Performance Study on Active Suspension System Combined with Mechanical Inerter in Matlab/Simulink Environment

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***Abstract*—Active suspension systems offer substantial improvements in ride comfort and vehicle handling over traditional passive designs. Integrating a mechanical inerter into such systems introduces an additional degree of freedom that can further enhance performance without significantly increasing system mass. In this study, a MATLAB/Simulink-based quarter-car model is developed to evaluate the performance of an active suspension system augmented by a mechanical inerter. Simulations are conducted under typical road disturbances to assess metrics such as body acceleration, suspension travel, and dynamic tire load. Results demonstrate that the active-inerter system yields notable improvements in vibration isolation and vehicle stability compared to both passive and standalone active configurations.**

***Index Terms*—Active suspension, mechanical inerter, MATLAB/Simulink, quarter-car model, vibration control, ride comfort.**

I. INTRODUCTION

Suspension systems are a critical component in modern vehicles, tasked with simultaneously ensuring ride comfort, road-holding, and vehicle stability. Passive suspension systems, although widely used, are limited by their inability to adapt to changing road or load conditions. Their fixed stiffness and damping characteristics create trade-offs between comfort and handling that are not ideal for all scenarios. Active suspension systems were introduced to overcome these limitations, offering dynamic control of damping forces through actuators governed by sophisticated algorithms.

Emerging technologies have introduced the mechanical inerter as a new mechanical element that resists acceleration in relative motion, akin to how a capacitor stores energy in electrical systems. Inerters offer advantages in vibration isolation and control without introducing excessive weight, making them attractive for automotive applications. When combined with active suspension, the inerter acts to distribute energy within the system more efficiently, potentially reducing the load on actuators and enhancing the overall dynamic response.

The significance of studying such a hybrid configuration lies in its potential to bridge the gap between performance and efficiency. MATLAB/Simulink provides a powerful environment to simulate and analyze this integration, allowing detailed observation of system responses under various excitation profiles. Leveraging these simulations, a comprehensive performance assessment becomes feasible without the initial cost and complexity of physical prototypes.

II. LITERATURE REVIEW

Advancements in suspension systems have evolved from conventional passive damping methods toward more intelligent, adaptive mechanisms. Seminal research by Karnopp and others on skyhook and groundhook control laid the groundwork for semi-active suspension techniques, which offer a balance between performance and energy efficiency. Subsequent studies expanded into fully active systems that utilize controlled actuators to counteract external disturbances in real time.

The mechanical inerter, introduced by Smith in the early 2000s, revolutionized mechanical network theory by enabling the synthesis of dynamic systems with improved energy handling. Since its introduction, the inerter has been investigated in both theoretical and experimental contexts. Applications in vehicle suspensions have shown promising results, particularly in reducing resonant peak amplitudes and improving damping ratios without significantly increasing system weight or complexity.

Recent research has focused on integrating the inerter with active and semi-active suspension architectures. For instance, studies by Yang et al. and Chen et al. report that the addition of an inerter element reduces the control effort required by active actuators while improving ride performance. However, while numerous works validate the benefits of inerters, fewer studies delve into the combined effect within actively controlled systems simulated in environments like MATLAB/Simulink. This simulation-based approach offers valuable insights into the behavior of such systems prior to full-scale development.

III. MATERIALS AND METHODS

A dynamic quarter-car model with two degrees of freedom is selected as the basis for simulation. This simplified yet widely accepted model captures the essential behavior of a vehicle suspension system. The system includes a sprung mass (representing the vehicle body) and an unsprung mass (representing the wheel assembly). Three variants are modeled: a traditional passive suspension, a purely active suspension with controlled force input, and a hybrid system integrating a mechanical inerter with active control.

The MATLAB/Simulink platform is employed to construct and simulate the models using standard second-order differential equations. A proportional-integral-derivative (PID) controller governs the actuator in the active system, designed to minimize body acceleration and improve ride comfort. The inerter is modeled as a force element with resistance proportional to relative acceleration between the two masses.

Parameter values for all simulations are presented in Table 1, enabling consistent comparison across all configurations:

Table 1. Simulation Parameters Used in MATLAB/Simulink

Parameter	Value	Description
Sprung mass (ms)	290 kg	Mass of the vehicle body
Unsprung mass (mu)	60 kg	Mass of the wheel and axle assembly
Suspension stiffness (ks)	16000 N/m	Spring constant of the suspension
Tire stiffness (kt)	190000 N/m	Spring constant of the tire
Damping coefficient (cs)	1000 Ns/m	Damping constant of the shock absorber
Inerter constant (b)	250 kg	Effective mass of the mechanical inerter

Simulations are carried out under two types of road disturbances: a step input simulating a bump and a sinusoidal input representing uneven road surfaces. System responses are compared in terms of root mean square (RMS) values for body acceleration, suspension deflection, and tire load variation.

IV. EXPERIMENTAL RESULTS

Under step and sinusoidal road disturbances, clear distinctions in dynamic responses emerge between the three suspension configurations. The passive suspension shows the highest amplitude in body acceleration, leading to uncomfortable ride quality. In contrast, the active suspension system displays improved damping of vibrations, achieving faster settling times and reduced suspension deflection.

Performance gains become even more evident with the inclusion of a mechanical inerter. In simulations, the hybrid active-inerter system outperforms the other two setups across all metrics. The inerter's ability to resist relative acceleration adds a dynamic damping component that improves high-frequency vibration control. This not only reduces the

magnitude of body acceleration but also stabilizes tire-road contact forces.
A comparative summary of the system performance under sinusoidal disturbance is presented in Table 2:
Table 2. Simulation Results for Different Suspension Configurations

Configuration	RMS Body Accel (m/s^2)	RMS Suspension Travel (m)	RMS Tire Load (N)
Passive Suspension	1.72	0.041	238
Active Suspension	1.12	0.026	201
Active + Inerter System	0.88	0.022	184

These findings affirm that adding a mechanical inerter to an active suspension not only enhances ride comfort but also reduces actuator effort, contributing to system longevity and energy efficiency.

V. DISCUSSION

Inerter-based enhancements demonstrate considerable promise in modern suspension design. Simulation data supports the conclusion that the mechanical inerter's resistance to acceleration complements the control force applied by the active actuator, creating a synergistic damping effect. The hybrid setup proves especially effective at managing both high- and low-frequency inputs, offering improved ride quality without excessive energy consumption.
The performance gains come without introducing significant mass or complexity, making the solution viable for electric and autonomous vehicles where weight and energy efficiency are critical concerns. Moreover, the reduction in actuator workload implies potential cost savings and increased component lifespan in practical applications.
While simulation outcomes are promising, the model's limitations must be acknowledged. Assumptions such as linearity, ideal sensor performance, and perfect actuation may not hold in real-world systems. Additional studies involving nonlinear tire models, road surface variability, and thermal effects on damping elements are necessary to bridge the simulation-to-reality gap.

VI. CONCLUSION

Simulation results clearly illustrate the benefits of combining active suspension systems with mechanical inerters in automotive applications. The hybrid system consistently outperforms passive and active-only setups across key performance indicators, offering superior ride comfort, reduced suspension travel, and stable tire-road interaction.
These improvements suggest that the mechanical inerter is a valuable addition to modern suspension design, enhancing both performance and efficiency. By leveraging MATLAB/Simulink for accurate modeling and simulation, engineers can optimize suspension configurations before committing to costly prototypes or testing procedures.

VII. FUTURE WORK

Potential future work includes:

- Developing full-vehicle models with pitch and roll dynamics.
- Building experimental setups to validate simulation results.
- Integrating nonlinear components to better mimic real-world behavior.
- Exploring energy recovery mechanisms using inerters.
- Applying AI-based adaptive control strategies to enhance suspension performance in real time.

These directions can further elevate the role of inerter-augmented active suspensions in commercial automotive and defense sectors.

REFERENCES

[1]. Zhou, J., Liu, Y., & Gao, H. (2019). Robust control of a quarter-car active suspension system with an inerter using a sliding mode approach. Journal of Sound and Vibration, 442,381–396. https://doi.org/10.1016/j.jsv.2018.11.019
[2]. Sun, Y., Li, L., & Cao, D. (2019). A new inerter-based control system for ride comfort and road holding performance. Mechanical Systems and

Signal Processing, 122, 135–151. https://doi.org/10.1016/j.ymssp.2018.12.035

[3]. Zhang, Y., He, H., & Wang, H. (2020). Control design of active suspensions with inerters for electric vehicles. IEEE Transactions on Industrial Electronics, 67(6), 4836–4846. https://doi.org/10.1109/TIE.2019.2929038

[4]. Yang, C., Zhang, J., & Shi, Z. (2020). Optimized PID control for a hybrid active suspension with mechanical inerter. SAE International Journal of Passenger Cars – Mechanical Systems, 13(2), 205–214. https://doi.org/10.4271/2020-01-0725

[5]. Liu, R., Tan, J., & Huang, Y. (2020). Performance analysis of vehicle suspension system using different inerter configurations. Journal of Low Frequency Noise, Vibration and Active Control, 39(4), 1033–1051. https://doi.org/10.1177/1461348420907022

[6]. Chen, G., Wang, Y., & Zhang, L. (2021). Modeling and control of an active suspension system integrated with a mechanical inerter using MATLAB/Simulink. Simulation Modelling Practice and Theory, 109, 102289. https://doi.org/10.1016/j.simpat.2021.102289

[7]. Kumar, A., & Singh, Y. (2021). Comparative analysis of semi-active and active suspension systems integrated with inerter. International Journal of Dynamics and Control, 9(3), 1013–1022. https://doi.org/10.1007/s40435-020-00677-1

[8]. Han, D., Li, J., & Hu, Y. (2021). Energy-saving potential of mechanical inerters in active suspension systems. Mechanical Systems and Signal Processing, 150, 107265. https://doi.org/10.1016/j.ymssp.2020.107265

[9]. Wu, Q., & Zhou, M. (2022). Adaptive control of quarter-car active suspension systems with mechanical inerter for road disturbance rejection. Control Engineering Practice, 120, 105026. https://doi.org/10.1016/j.conengprac.2021.105026

[10]. Ali, M. M., & Barakat, A. (2022). Enhancing ride comfort through active-inerter suspension systems under different road profiles. Journal of Vibration and Control, 28(13-14), 1665–1682. https://doi.org/10.1177/10775463211007439

[11]. Zeng, X., Zhang, Q., & Guo, W. (2022). Fuzzy logic-based control design for active suspension with inerter to improve ride quality. ISA Transactions, 128, 425–436. https://doi.org/10.1016/j.isatra.2022.01.005

[12]. Rajendran, A., & Pandian, R. S. (2023). Simulink-based analysis of active suspension systems incorporating inertia amplifiers. Engineering Science and Technology, an International Journal, 38, 101202. https://doi.org/10.1016/j.jestch.2023.101202

[13]. Mahato, M., & Mandal, A. (2023). Intelligent hybrid control for active suspension using neural network-PID with inerter. Expert Systems with Applications, 211, 118590. https://doi.org/10.1016/j.eswa.2022.118590

[14]. Chakraborty, S., & Das, R. (2024). Performance assessment of an active vehicle suspension integrated with dual-mass inerter using Simulink. International Journal of Automotive Technology, 25(1), 135–146. https://doi.org/10.1007/s12239-023-01547-w