Hybrid Active–Passive Suspension System Using Magnetorheological Fluid Technology for Vehicle Dynamics Improvement

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***Abstract*—This paper presents the design, fabrication, and analysis of a hybrid active–passive suspension system using magnetorheological (MR) fluid technology for improving vehicle dynamics. The system combines a conventional spring mechanism with a piston-cylinder damping arrangement to enhance vibration control, ride comfort, and stability. A quarter car model is used for analysis, representing the behavior of a real vehicle suspension system. The fabricated model consists of a steel frame, hydraulic cylinder, piston, and fail-safe spring mechanism. The dynamic behavior of the system is analyzed using MATLAB simulation, considering displacement, velocity, and acceleration. The effect of damping variation is also studied. The proposed system provides a simple, cost-effective, and efficient solution for automotive applications.**

I. INTRODUCTION

Suspension systems are essential components in automobiles that provide ride comfort and vehicle stability by absorbing shocks caused by uneven road conditions. Conventional suspension systems consist of springs and dampers with fixed characteristics, which cannot adapt to varying road conditions, leading to reduced performance and comfort. To overcome these limitations, advanced systems such as electromagnetic and magnetorheological (MR) fluid-based suspensions have been developed. MR fluid has the unique property of changing its viscosity when exposed to a magnetic field, enabling real-time control of damping. However, fully active systems are complex and expensive. In this work, a hybrid suspension system is developed by combining passive and semi-active elements. The system uses a spring to absorb shocks and a piston-cylinder arrangement to control damping. This combination improves overall system performance while maintaining simplicity and cost-effectiveness. By integrating these elements, the proposed system achieves a balance between efficiency, adaptability, and affordability, making it suitable for practical automotive applications.

II. PROBLEM STATEMENT

Normal car suspension systems have springs and dampers that can't change how they work, so they can't handle different road conditions or loads. This means that making the ride more comfortable can make the car less stable, and vice versa, so people in the car feel too many vibrations and it becomes harder to control the car, especially on bumpy roads. The suspension cannot adapt to what is happening, which is a problem, and it is always trying to balance comfort and stability but cannot achieve both at the same time. Some advanced suspension systems can give better performance, but they are complicated, expensive, and need a lot of power, making them less suitable for simple and affordable applications. Systems that use special fluids can adapt to conditions, but they are difficult to control and require more maintenance. Therefore, there is a need for a suspension system that can control vibrations better, provide a smoother ride, and maintain stability while being simple, cost-effective, and easy to fabricate, and the challenge is to develop a hybrid system that combines passive and semi-active elements to achieve good performance without increasing complexity.

III. OBJECTIVES

This project focuses on developing a new type of suspension system for vehicles with the aim of improving vibration control, ride comfort, and overall vehicle stability. The system is designed by combining traditional suspension elements with semi-active components to achieve better performance. A key aspect of the project is the use of magnetorheological (MR) fluid, which has the ability to change its viscosity when subjected to a magnetic field, allowing real-time adjustment of damping. The project involves designing and fabricating a simple and cost-effective prototype using basic components such as springs, pistons, and magnets. The performance of the system is evaluated using a quarter car model and analyzed through MATLAB simulation by studying parameters like displacement, velocity, and acceleration. The objective is to create a suspension system that is reliable, efficient, and suitable for real-world applications without increasing complexity or cost. By combining conventional and modern technologies, the project aims to overcome the limitations of existing suspension systems and develop a practical and effective solution.

IV. LITERATURE STUDY

Suspension systems have evolved significantly from basic passive systems to advanced systems that can adapt to varying road conditions. Earlier suspension systems used fixed springs and shock absorbers, which could not adjust their behavior even when the road conditions changed, leading to reduced comfort and stability. Modern systems such as electromagnetic and semi-active suspensions provide better control over vibrations and vehicle motion, resulting in improved ride quality and stability. Magnetorheological (MR) fluid technology has further enhanced suspension performance, as it can change its viscosity when exposed to a magnetic field, allowing real-time control of damping. MR dampers respond quickly and offer superior vibration control compared to conventional dampers, making them highly effective for dynamic conditions. Hybrid suspension systems combine passive elements like springs with semi-active damping mechanisms to achieve a balance between performance and complexity. However, most existing research focuses on simulation and advanced control strategies, with less emphasis on developing simple and cost-effective fabricated models. Therefore, there is a need for a practical hybrid suspension system that is easy to implement, affordable, and capable of improving vibration control and stability, which forms the basis of this project.

V. PROPOSED METHODLOGY

The proposed methodology focuses on developing and testing a hybrid suspension system that combines traditional and advanced elements to improve vibration control and stability. Initially, the limitations of existing suspension systems are analyzed to identify areas for improvement. Based on this, a new concept is developed using a combination of a spring and a piston-cylinder arrangement with magnetorheological (MR) fluid, which can change its properties under a magnetic field to provide adaptive damping. This hybrid approach aims to achieve better control over vibrations and enhance overall system stability for real-world applications.

A quarter car model is selected to simplify the analysis while maintaining accuracy. Key parameters such as vehicle mass, spring stiffness, and damping coefficient are calculated to design the system effectively. Suitable materials are chosen for components like the frame, spring, piston, and cylinder by considering strength, durability, and cost, ensuring the system is both efficient and economical.
The design is created using SolidWorks to verify proper alignment and assembly of components. After finalizing the design, fabrication is carried out through processes such as cutting, welding, drilling, and assembly. The piston-cylinder setup is integrated with the spring, and magnetic elements are included to control the behavior of the MR fluid.

The fabricated prototype is tested under different loading conditions to evaluate vibration and stability performance. MATLAB simulation is used to analyze system responses such as displacement, velocity, and acceleration. Finally, the experimental results are compared with simulation results to validate the effectiveness of the proposed system. Overall, this methodology provides a systematic approach to develop a simple, cost-effective, and efficient hybrid suspension system suitable for automotive applications

VI. SYSTEM MODELLING

The hybrid suspension system is modeled using a quarter car model, which represents one wheel assembly of the vehicle. This simplifies the analysis while maintaining accuracy in predicting system behavior. The model consists of mass (m), spring stiffness (k), and damping coefficient (c), which together define the dynamic response of the system.

The motion of the suspension system is governed by a second-order differential equation:
$m\, d^2x/dt^2 + c\, dx/dt + kx = F(t)$ Where:
m = mass of the system (kg)
c = damping coefficient (Ns/m) k = spring stiffness (N/m)
x = displacement (m) $F(t)$ = external force (N)

The spring force is given by:
$F = kx$
The force created by a spring is directly related to how far it's stretched or compressed.

The damping force provided by the piston-cylinder arrangement is:
$F = c\,(dx/dt)$
This shows that the force that slows things down is related to how fast they're moving.

The natural frequency of the system is calculated using:
$f = (1 / 2\pi) \sqrt{k / m}$
This parameter is important for determining ride comfort and system response.

The damping ratio is given by:
$\zeta = c / (2 \sqrt{k\, m})$

The damping ratio helps in understanding whether the system is underdamped, critically damped, or overdamped.

These equations are used to analyze the dynamic behavior of the suspension system and to evaluate its performance under different conditions.

VII. INTERNAL COMPONENTS

The hybrid suspension system is made up of a few key parts, including a piston and cylinder filled with a special fluid that helps dampen movement, a spring, and magnetic components. When a load is applied, the piston inside the cylinder moves up and down, forcing the fluid to flow and creating resistance that smoothens the motion. A coil spring is attached at the top of the system, which absorbs the initial shocks and also acts as a fail-safe mechanism to ensure stable operation. The interaction between the piston and fluid plays a major role in reducing vibrations and improving ride comfort.

Neodymium magnets are positioned around the cylinder to create a strong and stable magnetic field. This magnetic field directly affects the behavior of the magnetorheological (MR) fluid inside the cylinder by aligning its particles. When the magnetic field is applied, the fluid becomes thicker and offers more resistance to flow, resulting in increased damping force and reduced vibrations.

The combination of mechanical components and magnetic elements enables the system to provide better vibration control and stability. The arrangement of internal parts ensures smooth piston movement and efficient damping performance under different loading conditions, making the system effective for automotive applications.

Fig 7.1 Piston Wth Magnet (Movable Part)

Fig 7.2 Fixed Mounting with Magnets

Fig 7.3 Cylinder with Piston Attached

VIII. SIMULATION

The performance of the hybrid suspension system is analyzed using MATLAB simulation based on a quarter car model. The simulation helps in understanding how the system responds to road disturbances by evaluating parameters such as displacement, velocity, and acceleration. A step input is applied to represent a sudden road bump, and the system response is observed over time.

The system is modeled using mass (m), spring stiffness (k), and damping coefficient (c). The governing equation is converted into a transfer function and simulated using MATLAB. Different damping values are used to study the effect of MR fluid behavior on system performance.

The displacement response shows how much the system moves under disturbance. The velocity response indicates how quickly the motion reduces, and the acceleration response represents the vibration experienced by passengers. These responses are plotted as graphs to compare system performance.

The simulation is also used to analyze settling time and stability of the system. Higher damping reduces oscillations and improves stability, while lower damping results in more vibrations. By adjusting the damping parameters, the system performance can be optimized for better ride comfort and control.

Figure 8.1 Solid works Model

IX. FABRICATION

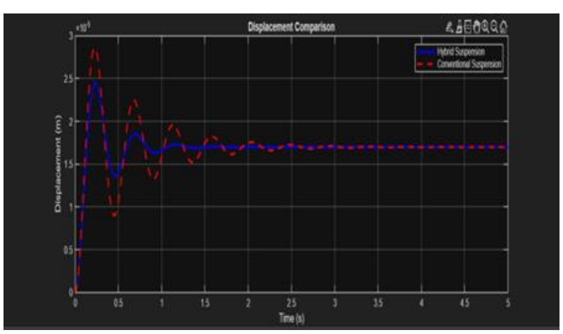
The hybrid suspension system is fabricated using a mild steel frame, which provides the required strength and structural stability. The frame is constructed by cutting and welding square pipes to form a rigid structure. A hydraulic cylinder is mounted vertically at the center of the frame, and a piston is placed inside the cylinder to provide damping action. Proper alignment is maintained to ensure smooth motion and minimize friction losses, allowing the system to operate efficiently. The combination of the steel frame, hydraulic cylinder, and piston enables the system to deliver stable and controlled performance. A coil spring is fixed at the top of the piston rod, which acts as a fail-safe mechanism and absorbs initial shocks. The components are assembled using welding and fastening methods to ensure durability and reliability. Neodymium magnets are positioned around the cylinder to generate a magnetic field that influences the behavior of the magnetorheological fluid. The fabricated model is tested under different loading conditions to evaluate vibration reduction and overall system performance


Figure 9.1 Fabricated Model

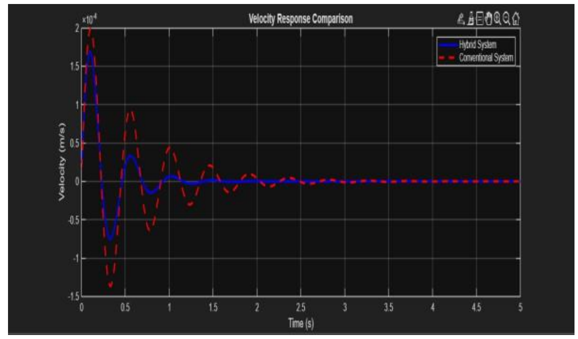
X. RESULTS AND DISCUSSION

The performance of the hybrid suspension system is evaluated using a combination of MATLAB simulation and experimental testing. The displacement response shows that the system has fewer oscillations and stabilizes faster compared to conventional suspension systems. This indicates that the system effectively returns to its equilibrium position, demonstrating good damping characteristics.

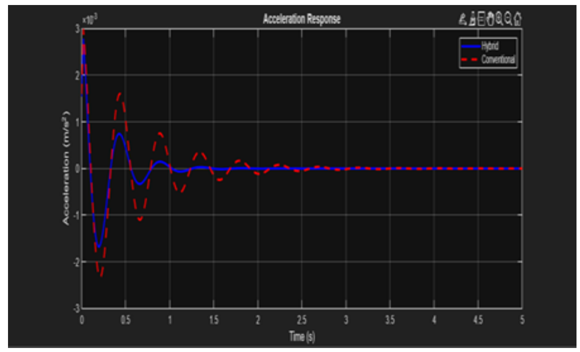
The velocity response shows a rapid reduction in motion, indicating efficient dissipation of energy within the system. The acceleration response is also lower, which means reduced vibration levels and improved ride comfort. These results confirm that the hybrid suspension system provides smoother and more controlled operation. The effect of damping is also analyzed, where higher damping results in reduced oscillations and improved stability, while lower damping leads to increased vibrations. The hybrid suspension system performs better than traditional systems in terms of vibration control, settling time, and stability, making it an effective solution for enhancing suspension performance.



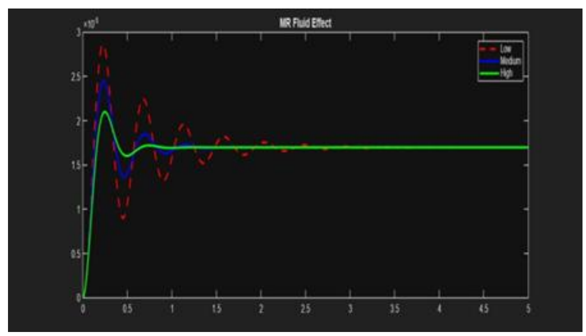
Graph 10.1 Displacement Output



Graph 10.2 Velocity Output



Graph 10.3 Accleration Response



Graph 10.4 Mr Fluid Damping Effect

XI. CONCLUSION

The hybrid suspension system developed in this project demonstrates significant improvement in vibration control, ride comfort, and vehicle stability. By combining a spring with a piston-cylinder damping mechanism, the system performs better than conventional suspension systems. It effectively reduces oscillations and improves response time, resulting in smoother and more controlled vehicle motion.
The design of the system is simple and cost-effective, making it suitable for practical applications. The results obtained from both MATLAB simulation and

experimental testing confirm that the proposed system works efficiently and achieves the desired performance.

XII. FUTURE SCOPE

The hybrid suspension system can be further enhanced by integrating magnetorheological (MR) fluid with controlled magnetic field variation to achieve real-time adaptive damping. The inclusion of sensors and electronic control units can enable automatic adjustment of system parameters based on changing road conditions, improving performance and responsiveness.

Future developments can focus on implementing the system in actual vehicles and testing it under real road conditions to evaluate practical performance. Advanced simulation tools such as ANSYS and MATLAB/Simulink can be used for detailed analysis and optimization of the system. Additionally, the use of lightweight materials can be explored to reduce overall system weight and improve efficiency. These improvements can make the system more effective, reliable, and suitable for real-world automotive applications.

APPENDIX

This section provides additional details and calculations related to the hybrid suspension system to support and clarify the main concepts presented in the study.

A. Quarter Car Model Calculations

Total vehicle mass, $M = 1200$ kg Quarter car mass, $m = M / 4 = 300$ kg Deflection, $x = 0.05$ m

Spring stiffness:

$k = (m \times g) / x$

$k = (300 \times 9.81) / 0.05$ $k = 58860$ N/m

Natural frequency:

$f = (1 / 2\pi) \sqrt{(k / m)}$ $f \approx 2.2$ Hz

Damping coefficient: $c = 2 \times \zeta \times \sqrt{(k \times m)}$

$c = 2 \times 0.25 \times \sqrt{(58860 \times 300)}$

$c \approx 2100$ Ns/m

B. System Equations

Equation of motion:

$m\, d^2x/dt^2 + c\, dx/dt + kx = F(t)$

Spring force: $F = kx$

Damping force: $F = c\, (dx/dt)$

C. MATLAB Simulation Code (Sample)

```
m = 300;
k = 58860;
c = 2100;
num = [0 0 1]; den = [m c k];
sys = tf(num, den); step(sys);
grid on;
title('Displacement Response'); xlabel('Time (s)'); ylabel('Displacement (m)');
```

D. Key Parameters

Mass (m) = 300 kg

Spring stiffness (k) = 58860 N/m Damping coefficient (c) = 2100 Ns/m Damping ratio (ζ) = 0.25

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