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Control of the Quarter Vehicle Model with an Innovative Delayed Resonator Optimized by Genetic Algorithm

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Genetik Algoritma ile Optimize Edilmiş Yenilikçi bir Gecikmeli Rezonatör ile Çeyrek Taşıt Modelinin Kontrolü

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Öz

Bu çalışma, çeyrek araç modelini kullanmış ve aktif süspansiyon sistemini düzenlemek için bir gecikmeli rezonatör kontrol yaklaşımı uygulamıştır. Geleneksel gecikmeli rezonatörün aksine, bu çalışmada kuvvet sinyali konum, hız ve ivme gecikmeli rezonatörün uygulanmasıyla üretilir. gecikmeli rezonatör denetleyicisinin tüm parametreleri, genetik algoritma yaklaşımı kullanılarak belirlenmiştir. Sonuçlar, gecikmeli rezonatörü entegre etmenin süspansiyon sisteminin performansını önemli ölçüde iyileştirdiğini göstermektedir. Sistemin ivme, hız ve konum değişkenlerini kapsayan uygulanan kuvvet, kapsamlı olduğu için her koşulda başarılı olma kapasitesine sahiptir. Bu kapsamlı kontrolör, kontrol sisteminin başarılı bir şekilde çalışması için hayati öneme sahiptir.

Anahtar Kelimeler *Gecikmeli Rezonatör, Genetik Algoritma, Aktif Süspansiyon Sistemi, Çeyrek Araç Modeli*

Abstract

This study utilized a quarter vehicle model and implemented a delayed resonator control approach to regulate the active suspension system. In contrast to the conventional delayed resonator, the force signal in this study is generated through the implementation of the position, velocity, and acceleration delayed resonator. The all parameters of the delayed resonator controller were determined using the genetic algorithm approach. The results suggest that integrating the delayed resonator significantly improves the performance of the suspension system. The applied force, which encompasses acceleration, velocity, and position variables of the system, remains stable under all conditions. This comprehensive controller is vital for the successful operation of the control system.

Keywords *Delayed Resonator, Genetic Algorithm, Active Suspension System, Quarter Car Model*

1. Introduction

The evolution of suspension systems in automobiles is a testament to the ongoing quest for heightened comfort and performance. In the nascent stages of automotive development, rigid suspension systems were prevalent, showcasing limited adaptability to diverse road conditions (Avinash et al. 2020). The inherent drawback of these early systems was the direct transmission of shocks and vibrations from the road to both the vehicle and its occupants.

With the advancement of automotive technology, engineers embarked on a mission to overcome these challenges by introducing more sophisticated suspension designs. The mid-20th century witnessed a pivotal moment with the advent of independent suspension systems. This groundbreaking innovation permitted each wheel to move autonomously, resulting in enhanced stability and a smoother driving experience. Following this milestone, the automotive industry experienced a surge in the introduction of various suspension types, such as MacPherson struts, double-wishbone suspensions, and torsion beam suspensions (Cronin 1981, Vignesh et al. 2019, Shimatani et al. 1999). Each of these systems brought distinct advantages to the realms of handling and comfort.

In the modern automotive landscape, suspension systems have evolved into three main categories: passive, semi-active, and active suspensions (Smith and Swift 2016, Koulocheris et al. 2017, Goyal and Sharma 2017). Passive systems, relying on fixed mechanical

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components for shock absorption, offer a certain comfort level but lack real-time adaptability to changing road conditions. Semi-active systems provide a compromise between passive and active systems, incorporating adjustable elements for modification based on driving conditions, offering a balance between comfort and performance with some adaptability. Active suspension systems, utilizing advanced electronic sensors and actuators, represent the pinnacle of technology by actively adjusting settings in real-time, ensuring optimal comfort and stability. Despite their higher complexity and cost, they have gained popularity for superior performance, enhancing the overall driving experience.

In active suspension systems, a crucial mechanism involves the generation of a counteracting force proportional to the forces between the wheels and the road, effectively balancing the acceleration induced by the road. To determine this force, a controller is employed. Commonly used controllers in automobiles include the Fuzzy Logic Controller (FLC), PID, and Sliding Mode Control (Mutlu 2023, Şahin and Ayas 2019, Karaman and Kayisli 2017). Although not as widely used as these controllers, the Delayed Resonator is also employed in vehicle control. The Delayed Resonator, discovered by Olgac in 1994, has found applications in the control field (Olgac and Hansen 1994). It incorporates delayed control of the selected parameter.

In this field, various optimization methods are employed to fine-tune and enhance the performance of suspension systems. These methods play a crucial role in determining the most effective parameters for achieving the desired balance between comfort and performance. Among the optimization techniques commonly utilized are the Ziegler-Nichols method, particle swarm optimization, and genetic algorithms (Huba et al. 2021, Eser et al. 2021). Each method has its unique advantages and disadvantages, contributing to the broader exploration of efficient suspension system designs.
While numerous optimization approaches exist, the genetic algorithm has demonstrated remarkable success (Caner and Gülseren 2010). Despite its complexity, this algorithm stands out for its ability to find optimal solutions within a vast parameter space. Therefore, it has been chosen for implementation in this study due to its effectiveness.

The primary objective of this study is to enhance the performance of the suspension system by utilizing the delayed resonator. In contrast to the conventional delayed resonator, the force signal is generated through the implementation of the position, velocity, and acceleration delayed resonator. To clearly demonstrate the effect, a quarter vehicle model was selected, and the coefficients employed in the study were determined using the Genetic Algorithm.

2. Materials and Methods

2.1 Mathematical Model

The vehicle suspension model can be modeled in three different ways as quarter, half and full vehicle. In terms of simplicity and clarity, the quarter car model is the most preferred model.

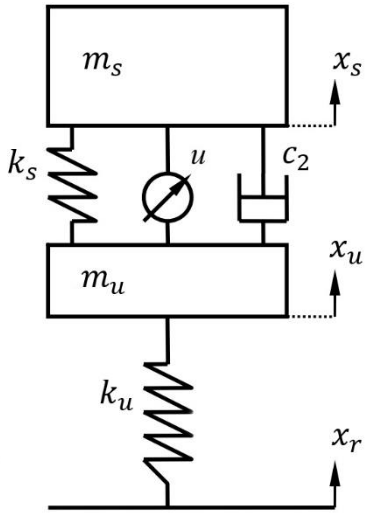

Figure 1. Physical model of quarter car

$$m_s\ddot{x}_s + c_s(\dot{x}_s - \dot{x}_u) + \ldots$$
$$\ldots\ k_s(x_s - x_u) = u \quad (1)$$

$$m_u\ddot{x}_u + c_s(\dot{x}_u - \dot{x}_s) + \ldots$$
$$\ldots\ k_s(x_u - x_s) + k_u(x_u - x_r) = -u \quad (2)$$

The physical model of a quarter car is shown in Figure 1. In this figure; The unsprung mass is denoted by m_u, the sprung mass by m_s, the damping coefficient of the suspension system by c_s, the coefficient of wheel spring by k_u, and the coefficient of suspension spring by k_s. The specific values for these parameters are provided in Table 1.

Table 1. Quarter car suspension parameters (Palanisamy and Karuppan 2016)

Parameter	Symbol	Value (Unit)
Sprung mass	m_s	290 (kg)
Unsprung mass	m_u	59 (kg)
Damping coefficient	c_s	1000 (Ns/m)
Coefficient of wheel spring	k_u	190000 (N/m)
Coefficient of suspension spring	k_s	16812 (N/m)

To make study comprehensive, three distinct types of road input were tested in this study. Initially, the ISO road was preferred for how this system respond to continuous road that we can see very offen in daily life. After that, the step and bump inputs were implemented to obtain sudden road performance of our system.

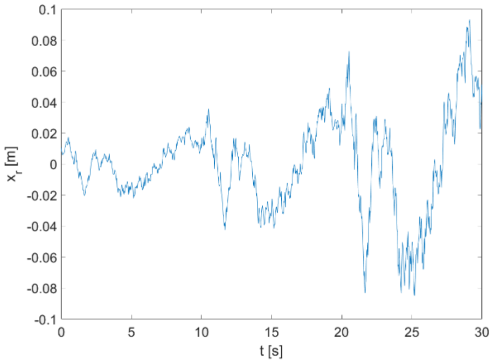

Figure 2. Iso road profile

Iso path include 3 different qualities. First quality road is A-B quality highway, the second and third roads are B-C and C-D quality road preferred for compelling situation. All quality roads are tested for 10 seconds, respectively.

$$G_d(n) = G_d(n_0) * \left(\frac{n}{n_0}\right)^{-w} \tag{3}$$

where, G_d is displacement PSD in m^3, n is the spatial frequency, n_0 = 0.1 cycles/m in the reference spatial frequency and w is the exponent of the fitted PSD.

Table 2. ISO 8608 thresholds of the first three classes (ISO 8608, 2016) (A-C)

ISO 8608 class	$G_d(n)(10^{-6} * m^3)$
A (very good)	<32
B (good)	32-128
C (average)	128-512

Two different inputs also tested, their characteristics are different from the first.

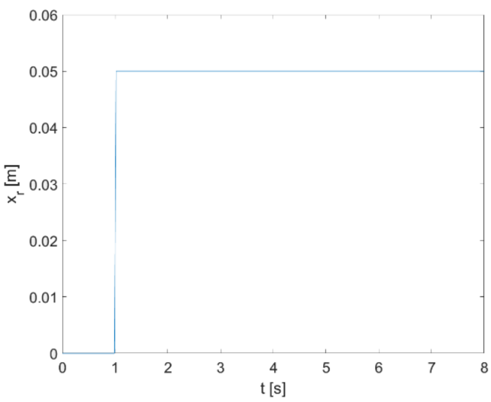

Figure 3. Step road profile

One of them is step, in this input, the behaviour of the car after climbing the 0.05m high step was observed.

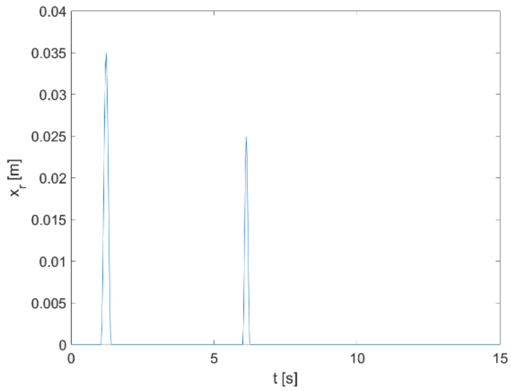

Figure 4. Bump road profile

The last input is bump, in this input, two short-term impacts that first of which is 0.035m high and the second 0.025m high were applied to system.

2.2 Control Algorithm

In order to keep the system more stable, a suitable control algorithm was chosen with the system. The system was controlled by the Delayed Resonator and the coefficients were optimized by the Genetic Algorithm.

Delayed Resonator multiplies a parameter in the system with a coefficient and the resulting force is reflected to the system with a delay.

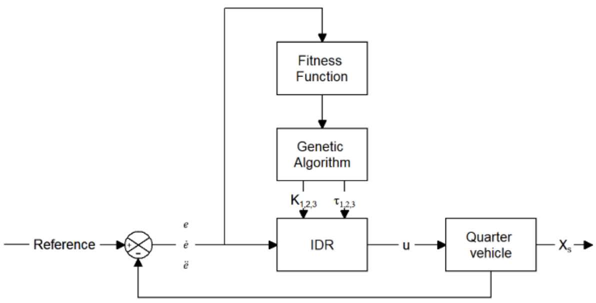

Figure 5. IDR optimized with GA

$$u = K_1\ddot{e}(t-\tau_1) + K_2\dot{e}(t-\tau_2) + K_3 e(t-\tau_3) \tag{4}$$

In this equation; K_1, K_2 and K_3 represents coefficient of acceleration, velocity and position. τ_1, τ_2 and τ_3 represents delay of acceleration, velocity and position.

$$\ddot{e} = \ddot{x}_{s_{ref}} - \ddot{x}_s \tag{5}$$

$$\ddot{x}_{s_{ref}} = 0 \tag{6}$$

$$\dot{e} = \dot{x}_{s_{ref}} - \dot{x}_s \tag{7}$$

$$\dot{x}_{s_{ref}} = 0 \quad (8)$$

$$e = x_{s_{ref}} - x_s \quad (9)$$

$$x_{s_{ref}} = x_r \quad (10)$$

A flexible control mechanism was obtained by controlling the system with acceleration, velocity and position errors.

Genetic Algorithm is an optimization method that is commonly used in control or optimization studies. Genetic Algorithm needs an Goal Function to work. This Goal Function is tried to be approximated to zero by the Genetic Algorithm. In this study, IAE (Integral Absolute Error) and ISE (Integral Square Error) criteria were used to determine Goal Function.

$$IAE = \int_0^\infty |e(t)|\, dt \quad (11)$$

$$ISE = \int_0^\infty e^2(t)\, dt \quad (12)$$

The parameters to be controlled in suspension systems are acceleration and position. These parameters are used in the criteria. A correction constant k is used to equalize its effects.

$$G_1 = k * IAE_p + IAE_a \quad (13)$$

$$G_2 = k * ISE_p + ISE_a \quad (14)$$

G_1 and G_2 represent Goal Functions, k represents the correction coefficient, $IAE_p$and ISE_prepresents errors of position, $IAE_a$and ISE_arepresents errors of acceleration. In order to determine the correction coefficient, the acceleration and position values according to the ISO input were taken into account. Since the distance between the extreme points is approximately 50 times, the correction coefficient was determined as 50.

After defining the desired function to be optimized, the Genetic Algorithm was employed to determine the Delayed Resonator coefficients. This algorithm utilizes random numbers within specified boundaries, treating each number as an individual within a given population. Once a predetermined number of populations is generated, the algorithm assesses the Goal Function value of each individual in the population. It identifies and records traits that closely align with the desired objective as genes. Genes that are closer to the optimized value are passed on to the next generation, while distant genes are discarded and replaced with new genes to prevent being stuck at local minimums. Moreover, new individuals are introduced in each population independently from previous genes, ensuring that the algorithm continues to explore the search space and avoids premature convergence.

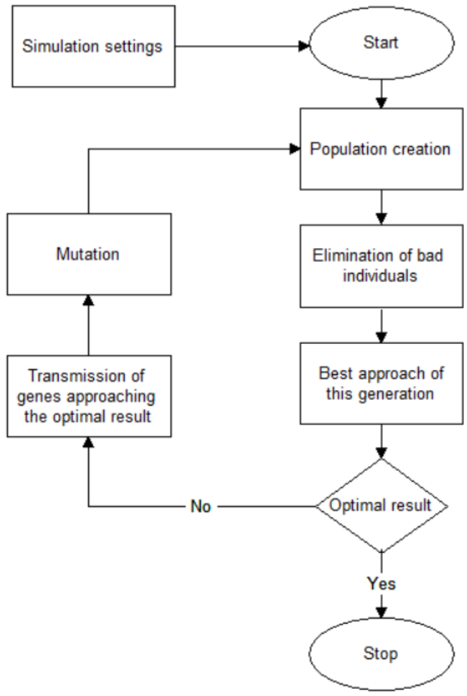

Figure 6. The flowchart of Genetic Algorithm

In this study, the lower limit of the delay time τ was determined as 0 and the upper limit was determined as 1, the lower limit of coefficient K was determined as 0 and the upper limit was determined as 1000 for all parameters, the population number was 200 and the mutation rate was 20%.

The optimal value of τ_1, τ_2 and τ_3 was determined as 0.117, 0.175 and 0.608. The optimal value of K_1, K_2 and K_3 was determined as 118.995, 429.337 and 481.545.

3. Results and Discussions

Based on the information provided, Table 3 exhibits the Goal Function values associated with the ISO road input, while Table 4 illustrates the identical values for the step input, and Table 5 showcases the values for the bump input.

Table 3. G_1 and G_2 results according to ISO road input

	G_1	G_2
Passive	43.82	56.34
IDR	38.71	46.87

Table 4. G_1 and G_2 results according to step entry

	G_1	G_2
Passive	2.73	4.30
IDR	1.67	3.55

Table 5. G_1 and G_2 results according to bump entry

	G_1	G_2
Passive	3.52	1.99
IDR	2.14	1.62

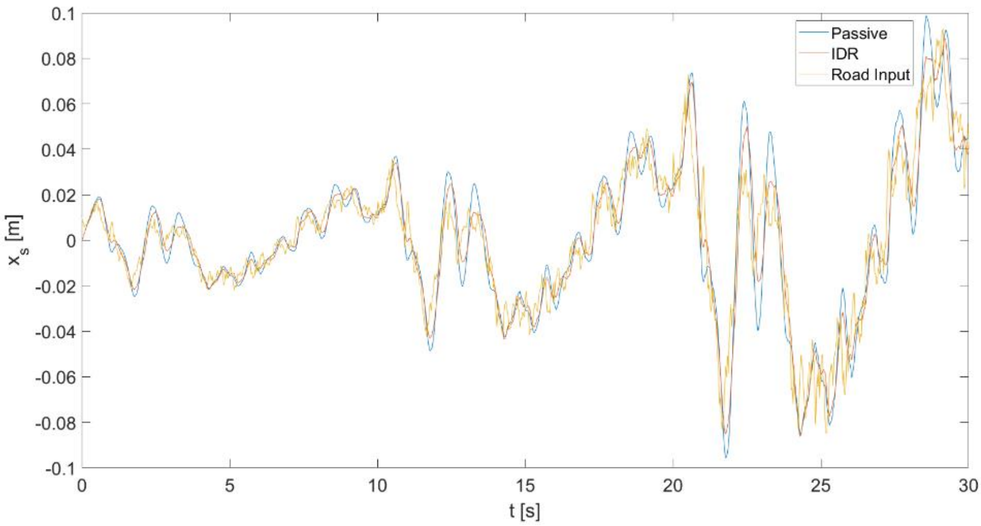

Figure 7. The position-time graph of all systems according to ISO path entry

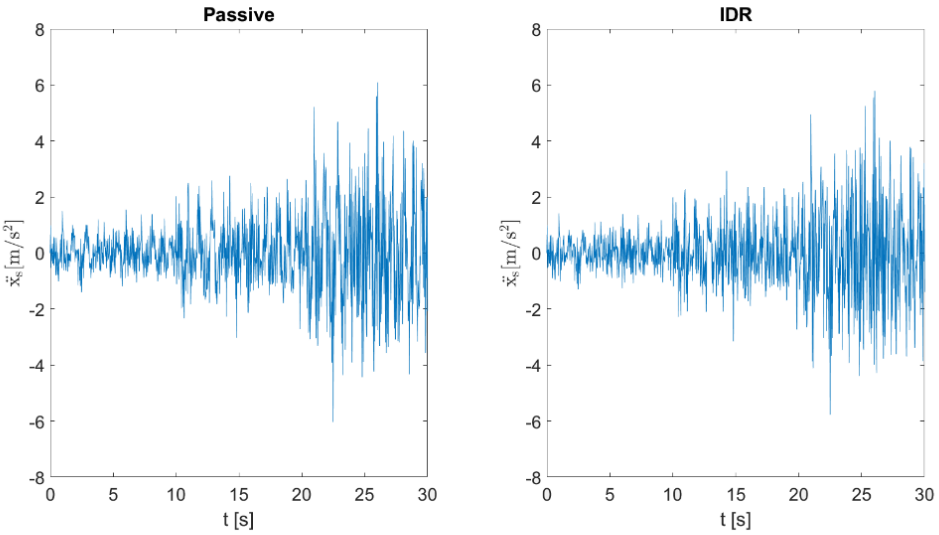

Figure 8. The acceleration-time graph of all systems according to ISO path entry

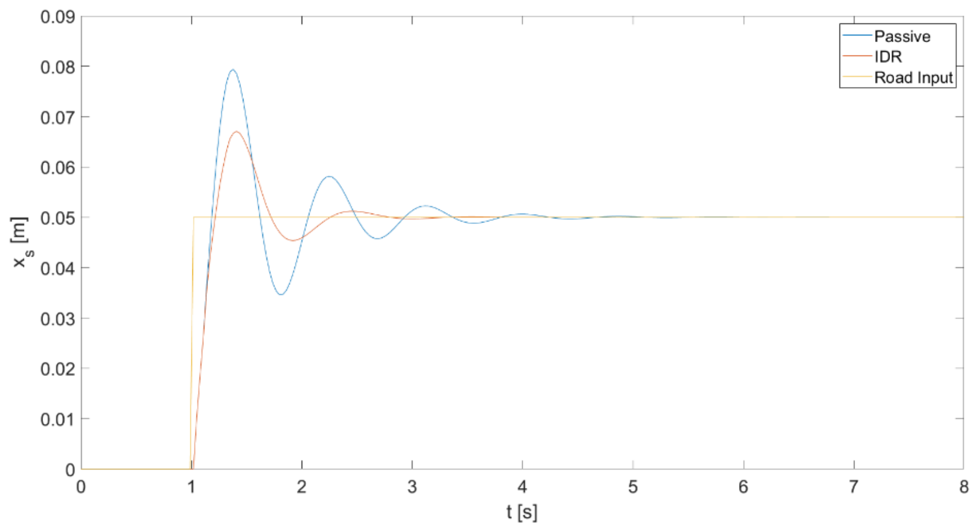

Figure 9. The position-time graph of all systems according to step entry

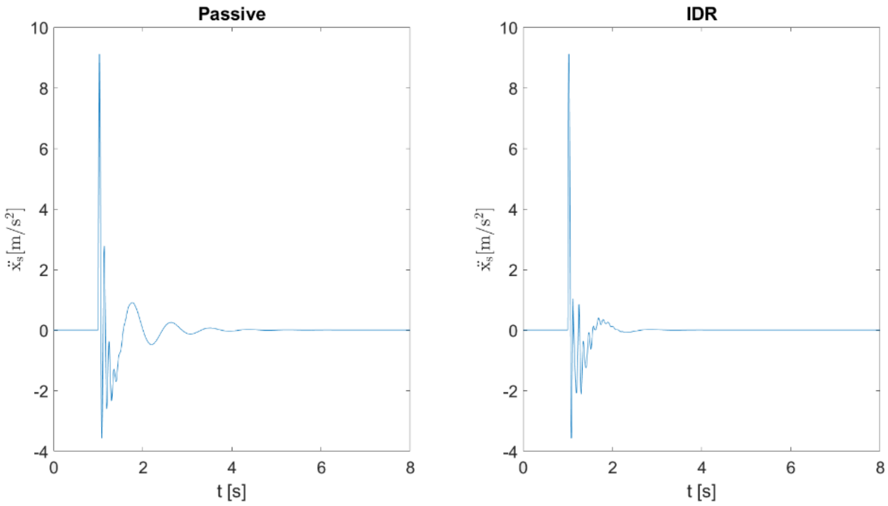

Figure 10. The acceleration-time graph of all systems according to step entry

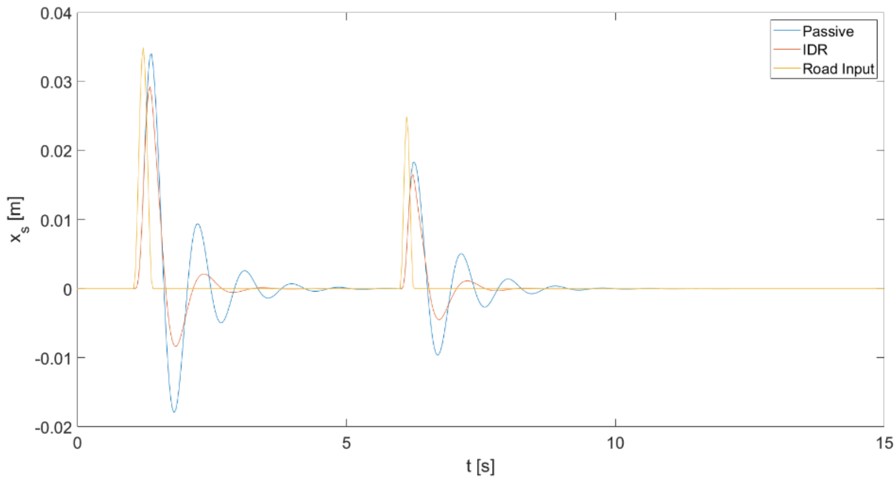

Figure 11. The position-time graph of all systems according to bump entry

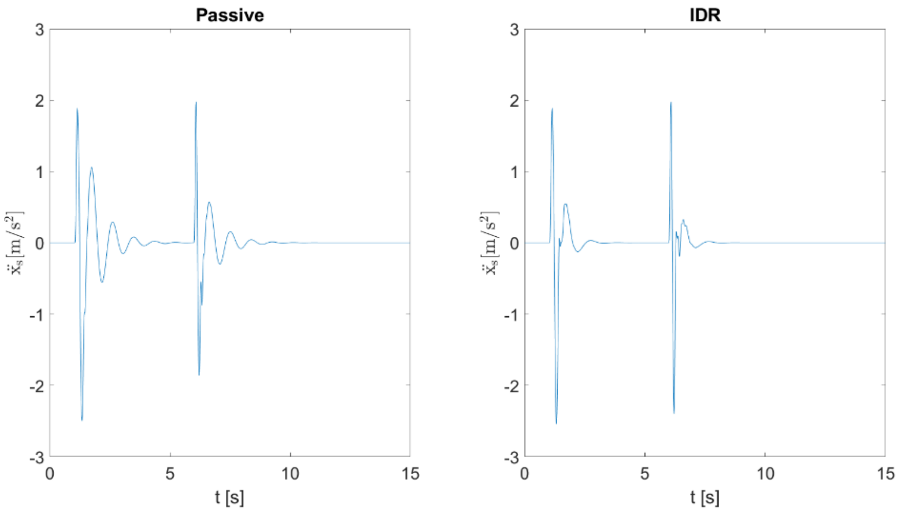

Figure 12. The position-time graph of all systems according to bump entry

Figure 7 depicts the graphical representation of the position variable x_s pertaining to the ISO path input, while Figure 8 illustrates the acceleration of x_s for each case. Similarly, Figures 9 and 10 illustrate the graphical depictions for the step input, and Figures 11 and 12 showcase the behavior corresponding to the bump input. The superiority of the IDR controller is more evidently manifested in the position graphs of the spring-mass system in comparison to the passive state. Due to the inherent time delay in the structure of the IDR controller, it has not provided a visually noticeable response to sudden lane changes in the ISO road input, as evident in Figure 8. However, there has been a significant numerical improvement. Similarly, due to the same reason, it could not prevent the initial acceleration, as depicted in Figure 10, but it has achieved a highly successful outcome for a controller in the continuation of the graph. These deficiencies arising from the time delay can be addressed in future studies by adding another controller to the system.

4. Conclusions

The current investigation conducted an in-depth exploration by utilizing a quarter vehicle model as the basis and implementing a sophisticated IDR control mechanism to effectively regulate the active suspension system. Through the prudent employment of the genetic algorithm methodology, the essential parameters governing the delayed resonator controller were systematically determined, facilitating an optimal configuration tailored to the specific requirements of the suspension system.

The results of the study unequivocally advocate the profound advantages of integrating the Delayed Resonator within the suspension system. Notably, the incorporation of this innovative control approach resulted in a significant enhancement in the overall functionality and performance of the suspension system. By intelligently leveraging the delayed resonator, the system's dynamic behavior was meticulously managed, ultimately leading to an enhanced level of ride comfort and stability.

An exceptional feature of the proposed controller lies in its holistic approach to addressing the entire spectrum of acceleration, velocity, and position variables. Remarkably, the exerted force demonstrated an extraordinary level of resilience and robustness, retaining stability across a diverse range of operating conditions. This inherent capability of the controller to comprehensively encapsulate all relevant system variables ensures that the suspension system remains highly adaptable and responsive, even in the face of challenging and dynamic scenarios.

Given the central role played by the active suspension system in guaranteeing the safety, comfort, and overall performance of the vehicle, the successful incorporation of the comprehensive delayed resonator controller is undoubtedly a crucial milestone. By striking an optimal balance between ride comfort and road-holding ability, the proposed control mechanism paves the way for enhanced driving experiences and improved vehicle dynamics.

In conclusion, this research highlights the remarkable potential of the position, velocity, and acceleration delayed resonator control strategy coupled with genetic algorithm-based parameter estimation to revolutionize active suspension systems. The profound improvements witnessed in the suspension system's performance, together with its inherent stability and adaptability, underscore the significance of this comprehensive controller in achieving a triumphant outcome for the entire control system. It is anticipated that the outcomes of this study will contribute substantially to the advancement of vehicular engineering and foster the development of cutting-edge suspension technologies for safer, smoother, and more enjoyable rides in the future.

Declaration of Ethical Standards
The authors declare that they comply with all ethical standards.

Credit Authorship Contribution Statement
Author-1: Conceptualization, investigation, methodology and software, visualization and writing – original draft.
Author-2: Conceptualization, investigation, methodology and software, supervision and writing – review and editing.

Declaration of Competing Interest
The authors have no conflicts of interest to declare regarding the content of this article.

Data Availability
All data generated or analyzed during this study are included in this published article.

Acknowledgement

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