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Performance Optimization of Semi-Active Quarter Car Suspension Utilizing Variable Spring Configurations Using Simulink

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ABSTRACT
The main goal of this research is to use Simulink to optimise quarter-car semi-active suspension systems employing variable spring configurations. Semi-active suspensions are advanced systems that adjust damping characteristics in real-time to achieve a balance between ride comfort and handling performance. The purpose of this study is to investigate the possibility of improving overall suspension performance by adding a second spring in parallel with the main suspension spring. A precise model of the quarter-car suspension system will be developed using Simulink. The vehicle mass, primary suspension spring, semi-active damper, and extra spring will be all included in the model. The semi-active damper will be controlled by a PID controller. The research includes simulating parallel and series configurations of the additional spring to analyze their effects on suspension behavior. Key aspects under investigation include how these configurations impact ride comfort, handling stability, and the distribution of forces within the suspension system. This research contributes to advancing the understanding of how variable spring configurations can be utilized to optimize semi-active suspension systems, offering insights that may benefit automotive industry in designing more effective and efficient suspension solutions for modern vehicles.

Keywords: Semi-active suspension, PID, Spring configuration, Simulink

1. Introduction

The suspension system is a combination of components that successfully work together to preserve the automobiles from road disturbances. The vehicle's suspension system, composed of springs and dampers, provides insulation between the body and wheel and axle, reducing shocks and vibrations from uneven road surfaces, preventing excessive rebounding. In order to do this, the suspension system consists of shock absorbers like springs and dampers, which distribute road irregularities and regulate vibrations to prevent excessive vehicle rebounding. There are three types of suspension system that are active suspension system, passive suspension system and semi active suspension system. Semi-active suspension systems combine active and passive suspension systems, providing a costeffective and adaptable driving experience.They adjust shock absorber damping force based on road surface feedback. A Proportional-Integral-Derivative (PID) controller is a common feedback control technique used in engineering and automation systems, adjusting control variables based on proportional, integral, and derivative terms. Recent research indicates that enhancing the traditional quarter-car model (CM) through the addition of an auxiliary spring can significantly enhance suspension performance, especially in terms of ride comfort and road stability, while resulting in only a minimal decrease in operational space[1].This study explores the use of variable spring configurations in a semi-active suspension system to further improve performance. By dynamically altering the spring stiffness, the system can better adapt to road conditions, optimizing ride comfort, road holding, and suspension travel. Using Simulink for simulation, the research aims to model, analyze, and optimize the suspension system, offering a cost-effective method to improve vehicle dynamics.

2. Literature Review

The article of the literature presents a complete evaluation of current advances and data about semi-active suspension systems. Considering semi-active suspension systems can provide an appropriate balance among ride comfort and handling performance, they have drawn a lot of focus in the field of automobile engineering. Unlike passive suspensions, which have fixed damping characteristics, semi-active suspensions alter damping in real-time to respond to changing road conditions. Early studies, such as those conducted by Nyoman Bangsing et al. (2003), demonstrated the effectiveness of semi-active suspensions using a quarter-car model. Their testing results demonstrated improved sprung mass acceleration reduction in low-frequency ranges (1-4 Hz) as compared to passive systems; however, the performance declined at higher frequencies (5-9 Hz).In an effort to improve comfort and road holding, later research has further improved semi-active suspension control strategies by combining sophisticated algorithms such robust control, skyhook, and hybrid approaches. The development of contemporary suspension technology is still influenced by the fundamental discoveries made by this research[2]. In 2007, Khajavi and Abdollahi show a comparison between two alternative car suspension systems: an optimized passive system and a semi-active fuzzy logic driven one. The research assesses the ride and handling features of both systems and indicates that the semi-active system gives greater performance in terms of comfortable

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riding and handling. The study proposes examining the semi-active system as a more effective approach for strengthening car suspension systems [3]. Because PID controllers are easy to use and a great way to improve handling and ride quality, semi-active suspension systems have seen a lot of use of them. K. Dhananjay Rao employed a PID controller to model and simulate a quarter-car suspension system using MATLAB Simulink in his 2014 work. Important aspects of vehicle dynamics, including body displacement, body acceleration, and wheel deflection, were well captured by the study's linear model. Rao showed that the PID-controlled semi-active suspension system might greatly outperform passive systems in terms of body and wheel displacement performance by using two different road profiles as input.This research correlates with larger trends in car suspension control, where PID control maintains an effective option for real-time suspension adaptation due to its simplicity, despite the introduction of more advanced control schemes including adaptive and fuzzy logic controllers[4]. Developing suspension systems with variable stiffness and damping has been a key priority for enhancing vehicle road handling and ride comfort, particularly with changing loads. In their 2016 research, Lalitkumar Maikulal Jugulkar, Shankar Singh, and Suresh Maruti Sawant addressed the limits of passive shock absorbers, which are built for fixed standard loads and struggle to retain performance when vehicle mass deviates from the norm. They showed that the system could react to variations in sprung mass, improving comfort and handling, by combining a system with two helical springs and a variable fluid damper that modifies damping intensity across four discrete levels.Prototype testing and numerical simulations with MATLAB Simscape and Simulink demonstrated a 15% increase in peak acceleration over conventional passive systems. This study adds to the increasing corpus of research on active and semi-active suspension systems that aims to improve comfort and performance by attaining adjustable stiffness and damping for a range of driving situations[5].In 2021 Kumar et al. analyses the behavior of a suspension system by employing a detailed model of the whole vehicle. It compares the efficiency of passive and active suspension systems. The paper offers the dynamic equation and state-space formulation for the whole vehicle model and explores the reaction of the suspension system in an open-loop configuration under diverse road conditions. Additionally, the paper builds a basic Proportional Integral Derivative (PID) feedback and feed-forward controller for the active suspension system employing transfer functions. The responses of both passive and active suspension systems are compared for different road inputs, and the impact of factors like suspension stiffness, static stability factor, time delay, and discrete-time sampling on the active suspension system are investigated. The results reveal that the active suspension technology effectively eliminates body bounce, pitch, and roll, while boosting ride comfort and vehicle control[6].Haonan He et al. in 2021 studies the use of an inerter in boosting the functioning of an activepassive combined vehicle suspension system. The inerter, a device capable of augmenting damping and boosting the suspension's shock absorption capacity, was shown to greatly increase the ride comfort and stability of the vehicle, especially while driving at high speeds or on uneven road conditions. Additionally, the researchers designed a control algorithm to maximize the suspension system's performance in combination with the inerter. The results imply that integrating an inerter has promise as a possible strategy for upgrading car suspension systems[7].In 2023, Haonan He et al. released a publication which proposes a revolutionary method to the design of optimum passive-active-combined suspensions in road vehicles. It extensively explores alternative suspension designs employing predefined components and takes into consideration the practical ramifications of physical actuators. This strategy considerably optimizes the balance between ride comfort and the active force demanded, exceeding older ways. Moreover, it displays flexibility and adaptation to diverse vehicle types and control systems, therefore offering potential for boosting suspension effectiveness and energy efficiency. Along with the result they also mentioned about the change in spring configuration of semi active suspension as future work in this research[8].

3. Flowchart of the study

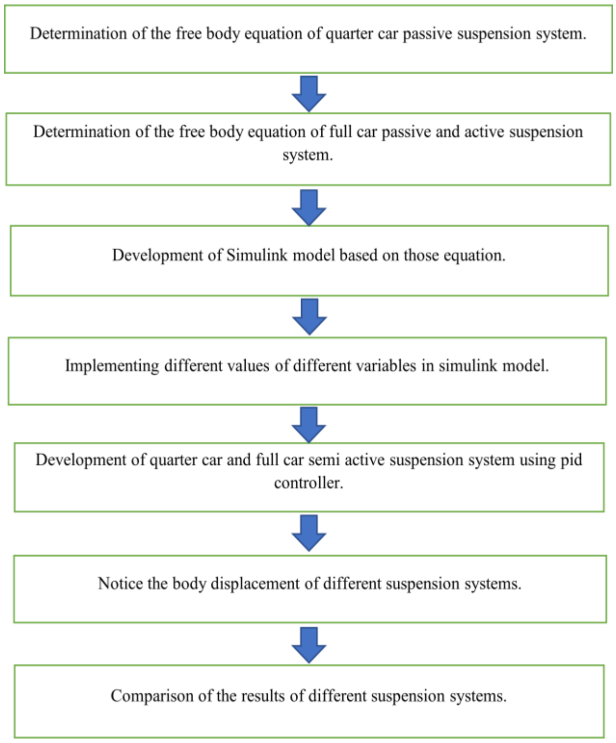

Fig 1. Flowchart of the methodology

4. Mathematical model

The 2DOF suspension system's dynamic behavior can be described using second-order ordinary differential equations (ODEs), assuming linear motion and ignoring friction and non-linearities, resulting in semi-active suspension system governing equations:

$$M1\ddot{X}1 + b1(\dot{X}1 - \dot{X}2) + k1(X1 - X2) = 0 \quad (1)$$

$$M2\ddot{X}2 + b1(\dot{X}2 - \dot{X}1) + k1(X2 - X1) + b2\dot{X}2 + k2X2 = b2\dot{W} + k2W \quad (2)$$

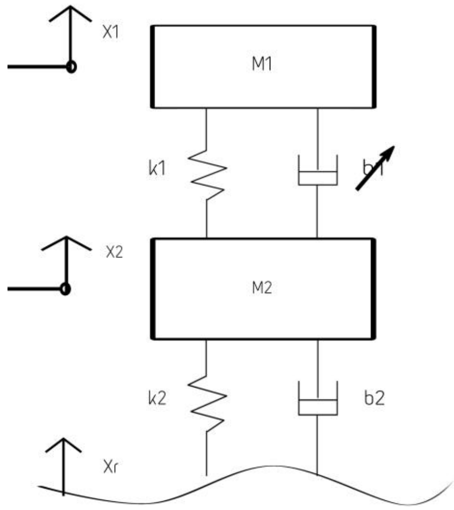

Fig 2. Quarter car semi active suspension model.

The Quarter Car Model for Passenger Car has a Semi Active suspension system, with parameters like M1=241.5 kg, M2=41.5kg, K1=6000 N/m, K2=14000 N/m, b1=1200 N-s/m, b2=1500 N-s/m and an extra spring with coefficient of spring K3=2000 N/m which is used alternately in parallel and series and a PID controller: Kp= 1.2, Ki= 5, Kd= 0.2.

5. Simulation Data Analysis

The simulation uses equations from section 1 to 2, with the step function as the input, revealing the motion of the car's body and wheels.

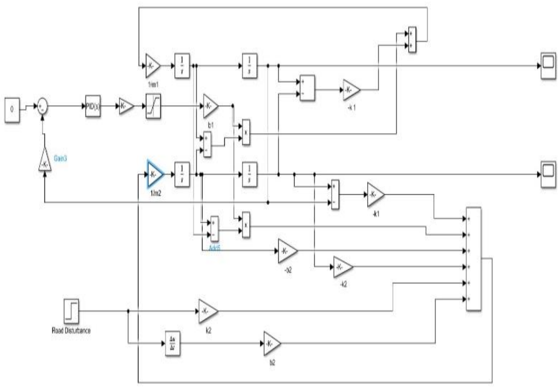

Fig 3. Quarter car semi active suspension system.

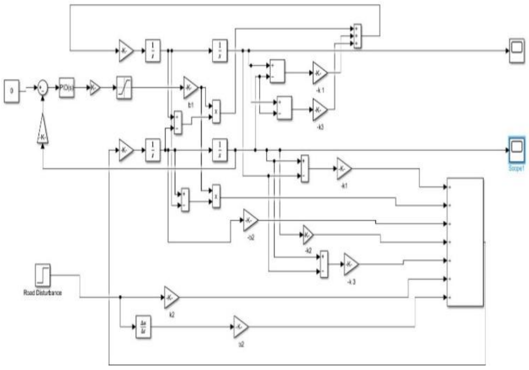

Fig 4. Quarter car semi active suspension system with an extra spring in series.

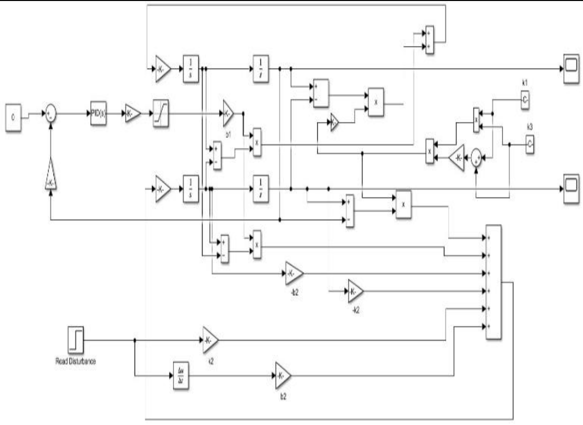

Fig 5. Quarter car semi active suspension system with an extra spring in series.

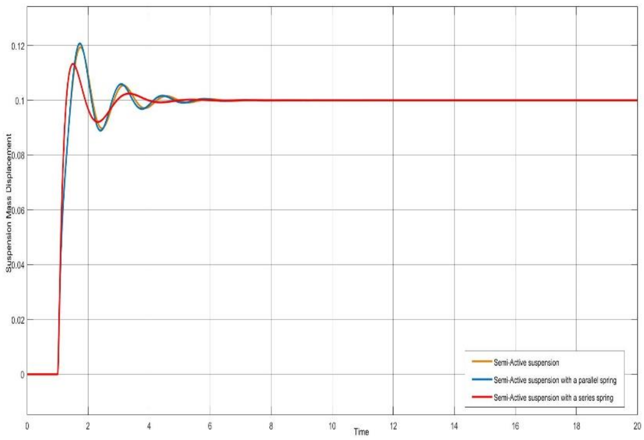

Fig 6. Body displacement vs Time.

In Figure 6, the body displacement of the car is measured, revealing an overshoot of 0.057m and a settling time of 8 seconds for Semi active suspension system. For the simulation of Semi-active active suspension with an extra spring in parallel, getting an overshoot of 0.05m and a settling time less than 8 seconds. The graph also presents an overshoot of 0.03m and a settling time is about 6 seconds of the Semi-active suspension with a spring in series.

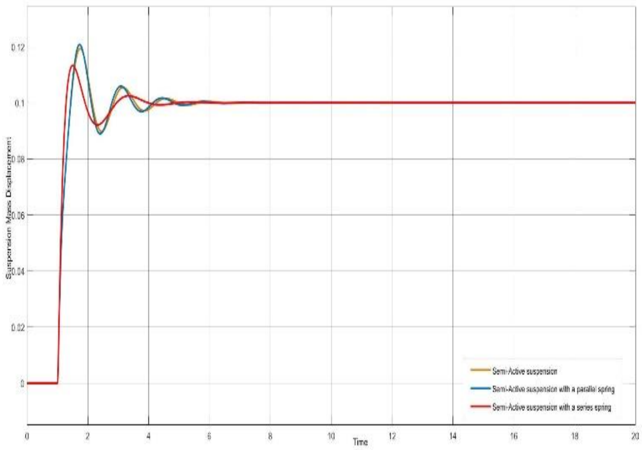

Fig 7. Suspension displacement vs Time.

In Figure 7, the suspension mass displacement of the car is measured, revealing an overshoot of 0.02m and a settling period of 8 seconds in conventional Semi-active suspension. For Semi-active suspension with a spring in parallel has an overshoot less than 0.02m and a settling period of about 7 seconds. On the other hand, the suspension mass displacement of the Semi-active suspension with an extra spring in series is measured, revealing an overshoot nearly about 0.015m and a settling period of about 5 seconds from this figure.

6. Result

Table 1: Comparison of overshoot between quarter car semi-active suspension, semi-active suspension with a spring in parallel and in series.

Types	**Overshoot**		
	Semi-active	**Semi-Active with a spring in parallel**	**Semi-Active with a spring in series**
Body Displacement	0.057 m	0.05 m	0.03 m

Table 2: Comparison of settling time between quarter car semi-active suspension, semi-active suspension with a spring in parallel and in series.

Types	**Settling Time**		
	Semi-active	**Semi-Active with a spring in parallel**	**Semi-Active with a spring in series**
Body Displacement	8 sec	8 sec	6 sec

The analysis of the body displacement data presented in Table 1 and Table 2 indicates that the semi-active suspension system utilizing a series spring configuration surpasses both the semi-active suspension system with a parallel spring arrangement and the conventional semi-active suspension system. Notably, the series configuration exhibits lower overshoot and shorter settling time, which signifies improved damping characteristics and a more rapid stabilization of the system. This finding highlights the advantages of the series spring setup in optimizing the dynamic response and overall performance of semi-active suspension systems. Less vibration will be felt that may provide good riding experience and further congenial driving and passenger experience can be maintained. Consequently shorter settling time might reduce concerns of disturbances. The series spring configuration in the semi-active suspension [1] reduces overshoot and settling time, enhancing ride comfort by minimizing oscillations than conventional and parallel.

Table 3: Comparison of settling time between quarter car semi-active suspension, semi-active suspension with a spring in parallel and in series.

Types	**Settling Time**		
	Semi-active	**Semi-Active with a spring in parallel**	**Semi-Active with a spring in series**
Body Displacement	8 sec	7 sec	5 sec

Table 4: Comparison of overshoot between quarter car semi-active suspension, semi-active suspension with a spring in parallel and in series.

Types	**Overshoot**		
	Semi-active	**Semi-Active with a spring in parallel**	**Semi-Active with a spring in series**
Body Displacement	0.02 m	0.02 m	0.015 m

As illustrated in Tables 3 and 4, the semi-active suspension system featuring a spring arranged in series demonstrates enhanced performance in the suspension displacement analysis. It achieves lower overshoot and a shorter settling time when compared to both the semi-active suspension system with a parallel spring and the standard semi-active suspension. This finding emphasizes the efficacy of the series spring configuration in reducing displacement fluctuations and improving the system's responsiveness to dynamic changes.

7. Conclusion

The performance analysis of a quarter-car semi-active suspension system with variable spring configurations using Simulink demonstrates that the system with an extra spring in series outperforms the parallel configuration in terms of ride comfort and dynamic response. The series spring configuration effectively handles road disturbances with reduced overshoot and a quicker settling time. The series setup's lower stiffness facilitates smoother energy absorption and faster system stabilization. The parallel spring configuration offers more stability but sacrifices comfort due to higher stiffness, resulting in more overshoot and longer settling time. The study suggests that series structures are more suitable for applications requiring comfort and control, while parallel configurations are better suited for stability-sensitive situations.

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