SIMULATION STUDY OF VIBRATION OF 5-SEAT SEDAN

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ABSTRACT

This paper presents the simulation and evaluation process of the vibration of a 5-seat sedan using a seven-degree-of-freedom model, built and simulated using MATLAB/Simulink software. The model focuses on key components of the vehicle's suspension system, analyzing their impact on the vehicle's vibration behavior during motion. Simulations are conducted at various speed ranges to investigate how the vehicle's vibrations change with speed and operating conditions. After the simulations, the obtained results are used to assess the vibration levels of the 5-seat sedan under different driving conditions. Conducting simulations at different speeds provides a detailed and accurate understanding of the vehicle's response in diverse traffic situations, enhancing the reliability of the research outcomes. The simulation results will then be compared with experimental data collected from real-world tests to verify and adjust the model's input parameters, providing a solid foundation for future studies on vehicle vibration.

Keywords: *Vehicle oscillation, vehicle dynamics, vehicle comfort, vehicle suspension simulation.*

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1. INTRODUCTION

The vibrations of vehicles are a critical factor directly affecting the stability, safety, and comfort of passengers during transportation. Particularly for vehicles like cars, studying and evaluating vibrations helps improve driving performance, enhance the durability of components, and minimize negative impacts from external factors such as terrain and road conditions.

In vehicle vibration studies, many works have employed kinematic simulations and mechanical analyses to assess the interaction between vehicle components and the environment. These studies mainly focus on optimizing suspension systems and improving performance while reducing the impact of vibrations on passengers. For instance, the study by Smith et al. [1] simulated vehicle vibrations on rough roads but only addressed certain road conditions without extending to realistic scenarios such as variations in load or travel speed. Chen and Zhang [2] used a multi-body model to analyze vibrations under autonomous driving conditions, but the assumptions about suspension systems and the environment did not fully reflect real-world traffic scenarios. Kumar et al. [3] simulated the vibrations of the 5-seat sedan, but the lack of experimental data and real-world testing resulted in simulation outcomes that were inaccurate under actual operating conditions.

This paper employs a state-space model combined with kinematic simulation using Matlab-Simulink software to more accurately represent real-world scenarios that the 5-seat sedan may encounter. Additionally, this study considers multiple simultaneous influencing factors, including travel speed and varying road characteristics, allowing for a broader and more realistic evaluation of vehicle vibrations. This approach not only provides reliable results but also offers improvement recommendations for vehicle design and operation.

2. MODEL OF THE SUSPENSION SYSTEM FOR THE 5-SEAT SEDAN

2.1. Analysis of Vehicle Structure and Assumptions

Cars are designed with a symmetric mass distribution across the longitudinal plane. The vehicle body is divided into sprung masses at the front and rear, corresponding to the front and rear axles. It is assumed that in modeling the vehicle's dynamics, the car has a symmetry axis along its longitudinal direction. The car body is considered a flat plate with a concentrated mass at its center of gravity.

For the analysis of vehicle vibrations during straight-line motion, the car body exhibits three degrees of freedom: vertical translational motion along the z-axis, and two angular motions, φ_y (pitch angle - rotation about the horizontal y-axis) and φ_x (roll angle - rotation about the vertical x-axis). The axles (front and rear) are unsprung masses modeled as point masses with m_1, m_2, m_3, m_4, located at their respective centers of gravity.

Each wheel has one degree of freedom, represented by vertical translational motion (ξ_1, ξ_2, ξ_3, ξ_4). The car body is connected to the wheels through a suspension system characterized by stiffness coefficients C_i and damping coefficients K_i. Tires are represented by linear elastic and damping elements with stiffness coefficients C_{R1}, C_{L2}, C_{L3}, C_{R4} and damping coefficients K_{R1}, K_{L2}, K_{L3}, K_{R4}.

The wheels interact with the road surface through stiffness coefficients C_{Li}, C_{Ri} and minimal damping coefficients K_{Ri}, K_{Li}, which are approximately zero. The model neglects tire drags, aerodynamic effects, and assumes point contact between the tires and the road.

Sources of vehicle vibrations include vehicle velocity over road irregularities, inertial forces, and natural environmental conditions. When a vehicle moves over uneven road surfaces at various speeds, vibrations arise in both the unsprung and sprung masses. The velocity of the vehicle as it encounters road irregularities is the primary excitation source for vehicle vibrations [4].

2.2. Vehicle structural model

Based on the structural analysis of the 5-seat sedan combined with the assumptions outlined above, the spatial model for the vehicle is illustrated in Fig. 1.

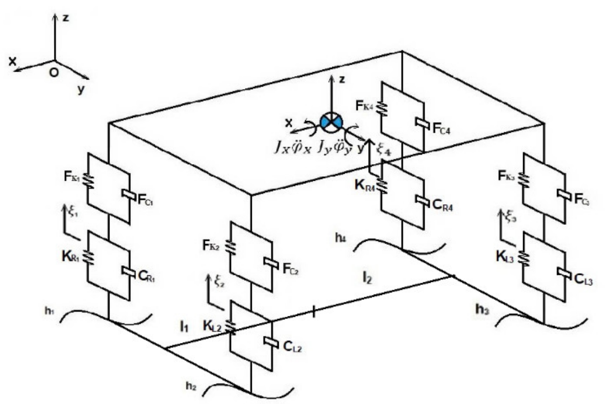

Fig. 1. Model structure of the 5-seat sedan

2.3. Vehicle computational model

By combining the structural model of the vehicle with physical laws, a system of seven mathematical equations describing the vehicle's vibrations has been established. These equations account for the dynamics of the car body, the roll angle of the body, the pitch angle of the body, and the vibrations of the four wheels. The equations are as follows:

$$\begin{aligned} m_1\ddot{\xi}_1 = {} & -\dot{\xi}_1K_1 + \dot{z}K_1 - \dot{\varphi}_x bK_1 \\ & - \dot{\varphi}_y l_1K_1 - \xi_1(C_1 + C_{L1}) + zC_1 \\ & - \varphi_x bC_1 - \varphi_y l_1C_1 + h_1C_{L1} \end{aligned} \quad (1)$$

$$\begin{aligned} m_2\ddot{\xi}_2 = {} & -\dot{\xi}_2K_2 + \dot{z}K_2 + \dot{\varphi}_x bK_2 - \dot{\varphi}_y l_1K_2 \\ & - \xi_2(C_2 + C_{L2}) + zC_2 + \varphi_x bC_2 \\ & - \varphi_y l_1C_2 + h_2C_{L2} \end{aligned} \quad (2)$$

$$\begin{aligned} m_3\ddot{\xi}_3 = {} & -\dot{\xi}_3K_3 + \dot{z}K_3 + \dot{\varphi}_x bK_3 + \dot{\varphi}_y l_2K_3 \\ & - \xi_3(C_3 + C_{L3}) + zC_3 + \varphi_x bC_3 \\ & + \varphi_y l_2C_3 + h_3C_{L3} \end{aligned} \quad (3)$$

$$\begin{aligned} m_4\ddot{\xi}_4 = {} & -\dot{\xi}_4K_4 + \dot{z}K_4 - \dot{\varphi}_x bK_4 + \dot{\varphi}_y l_2K_4 \\ & - \xi_4(C_4 + C_{L4}) + zC_4 - \varphi_x bC_4 \\ & + \varphi_y l_2C_4 + h_4C_{L4} \end{aligned} \quad (4)$$

$$\begin{aligned} m_a\ddot{z} = {} & -\dot{z}.(K_1 + K_2 + K_3 + K_4) + \dot{\xi}_1K_1 \\ & + \dot{\xi}_2K_2 + \dot{\xi}_3K_3 + \dot{\xi}_4K_4 \\ & + \dot{\varphi}_X b(K_1 - K_2 - K_3 + K_4) \\ & + \dot{\varphi}_y(l_1K_1 + l_1K_2 - l_2K_3 - l_2K_4) \\ & - z(C_1 + C_2 + C_3 + C_4) + \xi_1C_1 + \xi_2C_2 \\ & + \xi_3C_3 + \xi_4C_4 + \varphi_X b(C_1 - C_2 - C_3 + C_4) \\ & + \varphi_y(l_1C_1 + l_1C_2 - l_2C_3 - l_2C_4) \end{aligned} \quad (5)$$

$$\begin{aligned} J_x\ddot{\varphi}_x = {} & \dot{z}b(K_1 - K_2 - K_3 + K_4) - \dot{\xi}_1bK_1 + \dot{\xi}_2bK_2 \\ & + \dot{\xi}_3bK_3 - \dot{\xi}_4bK_4 - \dot{\varphi}_x b^2(K_1 + K_2 + K_3 + K_4) \\ & - \dot{\varphi}_y b(l_1K_1 - l_1K_2 + l_2K_3 - l_2K_4) \\ & + zb(C_1 - C_2 - C_3 + C_4) - \xi_1bC_1 \\ & + \xi_2bC_2 + \xi_3bC_3 - \xi_4bC_4 \\ & - \varphi_x b^2(C_1 + C_2 + C_3 + C_4) \\ & - \varphi_y b(l_1C_1 - l_1C_2 + l_2C_3 - l_2C_4) \end{aligned} \quad (6)$$

$$\begin{aligned} J_y\ddot{\varphi}_y = {} & \dot{z}(l_1K_1 + l_1K_2 - l_2K_3 - l_2K_4) - \dot{\xi}_1l_1K_1 \\ & - \dot{\xi}_2l_1K_2 + \dot{\xi}_3l_2K_3 + \dot{\xi}_4l_2K_4 \\ & - \dot{\varphi}_x b(l_1K_1 - l_1K_2 + l_2K_3 - l_2K_4) \\ & - \dot{\varphi}_y(l_1^2K_1 + l_1^2K_2 + l_2^2K_3 + l_2^2K_4) \\ & + z(l_1C_1 + l_1C_2 - l_2C_3 - l_2C_4) - \xi_1l_1C_1 \\ & - \xi_2l_1C_2 + \xi_3l_2C_3 + \xi_4l_2C_4 \\ & - \varphi_x b(l_1C_1 - l_1C_2 + l_2C_3 - l_2C_4) \\ & - \varphi_y(l_1^2C_1 + l_1^2C_2 + l_2^2C_3 + l_2^2C_4) \end{aligned} \quad (7)$$

3. VIBRATION SIMULATION

3.1. Sinusoidal road profile model

The equation for a sinusoidal road profile is:

$$h = A\sin 2\pi v\lambda.tj \quad (8)$$

A: amplitude of road profile, A = 90mm

v: vehicle's velocity

λ: wavelength of road, $\lambda = 2$ (m)

t(j): simulation time corresponding to the distance and velocity at time j, t(j) is assumed to start from 0 to 10(s) with a step of 0.001(s).

The Simulink model diagram for simulating a sinusoidal road profile as show in Fig. 2.

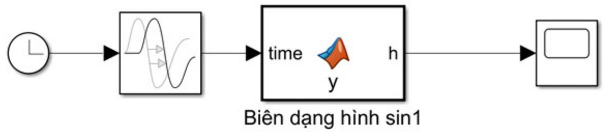

Fig. 2. Sinusoidal road profile simulation

Simulation results of amplitude of the sinusoidal road profile as shown in Fig. 3.

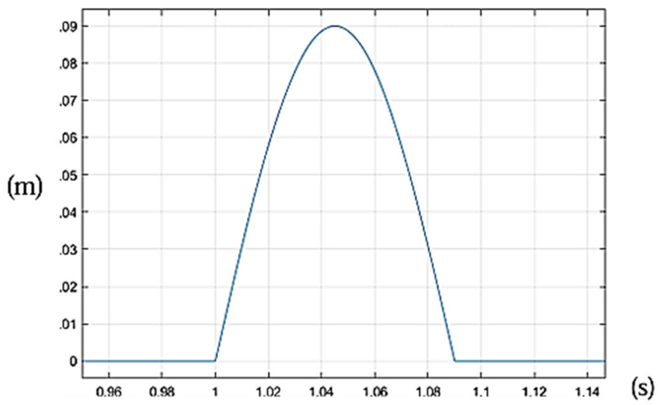

Fig. 3. Amplitude of the sinusoidal road profile

3.2. Vehicle vibration simulation in Matlab - Simulink

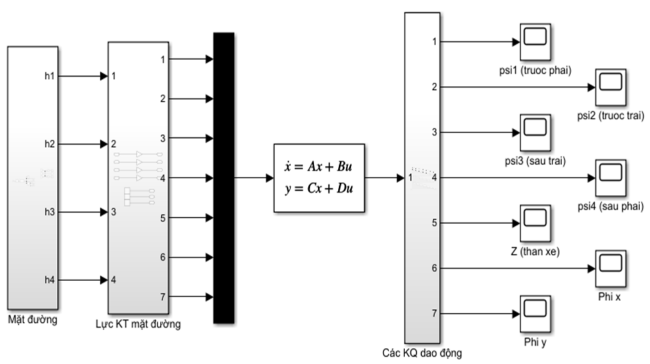

Fig. 4. Simulating vibration of the 5-seat sedan in Simulink

The vehicle model in Simulink can be briefly described as follows: the roadblock generates bump signals representing the road profile. The road excitation force block receives the bump signals from the roadblock and applies excitation forces to the four wheels. Seven input signals are combined using a Mux block into a single signal, which serves as the input to the state equation. The results block receives twenty-one output signals corresponding to the displacement, velocity, and acceleration of the vehicle body and the four wheels. The vibration simulation diagram of the vehicle in Simulink is shown in Fig. 4.

4. RESULTS AND EVALUATION

4.1. Results

The simulation process is performed with the vehicle's uniform moving speeds of 20, 50, 80, 100km/h respectively. The simulation results are shown in Figs. 5, 6, 7, and 8.

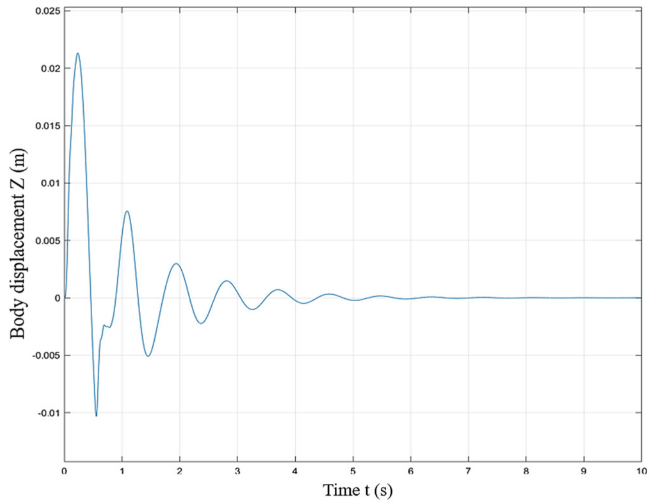

Fig. 5. The displacement of the vehicle body when encountering a sinusoidal bump at a speed of 20km/h

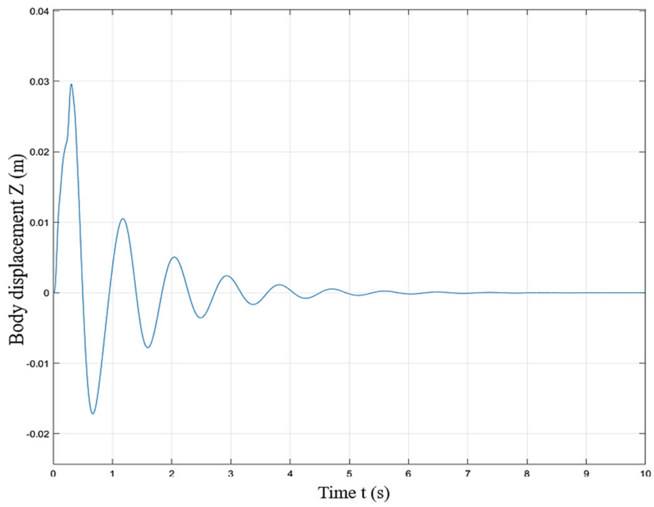

Fig. 6. The displacement of the vehicle body when encountering a sinusoidal bump at a speed of 50km/h

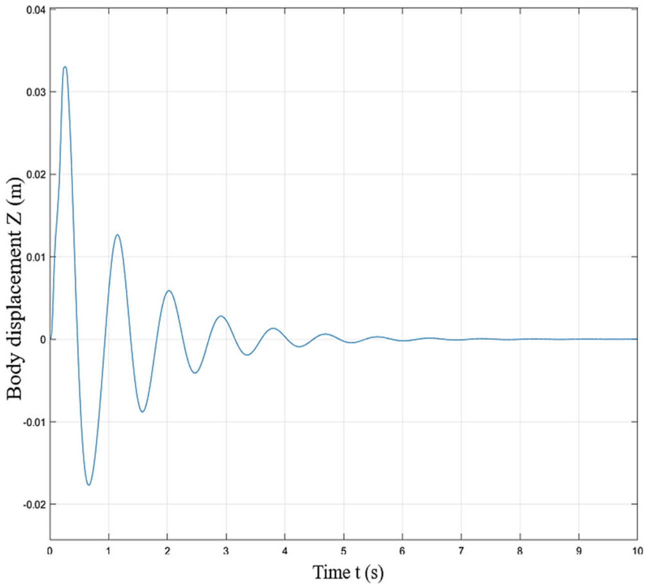

Fig. 7. The displacement of the vehicle body when encountering a sinusoidal bump at a speed of 80km/h

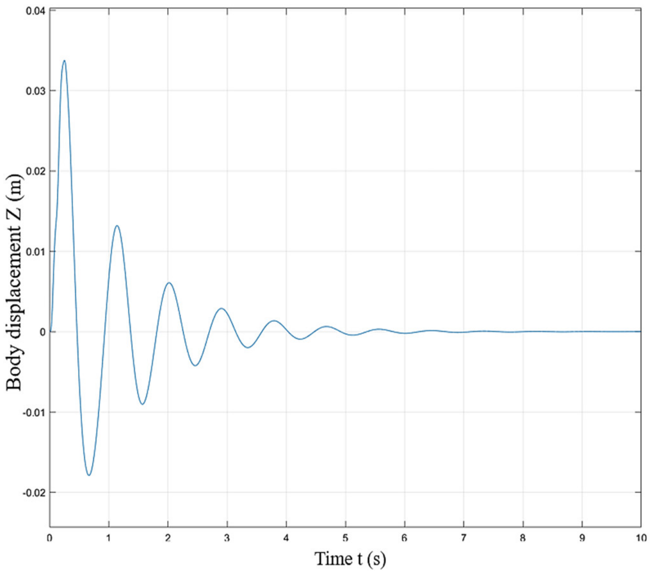

Fig. 8. The displacement of the vehicle body when encountering a sinusoidal bump at a speed of 100km/h

From the displacement results of the vehicle body when encountering a sinusoidal road profile at speeds of 20, 50, 80, and 100km/h, it is observed that the average time for the suspension system to dampen the vibrations is approximately 4 seconds. When the vehicle begins to traverse the sinusoidal bump, the amplitude of the vehicle body vibration increases from 0.022m at 20km/h to 0.035m at 100km/h. However, the time required to dampen the vibrations and stabilize the vehicle remains relatively unchanged at around 4 seconds. Thus, it is evident that driving over sinusoidal bumps at a speed of approximately 20km/h ensures stable operation of the suspension system. At this speed, the vibration amplitude of the vehicle body is smaller compared to higher speeds, allowing the suspension system to dampen the vibrations more effectively. Driving at higher speeds forces the suspension system to suppress vibrations more abruptly, reducing the longevity of suspension components.

Regarding the acceleration values at the contact points of the vehicle body, they fluctuate during the initial phase when the sinusoidal road profile impacts the vehicle. After this initial phase, the acceleration values return to a steady, harmonic state. Lower-level headings remain unnumbered; they are formatted as run-in headings.

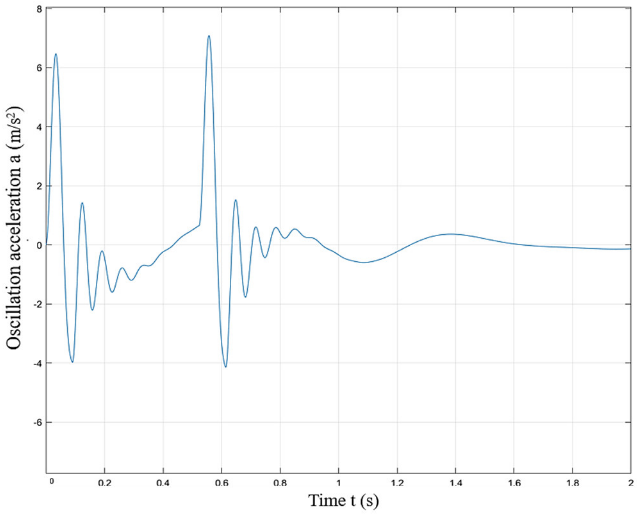

Fig. 9. The acceleration of the vehicle body when the vehicle passes over a sinusoidal road bump at a speed of 20km/h

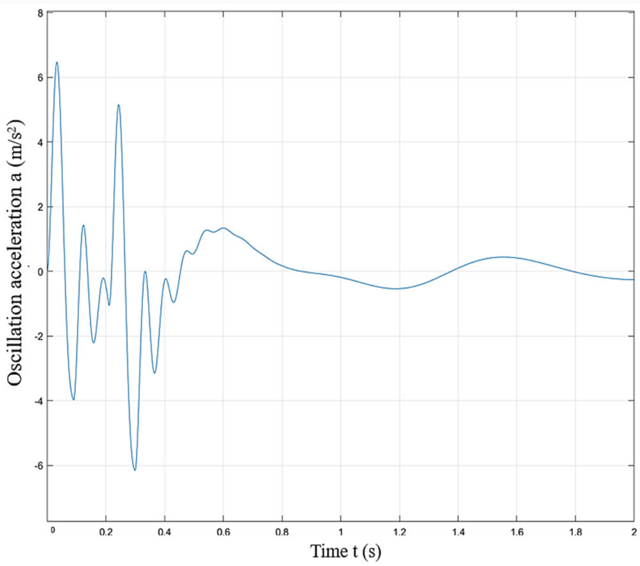

Fig. 10. The acceleration of the vehicle body when the vehicle passes over a sinusoidal road bump at a speed of 50km/h

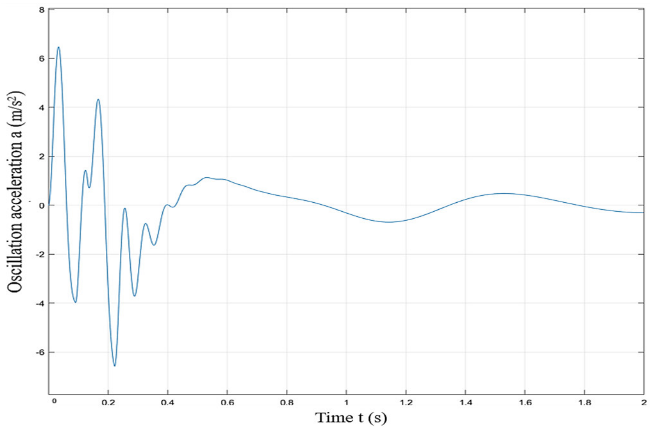

Fig. 11. The acceleration of the vehicle body when the vehicle passes over a sinusoidal road bump at a speed of 80km/h

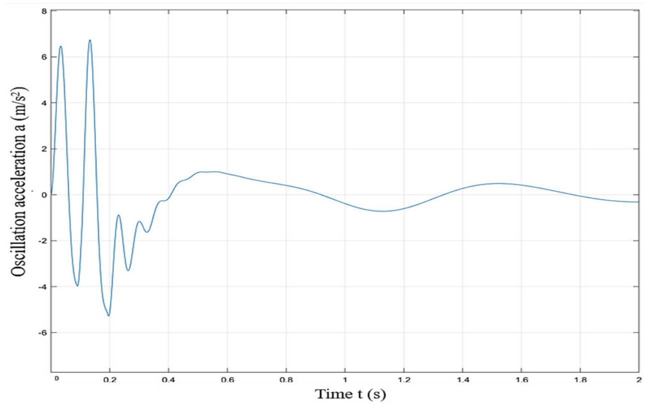

Fig. 12.The acceleration of the vehicle body when the vehicle passes over a sinusoidal road bump at a speed of 100km/h

4.2. Evaluation

4.2.1. Criteria for evaluating the impact of vibrations.

To evaluate ride comfort, the paper employs the root mean square (R.M.S) acceleration criterion ($a_{r.m.s}$). According to the ISO-2631 standard, the impact of vibrations on vehicle occupants is assessed based on the R.M.S value of the acceleration, as given by Equation (9) [5].

$$a_{r.m.s} = \left(\frac{1}{T}\int_0^T a_w^2(t)dt\right)^{\frac{1}{2}} \quad (9)$$

Where $a_w(t)$ (m/s^2) is the time-dependent vibration acceleration, T is the measurement duration (in seconds).

Table 1. The level of human vibration discomfort based on the RMS value

$a_{r.m.s}$ (m/s^2)	Comfort Level
Less than 0.315	Not uncomfortable
From 0.315 to 0.63	Slightly uncomfortable
From 0.5 to 1.0	Moderately uncomfortable
From 0.8 to 1.6	Uncomfortable
From 1.25 to 2.5	Very uncomfortable
More than 2.0	Extremely uncomfortable

The vibration acceleration values required to ensure human comfort must be less than 0.315m/s^2, as shown in Table 1.

4.2.2. Evaluation

The simulation at four different speeds shows that when the two wheels encounter a bump, the average acceleration of the vehicle body exceeds 2m/s^2, causing extreme discomfort and indicating very low ride comfort. At a speed of 20km/h, this low comfort level lasts for 0.1 seconds for both the front and rear wheels as they pass over the bump. During the next 0.1 seconds, the acceleration decreases from 1.3m/s^2 to below 0.315m/s^2, at which point the vehicle returns to a comfortable state. For higher speed ranges, the duration of discomfort increases proportionally with the vehicle's speed. This demonstrates that drivers should move at a slow speed when traversing sinusoidal road bumps to ensure both ride comfort and the safety of the vehicle's systems.

5. CONCLUSION

From the study and simulation of the differential equation systems, the vibration behavior of the 5-seat sedan was analyzed across different speed ranges when encountering sinusoidal road bumps. The optimal speed at which the vehicle's suspension system can most effectively dampen vibrations while ensuring ride comfort during movement was identified. The vibration analysis results for the 5-seat sedan at various speed ranges over sinusoidal single bumps demonstrate that the existing suspension system parameters meet the ride comfort criteria for passenger cars.

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