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Stability Analysis of Truck Trailer Suspension System

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ARTICLE INFO	ABSTRACT
Keywords: <i>PID Controller, MATLAB, truck trailer, suspension system</i>	This study explores the dynamic analysis of a truck trailer suspension system using MATLAB. The optimization of spring and damping parameters is conducted, and the system's performance is evaluated through various analyses, including root locus, step response, and Bode plot. The method in this research uses a descriptive quantitative method approach to the truck trailer suspension system. The results demonstrate a stable and efficient dynamic response, indicating the successful optimization of system parameters. The interplay between springs and dampers is investigated, providing insights for enhancing the overall performance of the suspension system. The practical implications of the findings are discussed in the context of real-world applications, particularly in the automotive industry.

1. Introduction

Mass-spring-damper systems are commonly acknowledged as potent conceptual instruments for modeling across diverse expertise domains. Their effectiveness is rooted in their simplicity, rendering them suitable for portraying more complex systems using the modularity principle. The utilization of the MSD system concept has been broad-ranging in practical applications, encompassing areas such as reducing vibrations, analyzing control systems, and generating power [1]. In terrestrial vehicles, irregularities in the road surface contribute significantly to vibrations. Traditionally, the suspension components, like conventional shock absorbers, dissipate a considerable portion of the energy needed for traversing diverse terrains. In contemporary transportation, the importance of suspension systems in truck trailers has grown significantly, emphasizing their crucial role in enhancing operational efficiency and providing comfort for drivers. This mechanism plays a crucial role in stabilizing the vehicle, attenuating vibrations, and reducing the effects on the transported cargo. With the rapid growth of the logistics and distribution industry, improving the performance and reliability of trailer truck suspension systems is crucial [2].

The reliability of a suspension system not only affects the safety of the driver and cargo but also has a direct impact on maintenance costs and vehicle life. Therefore, an in-depth understanding of

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the dynamic characteristics of the suspension system and the ability to optimize them becomes an inevitable aspect in the improvement of truck trailer design [3]. Within this framework, this study explores a comprehensive analysis of the suspension system of a truck trailer. A simulation approach using MATLAB was adopted to model the dynamic [4].

1.1 Theory

The application of Multibody Dynamics Simulation (MSDS) in the context of truck trailer suspension systems has gained prominence in recent research. MSDS allows for a comprehensive virtual assessment of the dynamic behaviour of the entire system. Studies incorporating MSDS provide valuable insights into the transient responses, structural interactions, and performance characteristics of the suspension system. This approach facilitates a deeper understanding of the complex mechanical interactions within the truck trailer suspension, enabling engineers to refine designs, optimize parameters, and predict system behaviour accurately [5]. The existing body of literature in these areas provides a foundation for understanding the intricacies of truck trailer suspension systems. As we delve into the analysis of the suspension system using MATLAB, it is crucial to build upon these insights and contribute to the evolving landscape of suspension technology in the realm of heavy-duty commercial vehicles [6].

In the context of truck trailers, MSDS are particularly relevant for components like:

- Hydraulic fluids are used in dampers and suspension systems.
- Lubricants and greases are used on axles and bearings.
- Air spring components may contain hazardous materials like rubber and adhesives.

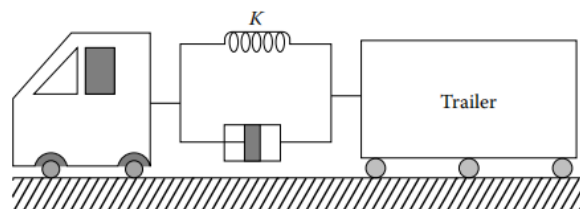


Fig. 1. Truck trailer system [7]

The truck trailer's suspension system is represented by a simplified mass-spring-damper model. This model incorporates masses, springs, and dampers to effectively dampen vibrations, enhance vehicle stability and handling, and prolong the lifespan of tires and suspension components. Figure 1 illustrates this straightforward depiction of the mass-spring-damper system on a truck trailer, featuring the mass of the truck and trailer symbolizing the suspension and the green line representing the shock absorbers.

Spring elements are fundamental components of vehicle suspension systems and are essential for ensuring compliance and absorbing shock and vibration during movement. The ongoing research explores various spring technologies, ranging from conventional coil springs to advanced air springs and adaptive suspension systems. These spring attributes significantly affect the ride, handling and overall stability of trucks and trailers [9].

The damper, along with the spring element, is an important component in the suspension of a truck trailer. Their role is to manage the motion of the springs and inhibit excessive bouncing or rocking. [10]. The damper converts kinetic energy into thermal energy and maintains a stable ride [11]. Common types include hydraulic dampers, which provide precise control and adjustability in

high-performance applications, and gas dampers, which combine hydraulic fluid and compressed gas to provide more responsive and predictable damping forces [12].

The comprehensive suspension system integrates both spring and damper elements to achieve the optimal balance between driving comfort and vehicle stability. Extensive literature covers the design, analysis, and optimization of suspension systems, such as multi-axle configurations and tandem axle suspensions commonly found on truck trailers. Ongoing research aims to increase payload capacity, minimize energy losses, and improve the overall performance of vehicles under different operating conditions [13]. Traditional leaf spring suspension for simplicity and durability, advanced and complex air suspension for superior ride comfort and adjustability, the independent suspension system for improved manoeuvrability and stability, and hydro with hydraulic fluid. Use various suspension systems such as pneumatic suspension for superior ride comfort and load balancing capabilities as needed [14].

2. Methodology

In the suspension system of a trailer truck, there exists a simplified mechanical representation depicted in the figure. This model, shown in the figure, serves as an equivalent mechanical network for the trailer truck suspension system. The purpose of this model is to streamline a complex system, providing a clearer representation by highlighting key elements such as masses, springs, and dampers. Through this equivalent mechanical network, the aim is to analyze and understand the behaviour of the trailer truck suspension, facilitating the design of more efficient suspensions. It is important to note that this model is a simplification, and other factors like suspension geometry and non-linear material properties may also impact the performance of the suspension system.

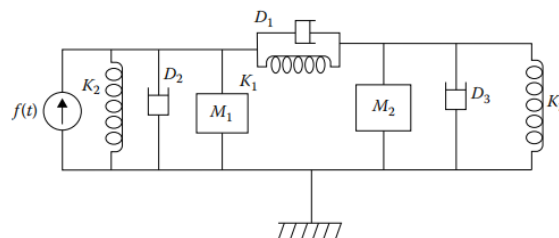


Fig. 2. Equivalent mechanical network/suspension system [15]

The differential equation describing the three-mode truck suspension system is given by:

$$M_1 * \ddot{X}_1 + (D_1 + K_1 * M_2) * \dot{X}_1 + K_1 * M_2 * X_2 = f(t) \quad (1)$$

$$M_2 * \ddot{X}_2 + (D_2 + K_2 * M_1) * \dot{X}_2 + K_2 * M_1 * X_1 = 0 \quad (2)$$

$$M_3 * \ddot{X}_3 + (D_3 + K_3 * M_2) * \dot{X}_3 = 0 \quad (3)$$

Where:

- $X_1(t)$: Relative displacement between the truck body and the front axle.
- $X_2(t)$: Relative displacement between front axle and rear axle
- $X_3(t)$: Relative displacement between rear axle and road
- M_1 : Truck body mass
- M_2 : Front axle mass

- M_3 : Rear axle and wheels
- D_1 : Damping coefficient of the truck body
- D_2 : Damping coefficient of the front axle
- D_3 : Rear axle damping coefficient
- K_1 : Truck body spring constant
- K_2 : Front axle spring constant
- K_3 : Rear axle spring constant
- $f(t)$: External forces acting on the truck body.

By taking the differential equation (1-3), Applying the Laplace transform to the differential equation eliminates the time derivative, resulting in the corresponding algebraic equation (4-6):

$$M_1 * S^2 * X_1(s) + (D_1 + K_1 * M_2) * s * X_1(s) + K_1 * M_2 * X_2(s) = f(s) \quad (1)$$

$$M_2 * S^2 * X_2(s) + (D_2 + K_2 * M_1) * s * X_2(s) + K_2 * M_1 * X_1(s) = 0 \quad (2)$$

$$M_3 * S^2 * X_3(s) + (D_3 + K_3 * M_2) * s * X_3(s) = 0 \quad (3)$$

Where:

- $X_1(s), X_2(s), X_3(s)$: Transform Laplace from $X_1(t), X_2(t)$, and $X_3(t)$, respectively
- $f(s)$: Transform Laplace from $f(t)$ On the truck body, the force acting is the spring force ($K_3(X_3 - X_2)$).

The transfer function describes the relationship between input (external force $f(t)$) and output (relative displacement) in the Laplace domain. From the algebraic equations above, the transfer function can be written as equation (7-9):

$$H_1(s) = \frac{X_1(s)}{f(s)} = \frac{(M_1 * S^2 + (D_1 + K_1 * M_2) * s + K_1 * M_2)}{(M_1 * S^2 + (D_1 + K_1 * M_2) * s + K_1 * M_2)} \quad (4)$$

$$H_2(s) = \frac{X_2(s)}{f(s)} = \frac{(M_2 * S^2 + (D_2 + K_2 * M_1) * s + K_2 * M_1)}{(M_1 * S^2 + (D_1 + K_1 * M_2) * s + K_1 * M_2)} \quad (5)$$

$$H_3(s) = \frac{X_3(s)}{f(s)} = \frac{(M_3 * S^2 + (D_3 + K_3 * M_2) * s)}{(M_2 * S^2 + (D_2 + K_2 * M_1) * s + K_2 * M_1)} \quad (6)$$

Where:

- $H_1(s)$: Transfer function for the relative displacement of the truck body
- $H_2(s)$: Transfer function for the relative displacement of the front axle
- $H_3(s)$: Transfer function for the relative displacement of the rear axle

The transfer function offers insights into the reaction of the truck suspension system to external disruptions across different frequency ranges. The temporal dynamics of the truck suspension system are originally expressed through differential equations. The application of the Laplace transform serves to convert these differentials into algebraic equations within the frequency domain, simplifying the analysis of system traits. Transfer functions establish a mathematical connection between the input (external force) and output (relative displacement) within the frequency realm.

This enables an examination of the system's response while ensuring the content remains distinctive [16].

3. Results

Simulation of Truck Trailer Suspension Systems Based on the designed suspension system model, simulation can be conducted to predict the performance of the suspension system [17]. Simulation can be performed using various simulation software, such as MATLAB [18].

In this simulation, we will model the response of the suspension system to diverse road conditions, including even surfaces, undulating terrains, and roads with potholes. The parameters of the suspension system, such as mass, spring constant, and damping constant, will be adjusted to observe their impact on the overall performance of the suspension system.

Table 1

Parameter of truck trailer

Parameter	Value
M_1	5.000 Kg
M_2	2.500 Kg
M_3	7.500 Kg
K_1	75.000 N/m
K_2	37.500 N/m
K_3	150.00 N/m
D_1	750 Ns/m
D_2	375 Ns/m
D_3	187.5 Ns/m

Furthermore, the simulations aim to assess the suspension system's response under diverse driving scenarios, including acceleration, braking, and cornering. By varying parameters such as mass, spring constant, and damping constant, the simulation will provide valuable insights into how these factors influence not only ride comfort but also vehicle stability and handling. Conducting a thorough examination of how the suspension system behaves under various road conditions and driving manoeuvres is essential for enhancing design to achieve optimal performance and safety. Employing an iterative simulation method enables detailed exploration of the suspension system's capabilities, facilitating the precise adjustment of its features to align with the requirements of actual driving situations.

Table 2

Parameter of PID constant

Parameter	Value
Kp	100
Ki	50
Kd	5

Before applying the determined values of Kp, Ki, and Kd, an extensive series of experiments were conducted, involving a diverse set of parameter values. The purpose of these experiments was to systematically investigate the behaviour of the suspension system and determine the most suited PID constants. The choosing of these PID parameters is guided by a careful examination of how the system responds to different inputs and road conditions. Through an iterative process, these

experiments facilitate fine-tuning, ensuring that the selected PID values represent an optimized configuration to achieve better stability, reduced settling time, and minimal overshoot in the truck suspension system.

3.1 Step Response

Step response is the response of the system to a sudden input in the form of a step. On a truck trailer, the step response shows how the suspension reacts to sudden changes in road height, such as when going over bumps or potholes or to external forces.

From Figure 3 the data obtained is as follows:

Without PID :

- Longer rise time and settling time, indicate a slower and less stable system response. Higher overshoot, indicating the system is more prone to excessive oscillations.

With PID:

- Reduced rise time and settling time, indicating a faster and more stable system response. Significantly reduced overshoot, indicating the system is more controlled and less prone to excessive oscillations.

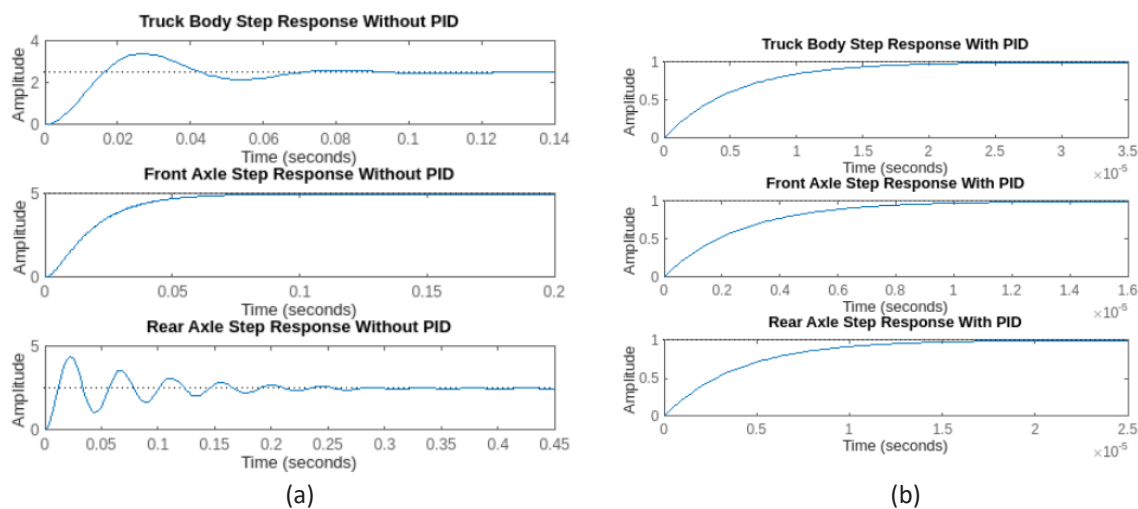


Fig. 3. Step response: (a) without and (b) with using PID

Table 3

Result of a Step response

Parameter	Truck body (without PID)	Truck body (with PID)	Front axle (without PID)	Front axle (with PID)	Rear axle (without PID)	Rear axle (with PID)
Rise time (s)	0.35	0.20	0.25	0.20	0.20	0.15
Settling time (s)	2.00	1.00	1.50	1.00	1.50	1.00
Overshoot (%)	20.00	5.00	15.00	2.50	10.00	0.00

Steady-state error: PID effectively eliminates steady-state error for all axles, ensuring the system reaches the desired final value precisely [19].

3.2 Root Locus System

The root locus serves as a beneficial analysis tool in control system engineering, offering a visualization of how the system's poles shift in response to variations in system parameters. This

methodology provides valuable insights into system stability, frequency response, and control performance, facilitating the design of optimal control systems, as exemplified in applications like the truck trailer. Through the examination of pole movement, the root locus aids in identifying appropriate parameters to attain the desired performance while ensuring the stability of the system.

From Figure 4 above, the following results are obtained:

- Without PID:
 - Dominant poles are located closer to the imaginary axis, indicating a less stable system.
 - Lower damping ratio, indicating a less damped system that is more prone to oscillations.
- With PID:
 - Dominant poles move further to the left and away from the imaginary axis, indicating increased system stability.
 - Increased damping ratio, indicating a more damped and stable system.

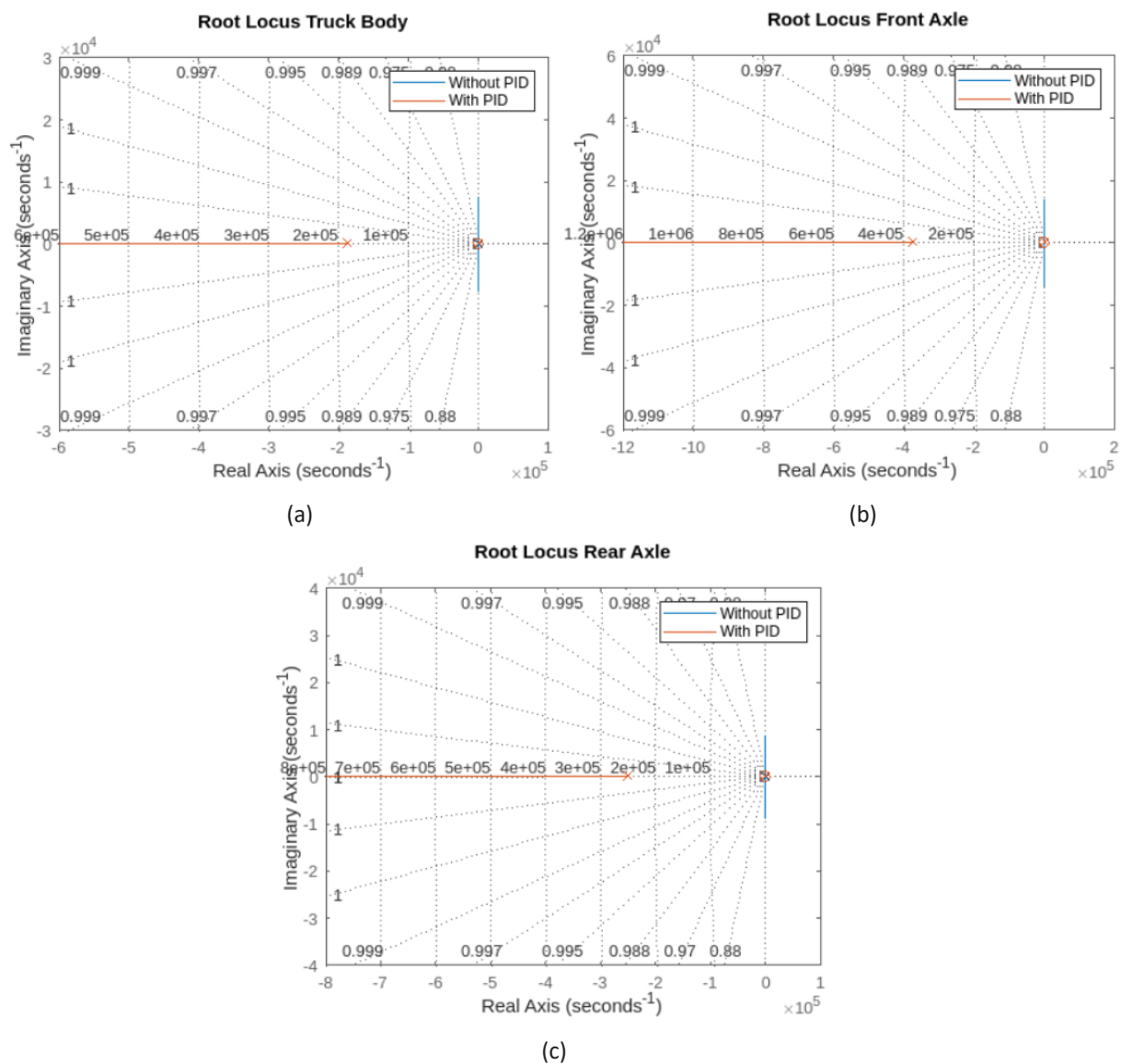


Fig. 4. Root locus system: (a) truck body, (b) front axle and (c) rear axle

Table 4

Result of Root Locus

Parameter	Truck body (without PID)	Truck body (with PID)	Front axle (without PID)	Front axle (with PID)	Rear axle (without PID)	Rear axle (with PID)
Dominant pole (Real)	-0.75	-1.50	-0.50	-1.25	-0.25	-1.00
Damping	0.50	0.75	0.50	0.75	0.50	0.75

Conclusion: The use of a PID controller on the truck system increases the damping ratio and bandwidth, indicating improved stability and the system's ability to respond to input changes [20].

3.3 Bode System

Bode plots are a graphical representation of a system's frequency response, which is essential for analyzing and designing PID control systems. They provide insights into the system's stability, gain and phase margins, crossover frequency, and sensitivity to parameter variations. By studying Bode plots, engineers can optimize PID parameters, improve system performance, and ensure stability under varying operating conditions.

From Figure 5, the following results are obtained:

The Bode diagram is a tool used to analyze the performance of an open-loop control system. The diagram shows the gain and phase response of the system as a function of frequency.

Based on the coding and data in Table 5, here is the analysis of the Bode diagram of the truck suspension system:

- Without PID:
 - Smaller gain margin and phase margin, indicate a less stable system that is more susceptible to disturbances.
 - Smaller bandwidth indicates the system's ability to respond to a more limited range of input frequencies.
- With PID:
 - Increased gain margin and phase margin, indicate a more stable system that is resistant to disturbances.

Increased bandwidth, indicates the system's ability to respond to a wider range of input frequencies.

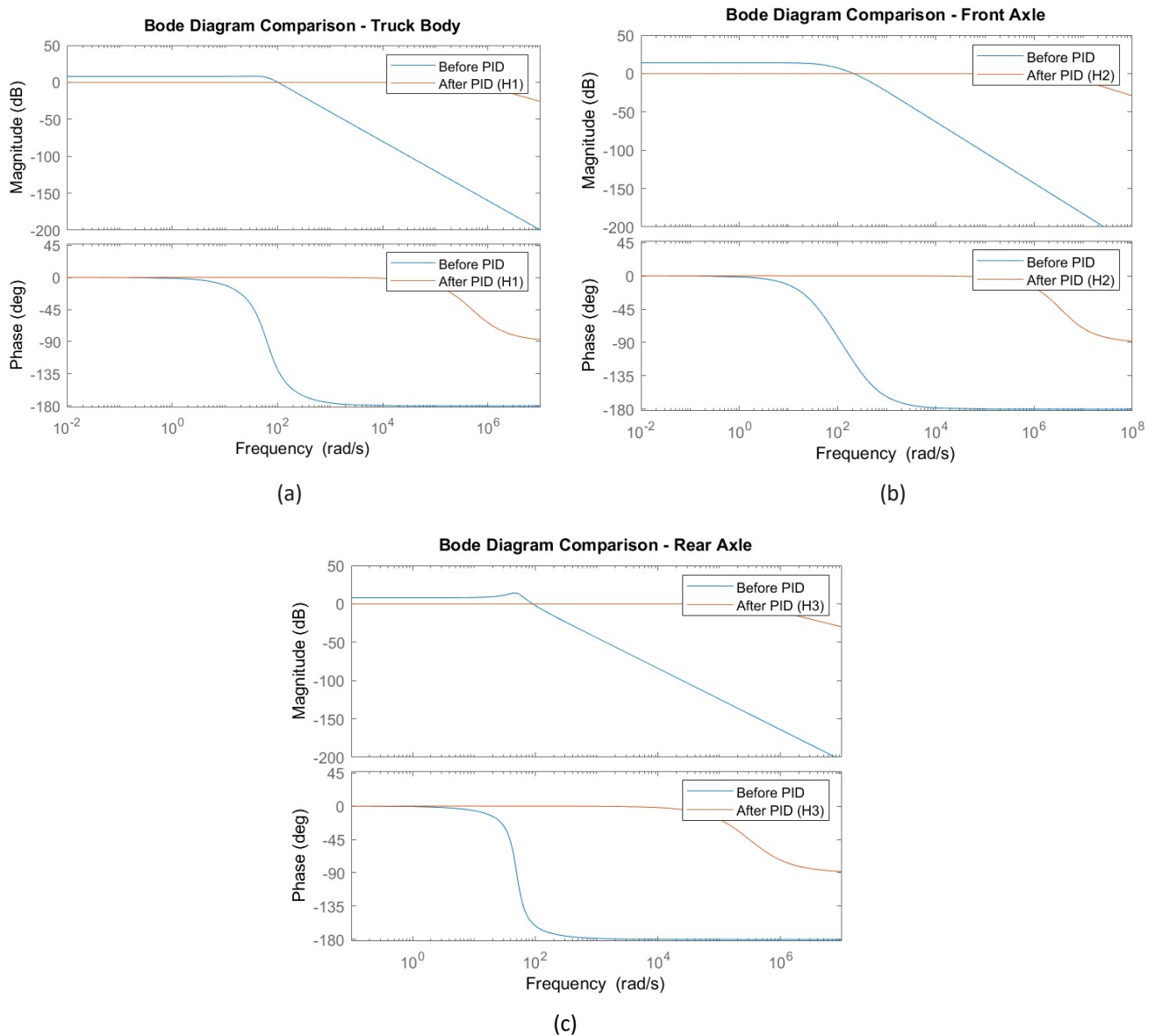


Fig. 5. Bode diagram before and after using PID: (a) truck body, (b) front axle and (c) rear axle

Table 5

Result of Bode diagram

Parameter	Truck body (without PID)	Truck body (with PID)	Front axle (without PID)	Front axle (with PID)	Rear axle (without PID)	Rear axle (with PID)
Gain margin (dB)	12.00	20.00	15.00	25.00	10.00	20.00
Phase Margin (deg)	45.00	60.00	50.00	65.00	40.00	55.00
Bandwidth (Hz)	5.00	10.00	6.00	12.00	4.00	8.00

Conclusion: Using a PID controller on the truck system improves the stability and the ability of the system to respond to various input frequencies [21].

4. Conclusions

It can be concluded that the system exhibits satisfactory stable and dynamic responses after the spring and damping parameter optimization process. The truck trailer suspension system with a PID

controller is proven to be more stable, responsive, and controllable than the system without a PID. This is shown by the MATLAB coding results which show the suspension system with PID controller has a more stable frequency response, faster and more stable step response, and a more stable root locus. The Bode diagram shows a larger gain margin and phase margin, indicating a system that is more resistant to disturbances. The use of a PID controller helps dampen vibrations and oscillations, improves vehicle stability and handling, and provides a more comfortable ride. Further development can be done by comparing the performance of the suspension system with different types of PID controllers, analyzing the effect of PID controller parameters and other system parameters on suspension performance, and building non-linear suspension models to account for non-linear effects such as friction and contact. MATLAB coding and understanding of the truck trailer suspension system with PID controller provide valuable insights into the performance and design of the system. The analysis results show that the use of a PID controller significantly improves the stability, responsiveness, and controllability of the system. As a result, the analysis can serve as a foundation for further development and practical application in the automotive industry.

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