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RESEARCH ARTICLE / ARAŞTIRMA MAKALESI

Enhancing Suspension System Control Performance Using PID Controller Incorporated Low-Pass Filter Optimizated with Genetic Algorithm

Genetik Algoritma ile Optimize Edilmiş Alçak Geçiren Filtre içeren PID Denetleyici Kullanılarak Süspansiyon Sistemi Kontrol Performansının Artırılması

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Abstract

In this study, a filter has been incorporated to enhance the performance of the PID controller, which is commonly used for controlling suspension systems. While designing this filter, the insipration has been the low-pass filter used in sliding mode controllers to prevent chattering and uncertainties in system parameters, unlike conventional PID controller filters. Additionally, the filtered force value was combined with the force value obtained from the PID controller using an equation based on a coefficient, and filter coefficients were optimized through genetic algorithms. As a result of the optimization, the designed controller was simulated for various road inputs that could be encountered, and results were obtained. By comparing the results obtained with a PID controller without a filter and without a controller, the performance of the designed controller is clearly shown according to IAE and ISE criteria. Robustness of the controller was evaluated under varying mass conditions and its performance was given as a table.

Keywords: *Filter PID, Genetic Algorithm, Active Suspension Systems, Robust Control*

Öz

Bu çalışmada, süspansiyon sistemlerinin kontrolü için yaygın olarak kullanılan PID kontrolcünün performansını arttırmak için bir filtre eklenmiştir. Bu filtre tasarlanırken, klasik PID kontrolcü filtrelerinden farklı olarak, kayan kipli kontrolcülerde çatırtıyı ve sistem parametrelerindeki belirsizlikleri önlemek için kullanılan düşük geçirgen filtreden esinlenilmiştir. Ayrıca filtrelenen kuvvet değeri, katsayıya dayalı bir denklem kullanılarak PID kontrolcüden elde edilen kuvvet değeri ile birleştirilmiş ve filtre katsayıları genetik algoritma aracılığıyla optimize edilmiştir. Yapılan optimizasyon sonucunda tasarlanan kontrolcü, karşılaşılabilecek çeşitli yol girişleri için simule edilerek sonuçlar elde edilmiştir. Kontrolcüsüz ve filtresiz PID kontrolcü ile elde edilen sonuçlar kıyaslanarak, tasarlanan kontrolcünün başarımı IAE ve ISE kriterlerine göre açıkça gösterilmiştir. Kontrolcünün gürbüzlüğü değişen kütle koşulları altında değerlendirilmiş ve performansı tablo halinde verilmiştir.

Anahtar Kelimeler: *Filtreli PID, Genetik Algoritma, Aktif Süspansiyon Sistemleri, Gürbüz Kontrol*

1. Introduction

Currently, the widespread use of automobiles has resulted in an increasing importance placed on suspension systems. Suspension systems offer significant advantages in terms of both road grip and vehicle comfort, thereby rendering their use inevitable for automobiles [1]. This has led to the emergence of new research areas aimed at optimizing and improving suspension systems [2,3]

In general, suspension systems link the vehicle body and wheels, allowing for relative movement between them [4]. Such systems are classified into three categories in the literature: passive, semi-active, and active suspension systems [5,6,7]. While passive systems were utilized in earlier days, they have become inadequate in terms of comfort with the advent of semi-active and active systems [8]. Semi-active systems are more effective than passive systems but consume less energy than active systems. Active systems, on the other hand, offer superior driving experiences but are less energy-efficient than semi-active systems [9].

A good suspension system should control both driving comfort and handling parameters in a balanced manner [10]. Hence, the selected controller should be carefully chosen. Commonly known controllers in the suspension field include Fuzzy Logic Controller (FLC) and Proportional-Integral-Derivative (PID) controllers, which can be applied in different fields [11,12]. In addition to controller selection, optimization of the controller is also essential. To achieve this, an optimization method suitable for the model should be selected. The most common optimization methods include Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) methods. Compared to PSO and GA, the Ziegler-Nichols method is faster but experimental [13,14,15]. Apart from driving safety and comfort, the applications of active control systems in suspensions are also encountered in the defense industry [16].

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Effective controller performance under changing and nonlinear conditions is crucial in real-world applications [17]. The PID controller's linear structure renders it non-robust, which is a significant drawback. Robustness is a crucial characteristic of a good controller because mass and force in the vehicle continually vary due to the variable weight of passengers and acceleration in the direction of gravity on bumps. As a result of the added filter and optimizations, the PID controller's robustness feature was enhanced, and its performance improved against varying mass, effectively endowed the PID controller with enhanced robustness, a vital attribute for its performance in the presence of changing and dynamic conditions. Furthermore, when PID is used alone, it achieves stability in a matter of seconds; however, the addition of the filter has expedited this process significantly. The introduction of the filter has not only reduced oscillations but has also led to a faster stabilization.

The significance of this enhancement goes beyond the realm of control theory. In the context of suspension systems, which play a pivotal role in automotive engineering, this improved controller performance carries substantial implications. Suspension systems are responsible for maintaining vehicle stability, comfort, and handling, especially when subjected to varying loads and terrain conditions [18,19]. The ability of the PID controller, bolstered by the added filter, to respond more effectively to fluctuations in mass and external forces aligns with the fundamental objectives of suspension systems. By achieving a faster and more precise response to these variations, the controller contributes to a smoother and safer ride, reducing wear and tear on vehicle components and enhancing overall driving experience. Thus, the enhanced robustness of the PID controller holds great promise in advancing the field of suspension system design and performance, offering potential benefits for a wide range of automotive applications.

In this study, a quarter car model was utilized, and the active suspension system was controlled by a PID controller incorporating a low-pass filter. The PID controller coefficients were determined using the Ziegler-Nichols method, and optimization of the filter and adaptation part was carried out using the Genetic Algorithm. The results indicate that the performance of the PID controller was significantly enhanced through the addition of the filter and adaptation parts.

2. Material and Method

2.1. Mathematical model

In vehicle modeling, three main models are typically used: the quarter car, half car, and full car models. The quarter car model was selected for this study to demonstrate the impact of the filter in a straightforward, simplified, and easy-to-understand manner.

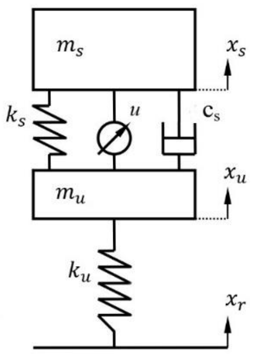


Figure 1. Physical model of quarter car

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

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

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

Parameter	Symbol	Value (Unit)
Quarter body mass	m_s	290 (kg)
Suspension spring coefficient	m_u	16812 (N/m)
Damping coefficient	c_s	1000 (Ns/m)
Wheel mass	k_u	59 (kg)
Wheel spring coefficient	k_s	190000 (N/m)

To simulate real-life scenarios as closely as possible, three distinct types of road inputs were utilized in this study. In addition to the continuous ISO input, step and bump inputs were implemented to assess how the system responds to sudden disturbances. This approach was employed to ensure that the study accounted not only for permanent effects, but also for any potential road irregularities that could arise. The ISO path used in the study consists of 3 different qualities. The first quality is the A-B quality highway, which is frequently used in cities. The other two grades were chosen as B-C and C-D to test the study in more demanding conditions.

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

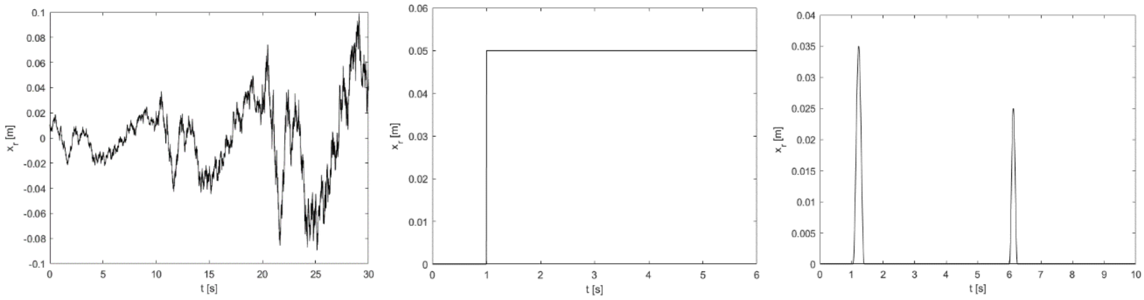
Where, G_d is displacement PSD in m^3, n is the spatial frequency, n_0 = 0.1 cycles/m in the reference spatial frequency and w is the exponent of the fitted PSD.

Three different road qualities mentioned in Table 2 were applied at 10 second intervals so that all of them could be tested. Thus, the continuity on the road was not disturbed and three different situations as road entrance were examined.

Table 2. ISO 8608 thresholds of the first three classes (A-C) [21,22]

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

Step and bump entrances, where we can examine possible distortions on the road, unlike the continuous road, were also examined. At the step entrance, the behavior of the vehicle after climbing the 0.05m high step was observed. At the bump entrance, two short-term impacts, the first of which is 0.035m high and the second 0.025m high, were applied to the vehicle and thus the resistance of the study to sudden impacts was also tested.



(a) (b) (c)

Figure 2. All road profiles (a) ISO (b) Step (c) Bump

2.2. Control algorithm

To enhance the performance of the system, appropriate control algorithms were chosen and optimized. A low-pass filter was integrated into the PID controller, and this filter was optimized using a genetic algorithm. Furthermore, the integration process itself was optimized using a genetic algorithm as well.

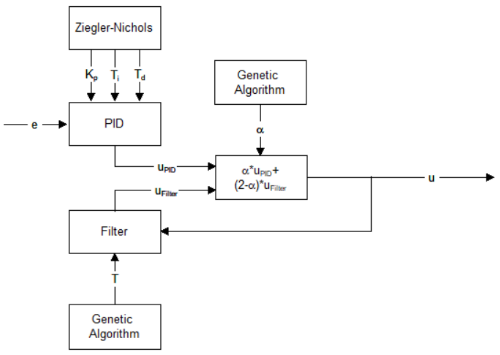


Figure 3. PID incorporated filter optimized GA

$$e = x_{s_{ref}} - x_s \quad (4)$$

$$x_{s_{ref}} = 0 \quad (5)$$

Utilizing an adaptive α value in lieu of a constant integration of the filter and PID controller enhanced the agility of the controller and amplified its efficacy.

$$u = \alpha * u_{PID} + (2 - \alpha) * u_{Filter} \quad (6)$$

The optimal value of the α was determined as 1.487 for the current system through the utilization of a genetic algorithm.

PID controller is one of the most common controllers used in suspension systems. It takes a selected parameter in the system as an error and multiplies them with a proportional coefficient after taking the error itself, its integral and its derivative. The resulting force enters the system as an input and the error is tried to be minimized. In this study, the position of the sprung mass was taken as the error parameter.

$$u_{PID}(t) = K_p * (e(t) + \frac{1}{T_i}\int_0^t e(t)dt + T_d \frac{de(t)}{dt}) \quad (7)$$

In this equation; K_p represents proportional coefficient; T_i represents integral coefficient and T_d represents derivative coefficient. These coefficients should be chosen carefully to minimize the error.

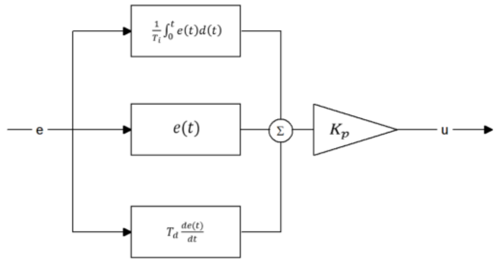


Figure 4. The block diagram of PID controller

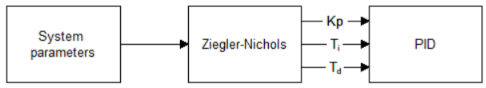


Figure 5. The block diagram of Ziegler-Nichols method

The Ziegler-Nichols method is a commonly preferred technique in suspension systems for determining the optimal controller parameters. This method involves subjecting the controller to sustained oscillation at a non-zero reference level and subsequently deriving the PID coefficients based on the resulting amplitude and coefficients. In this study, the Ziegler-Nichols method was employed to determine the optimal PID coefficients.

$$u_{Filter}(s) = \frac{1}{\tau s+1} u_{PID}(s) \quad (8)$$

In signal processing, using an averaging filter, especially a low-pass filter, is justified by the fact that the signal's fundamental characteristics are determined by its low frequencies, whereas high frequencies often reflect unaccounted dynamics.

To preserve the signal's slow component, the cutoff frequency of the low-pass filter must be chosen to be large enough while still removing high-frequency components. As a result, the filter's output tends towards the equivalent control, ensuring system stability. This approach eliminates the requirement for an accurate mathematical model of the system, thereby increasing the designed controller's practicality [23].

Unlike the empirical experimentation involved in the Ziegler-Nichols method, the Genetic Algorithm method relies on computational optimization to identify the optimal outcome within a defined range. To achieve this, the Genetic Algorithm establishes an objective function, which it endeavors to minimize based on its own predetermined criteria. Establishing an accurate goal function that aligns with the study is critical for optimization studies, as it ensures that the optimized results are aligned with the intended control objective.

In this study, IAE (Integral Absolute Error) and ISE (Integral Squared Error) criteria were used to determine the Objective Function. Acceleration and position, which are the two most important parameters for suspension systems, were chosen as the parameters to be used in these two criteria. However, since the values of the two parameters cannot be similar, a correction coefficient is used to ensure that their effects are the same.

$$G_1 = k * IAE_p + IAE_a \quad (9)$$

$$G_2 = k * ISE_p + ISE_a \quad (10)$$

G_1 and G_2 represent Goal Functions, k represents the correction coefficient, IAE_p and ISE_p represents errors of position, IAE_a and ISE_a represents 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.

Upon establishing the objective function to be optimized, the Filter and Adaptation coefficients were subsequently determined via the Genetic Algorithm (GA). The GA is a heuristic search algorithm inspired by the process of natural selection. In the context of this study, it was employed to fine-tune the controller parameters effectively.

The GA operates by creating a population of potential solutions, where each solution represents a set of coefficients for the filter and adaptation parts [24]. These coefficients are initially generated as random numbers within predefined bounds, effectively initializing the population [25]. Following this, the algorithm iteratively evaluates the fitness of each solution by assessing how well it aligns with the optimization objective. The fitness is determined based on the performance of the PID controller in reducing error and improving system response.

As the GA progresses through generations, it utilizes a mechanism akin to natural selection. Solutions that exhibit promising traits, i.e., coefficients that are closer to the desired objective, are marked as genes and carried forward to subsequent generations. This selective process helps refine the coefficients towards optimal values. Conversely, solutions with less favorable traits are discarded, ensuring that the algorithm avoids getting stuck at local optima.

Furthermore, the GA introduces diversity into the population by creating new individuals independently of the previous generations. This diversity is essential to explore the search space comprehensively, preventing premature convergence to suboptimal solutions. The combination of selective retention of promising coefficients and the introduction of novel solutions allows the GA to iteratively refine the PID controller's parameters, ultimately leading to the observed improvements in controller performance.

In summary, the Genetic Algorithm played a crucial role in the fine-tuning of the filter and adaptation coefficients, contributing significantly to the enhanced robustness and performance of the PID controller in the context of changing and dynamic conditions. In light of these details, an explanatory Genetic Algorithm flowchart is drawn in Figure 6.

In this study, the lower limit of the Filter coefficient τ was determined as 0 and the upper limit was determined as 4, the lower limit of the adaptation coefficient α was 0 and the upper limit was 2, the population number was 100, and the mutation rate was 20%. The optimal value of the τ parameter was determined as 0.149 for the current system through the utilization of a genetic algorithm.

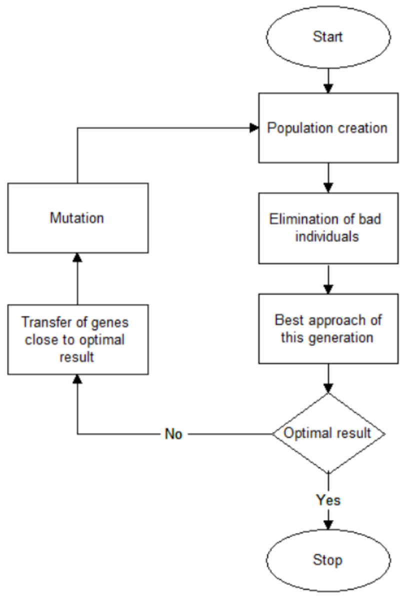


Figure 6. The flowchart of Genetic Algorithm

3. Results

According to the information presented, Table 3 displays the values of objective functions corresponding to the ISO road input, whereas Table 4 shows the same values for the step input, and Table 5 displays the values for the bump input.

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

	G_1	G_2
Passive	67.26	56.47
PID	33.73	64.21
Filter PID	30.43	53.72

Table 4. G_1 and G_2 results according to step entry

	G_1	G_2
Passive	2.731	4.317
PID	1.564	4.855
Filter PID	0.974	4.063

Table 5. G_1 and G_2 results according to bump entry

	G_1	G_2
Passive	3.456	1.989
PID	2.548	3.041
Filter PID	1.248	1.332

Upon analysis of the results obtained from the evaluation of the goal functions, it was observed that the Filter PID method exhibited superior performance compared to both the Passive and PID-only approaches. This particular method displayed enhanced responsiveness and dynamic behavior in the presence of abrupt load changes, such as Step and Bump inputs. Additionally, it demonstrated high effectiveness in tasks involving ISO road input.

Figure 7 presents the x_s graph pertaining to the ISO path input, while Figure 8 illustrates the acceleration of x_s for each case. In contrast, Figures 9 and 10 depict the graphs for the step input, and Figures 11 and 12 display the behavior corresponding to the bump entry.

The effectiveness of the Filter PID method is more clearly evident in the position graphs of the spring-mass system as compared to the passive and only PID cases.

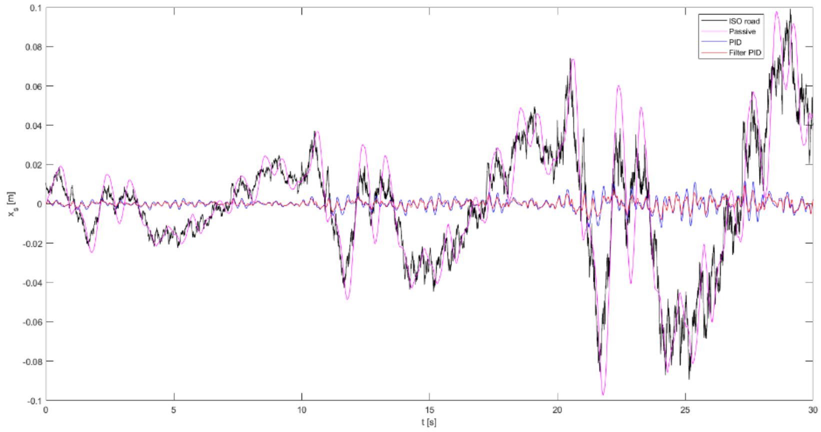


Figure 7. The position-time graph of all systems according to ISO path entry

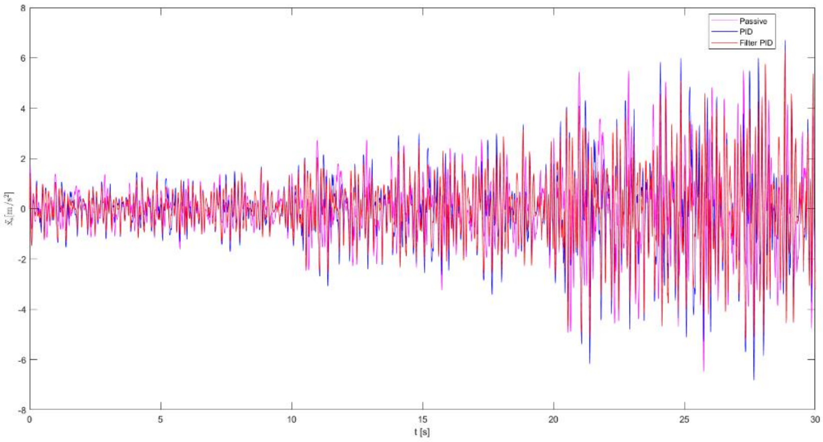


Figure 8. The acceleration-time graph of all systems according to ISO path entry

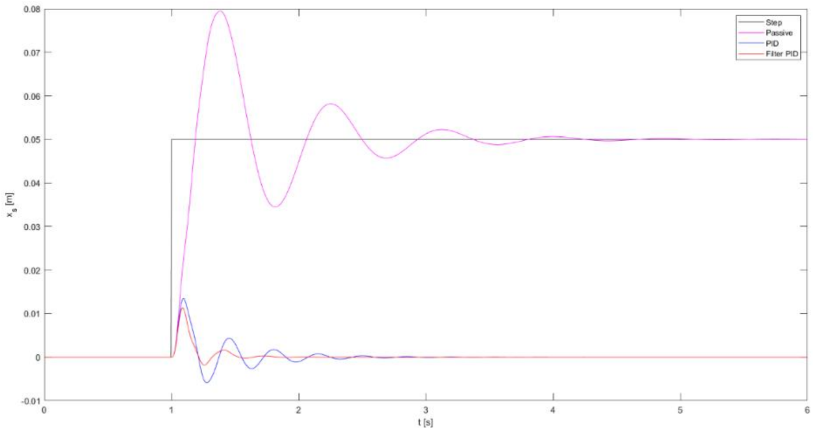


Figure 9. The position-time graph of all systems according to step entry

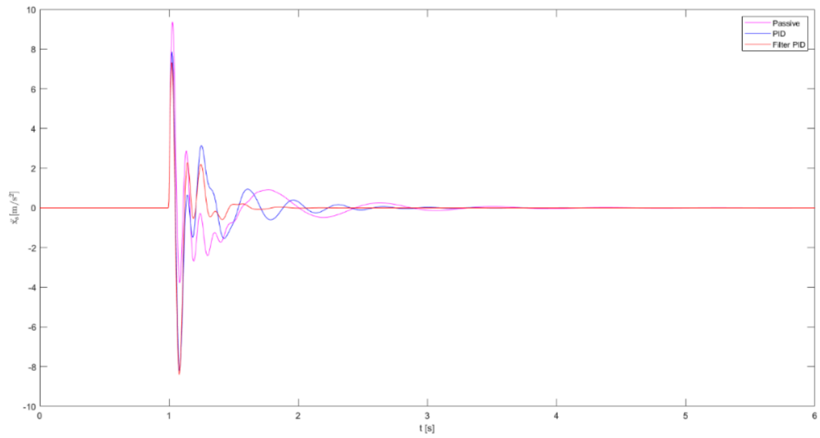


Figure 10. The acceleration-time graph of all systems according to step entry

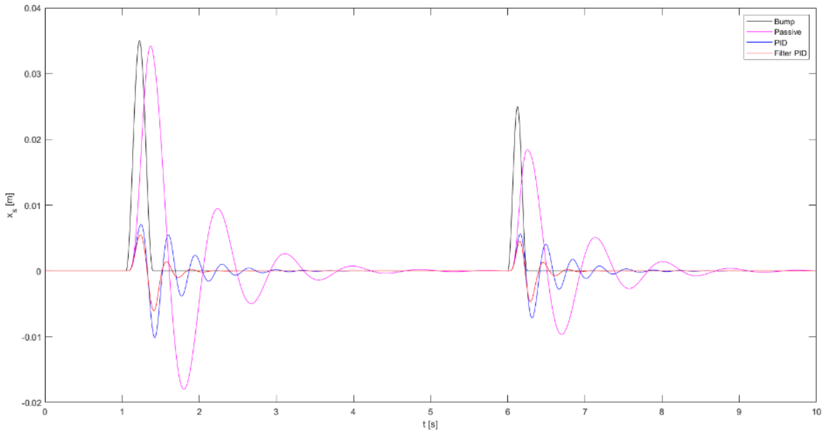


Figure 11. The position-time graph of all systems according to bump entry

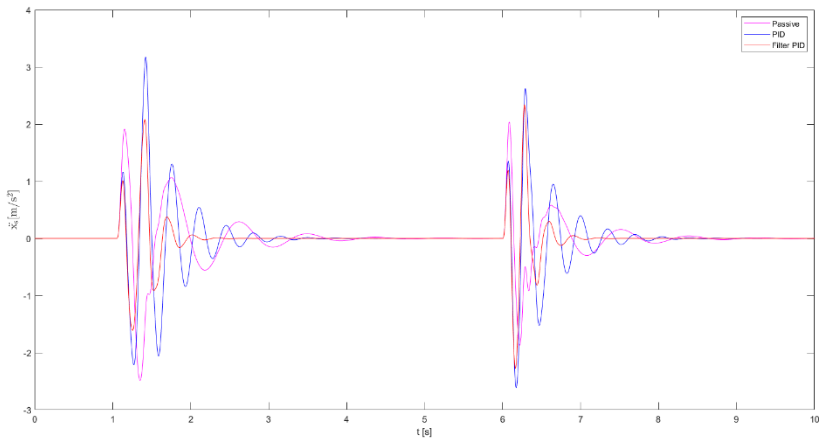


Figure 12. The position-time graph of all systems according to bump entry

To explain the relatively lesser control over acceleration values compared to position values, it's essential to consider that the optimizations were conducted with a goal function correction value set at 50. Reducing this value would render the coefficients more inclined towards enhancing acceleration. While Table 6 may not demonstrate substantial improvements for ISO input values, Tables 7 and 8 reveal a more significant enhancement, particularly for systems characterized by larger disparities between position and acceleration.

Table 6. ISE_a and IAE_a results according to ISO path entry

	IAE_a	ISE_a
Passive	28.84	56.18
PID	30.65	64.20
Filter PID	28.25	53.71

Table 7. ISE_a and IAE_a results according to step entry

	IAE_a	ISE_a
Passive	1.61	4.29
PID	1.39	4.85
Filter PID	0.90	4.06

Table 8. ISE_a and IAE_a results according to bump entry

	IAE_a	ISE_a
Passive	1.95	1.97
PID	2.21	3.05
Filter PID	1.10	1.34

In order to evaluate the robustness of the system, 10% increments are introduced to the mass of the spring-mass setup. The results obtained from these tests are presented in Table 9, Table 10, and Figure 13. Upon analysis of Table 9, it is observed that the Filter PID method maintains consistent performance even with an increase in mass, whereas the PID-only approach displays decreased performance as it is highly susceptible to changes in parameters. The passive system also experiences a reduction in performance but to a lesser extent than the PID-only method. Similarly, Table 10 reveals that although an increase in mass results in an improvement in acceleration, the Filter PID method continues to exhibit the highest performance.

Table 9. IAE_P results according to ISO path entry for mass change

Mass (kg)	*Passive*	*PID*	*Filter PID*
290	0.7685	0.0617	0.0436
319	0.7821	0.0649	0.0438
348	0.7930	0.0695	0.0443
377	0.8005	0.0761	0.0449
406	0.8047	0.0851	0.0456
435	0.8059	0.0995	0.0469

Table 10. IAE_a results according to ISO path entry for mass change

Mass (kg)	*Passive*	*PID*	*Filter PID*
290	28.81	30.65	28.25
319	26.72	28.68	25.84
348	24.97	27.45	23.90
377	23.45	26.94	22.30
406	22.18	26.75	20.99
435	21.03	27.65	19.91

Furthermore, Figure 13 depicts the position graph for the case with a 50% mass increase, where it is evident that the Filter PID method is unaffected by changes in mass. These results demonstrate that the Filter PID method provides superior robustness to the PID controller and effectively addresses one of its major shortcomings, which is its dependence on system parameters.

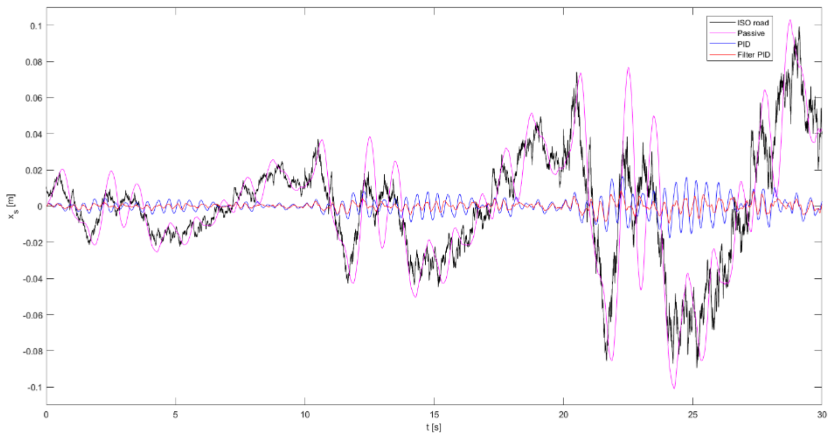


Figure 13. The position-time graph for 50% mass increase according to ISO path entry

Table 11. G_1 results according to ISO path entry for damping coefficient change

c_s (Ns/m)	*Passive*	*PID*	*Filter PID*
1000	67.26	33.73	30.43
900	67.25	32.27	28.97
800	67.48	30.80	27.50
700	68.04	29.34	26.02
600	69.06	27.91	24.54
500	70.85	26.56	23.07

Table 12. G_1 results according to ISO path entry for spring coefficient change

k_s (N/m)	*Passive*	*PID*	*Filter PID*
16812	67.26	33.73	30.43
15131	66.64	33.18	30.14
13450	65.83	32.68	29.90
11768	64.88	32.25	29.71
10087	63.86	31.88	29.58
8406	62.92	31.59	29.50

In order to further broaden the scope of the study, comparisons have not been limited solely to mass; the spring coefficient k_s and damping coefficient c_s have also been subjected to a 10% variation. Despite these changes, Filtered PID has managed to maintain its robustness. As can be seen in Tables 11, 12, 13 and 14, Filtered PID values are far from sudden changes.

4. Discussion and Conclusion

The current study utilized a quarter car model and employed a PID controller incorporating a low-pass filter to control the active suspension system. The Ziegler-Nichols method was employed to determine the coefficients of the PID controller, and Genetic Algorithm was utilized to optimize the filter and adaptation components. The results obtained from this study suggest that the incorporation of the filter and adaptation parts significantly improves the performance of the PID controller.

The linear structure of the PID controller results in poor performance when faced with changes in system parameters. Consequently, these controllers often fail to meet the essential evaluation criterion of robustness, which is a crucial characteristic for effective controllers. Nevertheless, the present study demonstrates that the integration of a filter with PID controllers can enhance their robustness. Consequently, this newly designed controller can be readily implemented in systems with variable parameters, thereby addressing the issue of poor performance associated with changes in system parameters.

Ethics committee approval and conflict of interest statement

There is no need for an ethics committee approval in the current article.

There is no conflict of interest with any person/institution in the current article.

Author Contribution Statement

İbrahim Şenaslan: Conceptualization, investigation, methodology and software, visualization and writing – original draft.

Boğaç Bilgiç: Conceptualization, investigation, methodology and software, supervision and writing – review and editing.

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