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Parametric Analysis of Vibration Energy Loss in Vehicle Suspension System

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Abstract

Vehicle suspension systems play a crucial role in enhancing passenger comfort during road travel and optimizing vehicle handling. From the perspective of ride comfort, these systems are primarily designed to mitigate the transmission of vibrations induced by road irregularities to the vehicle's passengers. However, an innovative approach involves designing these systems in such a way as to convert this wasted energy into usable forms, such as electricity. This research investigates the energy-harvesting potential of a single-degree-of-freedom vehicle model, evaluating the influence of various system parameters—including mass, stiffness, and damping—under different road classifications as defined by ISO 8608:2016, while also considering varying vehicle speeds. Additionally, a comparative analysis of energy dissipation across vehicles of different sizes is presented. The findings indicate that incorporating energy recovery mechanisms in suspension systems could be particularly advantageous for heavier vehicles especially in harsh road conditions, suggesting a promising avenue for improving energy efficiency in automotive design.

Keywords: regenerative shock absorber; energy harvesting; random vibrations; road irregularities

1. Introduction

One of the primary objectives in the design of vehicle suspension systems is to minimize disturbances and discomfort caused by road roughness and various driving conditions, such as acceleration, braking, and navigating curved roads. This optimization enhances vehicle safety and stability across different driving states and maneuvers. Suspension systems prevent the transmission of vibrations by converting vibratory energy into dissipated heat within shock absorbers. However, this vibrational energy can also serve as a valuable source for energy harvesting, potentially increasing vehicle efficiency and reducing fuel consumption. In recent decades, regenerative shock absorbers have garnered attention for their ability to convert wasted vibration energy into a usable form of electricity [1]. With the growing popularity of hybrid and electric vehicles in the market, the implementation of these systems is likely to become increasingly important for enhancing overall energy efficiency.

For the correct and optimal design, implementation, and evaluation of energy-harvesting systems, it is vital to first determine the potential for wasted energy within the suspension system. Zuo and Zhang [2] demonstrated, using two degrees of freedom (2-DOF) vehicle quarter model, that for road classes B and C at speeds of 40 km/h and 96 km/h, power dissipation ranged between 100 and 400 W. Wei and Taghavifar [3] employed 4-DOF vehicle half model subjected to harmonic excitation with a frequency of 2 Hz and an amplitude of 10 mm, simulating a smooth highway, which resulted in power losses of approximately 200 W and 160 W, respectively. Nakano and Suda [4] calculated the wasted power for a 6-DOF half-truck model to be around 55 W per damper. Taghavifar and Rakheja [5] developed a 7-DOF full-vehicle model to analyze the potential harvestable energy in the suspension system under various road class excitations at different speeds, while also investigating the effects of vehicle system parameters. Additionally, Gill et al. [6] measured dissipated energy for a typical commercial vehicle under various loading conditions, achieving results of 34 W per damper and total power dissipation of 150 W. Most studies indicate that total energy dissipation for commercial light vehicles typically falls within the range of 100 to 400 W.

In this article, the dissipated power within the suspension system of a single degree of freedom (SDOF) vehicle model is studied, focusing on the effects of road excitation and system parameters. The model is analyzed under three different road conditions, classified as A, D, and H, in accordance with the ISO 8608:2016 standard [7]. Additionally, three vehicle speeds—10 m/s, 20 m/s, and 30 m/s—are considered. The investigation addresses how the dynamic characteristics of the system, including mass, spring stiffness, and damping, influence power dissipation. Furthermore, energy waste is compared relative to vehicle size.

This paper is organized as follows: Section 2 outlines the equations governing the dynamics of the SDOF vehicle model, detailing the methodology for calculating its response to road input. Section 3 presents the results of the simulation of these equations, conducted using appropriate software to quantify the amount of wasted energy resulting from variations in vehicle parameters. Finally, the paper concludes with a summary of the findings and recommendations for future research directions.

2. Mathematical Model Development

In this section, SDOF vehicle equations, road input function, and vehicle response to road input are presented.

2.1 Vehicle Single Degree of Freedom Model

A SDOF model of a commercial vehicle is considered for energy loss calculations in this article, as shown in Fig. 1. The dynamic characteristics of the vehicle model are defined by a mass of m = 1200 kg, a spring stiffness of k = 400 kN/m, and a damping ratio of ξ = 0.5. The system is subjected to route irregularities considered as random base excitation while moving with a velocity of V. Using Newton's second law governing equation of motion is written as:

$$m\ddot{x} + c\dot{x} + kx = c\dot{y} + ky \tag{1}$$

in which, x represents the displacement of the vehicle body and y represents the displacement of the suspension system.

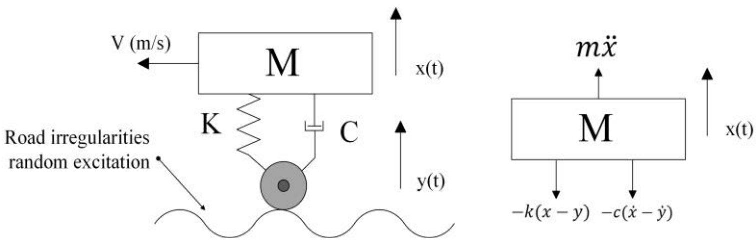


Figure 1 Vehicle SDOF model under road irregularities base excitation.

To determine energy lost in the shock absorber, it is vital to calculate the relative motion response, definde as $z = x - y$, which corresponds to the displacements of the spring and dampers. The relative motion frequency response function is evaluated as [8]:

$$|H(\omega)| = \left|\frac{Z}{Y}\right| = \sqrt{\frac{\omega^4}{(\omega_n^2 - \omega^2)^2 + (2\xi\omega_n\omega)^2}} \tag{2}$$

Frequency response function of system for both relative and body displacement is shown at Fig. 2.

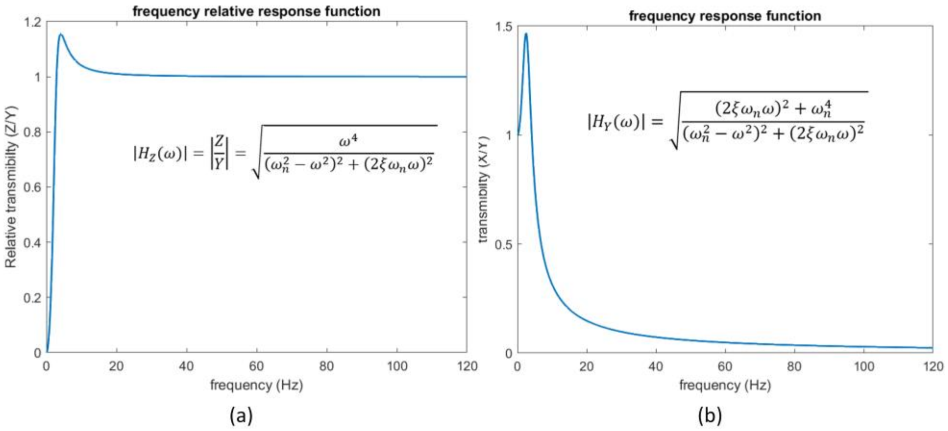


Figure 2 System frequency response function a) relative motion b) body motion.

2.2 Road Irregularities Random Excitation Model

Road surface irregularities and their corresponding random excitation are defined in accordance with the ISO 8608:2016 standard [7]. The road excitation is dependent on both vehicle velocity and road class. The standard categorizes roads into eight classes, ranging from the smoothest (Class A) to the roughest (Class D), with each class characterized by its respective power spectral density (PSD) function [9] pertaining to spatial frequency, as illustrated in Fig. 3. Spatial PSD can be converted to time frequency PSD by introducing vehicle velocity using the following equation:

$$PSD = \frac{G1 \times 2^{-2\log_2 \frac{f}{V}}}{V} \tag{3}$$

in which, V is vehicle velocity, f corresponds to frequency, and $G1$ is the amplitude of road PSD at a frequency of 1 Hz which is available in standard ISO 8608:2016 [7] in tabular format for different road classes.

2.3 System Response and Energy Dissipation

The PSD of the relative displacement response is evaluated using [10]:

$$S_z(f) = |H(f)|^2 S_y(f) \tag{4}$$

where S_y is PSD of road excitation which can be obtain from Eq. (3) and H_f is relative frequency response function.

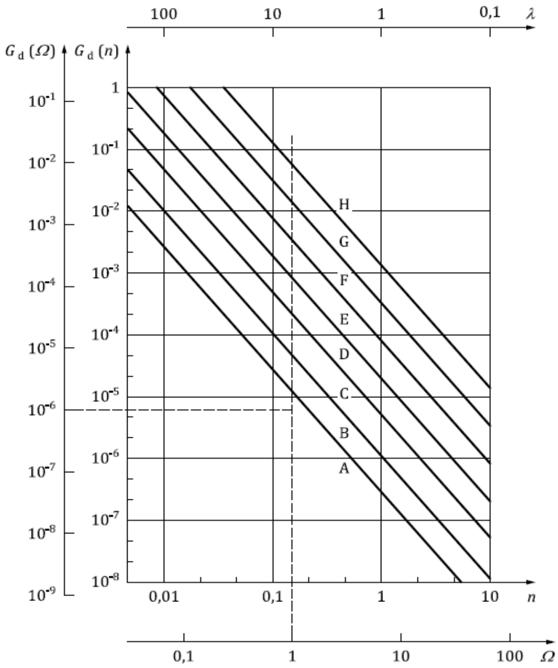


Figure 3 Road power spectral density function, according to ISO 8608:2016 standard [7].

The root mean square (RMS) value of this response represents the area under the response PSD diagram and can be determined by integrating the response PSD function over the relevant frequency range. This relationship can be expressed mathematically as:

$$\sigma_z{}^2 = \int_0^{\infty} S_z(f)df = \int_0^{\infty} |H(f)|^2 S_y(f)df \tag{5}$$

This method provides a quantitative measure of the relative displacement, facilitating the assessment of energy losses in the shock absorber system caused by road surface irregularities. The integration of the response PSD not only yields the RMS value but also encapsulates the effects of varying frequency components on the overall vehicle dynamics.

In the context of a narrowband process associated with the response PSD, the time response exhibits a dominant frequency that corresponds to the peak frequency of the PSD. It is important to note that this peak frequency is closely related to, but not identical to, the system's natural frequency. The RMS value of the energy lost during a complete cycle can be evaluated using the following equation, which requires the integration of the damping force across the cycle duration:

$$W_d = \oint c\dot{z}\, dz = \int_0^{\frac{2\pi}{\omega}} c\dot{z}^2\, dt = \pi c \omega \sigma_z{}^2 \tag{6}$$

Subsequently, the RMS value of the dissipated power is calculated by dividing the energy lost by the cycle period, as outlined in:

$$P = \frac{W_d}{T} = \frac{W_d}{\frac{2\pi}{\omega}} = \frac{1}{2} c\omega^2 Z^2 = 2c\pi^2 f^2 \sigma_z{}^2 \tag{7}$$

In both Eqs. (6) and (7), the angular frequency employed corresponds to the peak frequency identified in the response PSD.

3. Results and Discussion

Based on the equations outlined in Section 2, this section presents an analysis of the energy dissipation in the shock absorber. This analysis is conducted by varying the vehicle parameters to assess their impact on the amount of lost energy.

3.1 System Response and Energy Lost

Employing the relationships established in previous sections, the PSD of the vehicle's response and wasted energy under various road conditions and speeds can be determined. Fig. 4 demonstrates the effects of road conditions on route classes A, D, and H for a vehicle moving at a velocity of 20 m/s. As shown in the figure, the system exhibits a narrow band of response centered around its natural frequency; despite the randomness of the excitation. The response PSD increases as the road condition transitions from class A (smoothest) to class H (roughest), as expected.

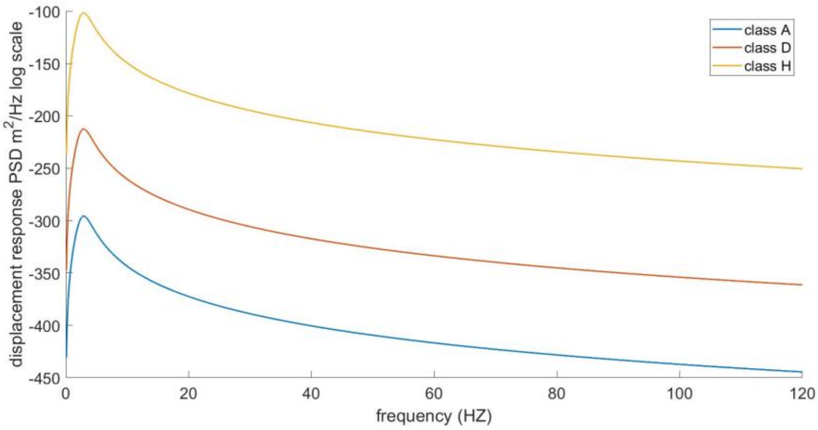


Figure 4 System relative displacement PSD for three road classes at a velocity of 20 m/s

Fig. 5 illustrates the effect of vehicle velocity on performance when operating on road class D, specifically at velocities of 10 m/s, 20 m/s, and 30 m/s. As the speed of the vehicle increases, the response amplitude also rises; however, the impact of velocity on the response is less significant compared to the influence of changes in road conditions.

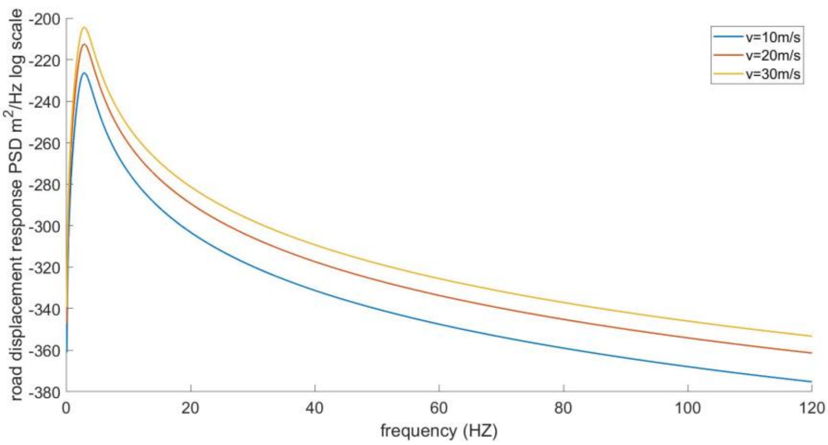


Figure 5 System relative displacement PSD for road class D at three vehicle speeds

Using Eq. (5) and integrating the response PSDs, the RMS value of relative displacement is calculated for various road conditions and velocity states, as reported in Table 1. The results indicate that as vehicle velocity and road roughness increase, the response values also rise. Considering road class D as representative of typical city routes, the displacements calculated in this analysis appear to be reasonable for commercial vehicles.

Table 1 RMS value of the relative displacement response in centimeters at three speeds on three road classes

Road class/speed	10 m/s	20 m/s	30 m/s
Class A	0.092	0.13	0.16
Class D	0.7	1.04	1.28
Class H	11	16.7	20.46

Using the results presented in Table 1 and applying Eq. (7), the dissipated power at the shock absorbers for various road conditions and velocity states is evaluated, as shown in Table 2. The analysis demonstrates that as road irregularities and vehicle speed increase, the power loss in the suspension system also rises. Although the vehicle's SDOF model is a simplified representation, the results are in good agreement with findings from other studies.[1] Notably, for typical road class D and an average speed of 20 m/s encountered during daily driving, approximately 100 W of power is dissipated in the suspension system. This energy loss presents a potential opportunity for power regeneration and improved vehicle efficiency.

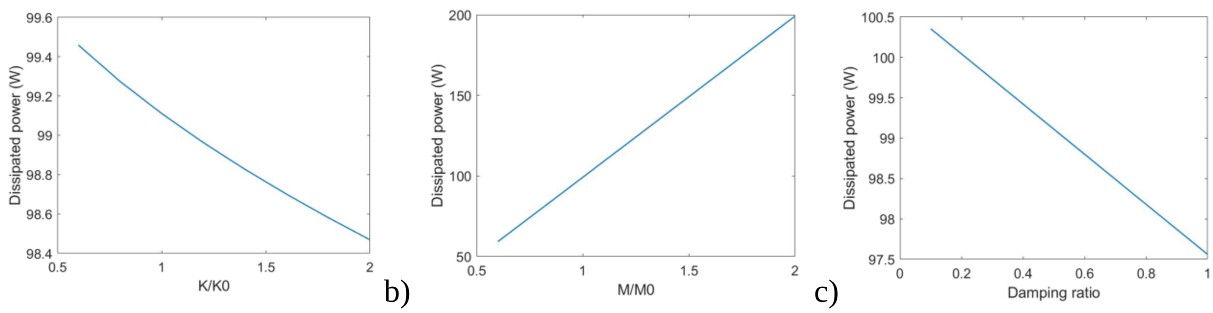
Table 2 Dissipated power in shock absorbers in Watts

Road class/speed	10 m/s	20 m/s	30 m/s
Class A	0.774	1.54	2.32
Class D	49.55	99.11	148.69
Class H	12686	25372	38059

3.2 Dissipated Power Sensitivity to System Characteristics

In addition to vehicle speed and road surface conditions, vehicle dynamic characteristics, including spring stiffness, vehicle mass (whether at full capacity or empty), and shock absorber damping, play significant roles in system response and energy loss. A sensitivity analysis of the parameters: mass, stiffness, and damping ratio is depicted in Fig. 6.

Among these parameters, mass has the most substantial impact on power dissipation, primarily due to its direct effect as demonstrated in Eq. (7). In contrast, stiffness and damping ratio exhibit minimal influence, allowing for adjustments for other purposes without impressing energy regeneration in the shock absorbers.



a) b) c)

Figure 6 Energy dissipation sensitivity to vehicle characteristics a) stiffness b) mass c) damping ratio for road class D with a velocity of 20 m/s

From Eq. (7), it is anticipated that an increase in vehicle size and mass will result in greater vibration energy. Fig. 7 shows the effect of vehicle mass, ranging from 1 ton to 20 tons, on energy dissipation in dampers. The data indicate a linear relationship between vehicle mass and energy lost in the dampers.

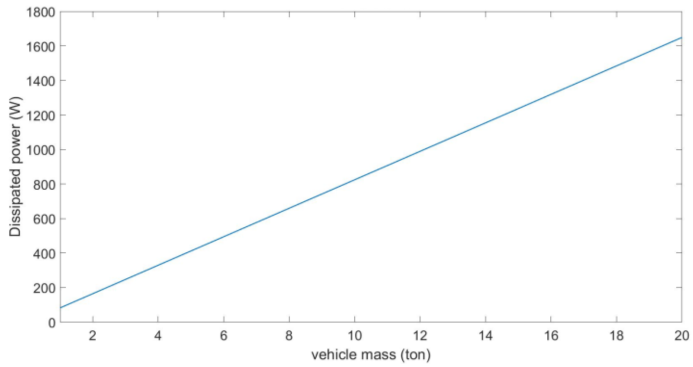


Figure 7 Effect of vehicle size on dissipated energy for road class D and velocity of 20 m/s

4. Conclusion

The vibration energy dissipated by the suspension system presents a promising opportunity for recycling and enhancing vehicle efficiency. In this research, a single-degree-of-freedom model of the vehicle has been investigated under various road speed conditions to analyze the potential energy loss at the shock absorbers. Additionally, the effects of system parameters such as mass, stiffness, and damping have been examined. The results demonstrated good agreement with existing studies, despite the simplicity of the SDOF model employed in this analysis. Under typical road conditions and speeds encountered in daily driving, approximately 100 W of power is wasted in a commercial vehicle. The sensitivity analysis has revealed that mass has a more significant impact on power loss compared to stiffness and damping. Consequently, adjustments to stiffness and damping can be made for other purposes without adversely affecting energy regeneration. Furthermore, energy dissipation is directly related to vehicle mass, indicating that heavier vehicles have greater potential for power regeneration from suspension system vibrations.

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