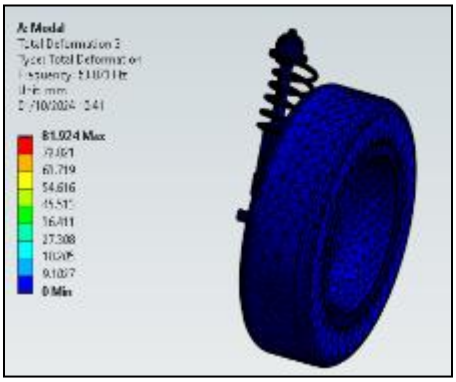


Figure 22 VDS 3rd Mode Shape (63.8Hz)

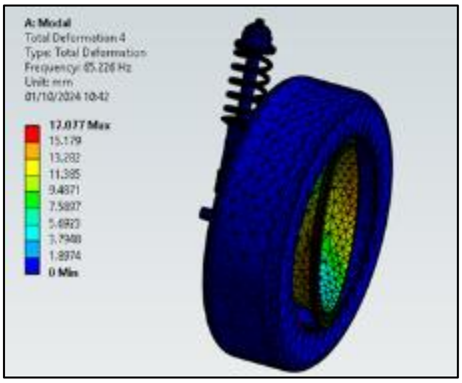


Figure 23 VDS 4th Mode Shape (65.23Hz)

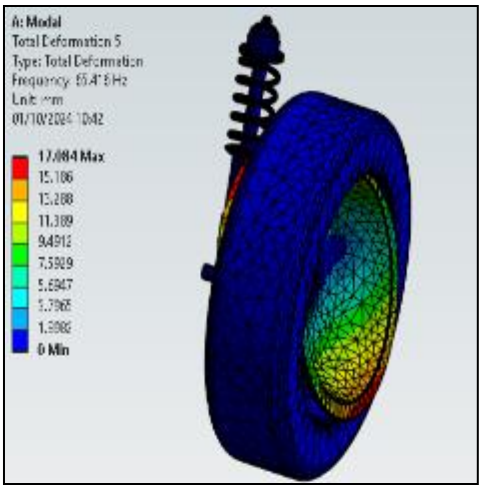


Figure 24 VDS 5th Mode Shape (65.42Hz)

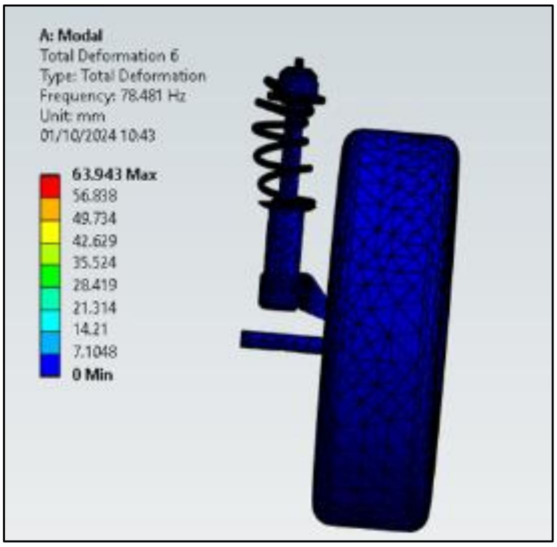


Figure 25 VDS 6th Mode Shape (78.48Hz)

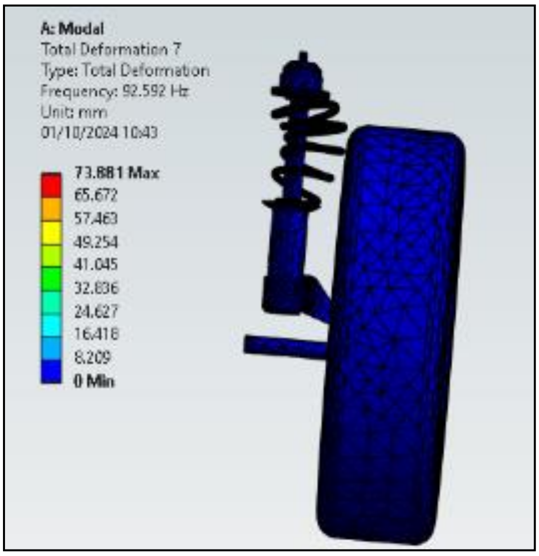


Figure 26 VDS 7th Mode Shape

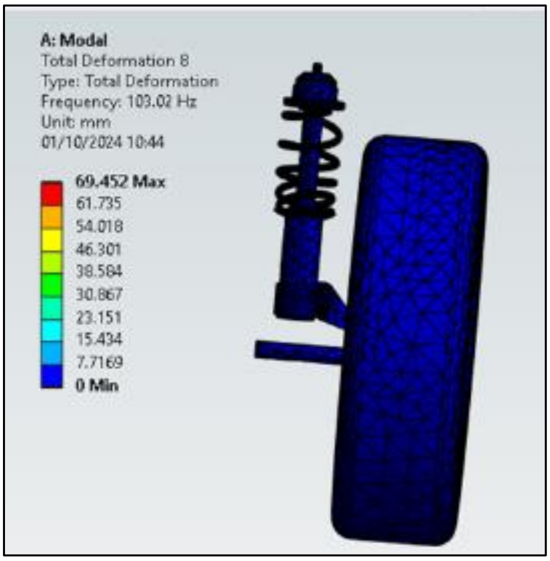


Figure 27 VDS 8th Mode Shape

The related frequencies at Eight (8) different modes after performing modal analysis on the vehicle damping system model is shown in Figurer 28.

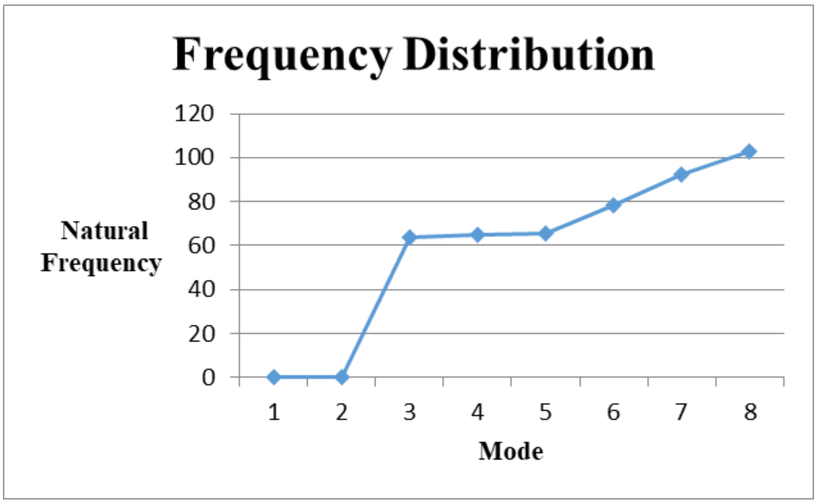


Figure 28 Mode-Frequency Distribution

Mode shapes (Figures 20 to 27) reveal how the damping system deforms at specific natural frequencies: 1st Mode Shape (0 Hz): Represents rigid body motion. 2nd to 8th Modes (25.4 MHz to 78.48 Hz): Show progressive dynamic behavior with increasing complexity in deformation.

As shown in Figure 28, the frequency range captured is typical for suspension systems under operating conditions. The variation in natural frequencies is directly influenced by the geometry, material properties, and boundary constraints of the model. For instance, increasing spring stiffness or using a denser material would shift frequencies upward, potentially avoiding resonance with road-induced vibrations.

4. Conclusion

The successful modeling and simulation of the vehicle damping system demonstrate its effectiveness in managing vibration and stress distribution under various operating conditions. The system, designed as a quarter-car suspension model, was evaluated using finite element analysis, revealing optimal stress and strain behavior across key components such as the spring coil, damper strut, and hub. Modal analysis further confirmed the system's ability to withstand vibration loads within its natural frequency range, highlighting its reliability in improving ride comfort and structural stability.

Despite these advantages, the damping system has some limitations. The current model assumes ideal boundary conditions and material uniformity, which may not fully capture real-world complexities such as wear, fatigue, and environmental degradation. Additionally, the absence of experimental validation introduces uncertainties in performance predictions under dynamic road profiles.

The potential applications of this simulation approach are broad, especially in the automotive industry, where it can guide the design of more efficient, durable, and comfortable suspension systems. By providing detailed insights into stress concentrations and mode shapes, this study supports the development of safer and longer-lasting vehicle components.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Alzahrani, F., Lee, Y., and Kim, S. (2021). Effects of environmental factors on vehicle suspension components. Journal of Mechanical Engineering, 47(3), 147-159.

[2] Bhanu Prakash, B., and Pratesh, J. (2021). Design and analysis of two-wheeler suspension system using different materials on ANSYS. International Journal of Mechanical Engineering and Robotics Research.

[3] Chandravanshi, P., Sharma, R. C., Sharma, N., and Pallig, S. (2014). Dynamic vibration dampers: Analysis of quarter-car suspension model. International Journal of Mechanical Engineering and Technology, 5(7), 102-110.

[4] Cheng, T., Zhao, H., and Xu, C. (2023). Advanced finite element analysis techniques for vehicle suspension systems. Finite Element in Analysis and Design, 180, 103438.Khurmi, R. S. and Gupta, J. K. A Textbook of Machine Design, (8th Edition) m2013.

[5] Cook, R. D., Malkus, D. S., and Plesha, M. E. (2007). Concepts and applications of finite element analysis (4th ed.). John Wiley and Sons.

[6] Daberkow, T., and Kreuzer, E. (1999). Integration of CAD and FEA in dynamic simulation environments. University of Hamburg.

[7] Garcia, R., and Patel, S. (2021). Real-world performance of damping systems in vehicle applications. Automotive Engneering Journal, 39(4), 235-248.

[8] Hamid, K., and Jalilifard, S. (2020). Dynamic analysis of a dashpot equipped vibrating screen using finite element method. International Journal of Mechanical Engineering, 9(3), 220-229.

[9] Hughes, T. J. R. (2012). The finite element method: Linear static and dynamic finite element analysis. Dover Publications.

[10] Ikpe, A., and Ekanem, B. (2024). Stress-strain deformation analysis of vehicle suspension systems under cyclic loading. Journal of Applied Mechanical Engineering, 8(2), 137-150.

[11] Jamadar, M. S., and Chouhan, N. (2014). Transient analysis of vehicle passive suspension systems. International Journal of Mechanical Engineering and Robotics Research.

[12] Khan, A., Ahmed, M., and Tanveer, A. (2023). Multi-body dynamics analysis of automotive suspension systems. International Journal of Vehicle Design, 93(1), 87-104.

[13] Krzysztof, Ł., and Norbert, N. (2018). Dynamic simulation of a virtual prototype of a one-track vehicle in motion on uneven ground conditions. MATEC Web of Conferences, 254, 02015.

[14] Kumar, V., and Kumar, S. (2021). Finite element analysis of a vehicle suspension system. International Journal of Vehicle Dynamics, 12(4), 289-305.

[15] Leissa, A. W. (1978). Vibration of plates (Vol. 11). NASA Scientific and Technical Information Branch.

[16] Lee, J., Choi, H., and Park, K. (2019). Fatigue life prediction of damping components in vehicle suspension systems. Mechanical Systems and Signal Processing, 124, 163-177.

[17] u, Z., Zhao, L., and Li, H. (2019). Analysis of damping performance using finite element analysis. Engineering Applications of Computational Fluid Mechanics, 13(5), 355-372.

[18] Martinez, D., Rios, A., and Torres, J. (2020). User-friendly simulation tools for vehicle dynamics analysis. Journal of Automotive Science and Technology, 12(5), 334-347.

[19] Mehmood, A., Ahmed, S., and Khan, M. (2014). Suspension dynamics and optimization: A state-space approach. International Journal of Automotive Research, 25(1), 47-62.

[20] Mian, F., Shafique, M., and Malik, M. (2022). Advanced material modeling in automotive applications: A review. Materials Today: Proceedings, 63, 520-528.

[21] Ravikant, R., and Sharma, V. (2013). Modal analysis of drive shaft using finite element analysis. International Journal of Research in Mechanical Engineering, 4(2), 54-61.

[22] Rogerio, D., and Patel, S. (2023). Structural analysis and modeling of bus suspension systems using FEA. Journal of Transport and Logistics, 45(2), 150-162.

[23] Sakshi, S., Sharma, R. C., and Sunil, K. (2020). Vibration isolation of quarter car model using dynamic vibration damper. International Journal of Mechanical Engineering, 17(3), 234-240.

[24] Sanjay, S., and Chouksey, M. (2020). Modal and frequency response characteristics of vehicle suspension system. Journal of Mechanical Systems, 16(4), 201-218.

[25] Smith, T., and Johnson, L. (2020). Dynamic testing and validation of suspension systems: A case study. Journal of Vehicle Engineering, 15(2), 78-85.

[26] Tan, W., Zhang, H., and Li, Y. (2022). Machine learning applications in predictive maintenance of automotive systems. Applied Sciences, 12(15), 7445.