ENHANCING VEHICLE WHEEL SUSPENSION TEST EQUIPMENT THROUGH TAGUCHI METHOD FOR OPTIMIZATION

by Agus W

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Abstract

The suspension system is of utmost importance in ensuring a comfortable driving experience. It plays a vital role in absorbing the vertical loads exerted by the vehicle's weight, driver, and passengers through its spiral springs and shock absorbers. Uneven road surfaces, such as potholes and bumps, can significantly impact the driver's comfort. This study investigates the suspension's performance and determines the optimal vibration value experienced by one of the vehicle's wheels under dynamic loads. The Taguchi method is employed in this research to identify the best dynamic load conditions for minimizing vibration in the suspension system. The approach adopted in the Taguchi method follows the "Smaller is better" principle. Several variables are considered in the analysis, including bump height, tire pressure on the wheels, vehicle body weight, and passenger weight. By evaluating these factors, the study aims to establish the optimal dynamic load conditions that minimize vibration in the suspension system. The study's results indicate that the optimum conditions are achieved with a mound height of 5 cm, a tire pressure of 32 psi, a load of 84 kg, and a dynamic load of 71 kg. Among the factors analyzed, mound height (factor A) and dynamic load (factor D) significantly contribute to the suspension's performance. In contrast, tire pressure (factor B) and passenger load (factor C) are considered insignificant. Under the optimized conditions, the suspension's vibration value experiences a notable reduction of 49.65%, showcasing the practical importance of the Taguchi method in enhancing driving comfort by fine-tuning the suspension system.

Keywords: Optimization, Vertical dynamic loads, Vehicle body weight, Suspension, Pneumatic actuator

1. Introduction

A vehicle's suspension system is an essential component responsible for providing a comfortable and stable ride for passengers. It plays a crucial role in maintaining the vehicle's stability and control. The primary function of this component is to absorb shocks and vibrations caused by uneven road surfaces and dynamic loads [1]. This serves to improve both driving comfort and safety. With the continuous advancement of automotive technology, it is crucial to optimize suspension systems to effectively cater to the growing needs and expectations of vehicle users.

Road surfaces are regularly traversed by a wide range of four-wheeled vehicles, creating dynamic loads that exhibit fluctuations. The loads seen result from changes in the magnitudes of dynamic loads and other variables, such as overloading (OL) and recurrent loading [2]. The fluctuation of loading is influenced by two factors: the wheelbase's varying weight and the vehicle's total weight. The effect of repeated loading (RL) circumstances is significantly affected by factors such as traffic flow repetitions, average traffic volume (measured in cars per hour) for each vehicle category, and the length of vehicles' exposure to the road surface.

The road surface is subjected to a range of dynamic stresses due to differences in the weights of vehicles of different classes that travel on it, including light, medium, and heavy vehicles. The variability in vehicle weights is a multifaceted problem that requires a thorough examination of several influencing factors directly and indirectly implicated in the phenomenon. A comprehensive examination is necessary to navigate the intricacies and enhance the efficiency of suspension systems [3]. Given the constraints above, it is essential to develop an efficient optimization approach that can accurately tackle the dynamic loads and vibrations experienced by the suspension system since these factors directly influence the condition of the road surface. An effective optimization strategy must include the complex interaction between several parameters, such as the distribution of the vehicle's weight, the state of the road, the traffic patterns, and the suspension components' stiffness [4].

The presence of well-designed springs and shock absorbers on each vehicle wheel serves the crucial purpose of reducing the impact of vertical dynamic loads transmitted to the road structure. As elucidated in references [2], this suspension system relies on a combination of springs and shock absorbers to effectively handle the vehicle's weight and provide a smooth and comfortable ride for its passengers. The suspension system's pivotal role becomes evident when navigating various road conditions, including irregular surfaces, bumps, and potholes. The springs are responsible for absorbing and distributing the force of the vehicle's weight, while the shock absorbers play a vital role in dampening the resulting vibrations and jolts. This collaborative effort ensures a stable and cushioned ride, preventing excessive bouncing or discomfort for the passengers [5].

However, the springs and shock absorbers interplay is crucial for optimal suspension performance. The tension spring's rigidity plays a significant role in determining how efficiently the shock absorber can counteract the forces arising from the road surface irregularities [6]. If the tension spring is overly rigid, the shock absorber may struggle to dissipate the impact energy effectively, leading to a harsh and uncomfortable ride. Conversely, if the tension spring is too soft, it may allow excessive vertical movement, resulting in bouncy and unstable ride quality. Therefore, achieving the right balance between spring rigidity and shock absorber efficiency is essential to strike the ideal compromise between road-holding capability and passenger comfort [7].

Taguchi's experimental design is a potent optimization strategy for determining the best response value. This method incorporates a well-planned experiment with several levels and components to analyze the reaction of interest comprehensively. Each of the three steps of design-system design, parameter design, and tolerance design-in the Taguchi approach to optimization is important in its own right [8]. Improved product performance and less overall production variability are two outcomes of the Taguchi method's integrated design phases, which give a planned and systematic approach to achieving optimum results. As a powerful optimization tool, it is used in many technical fields, particularly those that place a premium on accuracy, efficiency, and quality, such as the automotive, aerospace, electronics, and manufacturing sectors [9].

This study uses the Taguchi method to optimize suspension test equipment for one part of a vehicle wheel. The Taguchi method, a robust and widely recognized statistical approach, has gained popularity in various engineering fields for its effectiveness in improving product performance, quality, and reliability while minimizing costs and resources [10]. By employing the Taguchi method, this research aims to identify the optimal configuration of suspension test equipment that leads to superior performance and reduced vibrations in the vehicle's wheel assembly. The study involves understanding the impact of various factors on the suspension system's behavior and identifying the critical variables that significantly influence its performance.

The significance of this optimization lies in its potential to enhance the overall driving experience and road safety. A well-tuned suspension system can mitigate the effects of road irregularities, such as potholes and bumps, reducing discomfort for passengers and minimizing wear and tear on vehicle components. Furthermore, a properly optimized suspension system can improve vehicle handling and stability, crucial in avoiding accidents and ensuring driver confidence.

2. Literature Review and Problem Statement

The suspension system of vehicles is a critical component that directly influences ride comfort, vehicle stability, and handling characteristics [11]. Numerous studies have been conducted to optimize suspension design and performance using various methods and techniques. One notable approach that has gained popularity in recent years is the Taguchi method, known for its ability to identify and optimize the factors affecting product performance efficiently [12].

Due to its systematic and robust nature, researchers have applied the Taguchi method to diverse engineering fields, including automotive and mechanical engineering. The Taguchi method has been used in vehicle suspension systems to determine optimal settings for parameters such as spring rates, damping coefficients, tire pressures, and load distributions. Researchers have successfully improved suspension performance by employing this method while minimizing sensitivity to external disturbances.

In the paper [12], the researchers employed the Taguchi method to integrate vibration testing and robust optimization analysis. This approach allowed for an adequate evaluation of how various factors influence the suspension system's vibration behavior and facilitated the identification of optimal settings to minimize vibrations and improve ride comfort. By using this robust optimization technique, engineers could balance conflicting objectives, such as ride comfort and handling performance, resulting in well-balanced suspension designs. However, it is essential to recognize the assumptions and limitations of the Taguchi method and robust optimization approach, as they may impact the scope and potential challenges of the study's findings. Shedding light on these limitations can aid readers in understanding the study's implications more comprehensively.

The study [13] is an impressive effort focusing on a noteworthy aspect of automotive engineering. The application of the Taguchi method and the emphasis on rear suspension geometry provide valuable insights for optimizing vehicle handling. Improved handling has significant practical implications, directly affecting road safety and the overall driving experience. To enhance the overall contribution of the research to the field of vehicle dynamics and suspension design, it is essential to provide more detailed explanations of parameter selection, real-world validation, and consideration of trade-offs. The study has the potential to provide valuable insights into improving vehicle handling and promoting safer and more enjoyable driving experiences.

The study conducted by the researchers [14] is a significant and noteworthy addition to the field of automobile engineering. It provides valuable insights into the improvement of suspension system resilience. The use of the Taguchi technique, along with a targeted approach toward suspension parameters, offers pragmatic recommendations for attaining consistent and dependable suspension performance. Nevertheless, enhancing the research's overall effect and practical relevance may be achieved by providing more comprehensive explanations of parameter selection, undertaking a thorough analysis of findings, addressing the limits of the Taguchi technique, and doing real-world validation. Considering these factors, the research may serve as a significant reference for automotive engineers aiming to enhance suspension systems and vehicle performance.

The study mentioned above [15] shows potential in effectively addressing crucial elements of vehicle dynamics and ride quality. The incorporation of various components and the prioritization of enhancing ride comfort are significant contributions. Nevertheless, improving the research's overall effect and practical relevance may be achieved by offering more comprehensive elucidations of parameter selection, validation methodologies, careful evaluation of trade-offs, and the generalizability of results. By examining these many characteristics, the research has the potential to provide significant contributions in boosting the comfort experienced during vehicle rides and developing the design of suspension systems, ultimately leading to superior driving experiences.

The significance of suspension systems in vehicles and the potential advantages of utilizing the Taguchi method for optimization are well recognized. However, a noticeable dearth of research explicitly addresses the optimization of suspension test equipment. The study focuses on the lack of a structured and thorough method for designing and optimizing suspension test equipment for a specific component of a vehicle wheel. The current body of research primarily focuses on enhancing suspension design and tuning parameters while neglecting the crucial aspect of creating appropriate test equipment to assess suspension performance accurately. The lack of optimized test equipment can negatively affect the evaluation of suspension behavior. This can lead to inaccurate design decisions and decreased vehicle performance.

3. The aim and objectives of the study

This study aims to determine the optimal suspension vibration value in experimental test equipment with parameters mound height, tire pressure, payload, and dynamic load.

To achieve the objectives of this research, the objectives to be achieved are:

– to determine the optimal value of each parameter for suspension vibration: mound height, tire pressure, payload, and dynamic load;

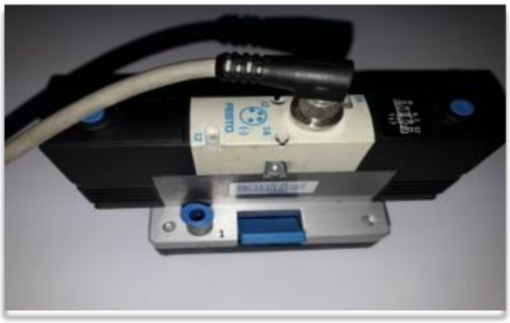
– to determine the most important suspension vibration characteristics (mound height, tire pressure, payload, and dynamic load).

4. Materials and Methods of Experiment

4. 1 Material

The material used in this study is essential for investigating and implementing the innovative approach to suspension system testing. Fig. 1 showcases the key components of creating a dynamic and controlled testing environment. Pneumatic cylinders (Fig. 1a) are crucial in generating the necessary vibrations in the suspension system. These cylinders act as vibration triggers, simulating various road conditions and dynamic loads that the suspension may encounter during real-world driving scenarios. Using pneumatic cylinders offers several advantages, including precise control over the magnitude and frequency of vibrations induced in the suspension. This level of control ensures that the testing conditions are repeatable and consistent, enabling researchers to isolate specific factors and accurately assess their impact on suspension performance.

(a)



(b)

Fig. 1. (a) Pneumatic Actuator (b) Memory valve 5/2

Additionally, incorporating 5/2 valve solenoids (Fig. 1b) enhances the pneumatic system's versatility. These solenoids enable rapid and efficient switching of the pneumatic cylinders, allowing for dynamic changes in the vibration patterns. By manipulating the 5/2 valve solenoids, researchers can simulate various road irregularities, such as potholes, speed bumps, and undulations, significantly affecting suspension behavior and passenger comfort. Using pneumatic cylinders and 5/2 valve solenoids as vibration triggers provides a unique and flexible approach to suspension testing. Traditional testing methods may not adequately replicate real-world conditions. Still, this experimental setup enables researchers to mimic a wide range of road surfaces and dynamic loads in a controlled laboratory environment. Integrating pneumatic cylinders and 5/2 valve solenoids as vibration triggers allows for a comprehensive investigation of suspension behavior under varying conditions. Researchers can observe how the suspension system responds to different vibration profiles, helping identify potential areas for improvement and optimization.

4. 2. Setup experimental

The successful method is the force exerted by the cylindrical thorax during the forward step, denoted by the unit N and written as Fef. This force is calculated by subtracting the theoretical force, Fk (N), from the frictional force, Rf (N) [16]. The result is the magnitude of this force. The entire load transfer mechanism against the asphalt road structure may be characterized using the equation of equilibrium of dynamic forces obtained from the Free Body Diagram (FBD) illustrated in Fig. 2 [17]. This equation can be determined by setting the frictional force Rf at a specific value (N) and then using this equation to represent the total load.

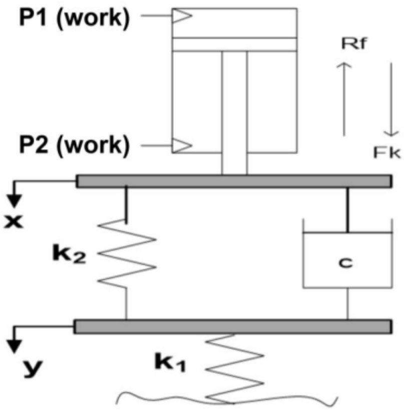


Fig. 2. The experimental loading mechanism of the system

Equations (1) and (2) mathematically express the effective thrust force exerted by the piston of the pneumatic cylinder, which is generated by the air pressure P2 (bar) [17]. The equations offer a valuable analysis of the forces and dynamic behavior of the pneumatic cylinder in the experimental setup. Equation (1) describes the correlation between air pressure P2 and effective thrust force Fef, illustrating the direct influence of pneumatic pressure on piston force. Equation (2) provides further insight into the various factors that contribute to the overall system performance, specifically focusing on the dimensions and characteristics of the cylinder and their impact.

$$F_k = \frac{\pi}{4} D^2 P_2 \tag{1}$$

$$F_{p2} = F_{ef} = F_k - R_f = F_k - 0.1F_k = 0.9F_k \tag{2}$$

where the force F-k. = 1.1, k – 2.y + c, y., and the effective force, F-ef.=, F-p2.= , k-2.y + c, y.

If the cylinder dimensions used in the experiment are set to 0.100 m, then based on equation (2), a compressive force is obtained on the suspension mechanism. The equation suggests that the compressive force, denoted as F_k, is related to the air pressure P_2 in the cylinder. The compressive force (Fk) value can be calculated using the provided relationship: F_k = 785 x P_2 [5]. This equation indicates that the compressive force is directly proportional to the air pressure P_2, with a constant of proportionality equal to 785.

The dimension D=100 mm corresponds to the diameter of the cylinder, and it plays a significant role in determining the compression force exerted on the suspension mechanism. The diameter of the cylinder influences the effective surface area exposed to the air pressure, directly affecting the overall force generated by the pneumatic cylinder. As the air pressure P_2 varies, the compressive force F_k changes accordingly. Researchers can regulate the compressive force applied to the suspension mechanism by controlling the air pressure. This control over the compressive force is crucial for fine-tuning the suspension system's behavior and optimizing its performance for different road conditions and vehicle loads. Equation (3) shows the new compressive force by suspension mechanism.

$$F_{p2} = 0.9 \text{ x } 785P_2 = 707P_2 = k_2y + c\dot{y} \quad (3)$$

When a spring is loaded, it undergoes shortening or deflection due to the law of action-reaction. According to this principle, the load applied to the spring is directly proportional to the magnitude of the deflection and is determined by the spring constant. This relationship between load, deflection, and the spring constant is fundamental to understanding the behavior of the suspension system. In the optimized suspension system context, the average displacement (x) is measured to be 0.009264 m. This average displacement represents the average amount the suspension system compresses or extends during its operation, reflecting its response to external forces such as road irregularities or driving conditions.

Furthermore, the maximum vertical acceleration observed in the optimized suspension system is 15.5707 m/s². Vertical acceleration refers to the rate of change of vertical velocity, and this value provides crucial insights into the suspension system's ability to absorb and dampen vibrations and shocks during vehicle operation. Combining the average displacement and the maximum vertical acceleration showcases the suspension system's effectiveness in providing a smooth and controlled ride experience. A well-optimized suspension system ensures that the vehicle's wheels maintain better contact with the road surface, minimizing vibrations and impacts transmitted to the vehicle's occupants.

The test spring utilized in the suspension system mechanism is of the "Helical" type, characterized by specific dimensions and specifications. The key dimensions of the spring include the inner diameter of the coil (Di) measuring 12.985 cm and the outer diameter of the coil (Do) measuring 15.815 cm. Additionally, the diameter of the spring wire (d) is 1.415 cm, and the number of coils (n) in the spring is 5 pieces. The spring material is specified as Chrome Vanadium, ASTM A231. This material choice significantly determines the spring's mechanical properties, including its strength, durability, and performance under varying conditions.

Furthermore, the modulus of stiffness (G) for the test spring is determined to be $7.929 \text{ x } 10^{10}$ Pa, equivalent to $7.929 \text{ x } 10^{6}$ N/cm². The modulus of stiffness represents the material's resistance to deformation under an applied load, and it is a crucial parameter for characterizing the spring's behavior. The test spring is classified as a "Helical compression spring," designed to absorb and store energy when subjected to compressive forces. Helical compression springs are widely used in various applications, including suspension systems because they provide support and absorb shocks. The spring constant (k_2) is an essential parameter determining the spring's stiffness. It is calculated using the equation (4) presented in reference [7]. The spring constant quantifies the relationship between the force applied to the spring and the resulting deflection or compression.

$$k_2 = \frac{Gd^4}{8n_aD^3} \quad (4)$$

In general, the vehicle's suspension system is crucial for providing a smooth and controlled ride experience. It typically consists of a spring and a shock absorber arranged in parallel. Each element plays a distinct role in enhancing vehicle dynamics and passenger comfort. The primary function of the suspension system is to support the vehicle's weight, including the body, engine, passengers, and cargo. By effectively distributing and absorbing the weight, the suspension system ensures that the car remains stable and balanced during motion, contributing to better handling and overall safety.

Additionally, the suspension system is responsible for maintaining proper wheel alignment. Proper alignment is crucial for even tire wear and optimal handling characteristics. By keeping the wheels aligned, the suspension system improves tire life and reduces the risk of uneven tire wear patterns. Fig. 3 showcases the passive suspension mechanism and the condition of the vehicle quarter loading structure. The passive suspension system is the conventional type of suspension that operates without active control systems. It relies on the mechanical properties of the spring and shock absorber to provide the desired ride characteristics.

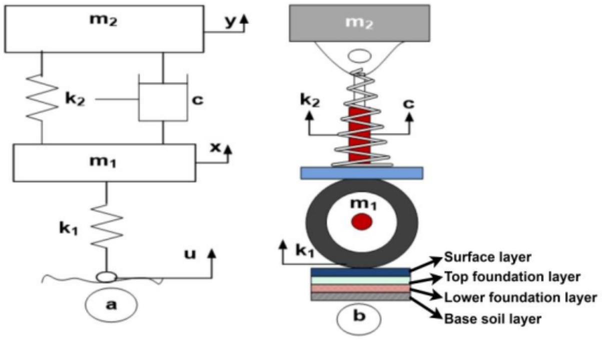


Fig. 3. (a) Passive suspension model (b) Suspension unit, shock absorber, axis, and wheels on road lining structure

The vehicle quarter loading structure in Fig. 3 illustrates the arrangement of the suspension components for one-quarter of the vehicle. This representation allows researchers and engineers to analyze the suspension's behavior and understand how it interacts with the vehicle's weight distribution. Examining Fig. 3, it becomes possible to calculate the force acting on the tire using equation (5) [11]. This equation likely represents a fundamental relationship that enables researchers and engineers to quantify the forces at play in the vehicle's suspension system.

$$F_{t1} = F_{ro} = 707\,P_2 + (k_1.x) \tag{5}$$

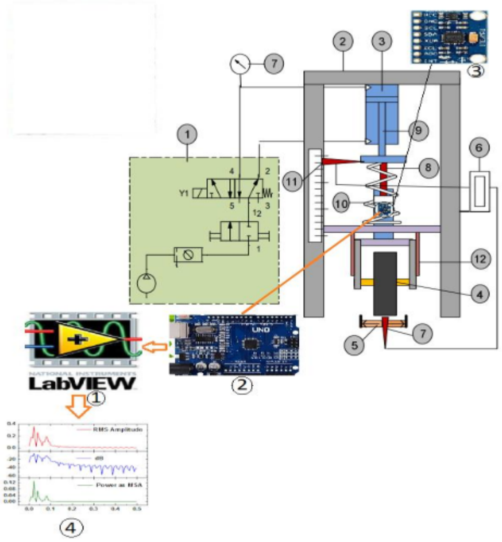
Equation (5) likely incorporates several variables, such as the spring constant, damping coefficient, tire characteristics, and the vertical displacement of the suspension. The spring constant and damping coefficient dictate the stiffness and damping characteristics of the suspension system, influencing its ability to absorb shocks and vibrations. On the other hand, tire characteristics play a vital role in determining tire grip and traction against the road surface.

The main components of this study, as illustrated in the research scheme in Fig.

4a, are fundamental to successfully implementing the experimental setup, facilitating data collection and analysis to achieve the study's objectives. The key components include Software LabVIEW, Arduino Uno, Accelerometer MPU6050, and Suspension Test Equipment. To begin with, the data retrieval process is executed by utilizing the Software LabVIEW (1). Acting as the central hub for data acquisition and analysis, the LabVIEW software, running on a laptop, allows researchers to effectively monitor and record various parameters related to the suspension system's performance during testing.

The Arduino Uno microcontroller (2) is a critical intermediary between the LabVIEW software and the experimental setup. It enables seamless communication and control over the Suspension Test Equipment, providing real-time data acquisition and system manipulation capabilities. The Accelerometer MPU6050 (3) is a pivotal sensor that captures and measures the vibrations occurring within the suspension system. Mounted on the Shock Absorber part of the Suspension Test Equipment, the MPU6050 continuously records vibration data, providing valuable insights into the suspension system's response to dynamic conditions. The resulting vibration data is then transformed into a Fast Fourier Transform (FFT) graph (4). This graph presents a comprehensive frequency domain representation of the vibrations, aiding researchers in understanding the suspension system's behavior and identifying potential areas for optimization and improvement.

The Prototype of the Suspension Test Equipment, as depicted in Fig. 4b, is a vital aspect of this research, offering a tangible and physical representation of the apparatus used in the experimental setup. This prototype is a valuable tool that allows researchers to conduct thorough assessments of the Suspension Test Equipment's physical characteristics and functionality, ensuring its suitability and accuracy for conducting the experiments.



(a)

(b)

Fig. 4. (a) Research Scheme (b) Experimental Test Equipment

Fig. 5 presents a crucial aspect of this research, showcasing the creation of the vibration program using the student edition version of LabVIEW 2019 software [18]. This program is the backbone of the data acquisition and analysis process, empowering researchers with the flexibility to tailor and control the entire testing procedure to suit their specific experimental requirements. The vibration program developed in LabVIEW 2019 software provides researchers with a powerful and intuitive platform for designing and executing suspension testing experiments. Its user-friendly interface allows researchers to easily conFig. and customize various parameters, such as vibration frequencies, amplitudes, durations, sampling rate, and data acquisition intervals.

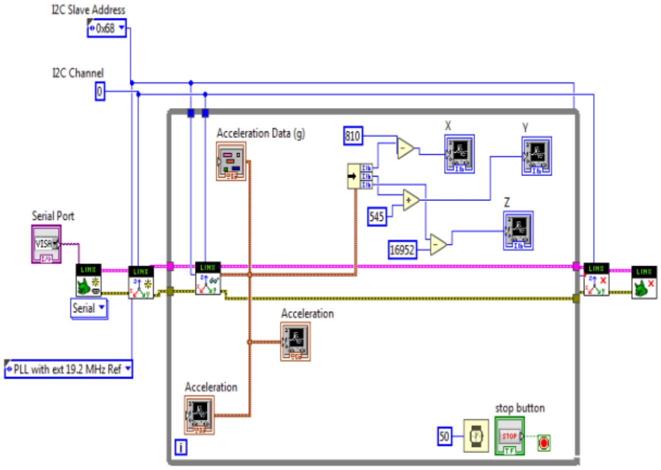


Fig. 5. Vibration program using LabVIEW 2019 version student software

The LabVIEW-based vibration program also offers advanced data analysis tools, allowing researchers to comprehensively process and interpret the collected vibration data. Researchers can perform various analyses, such as Fast Fourier Transform (FFT) analysis, time-domain analysis, and statistical analysis, to gain deeper insights into the suspension system's behavior and response to different vibration inputs. Furthermore, the program's data logging capabilities facilitate storing and retrieving large volumes of experimental data. This logging feature ensures that researchers have access to a comprehensive dataset for subsequent analysis, cross-referencing, and comparison, providing a solid foundation for drawing meaningful conclusions and making data-driven decisions.

4. 3. Taguchi method and analysis of variance

According to [10], the Taguchi method offers various advantages. One advantage is that accommodating multiple factors and quantities enables more efficient experimental design. Additionally, it allows for developing a process that consistently produces robust products, even in the presence of uncontrollable factors. Furthermore, it provides insights into the impact of different factors and the optimal values of control factors.

In this case, L represents the total number of possible combinations between the number of experiments (a), the number of levels (b), and the number of variables (c). For what is known as multiple-factor trials, the S/N ratio was created using the Taguchi Method. Researchers may always choose the highest-level factor value to maximize the quality attributes of the experiment because of the way the S/N ratio is defined. The signal-to-noise ratio (S/N ratio) is used to lessen noise's impact on quality metrics. The outcomes of quality-related procedures are quality attributes. The lower the S/N ratio employed, the better it was for this investigation. The higher performance, the lower the S/N ratio [19].

Analysis of Variance (ANOVA) is a valuable tool in the Taguchi method as it allows for the statistical analysis and interpretation of experimental data. The data type that can be analyzed is measurement results, which can be analyzed using Analysis of Variance for Variable Data. The confidence interval (CI) represents a range of values within which the true average value is expected to fall with a certain confidence level. It is determined by calculating the maximum and minimum values encompassing the desired confidence percentage. The confidence interval for the predicted mean is calculated using the formula provided in reference [20].

Data processing in this study was conducted using Taguchi's experimental design as the primary tool, continuing until the experiments yielded confirmatory results to identify the factors that significantly affected the suspension system's performance. The Taguchi method is a powerful statistical technique that enables researchers to efficiently explore a wide range of factors and their interactions, facilitating the identification of the optimal level settings for improved suspension behavior. Through the Taguchi method, researchers could systematically assess the impact of various factors on the suspension system's response to vibration inputs.

These factors could include suspension geometry parameters, spring rates, damping coefficients, tire pressure, and other relevant variables influencing ride comfort and handling characteristics.

Table 1. Determination of factors and Number of Level Values

No	Control factors	Unit	Level		
			1	2	3
1	Mount height (A)	Cm	5	10	15
2	Tire pressure (B)	Psi	28	30	32
3	Passenger load (C)	Kg	56	84	112
4	Dynamic load (D)	Kg	71	141	212

Table 1 provides a clear overview of the determined level settings for each factor under investigation. This table outlines the specific values or ranges chosen for the influential factors in the suspension system. These level settings represent the configuration points at which the experiments were conducted, allowing researchers to assess how variations in each factor affect the suspension system's response to vibrations. Combining the Taguchi method and the data presented in Table 1 provides valuable insights for suspension system optimization. By understanding which factors significantly influence the system's behavior and the optimal level settings for these factors, researchers can make informed decisions when refining the suspension design to achieve the desired performance objectives.

5. Results of Experimental Design on Suspension Test Equipment

5. 1. Research Design Results

The research design employed in this study was an orthogonal matrix L9 (34) with three replications, ensuring a well-structured and efficient experimental setup. The use of an orthogonal matrix allowed for the systematic variation of factors and levels, reducing potential bias and facilitating a comprehensive investigation of the suspension system's response to different conditions. The researchers employed a data retrieval process based on amplitude values to gather vibration data, a critical aspect of understanding the system's dynamic behavior. The use of FFT graphs [21] facilitated the analysis of frequency components present in the vibration data, providing a detailed view of the system's responses across different frequencies.

Table 2 presents the collected measurement results, providing a comprehensive record of the experimental outcomes. This table likely includes the recorded vibration amplitudes corresponding to each factor level combination and replication. The data retrieved from the measurements offers valuable insights into the suspension system's performance under various experimental conditions.

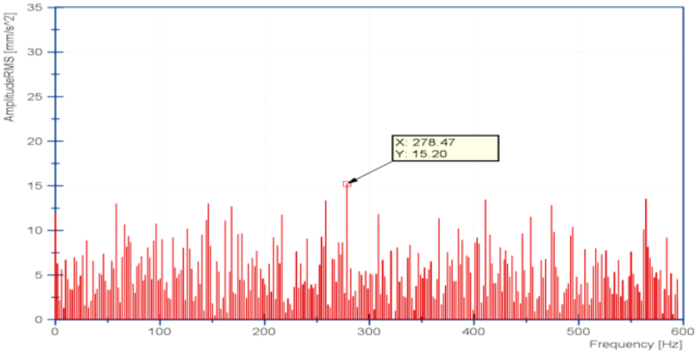
Table 2. Data retrieval of measurement results

Eks	Factor				Suspension Vibration Rating RMS FFT (mm/s^2)			
	A	B	C	D	I	II	III	Mean
1	5	28	56	71	15.20	14.79	15.82	15.27

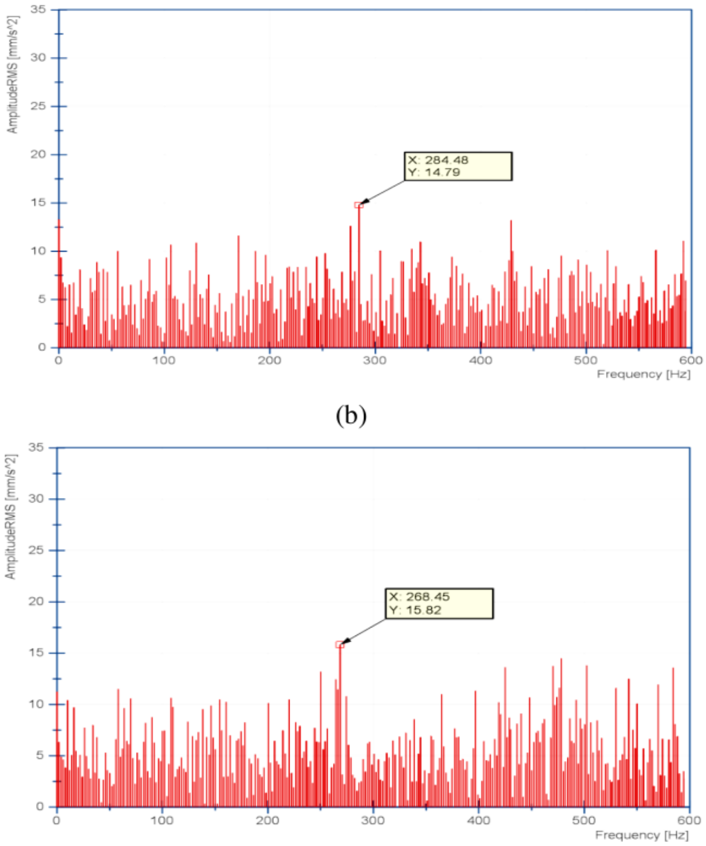
2	5	30	84	114	25.94	25.44	26.44	25.94
3	5	32	112	212	30.21	30.31	29.33	29.95
4	10	28	84	212	37.67	36.96	38.15	37.59
5	10	30	112	71	21.55	23.94	24.41	23.30
6	10	32	56	114	33.76	34.41	34.69	34.28
7	15	28	112	114	43.96	44.16	42.89	43.67
8	15	30	56	212	58.22	58.48	60.53	59.07
9	15	32	84	71	29.19	31.90	31.23	30.77

The experimental conditions yielded an average suspension vibration value of 33.31 mm/s². This measured value provides a crucial benchmark for evaluating the performance of the suspension system under specific test conditions. By comparing this average vibration value with other experimental setups or standard references, researchers can assess the effectiveness of the suspension system in dampening vibrations and providing a smooth ride experience. Additionally, it allows for a quantitative comparison of the system's performance against desired targets or industry standards.

The results of retrieving the vibration data from the suspension portion are shown in Fig. 6. The MPU6050 sensor was used to capture the amplitude acceleration data. This data was afterward translated into FFT signals to analyze the frequency components.



(a)



(c)

Fig. 6. Suspension vibration data retrieval in the form of FFT signals. (a) Replication I, (b) Replication II, and (c) Replication III

During Experiment 1, three replications were conducted to assess the amplitude of vibrations in the suspension system. The measured vibration amplitude in the first replication (Fig. 6a) was 15.20 mm/s^2. Subsequently, in the second replication (Fig. 6b), the amplitude reduced slightly to 14.79 mm/s^2. The highest vibration amplitude value, 15.82 mm/s^2, was recorded during the third replication (Fig. 6c). These varying results across the repetitions highlight the importance of conducting multiple trials to account for experimental variations and ensure reliable data collection. The slight variations in vibration amplitudes between replications demonstrate the dynamic nature of the suspension system's behavior and its sensitivity to various factors.

5. 2. Optimization using the Taguchi Method and Analysis of Variance

The evaluation of the S/N ratio is an essential component of this study because it enables the analysis of the quality attributes of each response in the suspension test equipment. In this study, the vibration response is evaluated based on the criterion of "the smaller, the better." Lower vibration values are generally preferred and seen as a sign of better performance in the suspension system. The S/N ratio is calculated for each experimental run to evaluate the effectiveness of different combinations. The ratio mentioned here is a numerical measure used to assess the signal-to-noise ratio. In this context, the signal refers to the desired response, which smaller vibration values indicate.

On the other hand, the noise represents the variability or deviation from the desired response. Table 3 displays the vibration values obtained from the suspension test equipment for the second and ninth combinations. The values provided comprehensively analyze the system's behavior by recording vibration responses under specific experimental conditions.

Table 3. Response table for suspension vibration

Level	Mound Heights	Tire Pressure	Passenger Load	Dynamic Load
1	-27.16	-30.33	-29.94	-26.94
2	-29.86	-30.36	-29.85	-30.60
3	-32.67	-30.00	-29.90	-32.15
Delta	-5.50	-0,03	-0.09	-5.22
Rank	1	3	4	2

Fig. 7 illustrates the ideal levels for each component, corresponding to the combinations resulting in the lowest values. It is worth noting that Factor A (Mound height) has been classified as Level 1, while Factor B (Tire pressure) has been designated as Level 3, and Factor C (Passenger load) has been seen to be at Level 2. Ultimately, it has been shown that Factor D (Dynamic load) exhibits the highest level of efficacy at Level 1. Identifying and implementing ideal level combinations play a crucial role in attaining optimal performance results for the suspension system. By selecting the minimum values for each element, researchers can discern the configurations that effectively reduce vibration levels, improve ride comfort, and maximize the overall performance of the suspension system.

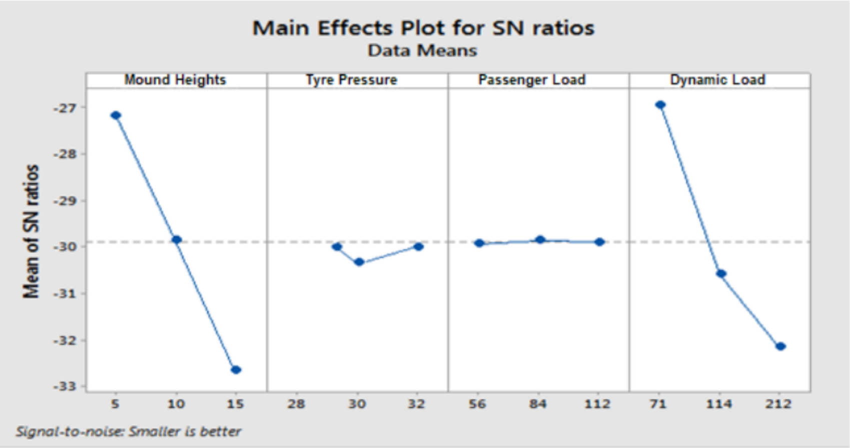


Fig. 7. Main Effects Plot of S/N Ratio on the Vibration value Acceleration RMS Suspension

Fig. 7 provides valuable insights into the optimal values for each parameter. The ideal configuration suggests a mound height of 5 cm, which strikes the right balance between road clearance and stability, ensuring efficient absorption of road irregularities and minimizing vibrations. The recommended tire pressure of 32 Psi contributes to optimal tire performance, enhancing traction and fuel efficiency while maintaining overall ride comfort. The specified passenger load of 84 kg also ensures that the suspension system can comfortably accommodate typical occupant weights, promoting a smooth and enjoyable ride experience. Lastly, the dynamic load of 71 kg, identified as the optimal value, underscores the importance of managing varying loads during different driving conditions. By calibrating the suspension to handle this dynamic load effectively, the vehicle can maintain stability, superior handling, and exceptional ride quality, even on challenging road surfaces.

Analysis of Variance (ANOVA) is a statistical method employed to examine the relationship between control parameters and quality characteristics in the context of the carburizing process of carbon steel under tension. This analysis helps determine the degree of contribution each control parameter has on the quality characteristics of the treated steel. The ANOVA results provide valuable insights into the significance of each control parameter in influencing the outcome of the carburizing process. By quantifying the contribution of each parameter, engineers and researchers can prioritize and optimize the most influential factors to achieve desired material properties.

The statistical analysis using ANOVA regression is conducted within the framework of the Taguchi Method, utilizing an orthogonal array L9 to design and conduct the experiments [17] efficiently. This enables researchers to explore various combinations of control parameters in a systematic and organized manner, ensuring comprehensive coverage of the parameter space. During the ANOVA regression analysis, if the obtained p-value is less than 0.05, it indicates a statistically significant relationship between the control parameters and the quality characteristics of the carburized carbon steel [9, 22]. In such cases, the ANOVA regression results are considered valid and reliable, offering valuable information on the impact of the control parameters on the carburizing process. The calculation results of the ANOVA S/N Ratio are presented in Table 5, providing a comprehensive summary of the statistical outcomes. These results offer a clear understanding of the relative contributions of each control parameter to the surface hardening characteristics of the carbon steel under tension.

Table 5. Analysis of variance analysis for suspension vibration

Source	DF	Sum of square	Mean of square	F-value	p-value	Persentage contribution
Mound Height	1	45.4527	45.4527	19.94	0.011	56.096
Tire Pressure	1	0.6761	0.6761	0.30	0.615	0.834

Passenger weight	1	0.0024	0.0024	0.00	0.976	0.003
Dynamic Load	1	34.8965	34.8965	15.31	0.017	43.067
Error	4	9.1168	2.2792			
Total	8	90.1445				

This study used the significance of the control parameters according to the confidence level of 95% and the p-value of 0.05. The calculated F value (F-Test) is the ratio mean square error against residues and is used to determine the significance of control factors. The F-test result calculated from the control factor is F (0.05) = 7.70. Based on the results of ANOVA calculations for the mean value and the value of the S/N ratio. Based on the contribution rate of the result, F count ≥ F table is factor A (Mound Height) and factor D (Dynamic load) influencing factors, while factor B and Factor C are factors that have no effect or are not significant.

The study's findings revealed that the parameter with the most significant contribution to suspension vibration is mound height, accounting for an impressive 56% of the overall impact. Mound height is crucial in determining the suspension system's behavior, directly affecting the vehicle's ability to absorb road irregularities and provide a smooth ride. Following closely behind, the dynamic load exerts a notable influence on suspension vibration, contributing approximately 43% to the overall effect. The dynamic load refers to the varying weight and forces experienced by the suspension system as the vehicle travels over different road conditions. Managing the dynamic load is essential for maintaining vehicle stability and ride comfort.

In contrast, the tire pressure's impact on suspension vibration was relatively negligible, contributing less than 0.1%. While tire pressure is vital for optimal tire performance and fuel efficiency, its influence on suspension vibration in this study appears minimal. Similarly, the passenger weight's effect on suspension vibration was even less significant, contributing less than 0.01%. While passenger weight does affect the overall load on the suspension system, its contribution to suspension vibration is comparatively minor in this specific context.

6. Discussion of The Result Optimization of Suspension Testing Equipment Using the Taguchi Method and Analysis of Variance

The vibration amplitude was 15.20 mm/s^2 on the first try at repeating Experiment 1 (Fig. 6a). This number shows the movement or oscillation experienced by the vehicle's suspension due to external forces acting on the car while it is in motion. The initial replication's recorded amplitude is useful information on the vibration level experienced. The vibration amplitude was measured to be 14.79 mm/s^2 in Replication 2 of Experiment 1, as shown in Fig. 6b. Compared to the original, this number suggests that the amplitude of the vibrations is somewhat reduced. Differences in amplitude values across replicates provide evidence for the potential effect of random variables or noise on experimental outcomes.

The vibration amplitude value of 15.82 mm/s^2, which is the highest recorded, was observed in the third replication of Experiment 1 (Fig. 6c). The value provided indicates the highest vibrations recorded during this replication. Based on the findings of the third replication, it can be inferred that the suspension system exhibited the highest degree of oscillation or vibration. The observed differences in vibration amplitude values across replications highlight the significance of conducting multiple replications in experimental studies. Replication is a valuable practice that allows for the consideration of uncertainties and random factors that could impact the results. It also enables a thorough evaluation of the system's behavior across various conditions, leading to a more comprehensive assessment.

Factor A, which represents the height of the mound, has been determined to be at Level 1. The optimal level for the suspension system's performance is at this level. This suggests that a lower mound height is beneficial in reducing vibration levels and enhancing ride comfort. The user states that Factor B, which represents tire pressure, is classified as Level 3. The data implies a correlation between higher tire pressure and better suspension performance. This correlation could potentially lead to improved handling and stability of the vehicle while driving [23, 24].

The variable C represents the passenger load and is observed at Level 2. The passenger load at this level is chosen to minimize vibrations and improve comfort for vehicle occupants. Factor D, which represents dynamic load, demonstrates the highest level of effectiveness at Level 1. The data suggest that a decrease in dynamic load is the most efficient approach for minimizing vibration levels and optimizing the performance of the suspension system.

Identifying and implementing ideal-level combinations is critical in achieving optimal results for the suspension system. Researchers can analyze the data by choosing the minimum values for each element. This allows them to determine which configurations are most effective in reducing vibration and enhancing ride comfort. Understanding this information enables the precise adjustment of the suspension system, resulting in an elevated driving experience, increased vehicle stability, and improved overall performance.

The analysis revealed that the height of the mound had the most significant influence on suspension vibration, accounting for 56% of the total impact. The parameter is referred to is of significant importance in influencing the behavior of the suspension system. It directly impacts the vehicle's ability to navigate road irregularities and effectively deliver a comfortable ride experience. Lower mound heights have been found to decrease vibrations and enhance ride comfort. On the other hand, higher mound heights tend to result in a bumpier ride experience. The dynamic load was observed to have a significant impact, accounting for approximately 43% of the total effect on suspension vibration. The dynamic load refers to the fluctuating weight and forces the suspension system undergoes when the vehicle encounters diverse road conditions. Effectively managing the dynamic load is essential for maintaining optimal vehicle stability and ensuring a smooth and comfortable driving experience.

The effect of tire pressure on suspension vibration was minimal, accounting for less than 0.1% of the overall impact. In this study, it is observed that while tire pressure is vital for achieving optimal tire performance and fuel efficiency, its implications for suspension vibration seem relatively insignificant. The data indicate that even slight changes in tire pressure have negligible impacts on suspension performance, at least based on the tested range. The impact of passenger weight on suspension vibration was minimal, accounting for less than 0.01% of the overall effect. The result of passenger weight on the suspension system's load is acknowledged, but its role in causing suspension vibration is considered relatively minor. Suspension performance is influenced significantly by factors like mound height and dynamic load.

The research is limited in terms of its scope. The research appears to have primarily concentrated on enhancing the suspension test equipment by applying the Taguchi method. However, the study may have overlooked the wider perspective of the complete vehicle suspension system. Although optimizing test equipment is important for conducting controlled experiments, it may not necessarily result in direct improvements in vehicle suspension performance in real-world scenarios. One potential limitation of the Taguchi method is its applicability to all potential variations of suspension systems. The complexity and variability of suspension designs may influence the effectiveness of the Taguchi method as an optimization technique. The study's findings may be limited due to the specific configuration and characteristics of the suspension test equipment. Further validation and adjustments may be necessary to apply these findings to other types of suspension systems.

7. Conclusions

1. The study successfully reached significant milestones in improving the performance of car suspension systems by optimizing the value conditions. The specified circumstances include a mound height of 5 cm, a tire pressure of 32 Psi, a passenger weight of 84 kg, and a dynamic load of 71 kg. These customized settings achieve a harmonious equilibrium by effectively absorbing road disturbances, maintaining stability, and reducing vibrations.

2. The analysis of variance results reveals the varying influences of factors considered in the study. Mound height (Factor A) has the most significant impact at 56%, ensuring effective handling of road irregularities and a stable driving experience. Dynamic load (Factor D) is also crucial, contributing 43% to maintaining vehicle stability and ride quality under different conditions. Conversely, factors B (Tire pressure) and C (Passenger weight) have minimal effects, less than 0.1%, on suspension vibration in this specific context, though they remain relevant for overall vehicle performance and safety.

3. Under optimal conditions, there was a decrease in suspension vibration value by 49.65%.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The datasets generated during and, or analyzed during the current study are available from the corresponding author on reasonable request.

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