RESEARCH ON BUILDING A SIMULATION MODEL TO EVALUATE VERTICAL OSCILLATION WHEN USING AIR SUSPENSION SYSTEMS AS A REPLACEMENT FOR LEAF-SPRING SUSPENSION SYSTEMS IN ELECTRIC VEHICLES

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ABSTRACT

This research paper evaluates the vertical oscillation of the vehicle body of electric vehicles using air suspension and leaf spring suspension systems. Simulations were performed with the vehicles moving on a random road surface of type C (ISO 8608:2016) at speeds from 20 to 80 km/h. The findings indicated that air suspension diminished the vertical acceleration of the vehicle body in comparison to leaf spring suspension. The average vertical acceleration decreased by approximately 12–15%, while the maximum acceleration value decreased by up to 21% at higher speeds. The research results indicate that air suspension significantly improves the vertical oscillation of the vehicle body of electric vehicles, especially in simulations of operation at medium and high speeds.

Keywords: *Air suspension system; leaf-spring suspension system; vehicle body vibration; ISO 8608:2016*

1. Introduction

In Vietnam, pneumatic suspension systems are widely used on large passenger cars, some on tourist cars, and double-decker sleeper buses. Pneumatic suspension systems have pneumatic elastic elements and can change stiffness thanks to their ability to withstand the compression of air in the reservoir, thereby changing the stiffness of the suspension system automatically or semi-automatically to suit the car's movement modes [8]. Some popular models used to simulate pneumatic suspension systems include Vampire, Nishimura, Simpac, Cebo, Quaglia and GENSYS [1, 6, 8]. Among them, the GENSYS air spring model describes relatively fully the processes occurring in the air spring [1, 8] and is therefore widely studied, developed and applied by researchers [3, 4, 5].

Domestic studies on pneumatic suspension systems in automobiles mainly focus on evaluating ride comfort, dynamic safety, and dynamic load reduction capabilities. Luong Van Van et al. [1] through experimental models showed that replacing leaf spring suspension with pneumatic suspension on a 1.25-tonne truck helps reduce body oscillation acceleration by 10–30%. Truong Manh Hung [8] and Nguyen Thanh Dong [2] used the GENSYS model to simulate passenger car oscillation, showing that all ride comfort indicators were significantly improved when applying pneumatic suspension systems. Meanwhile, Vu Thanh Niem [6] demonstrated the effectiveness of pneumatic suspension on semi-trailers in reducing dynamic load and increasing operational stability. Other studies such as those by Dang Ngoc Minh Tuan [0], Tran Van Hoang [11], and Nguyen Van Hoang [7] focused on optimising parameters, building oscillation models, and analysing the working characteristics of pneumatic suspension systems. However, most studies still limit model simplification, lack comprehensive experimental verification, and do not thoroughly explore modern control methods.

Many studies have been conducted on mechanical and pneumatic suspension systems, typically focusing on the oscillations of various types of automobiles under specific conditions, primarily large passenger cars, trucks, and specialized vehicles. There are no studies on electric cars manufactured and assembled in Vietnam. Therefore, the study of the application of pneumatic suspension systems on electric cars aims to evaluate the smoothness of the car when traveling on the road, providing comfort for both the driver and passengers. In this study, the criterion for evaluation is the average body acceleration value. According to the ISO 2631 standard, smoothness for the driver considers the combination of acceleration, frequency, and duration of impact. The average body acceleration as an evaluation criterion is determined as follows [5, 12]:

$RMS(\ddot{Z}) = 0,1\, m/s^2$ *A pleasant feeling*

$RMS(\ddot{Z}) = 0,315\, m/s^2$ *Causes fatigue*

$RMS(\ddot{Z}) = 0,63\, m/s^2$ *Causes health problems*

2. CONTENT

2.1. Dynamic model of a four-wheel drive electric vehicle

The structural model of an electric car used to investigate the smoothness of motion is the VinFast VF e34 car with an independent front suspension system and a dependent rear suspension system with 7 generalized coordinates, including:

- Three degrees of freedom that describe the motion of a suspended mass are: Z, φ, β

- Two degrees of freedom describe the motion of the mass not suspended from the front axle: Z_{11} and Z_{12}.

- The two degrees of freedom describing the motion of the mass not suspended from the rear axle are: Z_2, φ_2.

The basic assumptions when building the model are as follows:

- The mass of the vehicle body and axle are distributed symmetrically across the longitudinal plane.

- The vehicle was fully loaded, and all the people inside and the cargo formed a solid mass that contributed to the vehicle's overall weight.

- The suspended mass is considered absolutely rigid, with mass m and moments of inertia along the longitudinal and transverse axes passing through the center of gravity, J_x and J_y respectively. The vehicle body can perform three oscillations: translational oscillations along the vertical direction and angular oscillations along the longitudinal and transverse axes of the vehicle body.

- The unsprung mass is also considered absolutely rigid, with mass m_{11} (front left) and m_{12} (front right) at the front axle; the rear axle has mass m_2 and the mass moment of inertia of the rear axle is J_2. It only oscillates vertically and angularly around an axis through the center of gravity parallel to the direction of the car's movement.

- The positions of the longitudinal and lateral oscillation axes remain constant relative to the center of gravity when the car is in motion.

- The properties of the elastic components, of tires, etc., are linear properties.

- The wheels are always in contact with the road surface during movement. The road surface does not deform, the contact between the wheel and the road is point contact, the wheel has constant stiffness, and the tire's damping coefficient is ignored.

- Ignoring the influence of other sources of vibration within the vehicle, consider road surface unevenness as the only source of vibration.

- Ignore the effects of wheel slippage and friction in the wheel bearings.

- Ignore air resistance for the car.

➢ *Model of vehicle vibration when using a leaf-spring suspension system*

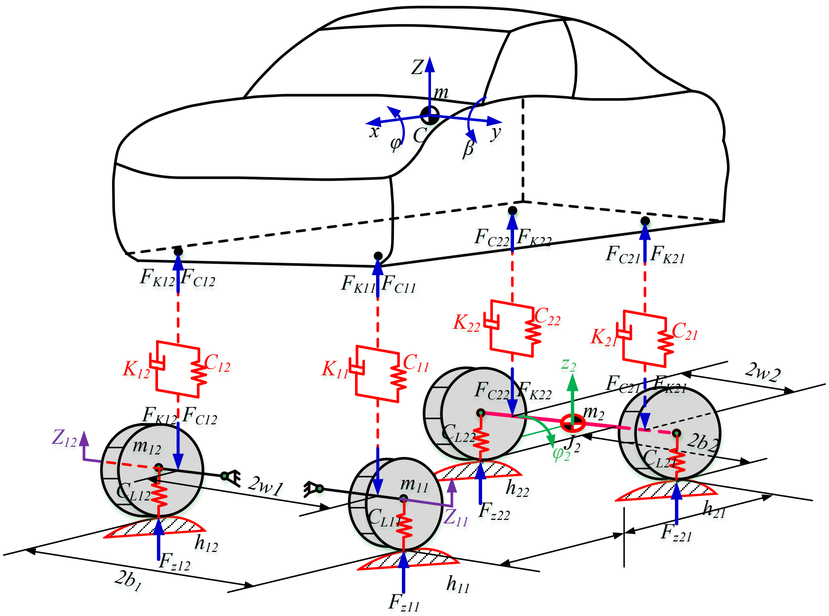

Figure 1. Dynamic model describing the oscillations of an electric vehicle using a leaf-spring suspension system

In there:

m – sprung mass [kg];

m_{11}, m_{12}, m_2 - The unsprung mass of the front left, front right, and rear axles, respectively [kg];

Z - Vertical displacement of the sprung mass [m];

Z_{11}, Z_{12}, Z_2 - Vertical displacement of the sprung mass of the front left, front right, and rear axles, respectively [m];

φ, β - These are the angles of rotation of the sprung mass around the x-axis and the y-axis, respectively [degree];

φ_2 - The angle of rotation of the sprung mass around the x-axis [degree];

J_x, J_y - The moment of inertia of the sprung mass rotates around the x and y axes, respectively [kg.m^2];

J_2 - Moment of inertia of a unsprung mass from the rear axle rotating around the x-axis [kg.m^2];

C_{11}, C_{12}, C_{21}, C_{22} - The suspension stiffness of front left, front right, rear left, and rear right, respectively [N/m];

K_{11}, K_{12}, K_{21}, K_{22} - The damping coefficient of front left, front right, rear left, and rear right, respectively [Ns/m];

C_{L11}, C_{L12}, C_{L21}, C_{L22} - The tire stiffness of front left, front right, rear left, and rear right, respectively [N/m];

w_1, w_2 - The distance from the center of the vehicle to the left or right suspension linkage point at the front and rear axles [m];

b - The distance from the center of the vehicle to the left or right wheel at the front and rear axles [m];

l_1, l_2 - The distances from the center of the vehicle to the center of the front axle and the rear axle, respectively [m];

h_{11}, h_{12}, h_{21}, h_{22} - The road surface bump heights at the front left, front right, rear left, and rear right wheels, respectively [m];

- The sprung mass consists of: translational motion along the vertical axis (Z), rotational motion around the x-axis (φ), and rotational motion around the y-axis (β).

$$m.\ddot{Z} = F_{K11} + F_{K12} + F_{K21} + F_{K22} + F_{C11} + F_{C12} + F_{C21} + F_{C22} \tag{1}$$

$$J_x.\ddot{\varphi} = \left(F_{K11} + F_{C11} - F_{K12} - F_{C12}\right).w + \left(F_{K21} + F_{C21} - F_{K22} - F_{C22}\right).b \tag{2}$$

$$J_y.\ddot{\beta} = -\left(F_{K11} + F_{C11} + F_{K12} + F_{C12}\right).l_1 + \left(F_{K21} + F_{C21} + F_{K22} + F_{C22}\right).l_2 \tag{3}$$

- The unsprung mass of the front axle consists of: the vertical translational movement of the left unsprung mass (Z_{u1}) and the vertical translational movement of the right unsprung mass (Z_{u2}).

$$m_{u1}.\ddot{Z}_{u1} = -F_{K11} - F_{C11} + F_{CL11} \tag{4}$$

$$m_{u2}.\ddot{Z}_{u2} = -F_{K12} - F_{C12} + F_{CL12} \tag{5}$$

- The mass not suspended from the rear axle includes: translational movement in the vertical direction (Z_{u3}), rotational movement around the x-axis (φ_u).

$$m_{u3}.\ddot{Z}_{u3} = -F_{K21} - F_{C21} - F_{K22} - F_{C22} + F_{CL21} + F_{CL22} \tag{6}$$

$$J_u.\ddot{\varphi}_u = \left(-F_{K21} - F_{C21} + F_{K22} + F_{C22}\right).b + \left(F_{CL21} - F_{CL22}\right).w \tag{7}$$

➢ *Model of vehicle vibration when using pneumatic suspension systems*

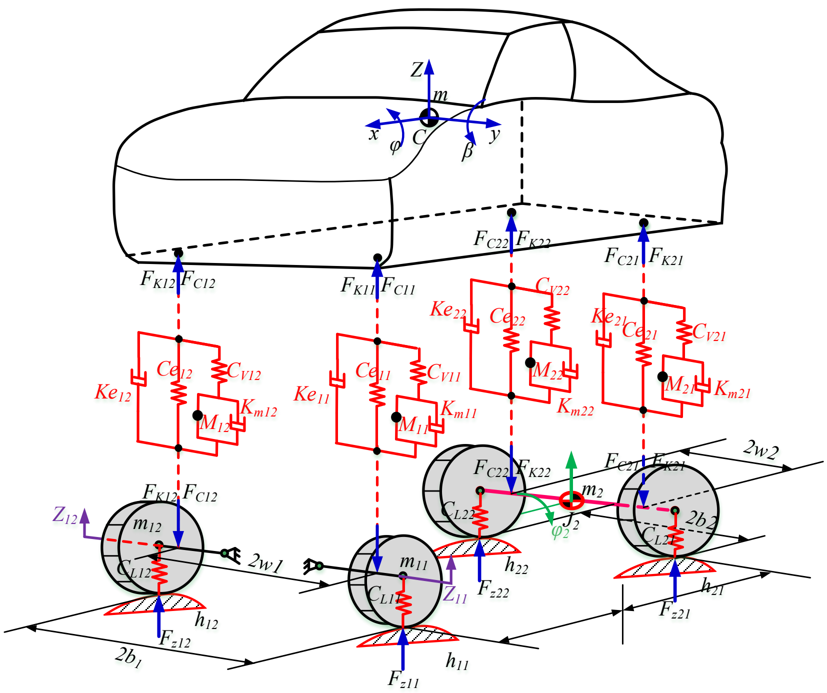

Figure 2. Dynamic model describing the oscillations of an electric vehicle using pneumatic suspension system

In there: C_{e11}, C_{e12}, C_{e21}, C_{e22} - The stiffness values of the air volume in the pneumatic balloons of the front left, front right, rear left, and rear right air suspension systems, respectively [N/m];

C_{v11}, C_{v12}, C_{v21}, C_{v22} - The stiffness values of the air volume in the auxiliary air tank and the piping of the front left, front right, rear left, and rear right pneumatic suspension systems, respectively [N/m];

K_{e11}, K_{e12}, K_{e21}, K_{e22} - The equivalent air resistance coefficients in the air suspension system's piping: front left, front right, rear left, and rear right, respectively [Ns/m];

K_{m11}, K_{m12}, K_{m21}, K_{m22} - The equivalent drag coefficients of the compressed air moving in the front left, front right, rear left, and rear right air suspension system pipes, respectively [Ns/m];

M_{11}, M_{12}, M_{21}, M_{22} - The equivalent air flow volumes in the booster tubes of the front left, front right, rear left, and rear right air suspension systems, respectively [kg].

- The sprung mass consists of: translational motion along the vertical axis (Z), rotational motion around the x-axis (φ), and rotational motion around the y-axis (β).

$$m.\ddot{Z} = F_{Ke11} + F_{Ke12} + F_{Ke21} + F_{Ke22} + F_{Cv11} + F_{Cv12} + F_{Cv21} + F_{Cv22} + F_{Ce11} + F_{Ce12} + F_{Ce21} + F_{Ce22} \quad (8)$$

$$J_x.\ddot{\varphi} = \left(F_{Ke11} + F_{Cv11} + F_{Ce11} - F_{Ke12} - F_{Cv12} - F_{Ce12}\right).w + \left(F_{Ke21} + F_{Cv21} + F_{Ce21} - F_{Ke22} - F_{Cv22} - F_{Ce22}\right).b \quad (9)$$

$$J_y.\ddot{\beta} = -\left(F_{Ke11} + F_{Cv11} + F_{Ce11} + F_{Ke12} + F_{Cv12} + F_{Ce12}\right).l_1 + \left(F_{Ke21} + F_{Cv21} + F_{Ce21} + F_{Ke22} + F_{Cv22} + F_{Ce22}\right).l_2 \quad (10)$$

- The unsprung mass of the front axle consists of: the vertical translational movement of the left unsprung mass (Z_{u1}) and the vertical translational movement of the right unsprung mass (Z_{u2}).

$$m_{u1}.\ddot{Z}_{u1} = -F_{Ke11} - F_{Km11} - F_{Ce11} + F_{CL11} \quad (11)$$

$$m_{u2}.\ddot{Z}_{u2} = -F_{Ke12} - F_{Km12} - F_{Ce12} + F_{CL12} \quad (12)$$

- The mass not suspended from the rear axle includes: translational movement in the vertical direction (Z_{u3}), rotational movement around the x-axis (φ_u).

$$m_{u3}.\ddot{Z}_{u3} = -F_{Ke21} - F_{Km21} - F_{Ce21} - F_{Ke22} - F_{Km22} - F_{Ce22} + F_{CL21} + F_{CL22} \quad (13)$$

$$J_u.\ddot{\varphi}_u = \left(-F_{Ke21} - F_{Km21} - F_{Ce21} + F_{Ke22} + F_{Km22} + F_{Ce22}\right).b + \left(F_{CL21} - F_{CL22}\right).w \quad (14)$$

With:

$$\begin{cases} F_{Ceij} = C_{eij}.\left(Z_{uij} - Z_{sij}\right) \\ F_{Cvij} = C_{vij}.\left(\xi_{ij} - Z_{sij}\right) \\ F_{Keij} = K_{eij}.\left(\dot{Z}_{uij} - \dot{Z}_{sij}\right) \\ F_{Kmij} = K_{mij}.\left|\dot{Z}_{uij} - \dot{\xi}_{ij}\right|^{\beta} sign\left(\dot{Z}_{uij} - \dot{\xi}_{ij}\right) \end{cases} \quad (15)$$

In there:

F_{Ceij} - Elastic force in a pneumatic spring [N];

F_{Cvij} - Elastic force in the auxiliary gas cylinder and tubing [N];

F_{Keij} - Pneumatic damping resistance [N];

Z_{sij}, $\dot{Z}_{sij}$ - Displacement, vertical velocity of the top surface of the pneumatic suspension balloon [m, m/s];

Z_{uij}, $\dot{Z}_{uij}$ - Displacement, vertical velocity of the bottom surface of the pneumatic suspension balloon [m, m/s];

ξ - Vertical displacement of the gas flow in the pipeline [m].

2.2. Simulation and evaluation of results

The type of road surface used in the simulation of electric vehicle vibrations is a random road surface according to the international standard ISO 8608, with road types A to H, as described in Figure 3 [10].

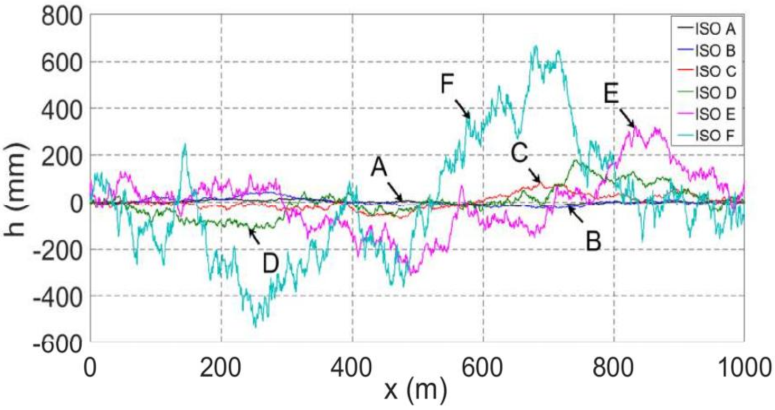

Figure 3. Random profile according to ISO 8608:2016

In this study, the authors investigated the ride comfort of electric vehicles when traveling on medium-quality roads (Type C roads) according to ISO 8608:2016 standards, with speeds ranging from 20 to 80 km/h when fully loaded. The evaluation parameters were the average and maximum acceleration of the vehicle body.

The vehicle's geometric parameters were determined by direct on-vehicle measurements. The stiffness and damping coefficients of the front and rear axles of the mechanical suspension system model and the equivalent stiffness of the front and rear tires and the moment of inertia of the vehicle body and axles were determined by referencing literature [3].

Table 1. Input parameters of the survey model [3]

Order	Parameter	Symbol	Value	Unit
1	The sprung mass in front left	m_{11}	98	kg
2	The sprung mass in front right	m_{12}	98	kg
3	The unsprung mass in rear axle	m_2	225	kg
4	Vehicle weight when fully loaded	m	1814	kg
5	Wheelbase	L	2,610	m
6	Distance from the center of gravity of the vehicle to the front axle	l_1	1,61	m
7	Distance from the center of gravity of the vehicle to the rear axle	l_2	1,265	m
8	Moment of inertia of the vehicle body around the longitudinal axis x	J_x	4390	kgm^2
9	Moment of inertia of the vehicle body around the horizontal axis y	J_y	16299	kgm^2
10	Moment of inertia of a unsprung mass around the x-axis	J_2	98	kgm^2

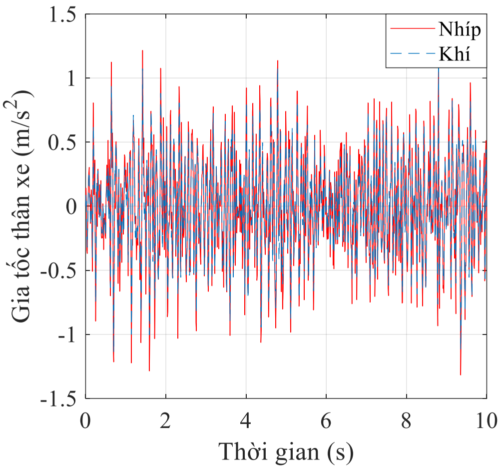

Figure 4: Vertical acceleration of the vehicle body, speed 20 km/h

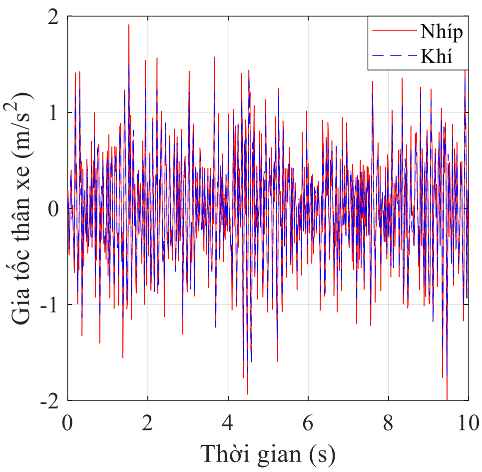

Figure 5: Vertical acceleration of the vehicle body, speed 80 km/h

At a speed of 20 km/h (Figure 4), both leaf spring and air suspension systems resulted in relatively small vertical acceleration of the vehicle body. However, the simulation results in Figure 4 show that when using the leaf spring system, the maximum acceleration values are higher, and the oscillations are less stable. Conversely, when using the air suspension system, the acceleration values have smaller oscillation amplitudes. The maximum and average acceleration values of the vehicle body when using the air suspension system are lower than when using leaf springs, demonstrating better oscillation absorption even at low speeds. This indicates that the air suspension system significantly improves ride comfort in urban driving conditions.

At 80 km/h, when using a leaf spring suspension, the vertical acceleration of the vehicle body is large, the oscillations are complex, and it tends to approach the resonance region, significantly reducing ride comfort and negatively impacting safety. When using a pneumatic suspension system, the amplitude of the vehicle body acceleration is smaller, and the maximum acceleration values are also lower due to the elasticity and self-adjusting capabilities of the pneumatic ballasts. This shows that using a pneumatic suspension system effectively limits the increase in vertical acceleration at high speeds, thereby significantly improving the ride comfort of the vehicle.

Table 2: Evaluating the ride comfort of air suspension systems compared to leaf spring suspension systems

Order	**Velocity (km/h)**	**Suspension systems**	**Root mean square vehicle acceleration (m/s^2)**	**Max vehicle acceleration (m/s^2)**
		Leaf spring	0,33	1,22
1	20 (km/h)	Air suspension system	0,29	1,14
		Reduction rate	**- 12,28%**	**- 6,99%**
		Leaf spring	0,34	1,32
2	30 (km/h)	Air suspension system	0,30	1,21
		Reduction rate	**- 12,55%**	**- 7,71%**
		Leaf spring	0,35	1,48
3	40 (km/h)	Air suspension system	0,31	1,29
		Reduction rate	**- 12,67%**	**- 13,15%**
4	50 (km/h)	Leaf spring	0,38	1,51

		Air suspension system	0,33	1,33
		Reduction rate	**- 13,31%**	**- 12,09%**
		Leaf spring	0,40	1,65
5	60 (km/h)	Air suspension system	0,35	1,38
		Reduction rate	**- 13,33%**	**- 15,91%**
		Leaf spring	0,42	1,78
6	70 (km/h)	Air suspension system	0,36	1,45
		Reduction rate	**- 14,60%**	**- 18,53%**
		Leaf spring	0,45	1,91
7	80 (km/h)	Air suspension system	0,39	1,51
		Reduction rate	**- 12,59%**	**- 21,30%**

Table 2 presents the results of comparing the vertical acceleration of the vehicle body between the two suspension systems, leaf spring and air suspension, in the speed range from 20 km/h to 80 km/h. The authors used two main evaluation criteria: average acceleration value and maximum acceleration value. At all surveyed speeds, the air suspension system consistently showed lower average vehicle body acceleration values compared to the leaf spring suspension system. At 20 km/h, the average vehicle body acceleration decreased from 0.33 m/s² (leaf spring suspension) to 0.29 m/s² (air suspension), a decrease of 12.28%. When the speed increased to 80 km/h, this value decreased from 0.45 m/s² to 0.39 m/s², a decrease of 12.59%. Regarding the maximum acceleration of the vehicle body... At a speed of 20 km/h, the maximum acceleration decreases from 1.22 m/s² to 1.14 m/s², a reduction of 6.99%. At a speed of 80 km/h, the reduction is even greater, with the maximum acceleration decreasing from 1.91 m/s² (leaf spring suspension) to 1.51 m/s² (air suspension), a reduction of up to 21.30%.

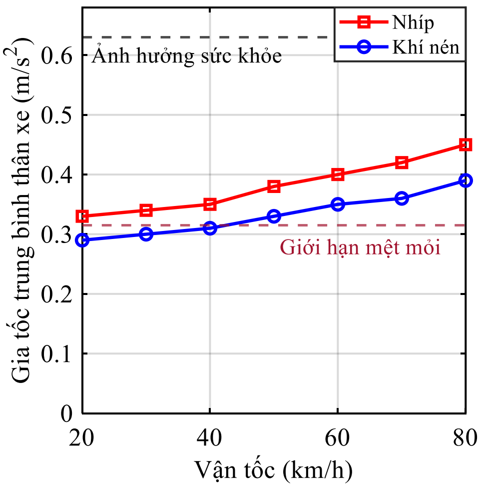

Figure 6: Compare the root mean square vehicle acceleration

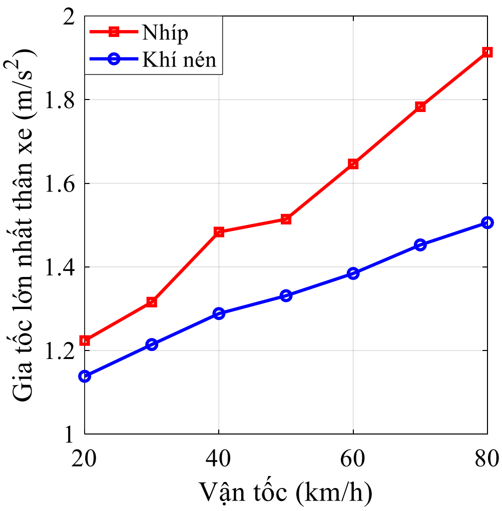

Figure 7: Compare the maximum vehicle acceleration

Figure 6 illustrates the average body acceleration values corresponding to speeds from 20 to 80 km/h. At 20 km/h, the difference in average body acceleration values when using the two types of suspension systems is smaller than at higher speeds, indicating better adaptability of the pneumatic suspension system under high-speed operating conditions. This stems from the nonlinear elastic characteristics and self-adjusting stiffness of the pneumatic ballast, allowing the pneumatic suspension system to absorb vibrations more effectively than traditional leaf spring suspension.

Figure 7 illustrates the error in maximum body acceleration between the two suspension systems. The results show that the difference between the pneumatic suspension and the leaf spring suspension increases with increasing speed. In the high speed range (from 60 km/h to 80 km/h), the maximum acceleration of the leaf spring suspension system increases rapidly, while the pneumatic suspension system tends to increase more slowly.

3. CONCLUSION

This paper constructs a 7-degree-of-freedom spatial dynamic model of an electric vehicle to evaluate ride comfort using leaf spring suspension and air suspension systems. Based on the mathematical model, vehicle oscillations are simulated under conditions of movement on a random road surface of type C according to the ISO 8608:2016 standard, with a speed range from 20 to 80 km/h. The results show that the air suspension system has lower vertical body acceleration values compared to the leaf spring suspension at all speeds studied. The average acceleration is reduced by approximately 12–15%, and the maximum acceleration is reduced by over 20% at high speeds. This confirms that the air suspension system has better oscillation absorption capabilities, significantly improving ride comfort in electric vehicles.

References

[1]. Luong Van Van (2024); "*Research, design and manufacture electronic control suspension systems for trucks transporting agricultural and aquatic products in the Mekong Delta"*, Ministry-level scientific research project.

[2]. Nguyen Thanh Dong (2024), "*Research on application of air suspension system to increase smoothness on 16-seat passenger bus in Vietnam"*, Master's Thesis, Vinh Long University of Technology Education.

[3]. Phan Thao My (2023), "*Developing a simulation model to study the braking efficiency of electric cars"*, Master's Thesis, Vinh Long University of Technology Education.

[4]. Luong Van Van, Nguyen Thanh Tung, (2023), "*Application of Air Suspension System on Multi-purpose Forest Fire Fighting Vehicle for Reducing Dynamic Load*", Journal of Vibration Engineering & Technologies. DOI: 10.1007/s42417-023-01069-2.

[5]. Lương Van Van, Nguyen Thanh Tung (2022), "*Automotive Dynamics textbook"*, Science and Technology Publishing House.

[6]. Vu Thanh Niem (2021), "*Research on suspension of the semi trailer truck in the orient reducing dynamic wheel load"*, Doctor's Thesis, Hanoi University of Science and Technology.

[7]. Nguyen Van Hoang, (2018) "*Research on the characteristics of a double wishbone pneumatic suspension system*", Master's Thesis, Hanoi University of Science and Technology.

[8]. Truong Manh Hung (2017), "*Research on vibrations of the buses using air-spring suspensions",* Doctor's Thesis, University of Transport and Communications.

[9]. Dang Ngoc Minh Tuan, (2017), "*Research on optimizing air suspension system design parameters for heavy-duty trucks to reduce adverse impacts on highway surfaces*", Master's Thesis, University of Industrial Technology – Thai Nguyen University.

[10]. ISO Thainguyen University 8608:2016 (2016), "*Mechanical oscillation-road surface profiles*". Reporting of Measured Data.

[11]. Tran Van Hoang, (2013), "*Research on air suspension systems in automobiles*", Master's Thesis, Hanoi University of Science and Technology.

[12]. ISO 2631-1 (1997). "*Mechanical vibration and shock-Evanluation of human exposure to whole-body vibration*", Part I: General requirements, The International Organization for Standardization.