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NONLINEAR SHOCK ABSORBER DYNAMIC ANALYSIS OF VEHICLE SUSPENSION SYSTEM USING PERFORMANCE INDICES

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Abstract: In this study, the behaviors of nonlinear shock absorber for both rebound and compression configurations are investigated for use on vehicles under a rounded road disturbance. The dynamic behavior of automotive suspension system is analyzed using a quarter-car model taking into account the nonlinearity of compression and rebound phases. Modeling and simulations are performed including the variation of the severity parameter and the performance metrics, such as ride comfort, suspension working space, and road holding, are evaluated using Root Mean Square (RMS) method for both nonlinear asymmetric and symmetric dampers. The performance indices are used to show the efficacy of the asymmetrical shock absorber systems. The comparative analysis exhibits that the asymmetrical shock absorber system with nonlinear characteristics provides a smoother and more progressive dynamic response. The implementation of an asymmetrical configuration demonstrates that it can improve highly the dynamic attenuation of the automotive shock absorber. Since lower acceleration levels are directly associated with improved ride comfort, the adoption of asymmetrical damping systems for vibration and impact attenuation represents a more effective solution for passenger vehicle applications.

Keywords: Performance indices, nonlinear asymmetric damper, nonlinear symmetric damper, shock absorber, suspension system, road disturbance, root mean square

1 Introduction

The suspension systems of vehicles serve as an interface device between the vehicle's wheel and the chassis. Their primary objectives extend beyond ride comfort and road handling, playing an important role in maintaining wheels to ground and improve road holding performance. Ride comfort refers to the level of comfort experienced by passengers within the moving of the vehicle. It depends on the ability of the suspension to isolate the vehicle body from vibration and shocks transmitted from the road to vehicle [1].

Significant advances have been developed in the field of vehicle suspensions. Therefore, many modern designs integrate more advanced technologies to ensure ride comfort, handling, and high safety. However, improvements in both comfort and handling have often been limited by the use of nonlinear damping parameters as in traditional shock absorbers [2-4]. Modern suspension systems have progressed from basic mechanical tool to complicate assemblies incorporating hydraulic, pneumatic, and electrical elements. The demand for enhanced comfort, handling, safety, and energy efficiency in automobiles has rendered suspension design progressively intricate. This review elaborates on the progression of suspension systems and the increasing demand for sophisticated simulation tools in design and development [5].

Nonlinear shock absorbers arise principally due to the damping force, which characterized by hysteresis, asymmetric damping (rebound versus compression phases). This nonlinearity plays a crucial role in determining the dynamic performance of vehicle suspension systems. Also, the nonlinearity is due to the velocity-dependent flow of hydraulic fluid through valves and orifices [6]. For low velocities of the piston, the fluid flow remains relatively smooth,

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resulting in moderate damping forces. As the velocity increases, valve opening limitations, turbulence, and pressure losses cause the damping force to increase nonlinearly. Extensive measurements of various shock absorber configurations focusing on different ride comfort characteristics were carried out and serve as a reference for both parameterization and the definition of required model accuracy [7-8].

Nonlinear asymmetric shock absorbers provide superior ride comfort and road holding compared to symmetric types by offering lower damping during compression and higher damping during rebound. These systems characterizing with non-proportional damping forces, improve stability and reduce seat vibration in vehicles [9-10]. To improve ride comfort, vehicle handling, and workspace, a method was presented based on multi-objective optimization using nonlinear asymmetrical dampers [11]. The suspension system parameters were optimized under sinusoidal road excitation using a model with five degrees of freedom. The obtained results indicated that the optimized viscous coefficients for five-objective optimization lead to 3.58% increase in ride comfort, 0.74% in vehicle handling ability, and 2.20% in workspace changes for the average of forward and rear suspension [12].

The dynamic performance of vehicle suspension systems is very influenced by the damping characteristics of the shock absorber. The behavior of nonlinear symmetric and nonlinear asymmetrical shock absorbers is investigated to evaluate their effects on ride comfort, ride working space, road holding, and overall vehicle stability [13-15]. A nonlinear symmetrical shock absorber exhibits identical damping characteristics during compression and rebound phases. The nonlinear damping force depends on the relative piston velocity with remaining symmetric characteristics. As a result, energy dissipation is uniformly distributed between the two phases of motion. This case, the damper provides predictable dynamic behavior and simplifies suspension design; however, it may represent a compromise between ride comfort and handling performance, particularly under severe road excitations [16].

Dynamic simulations reveal that the asymmetric shock absorber significantly reduces the root mean square (RMS) acceleration of the sprung mass compared to the symmetrical configuration, indicating improved passenger comfort. At the same time, the increased rebound damping enhances vibration attenuation and shortens settling time after disturbances. However, the asymmetric damper may lead to slightly increased suspension deflection, reflecting the trade-off between comfort and suspension travel [17-18]. Asymmetric shock absorbers improve vehicle safety without reducing passenger comfort and are therefore favored in off-road racing. Adjustable rebound damping is commonly used, as increased rebound damping enhances stability while maintaining comfort. Simulation results show that symmetric suspensions may perform better on random road profiles, whereas asymmetric suspensions are more effective when subjected to stepped or abrupt road excitations [19]. Bas du formulaire

Arshad et al. [20] introduces a novel suspension configuration to optimize shock absorber technology with energy regenerative principles. The main objective is to reduce the energy consumption. The study was elaborate in a frequency domain; it identifies the root causes of increased energy consumption and worsened vibration in traditional suspensions. Simulations show that this configuration significantly reduces acceleration by 7.04% and suspension power consumption by 10.47% at 60 km/h. On the other hand, a multi-objective optimization approach using nonlinear asymmetric dampers was proposed to enhance ride comfort, vehicle handling, and suspension workspace while maintaining a cost-effective passive suspension design [21]. A five degree of freedom vehicle model was developed and optimized under sinusoidal road excitation. The results showed average improvements of 3.58% in ride comfort, 0.74 % in vehicle handling, and 2.20 % in suspension workspace for both front and rear suspensions.

Silveira et al. [22] conducted a comparative analysis of symmetrical and asymmetrical suspension systems using both quarter-car and half-car models. Their results showed that asymmetrical suspensions generally provide smoother and more progressive ride performance, leading to improve passenger comfort [23]. Further studies presented the evolution of shock absorber design based on achieved dynamic characteristics, highlighting suspension performance through simulation based parameter tuning. These works emphasized suspension transmissibility and other key assessment criteria as essential tools for evaluating and optimizing suspension behavior [24-25].

In this contribution, both nonlinear symmetric and asymmetric shock absorbers were investigated and their effects on the dynamic response of vehicle undergoing step input from rounded road are analyzed. The modeling and behavior of two shock absorbers are presented and simulate using the quarter car model. The model is described taking into account the symmetric and asymmetric shock absorbers. The introduction of the performance indices used in analyze accompanied with the characteristics of dampers. The analyses include the variation of the severity parameter, asymmetry ratio, and the damping force. The performance indices and the accelerations are used to assess the efficacy of the asymmetrical systems compared to the symmetrical shock absorber.

2 Nonlinear asymmetrical and nonlinear symmetrical shock absorber model

2.1 Quarter car model

Many models are developed for the dynamical analysis of vehicles, varying from simpler models to more sophisticated ones. Figure 1 shows a two-degree-of-freedom shock absorption system. This system comprehends two subsystems connected in series. The base of the system represents the road on which the vehicle travels, whose irregularities cause the forces exciting the entire system. The lower subsystem comprehended by the mass m_u, the spring with elastic constant K_t. The upper subsystem composed by m_s, K_s, and C_s, which represent the proper suspension system and the sprung mass. The behavior of the whole system depends on the contribution of each subsystem, as on the interaction between them.

Tire damping is frequently neglected in models of automobile suspension, because it can provide small magnitude compared to that of shock absorber. The quarter-car model described in Figure 1 provides the principal components required to study and analyze the shock suspension's performance. $x_s(t)$ and $x_u(t)$ are the displacements of the suspended mass and the un-sprung mass, respectively, and $y_r(t)$ represents the road disturbance profile.

According to the classical theory of vibrations, the equations of motion for each subsystem depicted in figure 1, regarding vertical displacements relative to their respective equilibrium positions can be written as follows:

$$m_u\ddot{x}_u + f_{kt} - f_{cs} - f_{ks} + (m_s + m_u)g = 0 \tag{1}$$

$$m_s\ddot{x}_s + f_{ks} + f_{cs} + m_s g = 0 \tag{2}$$

In this study, both springs have a linear behavior, the spring forces $f_{ks}$and f_{kt} are proportional to the relative displacements.

$$f_{ks} = K_s(x_x - x_u) \tag{3}$$

$$f_{kt} = K_t(x_u - y_r(t)) \tag{4}$$

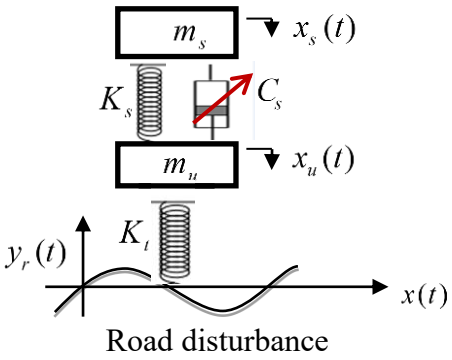


Fig. 1 Quarter-car model

2.2 Nonlinear symmetric and asymmetric shock absorbers

The design of shock absorbers was known many developments during a century from popular shock absorbers [26] to sophistical ones, as: smart, rheological damper, electronically controlled valves, and fluid dampers for modern cars [27].

The nonlinear damper force depends on the sign of the velocity. To perform the commutation of the absorber sign, the viscous damping parameter at rebound phase (C_r) and at compression (C_c), representing the nonlinear characteristic of the absorber, the nonlinear law of the fluid injected in the shock absorber can be expressed by

$$F_D = C_r v_{rel}^{n_r} \qquad v_{rel} < 0 \tag{5}$$

$$F_D = C_c v_{rel}^{n_c} \qquad v_{rel} > 0 \tag{6}$$

n_r and $n_r$are the nonlinear exponents of rebound and compression phases, respectively. For a nonlinear symmetric model, the tuning constants $C_r = C_c$ and exponent factors $n_r = n_c$, and the suspension fluid behaves as nonlinear asymmetric model if $C_r \neq C_c$ (Fig. 2).

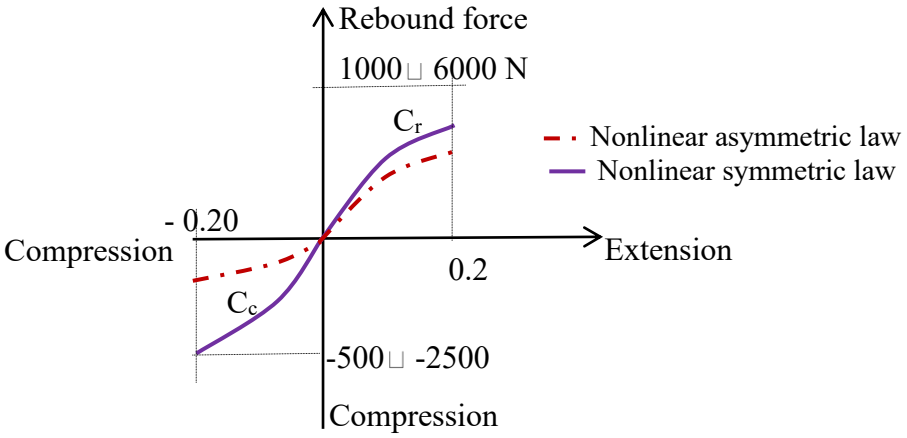


Fig. 2 Nonlinear symmetric and asymmetric dampers

Integrating equations (3-6) into (1) and (2), the accelerations of sprung mass and un-sprung mass become

$$\ddot{x}_s = -\frac{K_s}{m_s}(x_s - x_u) - \frac{\alpha C_c}{m_s} v_{rel}^{n_r} - g \tag{7}$$

$$\ddot{x}_u = -\frac{K_t}{m_u}(x_u - y_r(t)) + \frac{K_s}{m_u}(x_s - x_u) + \frac{C_c}{m_u} v_{rel}^{n_c} - (1 + \frac{m_s}{m_u})g \tag{8}$$

With $\alpha = \frac{C_r}{C_c}$ is the asymmetric ratio and g is the gravitational acceleration.

3 Performance indices

Three indices were used to quantify the performance of the shock absorbers: the ride comfort index (Rci), the ride working space index (Rwsi), and the road holding index (Rhi). Their relationships are formulated below.

$$Rci = \frac{\ddot{x}_s}{Rms(\ddot{x}_s)} \tag{9}$$

$$Rwsi = \frac{x_s - x_u}{Rms(x_s - x_u)} \tag{10}$$

$$Rhi = \frac{F_t - F_{static}}{Rms(F_t - F_{static})} \tag{11}$$

With the Root Mean Square; $Rms(.) = \int_0^T \frac{1}{T}(.)^2\, dt$

4 Road disturbance model

The vehicle travels irregularities of the road which are modeled according to the characteristics to be analyzed. Thus, it is possible to choose an appropriate any model provided in literature. In this work, the rounded step input is selected and described by the following relationship integrating the chassis's frequency and severity parameter [28].

$$y_r(t) = y_{max}[1 - (1 + \gamma\omega_n t)e^{-\gamma\omega_n t}] \tag{12}$$

y_{max} is the maximum amplitude of the road amplitude, γ is the severity parameter, ω_n is the natural frequency of the primary mass, and t is the time. The severity parameter γdescribes how strongly road irregularities affect the vehicle's comfort, stability, and safety. It assumed the values 1 (low impact), 10 (average severe impact), and 30 (more severe impact), used in this study (Fig. 3).

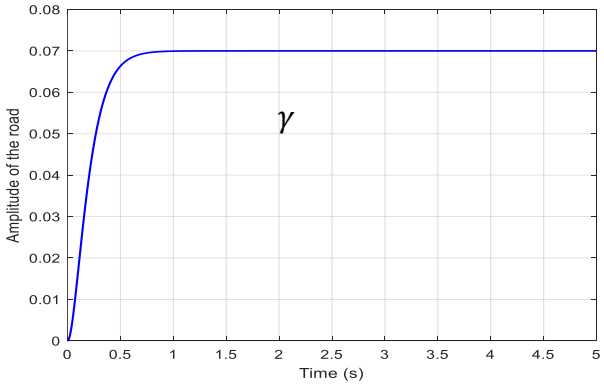


Fig. 3 Height of the road

5 Results and discussions

This section shows a comparison between the dynamic response of a quarter-car suspension system of the two model similar to that described in (Fig. 1) using a nonlinear symmetric and nonlinear asymmetric shock absorber. In this first case, $C_r = C_c = 1000$ N.s/m and $n_c = n_r = 1.40$ with severity parameter$\gamma = 10$, are chosen. The second case is aimed to the same problem with asymmetrical fluid behavior with $C_r = 2000$ N.s/m, $C_c = 1000$ N.s/m, $n_c = 0.80$, and $n_r = 1.40$.

Table 1: Parameters of the vehicle suspension model

Parameter	Unit	Value
Sprung mass	kg	250
Un-sprung mass	kg	40
Stiffness of spring	N. m^{-1}	22000
Stiffness of tire	N. m^{-1}	200000
Gravitational acceleration	$m.s^{-2}$	9.81

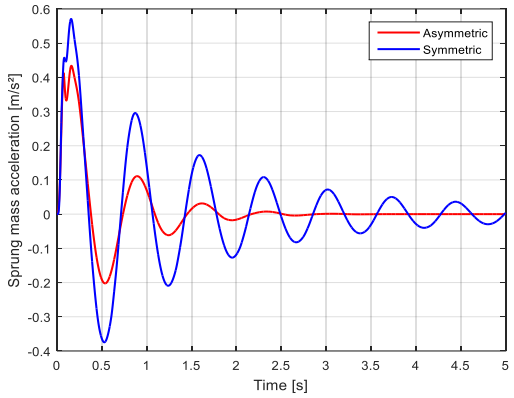
5.1 Deflection of nonlinear symmetric and nonlinear asymmetric shock absorber

Figure 4 shows time histories of the sprung mass acceleration for the symmetrical and asymmetrical systems, using the rounded step input with different road severities: $\gamma = 7.5$ (lower), $\gamma = 15$ (medium), and $\gamma = 30$ (severe). This section contains a comparison between two quarter-car systems similar to the model illustrated in Fig. 1, one in which C_s is symmetrical and another in which C_s is asymmetrical. The time history of the sprung mass acceleration describes the dynamic response of the vehicle to road excitations of varying severity levels. Figure 4 shows that increasing road severity significantly amplifies the sprung mass acceleration, leading to higher vibration levels and reduced ride comfort, precisely during the first times passing from $\gamma = 7.5$to $\gamma = 30$. This effect significantly pronounces using nonlinear symmetric damper while nonlinear asymmetric damping effectively suppresses acceleration peaks and shortens the transient response, particularly under severe road conditions.

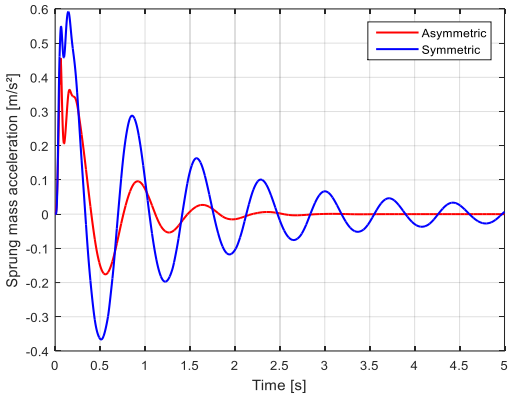
5.2 Performance indices

The time histories of performance indices, Rci, Rwsi, and Rhi, are shown on figure 5. For suspension system study, time histories of performance indices describe the ride comfort, ride working space, and road holding metrics evolve over time under road excitation. These figures reveal that nonlinear asymmetric damping significantly improves suspension behavior by reducing peak responses and accelerating the decay of oscillations. These improvements directly contribute to lower RMS values, demonstrating enhanced ride comfort and vehicle stability. The asymmetric damper improves the shock absorber behavior about 25% compared to symmetric damper. More, the ride comfort is well represented in both asymmetric and symmetric dampers (Fig. 5). Nonlinear symmetric damper presents more oscillations to achieve the steady state.

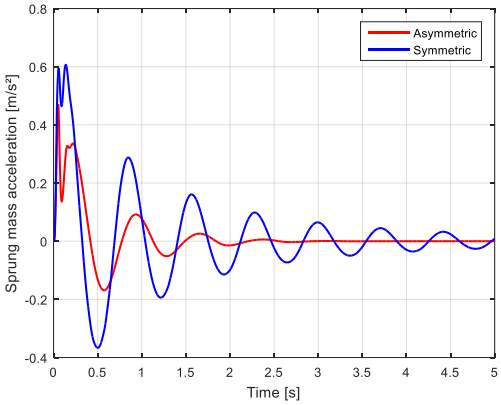
Ride comfort is evaluated using the acceleration of sprung mass with indices RMS. The damping characteristics, whether symmetric or asymmetric, play a crucial role quantifying the oscillations transmitted to the vehicle body. The comparison between symmetric and asymmetric damping reveals that asymmetric dampers provide superior ride comfort for asymmetric damper during the first time. During of the exposure of excitation time, the symmetric damper show a ride comfort compared to asymmetric damper using a moderate severity, $\gamma = 10$, (Fig. 6). This is due to their ability to independently control compression and rebound motions. By employing lower damping during compression, the system effectively isolates road-induced disturbances, while higher rebound damping suppresses oscillations and stabilizes the vehicle body.



(a)

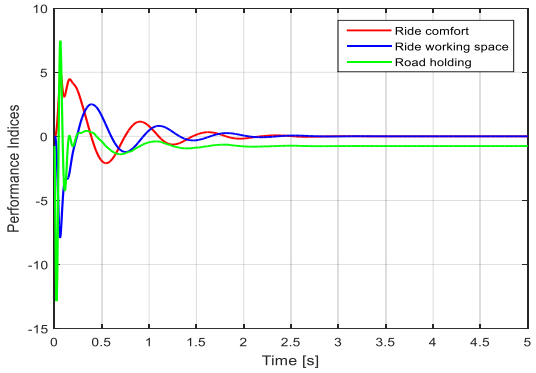


(b)

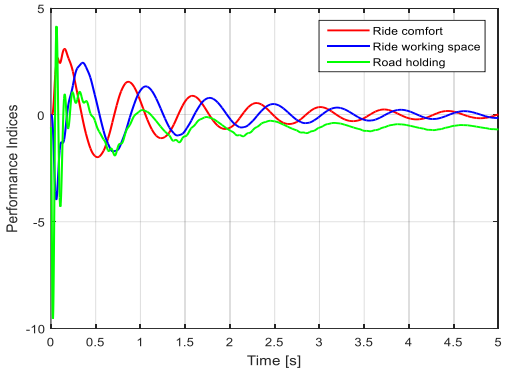


(c)

Fig. 4 Time histories of the sprung mass acceleration for the symmetrical and asymmetrical systems, using the rounded step input with severity $\gamma = 7.5$ (a), $\gamma = 15$ (b), and $\gamma = 30$ (c)



Asymmetric damper



(b) Symmetric damper

Fig. 5 Indices Rci, Rwsi, and Rhi for severity parameter$\gamma = 10$

The nonlinear symmetric and asymmetric systems have an important influence on the ride working space during the first time of road disturbance excitation (Fig. 7). This important effect can be estimated of 100% because suspension deflection is primarily affected by the spring stiffness and road disturbance amplitude, while damping forces act on the velocity and do not provide a restoring mechanism. Consequently, the damping characteristics have minimal effect on suspension travel under passive suspension configurations [29].

The time evolution of suspension working space reveals a strong dependence on damping characteristics. In symmetric damping, both compression and rebound phases lead to large displacement peaks and prolonged oscillations, due to an inefficient utilization of the suspension stroke. In contrast, asymmetric damping optimizes the working space by allowing

compliant motion during compression and enforcing stronger control during rebound. This directional damping strategy reduces excessive accelerates oscillation decay, and improves the overall dynamic stability of the system (Fig. 7). Consequently, asymmetric dampers achieve a more effective balance between ride comfort and suspension travel constraints under dynamic road excitation.

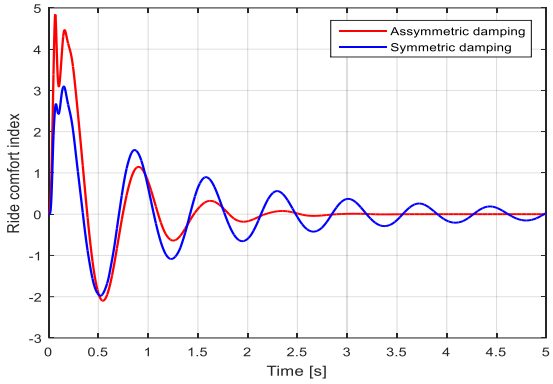


Fig. 6 Ride comfort index for $\gamma = 10$

Figure 8 shows the time history of the road holding index. However, the nonlinear asymmetric system shows superior performance by independently tuning rebound and compression damping. In this case, asymmetric and symmetric damper appear identical behavior excepted for the initial stages of the application of bounded road disturbance.

The asymmetry ratio $\alpha = \frac{C_r}{C_c}$ was varied into consideration to evaluate its influence on the ride comfort provided by both asymmetrical and symmetrical system. Figure 9 shows the results of the ride comfort index variation using the rounded step input (equ. 12). Although the ride comfort, Rdi, is inversely proportional with the asymmetric ratio for asymmetric damper while for symmetric damper, it decreases with the increase of the asymmetric ratio until a characteristic point that is about $\alpha = 2.5$. In the rest, the ride comfort index is proportional according to the asymmetric ratio (Fig. 9). In general, the asymmetric damping enhances ride comfort by reducing acceleration levels, improving vibration isolation, and ensuring faster dissipation of oscillations.

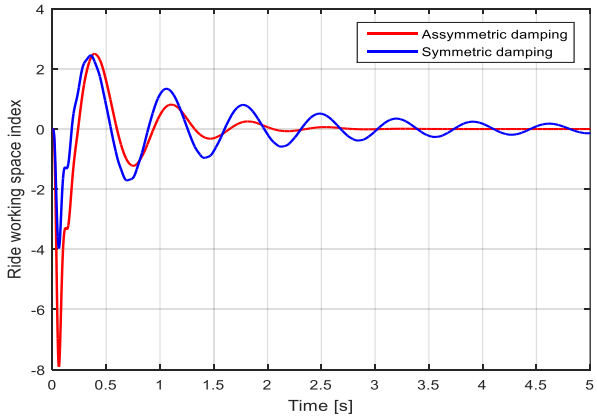


Fig. 7 Ride working space index for $\gamma = 10$

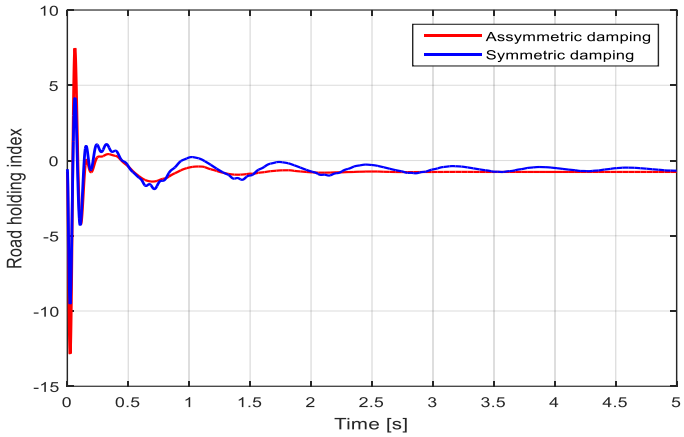


Fig. 8 Road holding index for $\gamma = 10$

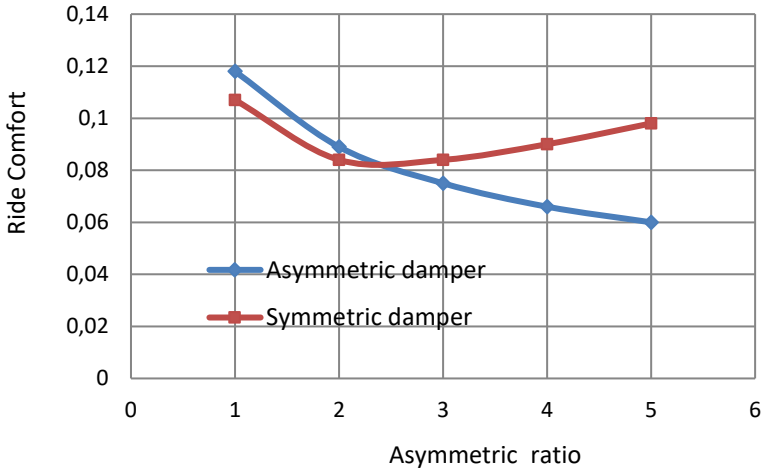
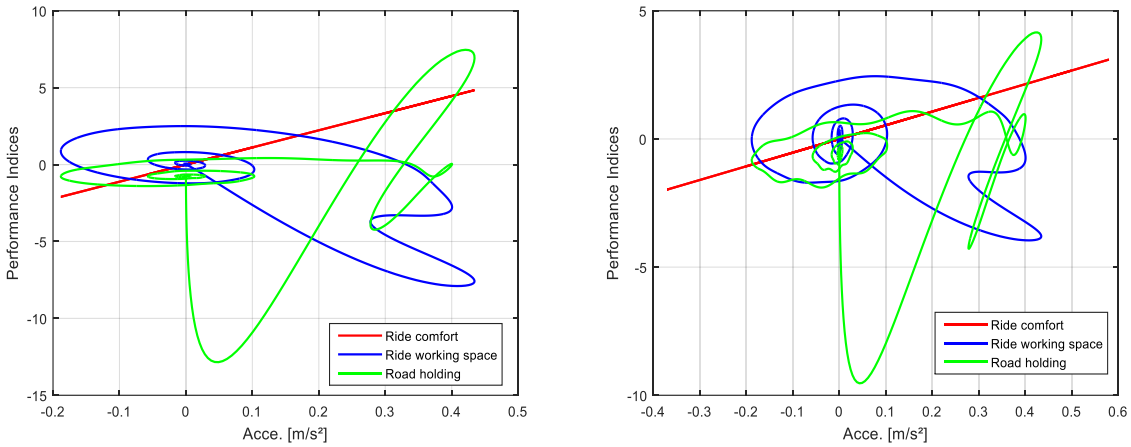


Fig. 9 Ride Comfort versus asymmetric ratio

Figure 10 illustrates the relationship between sprung mass acceleration and the main suspension performance indices, namely ride comfort, ride working space, and road holding, for both symmetric and asymmetric dampers. The obtained trajectories exhibit nonlinear and looped patterns, reflecting the acceleration-dependent asymmetric and symmetric nature of the suspension response under road excitation.

The ride comfort index shows a nearly linear increase with acceleration, indicating a direct dependence with dynamic response. As the acceleration amplitude increases, the comfort level deteriorates progressively due to higher energy transmission to the vehicle body. This behavior confirms that the ride comfort is predominantly governed by the global vibration measures RMS which increase with excitation intensity. Compared to symmetric damping, the smoother trend suggests that nonlinear asymmetric damping reduces sudden acceleration peaks, leading to a more gradual degradation of comfort.

In contrast, the ride working space index demonstrates a distinctly nonlinear response characterized by closed-loop trajectory. These loops indicate a phase lag between suspension deflection and acceleration, which is typical of both systems with symmetric and asymmetric damping properties. For symmetric dampers, the working space tends to be less controlled, with larger rebound excursions and extended oscillations. However, the asymmetric damping configuration improves the utilization of suspension stroke by allowing compliant motion during compression while restricting excessive rebound displacement. As a result, the working space is more efficiently managed, reducing the risk of mechanical limits such as bottoming.



Asymmetric (b) Symmetric

Fig. 10 Performance indices for varying acceleration of the asymmetrical (a) and symmetrical (b) systems using $\gamma = 10$

Road holding has a direct influence on the acceleration response of the suspension system. Poor tire road contact leads to significant fluctuations in acceleration, resulting degraded ride comfort and vehicle stability. The use of asymmetric damping provides an effective compromise by maintaining tire contact through higher rebound damping while limiting acceleration levels during compression. This balance enables simultaneous improvement in ride comfort and handling performance (Fig. 10).

A general observation highlights the inherent compromise between driving comfort, workspace, and road handling (Fig. 10). The reducing acceleration improves ride comfort; it may lead to increased suspension travel. The presence of nonlinear asymmetric damping helps mitigate this trade-off by providing adaptive energy dissipation: low damping during compression improves comfort, while high damping during rebound enhances stability and limits oscillations.

Conclusions

This study investigates the performance indices for both nonlinear asymmetric and symmetric automotive suspension system. The main conclusions of this work are as follows:

- Obtained results show that nonlinear asymmetric damping significantly enhances suspension performance, as evidenced by the reduction in sprung mass acceleration evaluated using RMS criterion.
- The analysis reveals that, for the asymmetric damper, the ride comfort index decreases with increasing asymmetric ratio. In contrast, for the symmetric damper, the ride comfort initially improves with the asymmetric ratio up to an optimal point, beyond which it deteriorates.
- Overall, asymmetric damping improves the ride comfort by reducing acceleration levels, enhancing vibration isolation, and increasing energy dissipation efficiency.
- An increase in road severity leads to a significant rise in sprung mass acceleration, particularly during the initial excitation phase, resulting in higher vibration levels and degraded ride comfort.
- The ride comfort index exhibits a nearly linear relationship with acceleration, whereas the ride working space index shows a nonlinear behavior characterized by closed-loop trajectories, indicating complex suspension dynamics.

- Furthermore, the road holding index plays a critical role in shaping the acceleration response, as poor tire–road contact leads to amplified acceleration peaks and reduced overall system stability.

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