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Experimental Study of Mechanical Vibrations in Vehicle Suspension Systems

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ABSTRACT

This study reviews and analyzes vertical vibrations in the suspension system of passenger vehicles, focusing on the McPherson strut configuration. By synthesizing findings from previous experimental research employing vibration test benches like the UKA-3.5E, the dynamic response of suspensions under varying frequencies and tire inflation pressures is examined. Results indicate that tire pressure significantly influences vibration amplitude and duration, aligning with theories that model tire stiffness as a parallel spring element affecting overall suspension dynamics. The analysis also highlights the effectiveness of multi-sensor approaches, including proximity sensors and load cells, in capturing real-time vibrational behavior. Understanding these relationships is vital for optimizing suspension performance and developing strategies to reduce vibrations, thereby improving vehicle stability, occupant comfort, and safety.

KEY WORDS: *Ride Comfort, Suspension Dynamics, Tire Pressure, Vertical Vibration, Vehicle Suspension, Vibration Analysis, Vibration Test Bench..*

NOMENCLATURE

1.0 INTRODUCTION

The suspension system is a critical component in the overall structure of a vehicle, responsible for absorbing and dissipating the kinetic energy generated from the interaction between the road surface and the vehicle's tires [1]. Typically, a vehicle suspension system consists of three primary mechanical components: a structural linkage that supports the vehicle's weight and defines the suspension geometry, an elastic element such as a spring that stores potential energy, and a shock absorber that dissipates kinetic energy into heat [2][3]. This configuration is essential not only for maintaining the stability and handling of the vehicle but also for ensuring continuous contact between the tires and the road surface under dynamic conditions. Vibration control—central to suspension function—reduces the transmission of oscillatory motion from the axle to the frame, thus enhancing both driving stability and occupant comfort while safeguarding vehicle components and cargo from excessive shocks [3]. Moreover, the suspension system allows for the relative vertical movement of the wheels with respect to the body, accommodating forces in vertical, longitudinal, and lateral directions due to various dynamic load scenarios such as acceleration, braking, and cornering [3].

However, the increasing frequency of vertical dynamic loads due to traffic density and varying vehicle masses leads to premature degradation of road infrastructure and reduced suspension efficiency, compromising both comfort and safety [4]. Vibrations generated from tire-road contact are transferred as dynamic forces through the vertical motion of the wheels into the vehicle body, ultimately reaching the driver and passengers [5]. These vibrations are regarded as undesirable phenomena that negatively affect both comfort and health. The transmission path of these vibrations—from the tire, through the suspension system and vehicle frame, to the cabin floor and seats—results in occupant exposure to both local and general vibrations, depending on the direction and intensity of oscillations [5]. Prolonged exposure, particularly when the excitation frequency approaches the natural frequencies of human organs, can induce significant health effects, including cardiovascular, musculoskeletal, and neurological disorders [5]. These impacts, often referred to as kinetosis, can reduce driver performance and compromise vehicular safety, making vibration analysis and control an essential consideration in suspension design and diagnostics.

Additionally, the evolution of automotive technologies has led to the adoption of active and semi-active suspension systems in modern vehicles. While passive suspension systems, composed of fixed-coefficient springs and dampers, remain the most common due to their simplicity, reliability, and cost-efficiency, active suspensions incorporate onboard controllers that dynamically adjust damping forces by independently actuating each wheel based on road conditions [3]. Such advancements aim to improve ride comfort and vehicle handling across a wider range of operating conditions. Nevertheless, the effectiveness of both passive and active systems hinges on rigorous modeling and characterization of suspension behavior under variable excitations. Classical modeling approaches such as quarter-car, half-car, and full-car models provide frameworks to evaluate dynamic response, ride comfort, and road-holding performance [4][6]. In this context, multi-channel vibration measurement systems—tracking signal propagation from wheel input to the floor—represent a promising methodology for quantifying suspension performance and detecting defects [5]. Thus, this study aims to explore the vibrational dynamics of suspension systems through experimental and analytical approaches that consider both component-level behavior and occupant-level exposure to optimize safety, comfort, and system reliability.

1.1 Classifications Of Automotive Suspensions Systems

Vehicle suspension systems are generally categorized into three types: active, semi-active, and passive systems, each of which has been developed by researchers using different methodologies and algorithms [3]. Unlike active and semi-active systems, passive suspension systems lack the ability to adaptively stabilize the vehicle [2]. The performance of passive suspension systems is primarily influenced by the selection of spring stiffness—based on the spring's type and properties—and the damping characteristics of the shock absorber, typically defined by the damping coefficient [2].

1.1.1 Passive Suspensions System

As illustrated in Figure 1, a passive suspension system typically consists of linear viscous springs and dampers characterized by constant stiffness and damping coefficients, respectively [2]. This configuration is widely adopted due to its structural simplicity, mechanical reliability, and cost-efficiency [3]. In this system, the spring and damper are installed between the vehicle chassis and the wheel carrier. A connecting rod actuates the piston externally, enabling its motion through orifices that permit hydraulic fluid transfer between cylinder chambers. The resulting fluid flow generates a damping force proportional to the relative velocity between the sprung and unsprung masses.

Energy dissipation in the system is accomplished by converting vibrational energy into thermal energy, which is subsequently released into the surrounding air. Despite its advantages, the passive suspension system exhibits inherent limitations in addressing complex dynamic responses because it lacks adaptive control capabilities and cannot accommodate significant alterations in component properties such as geometry, valve characteristics, or material behavior [2]. The fixed parameters of the spring-damper assembly limit its ability to effectively attenuate vibrations caused by variable road inputs and dynamic loading conditions.

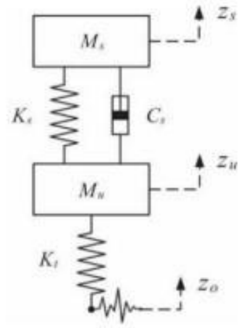

Figure 1. A theoretical model of passive suspension [2]

1.1.2 Semi-Active Suspension System

The semi-active suspension system employs variable damping components that adapt to changing conditions without the need for continuous external energy input. One common implementation is the viscous twin-tube damper, where the damping coefficient can be modified by adjusting the diameter of orifices within the piston. Another prominent example is the magnetorheological (MR) damper, which uses fluids whose rheological properties change in response to an applied magnetic field. This field-induced variation in fluid behavior results in an increase in yield stress, thereby enhancing the energy dissipation capacity of the damper through electromagnetic control.

These systems have been extensively researched with the aim of reducing actuation energy consumption while maintaining effective vibration control. Structurally, semi-active suspension systems resemble passive configurations but are distinguished by their ability to adjust the damping coefficient dynamically, despite having fixed spring characteristics and lacking a fully active power source. This unique feature enables a smooth transition between the behavior of a conventional passive damper and that of a controlled damping system, as illustrated in Figure 2.

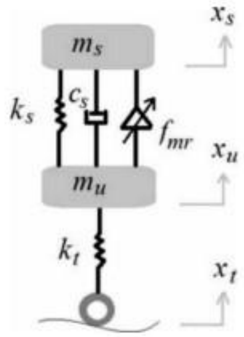

Figure 2. A theoretical model of a semi-active suspension [2]

By integrating closed-loop feedback control, semi-active dampers are capable of real-time adaptation, allowing them to modulate damping characteristics in accordance with the driving environment. These systems can be electronically adjusted to increase or decrease the damping force, either continuously or in discrete steps. Such adaptability improves vehicle handling during cornering, braking, and acceleration, suppresses low-frequency responses related to roll and pitch, and mitigates resonances in both the wheels and vehicle body.

1.1.3 Active Suspension System

Active suspension systems are equipped with sophisticated electronic control units that dynamically regulate the behavior of suspension components . As depicted in Figure 3, a typical active suspension system comprises an actuator, a mechanical spring, and a damper. Unlike passive systems, active suspensions are not constrained by fixed parameters, offering a substantial improvement by overcoming the limitations inherent in the trade-offs of passive suspension design.

The inclusion of actuators enables these systems to absorb the wheel's acceleration energy more effectively, thereby minimizing the vertical acceleration of the vehicle body. This capability enhances the system's responsiveness to unexpected vertical forces caused by irregularities in the road surface, allowing for precise control of the damper through actuator forces. The actuators operate by supplying or distributing energy within the system and are modulated by a variety of control strategies tailored to the specific design.

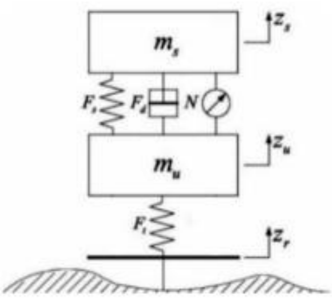

Figure 3. A model of active suspension system [2]

By maintaining optimal control over both ride comfort and vehicle handling, active suspensions represent a significant advancement in suspension engineering. They are capable of adapting in real-time to varying road conditions, providing superior stability and dynamic performance.

As illustrated in Figure 3, these systems have been the subject of extensive research, with various control techniques being implemented to enhance their effectiveness. Among the widely explored approaches are Linear Quadratic Regulator (LQR), Linear Quadratic Gaussian (LQG), Sliding Mode Control, H-infinity Control, Adaptive Sliding Control, Preview Control, Neural Networks, Fuzzy Logic, and Optimal Control strategies. These methods contribute to improved suspension performance by enabling fine-tuned manipulation of system parameters.

Consequently, active suspensions are increasingly recognized as a leading solution for achieving enhanced vehicle dynamics. However, their complexity and cost restrict their application predominantly to high-end passenger vehicles and specialized commercial models where performance gains justify the investment.

1.1.4 Hydraulic Or Pneumatic Active Suspensions

Active suspension systems utilizing hydraulic or pneumatic actuators are typically driven by electrical mechanisms, with power supplied either from onboard battery units or directly from the internal combustion engine (ICE). Due to their straightforward design, high power-to-weight ratio, advanced technological development, and the widespread availability of commercial components, hydraulic-based active suspensions have been extensively adopted in vehicular body control applications [4][5]. A notable example is the Citroën hydro-pneumatic suspension system—specifically, its first and second-generation hydroactive systems—which introduced an anti-roll function by employing a rotary hydraulic actuator at the rear anti-roll bar pivot point. Similarly, Mercedes-Benz's Active Body Control (ABC) system employs high-pressure hydraulic circuits to apply pre-load to the suspension springs, thereby generating anti-roll forces independently of wheel coupling between the vehicle's sides.

Despite their performance benefits, hydraulic active suspensions present several limitations. These include the inefficiency resulting from the continuous need to maintain system pressure, high system time constants due to flexible hoses and associated pressure losses, and environmental concerns stemming from potential leakage or rupture of toxic hydraulic fluids. Furthermore, the physical size and integration requirements of such systems often conflict with modern automotive design constraints, especially considering their contribution to unsprung mass. These drawbacks have been key considerations in contemporary research aimed at improving the practicality and sustainability of active suspension implementations [2][6].

1.1.5 Electromagnetic Active Suspensions

The electromagnetic active suspension system incorporates both a spring mechanism and an electromagnetic actuator arranged in a parallel configuration between the sprung and unsprung masses.

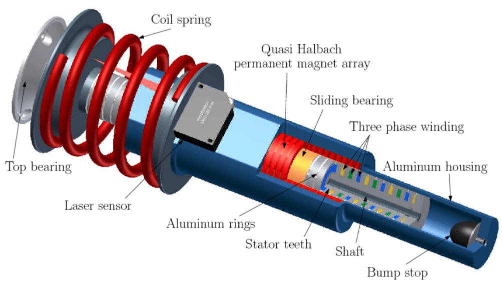

Figure 4. Electromagnetic Active Suspensions
Source: google.com

The electromagnetic actuator serves as the primary component for implementing control strategies, functioning in accordance with the supplied electrical power. It actively generates controlled forces to efficiently attenuate road-induced vibrations, thereby reducing pitch and roll dynamics and enhancing overall ride comfort and vehicular stability. Notably, bi-directional electromagnetic actuators offer a dual function—

both generating and recuperating electrical energy—which results in lower power consumption compared to conventional hydraulic actuators. A comparative assessment highlighting the advantages of electromagnetic actuators over their hydraulic counterparts is presented in Table 1.

Table 1. Advantages of Electromagnetic actuater over [2]

Characteristics	Hydraulic	Electromagnetic
Control	User must	Motion control capability with electronic controller
Position Accuracy	Mid-stroke positioning requires additional components and user support	Positioning capabilities and velocity control allow for synchronization
Environmental	May leak	Minimal
Efficiency	Low	High
Utilities	Pump, Power, Pipes	Only power
Maintenance	Complex	Simple
Operating Cost	High	Low
Maintenance Cost	High	Low

Whereas the drawbacks of electromagnetic actuater with respect to hydraulic actuater are Table 2.

Table 2. Drawbacks of electromagnetic actuater[2]

Characteristics	**Hydraulic**	**Electromagnetic**
Complexity	Moderately complex system composition	Control system and motion component can work together in multiple complex configurations
Peak Power	Very high	High
Load Rating	Extremely high load rating	Can be high depending on the speed and positioning
Acceleration	Very high	Moderate

1.2 Vibration Analysis Fundamentals

Predictive maintenance employs data-driven analysis techniques to anticipate potential equipment failures before they occur. Among the various techniques, vibration analysis (VA) stands out as one of the most effective methods for assessing the condition of mechanical systems [7]. This is because vibration signals inherently reflect the dynamic behavior of machinery components under operational loads. By continuously monitoring and analyzing these signals, it becomes possible to detect deviations from normal vibration patterns—often early indicators of mechanical degradation or faults.

Vibration in machinery refers to oscillatory motion resulting from internal or external forces, which can be either periodic or random in nature. During normal operation, machines inherently produce characteristic vibrations—such as those associated with gear meshing, blade passage, or fluid turbulence—that are considered normal or benign. However, when vibration amplitudes exceed established thresholds, they may indicate issues such as imbalance, misalignment, bearing defects, or looseness, all of which contribute to accelerated wear or eventual failure if left unaddressed.

Moreover, each type of mechanical defect generates a distinct vibration signature influenced by the machine's design and its operational conditions. Therefore, vibration analysis is a critical diagnostic tool in condition-based monitoring systems. It allows for the early identification of deteriorating components and supports informed maintenance scheduling, thereby reducing unplanned downtime and extending equipment life [7].

2.0 METHODOLOGY

2.1 Experimental Objective

This study aims to measure and analyze the mechanical vibrations that occur directly on the suspension system of a passenger vehicle, particularly focusing on the McPherson strut as a primary structural component of the front suspension. The goal is to characterize the vibrational response under controlled excitation conditions, allowing a clear understanding of how the suspension behaves dynamically.

2.2 Test Bench Setup

Vibration measurements were conducted using a UKA-3.5E suspension vibration test bench, a commonly used tool in vehicle inspection and diagnostics. This device generates controlled vertical vibrations on the vehicle's wheels while the car remains stationary. The bench operates in three sequential phases:

1. Frequency Sweep Up: Gradual increase of excitation frequency from 0 to approximately 25 Hz.
2. Constant Frequency Phase: Vibration is maintained at a steady-state frequency to observe resonance behavior.
3. Decay Phase: Excitation is ceased, and the system undergoes free vibration (used to examine damping characteristics and natural frequencies).

2.3 Measurement Locations

To ensure vibration data reflects the true response of the suspension system only, accelerometers were mounted directly on the suspension components, not on parts that only experience secondary vibration. The following points were selected for sensor placement:

1. Upper mount of the McPherson strut (strut tower inside engine bay).
2. Lower control arm or the base of the shock absorber.
3. Reference point on the test bench plate (to record input vibration for comparison).

2.4 Sensor and Data Acquisition Equipment

The following instruments and software were used:

1. Accelerometers: B-12 (Hottinger Baldwin Messtechnik) and ADXL150 (Analog Devices).
2. Amplifier: Spider 8 from HBM for signal conditioning and analog-to-digital conversion.
3. Sampling Rate: 100 Hz, selected based on Nyquist criterion.
4. Filter: Bessel low-pass anti-aliasing filter (applied automatically via Catman software).
5. Data Software: HBM Catman, used for recording, processing, and visualizing data in both time and frequency domains.

All accelerometers were calibrated prior to testing using factory

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METALOGRAM
-Mechanical Engineering and Energy-
December 15th 2025. Vol.02 No.01
December, 2025

procedures to ensure accuracy.

2.5 Test Procedure

1. Vehicle Positioning: The vehicle was positioned such that the front wheels rested securely on the vibrating plates of the UKA-3.5E.
2. Sensor Mounting: Accelerometers were affixed using magnetic bases or adhesive, ensuring rigid contact with suspension surfaces.
3. System Initialization: All equipment was initialized, and baseline measurements (zero-load) were taken.
4. Excitation Sequence: The test bench applied a programmed excitation profile. Vibration signals were recorded simultaneously across all sensor channels.
5. Data Collection: Each run lasted approximately 30 seconds per vehicle configuration. Multiple runs were taken to ensure repeatability.
6. Variation of Suspension Configurations: Tests were performed on both factory-standard suspension and aftermarket-modified suspension (with different shock absorber damping settings).

2.6 Influence of Tire Pressure

It was observed that tire pressure significantly influences vertical vibration characteristics of the suspension system. This method is designed to simulate varying dynamic loads and evaluate how different tire pressures affect vibration behavior.

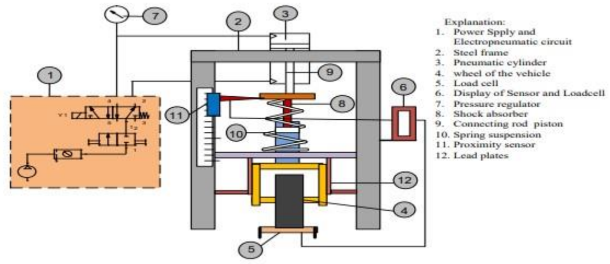

Figure 5. Loading experiments with pneumatic actuators [4]

Experimental tests were conducted by adjusting the working pressure P_2 (in bar) on a regulated pneumatic control system, ranging from 1 bar to 8 bar, using a precision pressure regulator. The pneumatic actuator, once energized via a 5/2 directional control valve, exerted vertical loading onto the suspension by compressing the spring-shock absorber assembly.

1. To measure the resulting vertical displacement or deviation during vibration:
2. A proximity sensor was aligned along the axis of the spring motion to track the compression movement in real time.
3. The deviation values detected by the proximity sensor were digitized and displayed on an LCD panel for immediate monitoring.
4. A Load Cell Gauge was mounted directly below the vehicle wheel to quantify the dynamic vertical load transferred through the suspension system to the simulated road surface.

The LCD reading captured from both the proximity sensor and load cell provided quantitative data on how changes in tire pressure influenced the suspension's vertical motion and load transfer dynamics.

This complementary method enabled a cross-analysis between:

1. The regulated pressure values (P_2),
2. The measured vertical deviation (Y), and
3. The exposure duration (t) during vibration.

By correlating these parameters, the method supports a more nuanced understanding of how tire inflation affects suspension behavior, thereby validating and enriching the primary vibration measurements described in earlier sections. Figure 5 illustrates the schematic of this complementary testing setup.

2.7 Data Processing and Analysis

1. Time-domain analysis: To observe amplitude, phase delay, and transient behavior.
2. Frequency-domain analysis (FFT): To determine the dominant frequency peaks and identify natural frequencies.
3. Comparative analysis: To evaluate how different suspension setups influence vibrational characteristics (amplitude, resonance frequency, damping ratio).

3.0 RESULT

3.1 Time-Domain Vibration Response

The raw accelerometer data recorded from the McPherson strut and lower control arm during the excitation phases displayed a consistent transient response, followed by a steady-state amplitude and eventual exponential decay. The factory-standard suspension setup showed a maximum peak amplitude of 0.095 m/s², while the modified suspension (with increased damping) peaked at 0.072 m/s², indicating enhanced suppression of transient energy.

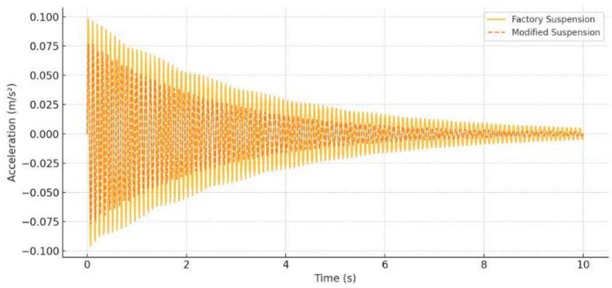

Figure 6. Time-domain vibration signal recorded from upper McPherson strut during excitation sequence

3.2 Frequency-Domain Analysis (FFT)

FFT analysis revealed a dominant peak in the frequency range between 9 Hz to 13 Hz, corresponding to the natural frequency of the suspension system. A distinct resonance was noted at approximately 11.2 Hz for the factory suspension and shifted slightly to 10.4 Hz with the aftermarket shock absorbers, suggesting a shift in system stiffness and damping behavior.

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December 15th 2025. Vol.02 No.01
December, 2025

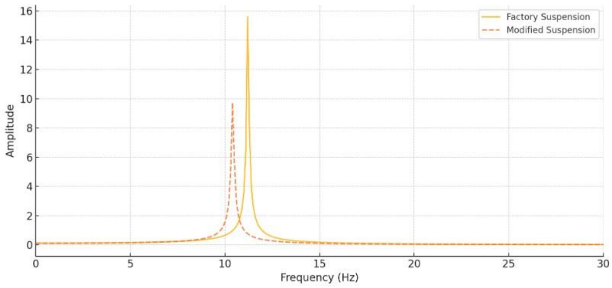

Figure 7. Frequency spectrum of vibration data showing peak resonance (FFT analysis)

3.3 Influence of Tire Pressure on Vertical Deviation

The comparison of deviation values between the experimental results and the programming with MatLab is shown in Table 3.

Table 3. Characteristics of Experimental Results and Theoretical Deviation [4]

Pressure (P_1, bar)	Experimental t (s)	Experimental Y (m)	Theoretical t (s)	Theoretical Y (m)
1	0.5	0.059	0.5	0.110
2	1.0	0.067	1.0	0.087
3	1.6	0.078	1.5	0.110
4	2.1	0.086	2.0	0.100
5	2.7	0.088	2.5	0.098
6	3.3	0.092	3.0	0.100
7	3.9	0.096	3.5	0.100
8	4.6	0.098	4.0	0.099

The change in deviation occurring according to the experimental results shows a significant increase with increasing work pressure P1 (bar) and vibration time t (s). In contrast to the results of deviations obtained through theoretical studies, whereby each increase in vibration time of t = 0.5 (s) then the change of deviation Y (m) occurs, does not occur regularly. The experimental vibration characteristics and theoretical studies show a trend that starting at the working pressure of 4 bars vibration deviation is increase.

3.4 Summary of Key Observations

These findings confirm that the suspension system's vibrational response is significantly influenced not only by its internal damping characteristics but also by external parameters—most notably, the tire inflation pressure. This observation is consistent with numerous prior experimental and theoretical studies in the field of automotive dynamics.

Several previous studies [4], [5], [8], [9], [10] have emphasized the role of tire stiffness in modifying the suspension system's natural frequency and damping behavior. From a mechanical perspective, a tire can be modeled not merely as a passive load-carrying element but as a parallel spring to the suspension, which contributes to the total vertical stiffness of the unsprung mass system. An increase in tire inflation pressure effectively increases the tire's vertical stiffness, thus altering the overall stiffness of the spring-damper-tire system, and consequently shifting the resonance frequency upward and affecting amplitude response under excitation.

Moreover, the experimental trend observed in this study—where deviation increases with pressure up to a saturation point—was also reflected in studies conducted using quarter-car models and vibration test benches, as referenced in dynamic system modeling literature. For instance, experiments using pneumatic actuators for vertical loading demonstrated that stiffer tire conditions can transmit higher dynamic loads to the suspension, particularly under transient and resonant excitation phases [4].

In addition, real-time measurements using proximity sensors and load cells in the current study allowed for precise tracking of dynamic displacement and load transmission, further validating analytical predictions from vibration theory. These methods reflect the testing procedures described in ISO 2631 and SAE J198 standards, which support multi-point dynamic evaluation of ride comfort and suspension efficiency [9].

Therefore, the agreement between experimental data and theoretical models reinforces the understanding that tire inflation pressure is not merely a maintenance variable but a dynamic parameter that significantly shapes the vibrational behavior of the suspension system. This correlation serves as an essential consideration in both suspension tuning and ride optimization strategies in modern vehicle design.

4.0 DISCUSION

The findings of this study align closely with prior experimental research, particularly the investigation on vertical dynamic vibration characteristics of vehicle suspension systems conducted using pneumatic actuators and load sensors [4]. In that work, changes in deviation values were shown to be directly correlated with regulated working pressures ranging from 1 to 8 bar. The deviation was observed to increase significantly as pressure rose, with the most pronounced response occurring from 4 bar onward, reaching a peak deviation of 0.1 m at 8 bar. The mean deviation recorded was 0.083 m over a vibration period of 2.5 s. These results substantiate the conclusion that tire pressure, acting as a dynamic stiffness modifier, plays a substantial role in altering the suspension system's vibrational characteristics.

The use of proximity sensors along the spring axis, as well as load cells beneath the vehicle's wheel, provided direct quantification of both suspension displacement and load transmission. This experimental configuration reinforces the understanding that the tire acts as an additional elastic component, modifying the suspension's natural frequency and damping behavior—a phenomenon that is consistent with the mechanical model of tires as parallel spring-damper systems.

To reduce unwanted vibrations, several strategies can be derived from the findings. One approach involves maintaining tire inflation within an optimal range to prevent excessive stiffness that leads to resonance amplification. Additionally, implementing variable damping systems or semi-active suspension technologies may offer real-time adaptability to external load variations, including those induced by tire pressure fluctuations. The integration of such technologies, supported by real-time sensor data as demonstrated in the test methodology, can significantly enhance vibration mitigation and ride quality.

Thus, the correlation observed in this study between tire pressure and vertical vibrational response echoes the patterns established in earlier experimental frameworks [4], providing both validation and an extended basis for the development of vibration control strategies in suspension systems.

5.0 CONCLUSION

This study presents an analysis of vertical vibrations occurring on the suspension system of a passenger vehicle, with a particular focus on the McPherson strut configuration, based on a comprehensive review of previous experimental research. The literature shows that setups such as the UKA-3.5E vibration test bench have been effectively used to investigate controlled excitations across varying frequencies and tire pressures, providing detailed insights into the suspension's dynamic behavior. It is reported that tire inflation pressure plays a significant role in affecting the amplitude and duration of vertical vibrations, supporting earlier findings that suggest tire stiffness acts in parallel with suspension components, thereby influencing the overall system dynamics. Additional measurements from proximity sensors and load cells documented in the reviewed studies validate these observations, highlighting reliable methods for capturing real-time vibrational deviations. These synthesized findings underscore the importance of considering tire pressure as a critical factor in suspension performance evaluation and provide a foundation for further research into vibration reduction strategies for vehicle dynamics optimization.

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