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A Study on the Effects of Tire Vertical Stiffness on Dynamic Load of DVM 2.5 Truck

Nguyen Thanh Tung(✉) and Luong Van Van(✉)

Vinh Long University of Technology Education, 73, Nguyen Hue Street, Vinh Long City, Vietnam
{tungnt, vanlv}@vlute.edu.vn

Abstract. The dynamic load acting on the vehicle has a variable value, it depends on the moving conditions, road quality and tire stiffness, etc. In this paper, the authors study on the effects of the tire vertical stiffness on dynamic load acting on DVM 2.5 truck. The method of structural separation multi-body system and the Newton–Euler equation are used to set the three-dimensional dynamics model. Matlab-simulink software is used to consider the effects of the tire vertical stiffness on dynamic load of DVM 2.5 truck. The results show that, when the tire vertical stiffness is increased, the maximum dynamic load acting on the tires, chassis and road rises and the transmission capacity drops. In order to ensure the dynamics safety and durability, a fully loaded DVM 2.5 truck is run on a class E road according to ISO 8608:2016, the speeds must be less than 50 kph and the tire vertical stiffness must be less than 912 kN/m.

Keywords: Tire vertical stiffness · Dynamic load · Vehicle dynamics safety

1 Introduction

The dynamic load acting on the vehicle is the cause of vibration, loss of dynamics safety, vehicle damage and road destruction. The specifications are used to evaluate the dynamic load acting on vehicle as following formulas:

(i) The maximum dynamic load factor acting on the chassis (η_{max}): This specification is used to evaluate the smooth movement and durability of the vehicle [1–3].

$$\eta_{\max} = \frac{F_{C\max} + F_{K\max}}{F_{\mathrm{G}}};\ \eta_{\max} \leq 1.5 \tag{1}$$

(ii) The maximum dynamic load factor acting on the tire (K_{dmax}): This specification is used to evaluate the dynamics safety, smooth movement and durability of the vehicle [1–3].

$$K_{d\max} = \frac{F_{CL\max}}{F_G} + 1;\ K_{d\max} \leq 2.5 \tag{2}$$

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(iii) The minimum dynamic load factor acting on the tire (K_{dmin}): This specification is used to evaluate the vehicle dynamics safety and tire transmission capacity [1–3].

$$K_{d\min} = \frac{F_{CL\min}}{F_G} + 1;\ 0 \le K_{d\min} \le 1 \tag{3}$$

$K_{dmin} = 0.5$ within the warning limit; $K_{dmin} = 0$ is the intervention limit.

2 The Three-Dimensional Dynamics Model

The method of separating the structure of the multibody system is used to build a three-dimensional (3D) dynamics model of DVM 2.5 truck is shown in Fig. 1 [4–6].

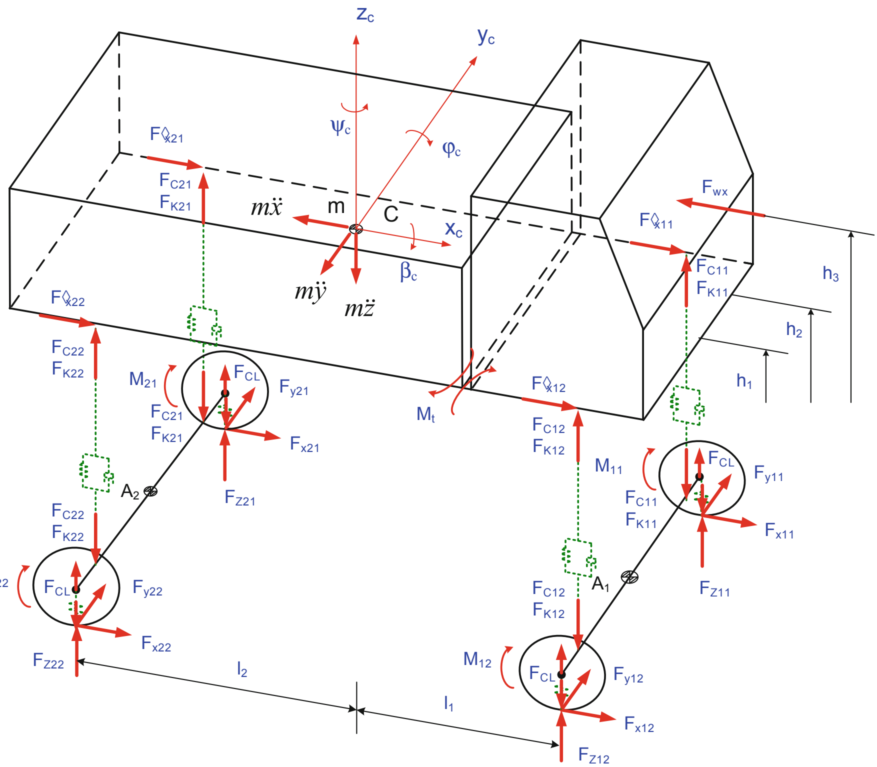


Fig. 1. Dynamics model of the DVM 2.5 truck

The Newton–Euler equations are used to build the system of dynamics equations for DVM 2.5 truck as follows [4–6] (Table 1):

$$m\ddot{x} = F_{x1j}\cos\delta_{1j} - F_{y1j}\sin\delta_{1j} + F_{x2j};\ j = 1\ \textit{is left wheel};\ i = 2\ \textit{is right wheel} \tag{4}$$

$$m\ddot{y} = F_{x1j}\sin\delta_{1j} + F_{y1j}\cos\delta_{1j} + F_{y2j};\ j = 1\ \textit{is left wheel};\ i = 2\ \textit{is right wheel} \tag{5}$$

$$J_z\ddot{\psi} = (F_{x1j}\sin\delta_{1j} + F_{y1j}\cos\delta_{1j})l_1 + (F_{xi2} - F_{xi1})b_i - F_{y2j}l_2 \tag{6}$$

$$m\ddot{z} = F_{Cij} + F_{Kij};\quad i = 1 \div 2;\ j = 1\ \textit{is left wheel};\ i = 2\ \textit{is right wheel} \tag{7}$$

$$J_y\ddot{\varphi} = (F_{C1j} + F_{K1j})l_1 - (F_{C2j} + F_{K2j})l_2 + M_{1j} + M_{2j}; j = 1\ \textit{is lef wheel};\ i = 2\ \textit{is right wheel} \tag{8}$$

$$J_x\ddot{\beta} = (F_{Ci2} + F_{Ki2} - F_{Ci1} - F_{Ki1})w_i;\ i = 1 \div 2 \tag{9}$$

$$m_{A1}\ddot{z}_{A1} = F_{CLij} + F_{KLij} - F_{Cij} - F_{Kij};\ i = 1 \div 2;\ j = 1\ \textit{is left wheel};\ i = 2\ \textit{is right wheel} \tag{10}$$

$$m_{A1}\ddot{y}_{A1} = F_{y1j};\ j = 1\ \textit{is left wheel};\ i = 2\ \textit{is right wheel} \tag{11}$$

$$J_{Ax1}\ddot{\beta}_{A1} = (F_{C11} + F_{K11} - F_{C12} - F_{K12})w_1 + (F_{CL12} + F_{KL12} - F_{CL11} - F_{KL11})b_1 - F_{y11}(r_{11} + \xi_{A11}) - F_{y12}(r_{12} + \xi_{A12}) \tag{12}$$

$$m_{A2}\ddot{z}_{A2} = F_{CL2j} + F_{KL2j} - F_{C2j} - F_{K2j};\ j = 1\ \textit{is left wheel};\ i = 2\ \textit{is right wheel} \tag{13}$$

$$m_{A2}\ddot{y}_{A2} = F_{y2j};\ j = 1\ \textit{is left wheel};\ i = 2\ \textit{is right wheel} \tag{14}$$

$$J_{Ax2}\ddot{\beta}_{A2} = (F_{C21} + F_{K21} - F_{C22} - F_{K22})w_2 + (F_{CL22} + F_{KL22} - F_{CL21} - F_{KL21})b_2 - F_{y21}(r_{21} + \xi_{A21}) - F_{y22}(r_{22} + \xi_{A22}) \tag{15}$$

$$J_{Ayij}\ddot{\varphi}_{ij} = M_{Aij} - M_{Bij} - F_{xij}r_{dij};\ i = 1 \div 2;\ j = 1\ \textit{is left wheel};\ i = 2\ \textit{is right wheel} \tag{16}$$

Table 1. A list of symbols and abbreviations

Symbols	Units	Explain
i		Axle number of the truck, i = 1 ÷ 2
j		j = 1 is left wheel; j = 2 is right wheel; j = 1 ÷ 2
δ	Degree	Front wheel turn angle
l_i	m	Longitudinal distance of axle i from mass center
h_2	m	Height of mass center from the ground
b	m	Lateral distance of the wheels
φ_{ij}	rad	Rotation angle of the ij wheel
β, φ, ψ	Degree	Rotation angle of the tractor body around the x, y, z axis
m, mA	kg	Mass and un-sprung mass of the truck
J_x, J_y, J_z	kgm^2	Moment of inertia about the x, y, z axis of the sprung mass
J_{Ayij}	kgm^2	Moment of inertia about the y-axis of the ij wheel
F_{Cij}	N	The suspension elastic force of the ij wheel
F_{Kij}	N	The suspension damping force of the ij wheel
F_{CLij}	N	The tire elastic force of the ij wheel
F_{xij}	N	The longitudinal force of the ij wheel
F_{yij}	N	The lateral force of the ij wheel
F_{zij}	N	The vertical force of the ij wheel
F_{Gij}	N	The static weight of the ij wheel
M_{Aij}, M_{Bij}	Nm	Driving torque and braking torque of the ij wheel

3 Survey Results and Discussions

Matlab-Simulink software is used to consider the tire vertical stiffness on dynamic load acting on DVM 2.5 truck. The DVM 2.5 truck is fully loaded and is run at speeds V_0 = [30, 40, 50, 60] kph on a class E road according to ISO 8608:2016 is shown in Fig. 2 [7].

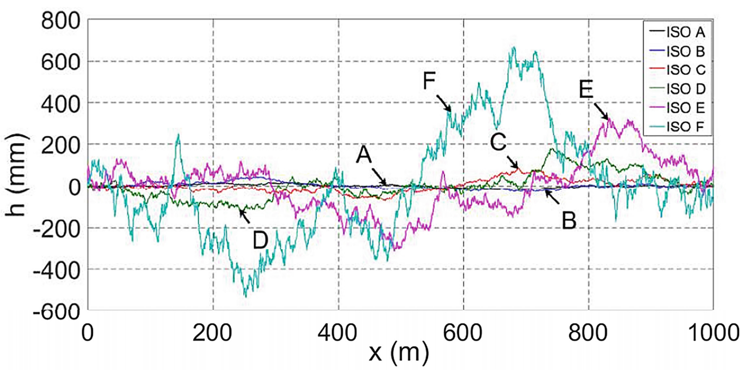
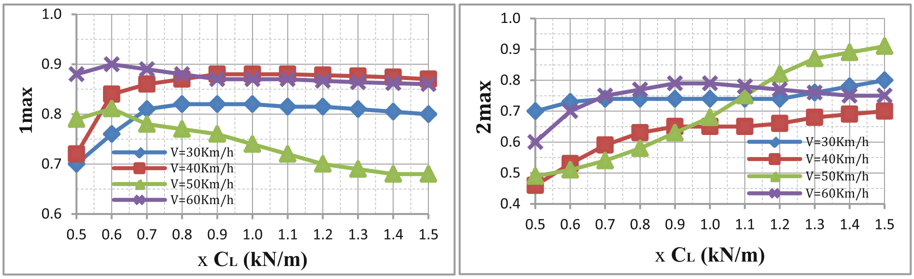


Fig. 2. Road surface according to ISO 8608:2016 standards

The tire vertical stiffness of the DVM 2.5 truck is C_L = 652 kN/m. When surveying, the tire vertical stiffness value is changed as C_{L0} = [0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5] C_L, the survey results are as follows:



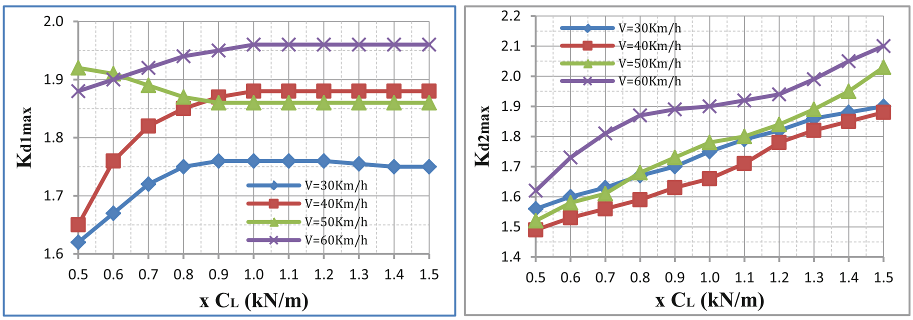
a. Front axle b. Rear axle

Fig. 3. Maximum dynamic load factor acting on the chassis

When the DVM 2.5 truck is run on a class E road at speeds V_0 = [30 ÷ 60] kph, if the tire vertical stiffness is increased from C_{L0} = [0.5 ÷ 1.5] C_L, the maximum dynamic load factor acting on the chassis at the front axle is about η_{1max} = [0.68 ÷ 0.88] shown in Fig. 3a. According to Fig. 3a, the value of the maximum dynamic load factor acting on the chassis at the front axle is $\eta_{1\,max} \leq \eta_{max} = 1.5$, the truck has smooth movement and durability.

When the DVM 2.5 truck is run on a class E road at speeds V_0 = [30 ÷ 60] km/h, if the tire vertical stiffness is increased from C_{L0} = [0.5 ÷ 1.5] C_L, the maximum dynamic load factor acting on the chassis at the rear axle is about η_{2max} = [0.46 ÷ 0.91] shown in Fig. 3b, $\eta_{2\,max} \leq \eta_{max} = 1.5$, the truck has smooth movement and durability.

Figure 4a is a graph showing the maximum dynamic load factor acting on the front tires when the DVM 2.5 truck is run on a class E road at speeds V_0 = [30 ÷ 60] kph. According to Fig. 4a, the tire vertical stiffness is increased from C_{L0} = [0.5 ÷ 1.5] C_L, the maximum



a. Front axle b. Rear axle

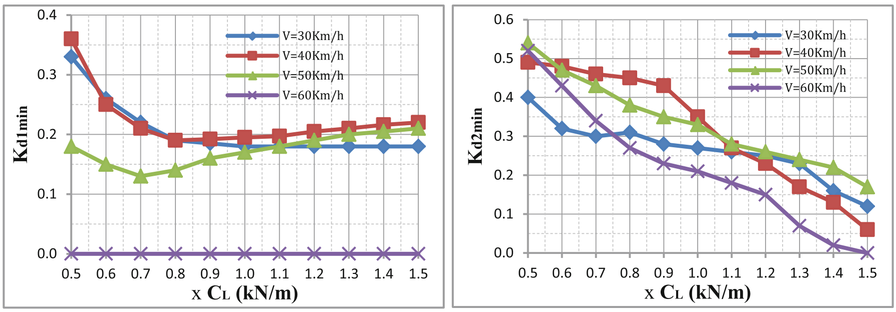
Fig. 4. Maximum dynamic load factor acting on the tires

dynamic load factor acting on the front tire is about K_{d1max} = [1.62 ÷ 1.96], $K_{d1\,max} \leq K_{d\,max} = 2.5$. The front tire of the DVM 2.5 truck has smooth movement and durability, and dynamics safety.

Figure 4b is a graph showing the maximum dynamic load factor acting on the rear tires when the truck is run on a class E road at speeds V_0 = [30 ÷ 60] kph. When the tire vertical stiffness is increased from C_{L0} = [0.5 ÷ 1.5] C_L, the maximum dynamic load factor acting on the rear tires is increased, K_{d2max} = [1.56 ÷ 2.1], $K_{d2\,max} \leq K_{d\,max} = 2.5$. The rear tires of the DVM 2.5 truck has smooth movement and durability, and dynamics safety.

The minimum dynamic load factor acting on the front tires when the DVM 2.5 truck is run on a class E road at speeds V_0 = [30 ÷ 60] kph shown in Fig. 5a. When the tire vertical stiffness is increased from C_{L0} = [0.5 ÷ 1.5] C_L, the minimum dynamic load factor acting on the front tires drops, K_{d1min} = [0.36 ÷ 0]. When the DVM 2.5 truck is run at V_0 = [30 ÷ 50] kph, K_{d1min} is within the warning limit, $0 < K_{d1min} \leq 0.5$. The front tires of the DVM 2.5 truck have dynamics safety and tire transmission capacity. When the DVM 2.5 truck is run at a speed of V_0 = 60 kph, the value of the minimum dynamic load factor acting on the front tires $K_{d1min} = 0$, K_{d1min} within the intervention limit. The front tires of the DVM 2.5 truck don't have dynamics safety and tire transmission capacity.

The minimum dynamic load factor acting on the rear tires is shown in Fig. 5b. When the tire vertical stiffness is increased from C_{L0} = [0.5 ÷ 1.5] C_L, the minimum dynamic load factor acting on the rear tires drops, K_{d2min} = [0.54 ÷ 0]. When C_{L0} = [0.5 ÷ 1.4] C_L, K_{d2min} is within the warning limit, $0 < K_{d2min} \leq 0.5$. The rear tire of the DVM 2.5 truck has dynamics safety and tire transmission capacity. When C_{L0} = 1.5C, K_{d2min} is within the intervention limit, $K_{d2min} = 0$. The rear tires of the DVM 2.5 truck don't have dynamics safety and tire transmission capacity.



a. Front tire b. Rear tire

Fig. 5. Minimum dynamic load factor acting on the tires

4 Conclusions

When the tire vertical stiffness is increased, the maximum dynamic load value on the tires, chassis and road rises, and the transmission capacity drops. Therefore, the smooth movement and durability, and dynamics safety of the DVM 2.5 truck drop. A fully loaded DVM 2.5 truck is run on a class E road according to ISO 8608:2016, the speeds must be less than 50 kph and the tire vertical stiffness must be less than 912 kN/m (or $CL0 \leq 1.4CL$), the DVM 2.5 truck is ensured dynamics safety and durability.

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