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A survey on the effects of bumpy road on the vibration of multi-purpose forest fire fighting vehicle

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A B S T R A C T

Multi-purpose forest fire fighting vehicles should carry a set of firefighting equipment such as high-pressure water pumps, tree cutters to create a fire isolation corridor, vacuum, and blowing machine high-speed wind sandblasting devices etc. The bumpy road and velocity of moving vehicles can affect the vibration response of these vehicles. Hence, in this research the vibration analysis of a Multi-purpose forest fire fighting vehicle mounted on a URAL4320 active three-wheel drive vehicle is simulated and analyzed. The effect of road bumping and speed of vehicle on the vibration parameters are studied via building mathematical models with 19 degree of freedom for simulating the suspension system of the investigated vehicle.

1. Introduction

Multi-purpose forest fire fighting vehicle manufactured by Vietnam is installed on Ural 4320 base vehicles (shown in Figs 1 and 2), on the vehicle with additional fire-fighting equipment. When a vehicle operates in a forest without a road, under the influence of forest ground, obstructions on the road and the impact of the fire-fighting system on the vehicle makes the vehicle very fluctuating. This can provide a fluctuating effect on the stability, durability and quality of the vehicle and its systems.

Fig. 1. Base vehicle Ural 4320

Fig. 2. Multi-purpose forest fire fighting vehicle

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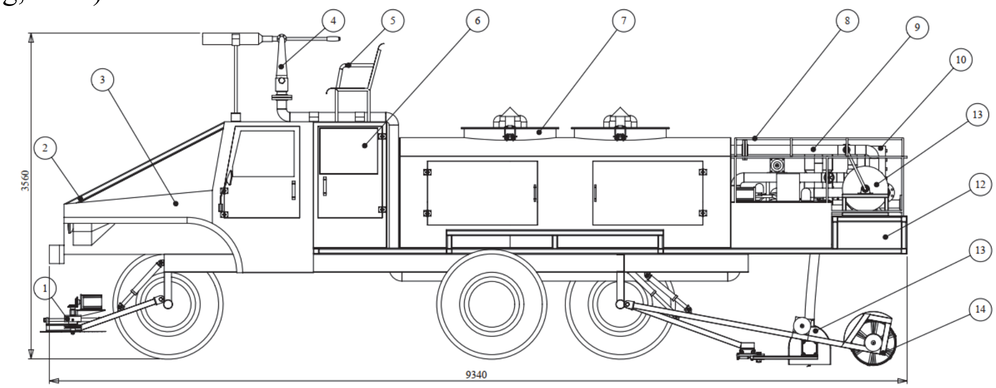
The main equipment of multi-purpose forest fire fighting vehicle are shown in Fig. 3 (Luong et al., 2018; Luong, 2010).



1) Tree cutting mechanism; 2) Tree cleaver; 3) Body; 4) Water sprayer; 5) Seat; 6) Cabin; 7) Water tank; 8) Back cover; 9) Pipe; 10) Table; 11) Plotting small nozzle; 12) Floorboard; 13) Dig system; 14) Lawn cutting mechanism.

Fig. 3. General design multi-purpose forest fire fighting vehicle.

Multi-purpose forest fire fighting vehicles are new equipment and the research on the dynamics of this type of vehicle is limited. To have a theoretical basis for the completion of multi-purpose forest fire fighting vehicles, it is necessary to survey a study on the dynamic behavior of this vehicle at operation condition. Indeed, it is necessary to study the fluctuation of multi-purpose forest fire fighting vehicles to find a reasonable working regime and promote the efficiency of the vehicles used in forest fire-fighting activities. A number of efforts have been done in the past for investigating the vibration of vehicles. For example, Mischke (1990) studied the vibration of passenger cars. A vibration model was considered to optimize the suspension system. Müller (1970) provided a spatial model describing all types of pneumatic wheel tractors. Hassaan & Mohammed (2015) modeled a 10 DOF independent suspension system and studied the vibration of the driver seat, passenger seat, and body using Matlab Simulink when the car is moving on the road at 36 km/h and 43 km/h. Griffin (1996) showed that the interior vibration of a vehicle has a significant effect on comfort and road holding capability. Sulaiman et al. (2012) studied a vibration body using Matlab Simulink and Trucksim by simulating the models at different speeds (36 km/h and 43 km/h). Mitra et al. (2013) modeled a 7 DOF independent suspension system and studied the effect of damping and suspension's coefficient on the vibration of the body using Matlab Simulink.

Nguyen (2013) studied the vibrations of the vehicle when operating firefighting on forest roads. Running in the forest is very limited. When the vehicle runs at high speed, in the context of large forest ground, the vibration of the large vehicle makes the car unstable and since the quality of some working systems on the vehicle are very low they may damage due to vibration. At the same time, it affects the smoothness of movement and causes the frame to be twisted (Nguyen 2013). This paper presents the methods and results of building mathematical models and examining the fluctuation of multi-purpose forest fire fighting vehicles when moving through the bumpy pavements with variable height and speeds. The results can be used for checking the durability of the frame and perfecting the suspension system.

2. Research method

To create model of the vehicle oscillation calculation the following assumptions were considered: (i) The suspended mass is treated as a solid mass; (ii) the chassis is twisted by different front and rear tilt angles; (iii) wheels always sticking to the road, ignoring the skidding of the wheels; (iv) vehicle fluctuations are considered movements around static equilibrium; (v) vehicle structure and symmetrical distribution of load across the vertical plane; (vi) ignoring the influence of air resistance and friction on the bearings of wheels; (vii) the weight of the vehicle and the water tank are rigidly connected to the floor. The Newton-Euler equation was utilized to set up the differential equation for vibration of suspended and non-suspended masses. The system of equations was solved by Matlab - Simulink software after determining the input parameters experimentally.

2.1. Building the vibration model of vehicle

The oscillating model of the multi-purpose forest fire truck is shown in Fig. 4. The structural model of the forest fire truck consists of 19 extrapolated coordinates (19 degrees of freedom) including 3 degrees of freedom describing the movement of the cabin (Z_c, θ_{cx}, θ_{cy}), 3 degrees of freedom describing the motion of the truck (Z_t, θ_{tx}, θ_{ty}), 3 degrees of freedom describing the motion of the body car (Z_s, θ_{sx}, θ_{sy}), 2 levels themselves due to the description of the front axle (Z_{u1}, θ_{u1}), 2 degrees of freedom describing the middle bridge (Z_{u2}, θ_{u2}), 2 degrees of freedom describe the rear axle (Z_{u3}, θ_{u3}), 2 degrees of tissue freedom for description of frontal cutting device (Z_4, θ_4) and 2 degrees of freedom for describing the rear lawn cutting mechanism (Z_5, θ_5).

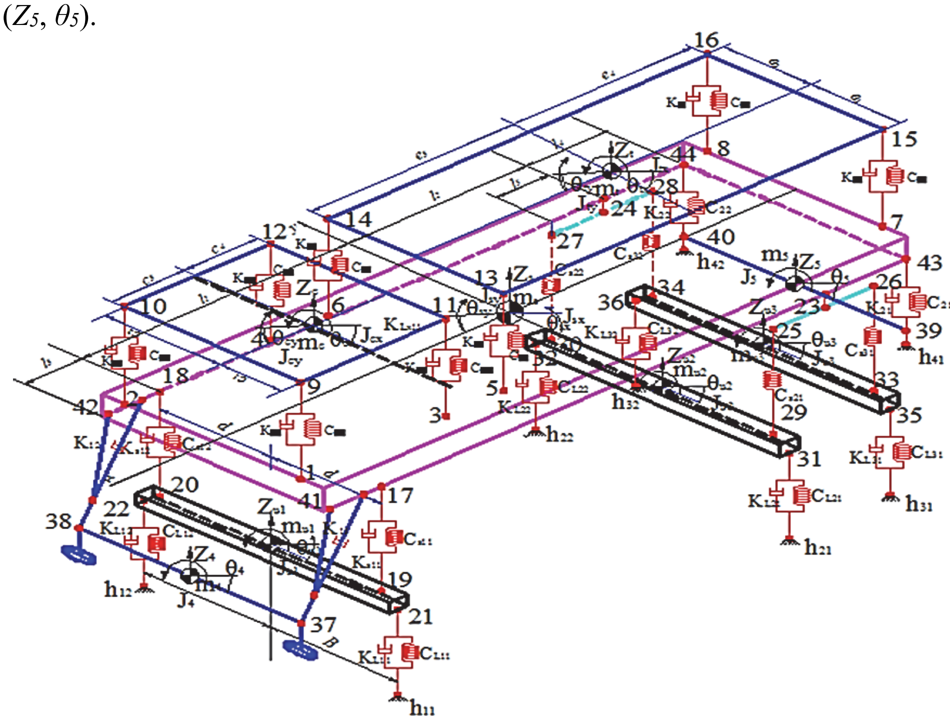


Fig. 4. Full car suspension model

Using the Newton-Euler equation, a system of differential equations (i.e. Eqs. 1 to 19) was built to describe the vibration of a multi-purpose forest fire fighting vehicle.

$$m_c\ddot{Z}_c + K_c\left[4\dot{Z}_c + 2\dot{\theta}_{cx}(c_1 - c_2) + \dot{\theta}_{cy}(c_3 - c_4) - 4\dot{Z}_s + 2\dot{\theta}_{sx}(c_2 - c_1) - 2\dot{\theta}_{sy}(l_1 + l_3) - 2\dot{\theta}_{sy}(l_1 + l_3 - c_3 - c_4)\right] \quad (1)$$

$$C_c\left[4Z_c + 2\theta_{cx}(c_1 - c_2) + \theta_{cy}(c_3 - c_4) - 4Z_s + 2\theta_{sx}(c_2 - c_1) - 2\theta_{sy}(l_1 + l_3) - 2\theta_{sy}(l_1 + l_3 - c_3 - c_4)\right] = 0$$

$$J_{cx}\ddot{\theta}_{cx} + K_c c_1\left[2\dot{Z}_c + 2\dot{\theta}_{cx}c_1 + \dot{\theta}_{cy}(c_3 - c_4) - 2\dot{Z}_s - 2\dot{\theta}_{sx}c_1 - \dot{\theta}_{sy}(2l_1 + 2l_3 + c_3 + c_4)\right] \quad (2)$$

$$-K_c c_2\left[2\dot{Z}_c - 2\dot{\theta}_{cx}c_2 + \dot{\theta}_{cy}(c_3 - c_4) - 2\dot{Z}_s + 2\dot{\theta}_{sx}c_2 - \dot{\theta}_{sy}(2l_1 + 2l_3 + c_3 + c_4)\right]$$

$$+C_c c_1\left[2Z_c + 2\theta_{cx}c_1 + \theta_{cy}(c_3 - c_4) - 2Z_s - 2\theta_{sx}c_1 - \theta_{sy}(2l_1 + 2l_3 + c_3 + c_4)\right]$$

$$-C_c c_2\left[2Z_c - 2\theta_{cx}c_2 + \theta_{cy}(c_3 - c_4) - 2Z_s + 2\theta_{sx}c_2 - \theta_{sy}(2l_1 + 2l_3 + c_3 + c_4)\right] = 0$$

$$
\begin{aligned}
&J_{cy}\ddot{\theta}_{cy}+K_c c_3\left[2\dot{Z}_c+\dot{\theta}_{cx}\left(c_1-c_2\right)+2\dot{\theta}_{cy}c_3-2\dot{Z}_s+\dot{\theta}_{sx}\left(c_2-c_1\right)-2\dot{\theta}_{sy}\left(l_1+l_3\right)\right]\\
&-K_c c_4\left[2\dot{Z}_c+\dot{\theta}_{cx}\left(c_1-c_2\right)-2\dot{\theta}_{cy}c_4-2\dot{Z}_s+\dot{\theta}_{sx}\left(c_2-c_1\right)-2\dot{\theta}_{sy}\left(l_1+l_3-c_3-c_4\right)\right]\\
&C_c c_3\left[2Z_c+\theta_{cx}\left(c_1-c_2\right)+2\theta_{cy}c_3-2Z_s+\theta_{sx}\left(c_2-c_1\right)-2\theta_{sy}\left(l_1+l_3\right)\right]\\
&-C_c c_4\left[2Z_c+\theta_{cx}\left(c_1-c_2\right)-2\theta_{cy}c_4-2Z_s+\theta_{sx}\left(c_2-c_1\right)-2\theta_{sy}\left(l_1+l_3-c_3-c_4\right)\right]=0
\end{aligned}\tag{3}
$$

$$
\begin{aligned}
&m_t\ddot{Z}_t+K_t\left[4\dot{Z}_t+2\dot{\theta}_{tx}\left(e_1-e_2\right)+2\dot{\theta}_{ty}\left(e_3-e_4\right)-4\dot{Z}_s+2\dot{\theta}_{sx}\left(e_2-e_1\right)-2\dot{\theta}_{sy}\left(e_3+e_4-l_2-l_4\right)+2\dot{\theta}_{sy}\left(l_2+l_4\right)\right]\\
&+C_t\left[4Z_t+2\theta_{tx}\left(e_1-e_2\right)+2\theta_{ty}\left(e_3-e_4\right)-4Z_s+2\theta_{sx}\left(e_2-e_1\right)-2\theta_{sy}\left(e_3+e_4-l_2-l_4\right)+2\theta_{sy}\left(l_2+l_4\right)\right]=0
\end{aligned}\tag{4}
$$

$$
\begin{aligned}
&J_{tx}\ddot{\theta}_{tx}+K_t e_1\left[2\dot{Z}_t+2\dot{\theta}_{tx}e_1+\dot{\theta}_{ty}\left(e_3-e_4\right)-2\dot{Z}_s-2\dot{\theta}_{sx}e_1+\dot{\theta}_{sy}\left(l_2+l_4\right)-\dot{\theta}_{sy}\left(e_3+e_4-l_2-l_4\right)\right]\\
&-K_t e_2\left[2\dot{Z}_c-2\dot{\theta}_{tx}e_2+\dot{\theta}_{ty}\left(e_3-e_4\right)-2\dot{Z}_s+2\dot{\theta}_{sx}e_2+\dot{\theta}_{sy}\left(l_2+l_4\right)-\dot{\theta}_{sy}\left(e_3+e_4-l_2-l_4\right)\right]\\
&C_t e_1\left[2Z_t+2\theta_{tx}e_1+\theta_{ty}\left(e_3-e_4\right)-2Z_s-2\theta_{sx}e_1+\theta_{sy}\left(l_2+l_4\right)-\theta_{sy}\left(e_3+e_4-l_2-l_4\right)\right]\\
&-C_t e_2\left[2Z_c-2\theta_{tx}e_2+\theta_{ty}\left(e_3-e_4\right)-2Z_s+2\theta_{sx}e_2+\theta_{sy}\left(l_2+l_4\right)-\theta_{sy}\left(e_3+e_4-l_2-l_4\right)\right]=0
\end{aligned}\tag{5}
$$

$$
\begin{aligned}
&J_{ty}\ddot{\theta}_{ty}+Ke_3\left[2\dot{Z}_t+\dot{\theta}_{tx}\left(e_1-e_2\right)+2\dot{\theta}_{ty}e_3-2\dot{Z}_s-\dot{\theta}_{sx}\left(e_2-e_1\right)-2\dot{\theta}_{sy}\left(e_3+e_4-l_2-l_4\right)\right]\\
&-K_t e_4\left[2\dot{Z}_t+\dot{\theta}_{tx}\left(e_1-e_2\right)-2\dot{\theta}_{ty}e_4-2\dot{Z}_s-\dot{\theta}_{sx}\left(e_2-e_1\right)+2\dot{\theta}_{sy}\left(l_2+l_4\right)\right]\\
&+Ce_3\left[2Z_t+\theta_{tx}\left(e_1-e_2\right)+2\theta_{ty}e_3-2Z_s-\theta_{sx}\left(e_2-e_1\right)-2\theta_{sy}\left(e_3+e_4-l_2-l_4\right)\right]\\
&-C_t e_4\left[2Z_t+\theta_{tx}\left(e_1-e_2\right)-2\theta_{ty}e_4-2Z_s-\theta_{sx}\left(e_2-e_1\right)+2\theta_{sy}\left(l_2+l_4\right)\right]=0
\end{aligned}\tag{6}
$$

$$
\begin{aligned}
&m_s\ddot{Z}_s+K_c\left[4\dot{Z}_s+2\dot{\theta}_{sx}\left(c_1-c_2\right)+2\dot{\theta}_{sy}\left(c_3+c_4\right)-4\dot{Z}_c+2\dot{\theta}_{cx}\left(c_2-c_1\right)+2\dot{\theta}_{cy}\left(c_4-c_3\right)\right]\\
&+K_t\left[4\dot{Z}_s+2\dot{\theta}_{sx}\left(e_1-e_2\right)+2\dot{\theta}_{sy}\left(e_3+e_4\right)-4\dot{Z}_t+2\dot{\theta}_{tx}\left(e_2-e_1\right)+\dot{\theta}_{ty}\left(e_4-e_3\right)\right]\\
&+K_{s1}\left[2\dot{Z}_s+2\dot{\theta}_{sy}l_1-2\dot{Z}_{u1}\right]+K_1\left[2\dot{Z}_s+2\dot{\theta}_{sy}\left(l_1+l_5\right)-2\dot{Z}_4\right]+K_2\left[2\dot{Z}_s-2\dot{\theta}_{sy}\left(l_2+l_4\right)-2\dot{Z}_5\right]\\
&+C_{c11}\left[Z_s+\theta_{sx}c_1+\theta_{sy}\left(l_1+l_3\right)-Z_c-\theta_{cx}c_1-\theta_{cy}c_3\right]+C_c\left[4Z_s+2\theta_{sx}\left(c_1-c_2\right)+2\theta_{sy}\left(c_3+c_4\right)-4Z_c+2\theta_{cx}\left(c_2-c_1\right)+2\theta_{cy}\left(c_4-c_3\right)\right]\\
&+C_t\left[4Z_s+2\theta_{sx}\left(e_1-e_2\right)+2\theta_{sy}\left(e_3+e_4\right)-4Z_t+2\theta_{tx}\left(e_2-e_1\right)+\theta_{ty}\left(e_4-e_3\right)\right]\\
&+C_{s1}\left[2Z_s+2\theta_{sy}l_1-2Z_{u1}\right]+C_{s2}\left[2Z_s+2\theta_{sy}\left(l_2-l_5\right)-2Z_{u2}\right]+C_{s3}\left[2Z_s-2\theta_{sy}\left(l_2+l_5\right)-2Z_{u3}\right]\\
&+C_1\left[2Z_s+2\theta_{sy}\left(l_1+l_3\right)-2Z_4\right]+C_2\left[2Z_s-2\theta_{sy}\left(l_2+l_4\right)-2Z_5\right]=0
\end{aligned}\tag{7}
$$

$$
\begin{aligned}
&J_{sx}\ddot{\theta}_{sx}+K_c c_1\left[2\dot{Z}_s+2\dot{\theta}_{sx}c_1+\dot{\theta}_{sy}\left(c_3+c_4\right)-2\dot{Z}_c-2\dot{\theta}_{cx}c_1-\dot{\theta}_{cy}\left(c_4-c_3\right)\right]-K_c c_2\left[2\dot{Z}_s-2\dot{\theta}_{sx}c_2+\dot{\theta}_{sy}\left(c_3+c_4\right)-2\dot{Z}_c+2\dot{\theta}_{cx}c_2-\dot{\theta}_{cy}\left(c_4-c_3\right)\right]\\
&+K_t e_1\left[2\dot{Z}_s+2\dot{\theta}_{sx}e_1+\dot{\theta}_{sy}\left(e_3+e_4-2l_2-2l_4\right)-2\dot{Z}_t-2\dot{\theta}_{tx}e_1-\dot{\theta}_{ty}\left(e_4-e_3\right)\right]-K_t e_2\left[2\dot{Z}_s-2\dot{\theta}_{sx}e_2+\dot{\theta}_{sy}\left(e_3+e_4-2l_2-2l_4\right)-2\dot{Z}_t+2\dot{\theta}_{tx}e_2-\dot{\theta}_{ty}\left(e_4-e_3\right)\right]\\
&+K_{s1}d\left[2\dot{\theta}_{sx}d-2\dot{\theta}_{u1}d\right]+K_1 d\left[2\dot{\theta}_{sx}d-2\dot{\theta}_4 d\right]+K_2 d\left[2\dot{\theta}_{sx}d-2\dot{\theta}_5 d\right]C_c c_1\left[2Z_s+2\theta_{sx}c_1+\theta_{sy}\left(c_3+c_4\right)-2Z_c-2\theta_{cx}c_1-\theta_{cy}\left(c_4-c_3\right)\right]\\
&-C_c c_2\left[2Z_s-2\theta_{sx}c_2+\theta_{sy}\left(c_3+c_4\right)-2Z_c+2\theta_{cx}c_2-\theta_{cy}\left(c_4-c_3\right)\right]+C_t e_1\left[2Z_s+2\theta_{sx}e_1+\theta_{sy}\left(e_3+e_4-2l_2-2l_4\right)-2Z_t-2\theta_{tx}e_1-\theta_{ty}\left(e_4-e_3\right)\right]\\
&-C_t e_2\left[2Z_s-2\theta_{sx}e_2+\theta_{sy}\left(e_3+e_4-2l_2-2l_4\right)-2Z_t+2\theta_{tx}e_2-\theta_{ty}\left(e_4-e_3\right)\right]+C_{s1}d\left[2\theta_{sx}d-2\theta_{u1}d\right]+C_{s2}d\left[2\theta_{sx}d-2\theta_{u1}d\right]+C_{s3}d\left[2\theta_{sx}d-2\theta_{u1}d\right]\\
&+C_1 d\left[2\theta_{sx}d-2\theta_4 d\right]+C_2 d\left[2\theta_{sx}d-2\theta_5 d\right]=0
\end{aligned}\tag{8}
$$

$$
\begin{aligned}
&J_{sy}\ddot{\theta}_{sy}+K_c\left(l_1+l_3\right)\left[2\dot{Z}_s+\dot{\theta}_{sx}\left(c_1-c_2\right)+2\dot{\theta}_{sy}\left(l_1+l_3\right)-2\dot{Z}_c+\dot{\theta}_{cx}\left(c_2-c_1\right)-2\dot{\theta}_{cy}c_3\right]\\
&-K_c\left(l_1+l_3-c_3-c_4\right)\left[2\dot{Z}_s+\dot{\theta}_{sx}\left(c_1-c_2\right)-\dot{\theta}_{sy}\left(l_1+l_3-c_3-c_4\right)-2\dot{Z}_c-\dot{\theta}_{cx}\left(c_2-c_1\right)+2\dot{\theta}_{cy}c_4\right]\\
&+K_t\left(e_3+e_4-l_2-l_4\right)\left[2\dot{Z}_s+\dot{\theta}_{sx}\left(e_1-e_2\right)+2\dot{\theta}_{sy}\left(e_3+e_4-l_2-l_4\right)-2\dot{Z}_t-\dot{\theta}_{tx}\left(e_2-e_1\right)-2\dot{\theta}_{ty}e_3\right]\\
&-K_t\left(l_2+l_4\right)\left[2\dot{Z}_s+\dot{\theta}_{sx}\left(e_1-e_2\right)-2\dot{\theta}_{sy}\left(l_2+l_4\right)-2\dot{Z}_t-\dot{\theta}_{tx}\left(e_2-e_1\right)+2\dot{\theta}_{ty}e_4\right]\\
&+K_s l_1\left[2\dot{Z}_s+2\dot{\theta}_{sy}l_1-2\dot{Z}_{u1}\right]+K_1\left(l_1+l_3\right)\left[2\dot{Z}_s+2\dot{\theta}_{sy}\left(l_1+l_3\right)-2\dot{Z}_4\right]-K_2\left(l_2+l_4\right)\left[2\dot{Z}_s-2\dot{\theta}_{sy}\left(l_2+l_4\right)-2\dot{Z}_5\right]\\
&+C_c\left(l_1+l_3\right)\left[2Z_s+\theta_{sx}\left(c_1-c_2\right)+2\theta_{sy}\left(l_1+l_3\right)-2Z_c+\theta_{cx}\left(c_2-c_1\right)-2\theta_{cy}c_3\right]\\
&-C_c\left(l_1+l_3-c_3-c_4\right)\left[2Z_s+\theta_{sx}\left(c_1-c_2\right)-\theta_{sy}\left(l_1+l_3-c_3-c_4\right)-2Z_c-\theta_{cx}\left(c_2-c_1\right)+2\theta_{cy}c_4\right]\\
&+C_t\left(e_3+e_4-l_2-l_4\right)\left[2Z_s+\theta_{sx}\left(e_1-e_2\right)+2\theta_{sy}\left(e_3+e_4-l_2-l_4\right)-2Z_t-\theta_{tx}\left(e_2-e_1\right)-2\theta_{ty}e_3\right]\\
&-C_t\left(l_2+l_4\right)\left[2Z_s+\theta_{sx}\left(e_1-e_2\right)-2\theta_{sy}\left(l_2+l_4\right)-2Z_t-\theta_{tx}\left(e_2-e_1\right)+2\theta_{ty}e_4\right]\\
&+C_{s1}l_1\left[2Z_s+2\theta_{sy}l_1-2Z_{u1}\right]-C_{s2}\left(l_2-l_5\right)\left[2Z_s-2\theta_{sy}\left(l_2-l_5\right)-2Z_{u2}\right]-C_{s3}\left(l_2+l_5\right)\left[2Z_s-2\theta_{sy}\left(l_2+l_5\right)-2Z_{u3}\right]\\
&+C_{11}\left(l_1+l_3\right)\left[2Z_s+2\theta_{sy}\left(l_1+l_3\right)-2Z_4\right]-C_2\left[2Z_s-2\theta_{sy}\left(l_2+l_4\right)-2Z_5\right]=0
\end{aligned}\tag{9}
$$

$$m_{u1}\ddot{Z}_{u1}+K_{s1}\left[2\dot{Z}_{u1}-2\dot{Z}_{s}-2\dot{\theta}_{sy}l_{1}\right]+K_{L1}\left(2\dot{Z}_{u1}-\dot{h}_{11}-\dot{h}_{12}\right)+C_{s1}\left[2Z_{u1}-2Z_{s}-2\theta_{sy}l_{1}\right]+C_{L1}\left(2Z_{u1}-h_{11}-h_{12}\right)=0 \tag{10}$$

$$J_{u1}\ddot{\theta}_{u1}+K_{s1}d\left[2\dot{\theta}_{u1}d-2\dot{\theta}_{sx}d\right]+K_{L1}B^{2}\left(2\dot{\theta}_{u1}-\dot{h}_{11}-\dot{h}_{12}\right)+C_{s1}d\left[+2\theta_{u1}d-2\theta_{sx}d\right]+C_{L1}B^{2}\left(2\theta_{u1}-h_{11}-h_{12}\right)=0 \tag{11}$$

$$m_{u2}\ddot{Z}_{u2}+K_{L2}\left(2\dot{Z}_{u2}-\dot{h}_{21}-\dot{h}_{22}\right)+C_{s2}\left[2Z_{u2}-2Z_{s}+2\theta_{sy}\left(l_{2}-l_{5}\right)\right]+C_{L2}\left(Z_{u2}-h_{21}-h_{22}\right)=0 \tag{12}$$

$$J_{u2}\ddot{\theta}_{u2}+K_{L2}B^{2}\left(2\dot{\theta}_{u2}-\dot{h}_{21}-\dot{h}_{22}\right)+C_{s2}d\left[+2\theta_{u2}d-2\theta_{sx}d\right]+C_{L2}B^{2}\left(2\theta_{u2}-h_{21}-h_{22}\right)=0 \tag{13}$$

$$m_{u3}\ddot{Z}_{u3}+K_{L3}\left(2\dot{Z}_{u3}-\dot{h}_{31}-\dot{h}_{32}\right)+C_{s3}\left[2Z_{u3}-2Z_{s}+2\theta_{sy}\left(l_{2}+l_{5}\right)\right]+C_{L3}\left(2Z_{u3}-h_{31}-h_{32}\right)=0 \tag{14}$$

$$J_{u3}\ddot{\theta}_{u3}+K_{L3}B^{2}\left(2\dot{\theta}_{u3}-\dot{h}_{31}-\dot{h}_{32}\right)+C_{s3}d\left[+2\theta_{u3}d-2\theta_{sx}d\right]+C_{L3}B^{2}\left(2\theta_{u3}-h_{31}-h_{32}\right)=0 \tag{15}$$

$$m_{4}\ddot{Z}_{4}+K_{1}\left[2\dot{Z}_{4}-2\dot{\theta}_{sy}\left(l_{1}+l_{3}\right)-2\dot{Z}_{s}\right]=0 \tag{16}$$

$$J_{4}\ddot{\theta}_{4}+K_{1}d\left[2\dot{\theta}_{4}d-2\dot{\theta}_{sx}d\right]=0 \tag{17}$$

$$m_{5}\ddot{Z}_{5}+K_{2}\left[2\dot{Z}_{5}+2\dot{\theta}_{sy}\left(l_{2}+l_{4}\right)-2\dot{Z}_{s}\right]+C_{2}\left[2Z_{5}+2\theta_{sy}\left(l_{2}+l_{4}\right)-2Z_{s}\right]=0 \tag{18}$$

$$J_{5}\ddot{\theta}_{5}+K_{2}d\left[2\dot{\theta}_{5}d-2\dot{\theta}_{sx}d\right]+C_{2}d\left[2\theta_{5}d-2\theta_{sx}d\right]=0 \tag{19}$$

The results of calculations for some cases of the vehicle motion and the corresponding values of the geometry and dynamic parameters are given in Table 1.

Table 1. Technical input data for multifunction forest fire fighting vehicle.

Symbol	Value	Symbol	Value	Symbol	Value
m_c	850 kg	m_5	1000 kg	K_{11}, K_{12}	2800 Ns/m
J_{cx}	200 kgm^2	J_5	1277 kgm^2	K_{21}, K_{22}	2800 Ns/m
J_{cy}	150 kgm^2	C_{c1}, C_{c2}, C_{c3}, C_{c4}	100000 N/m	c_1	0.7 m
m_t	8500 kg	K_{c11}, K_{c12}, K_{c21}, K_{c22}	750 Ns/m	c_2	0.6 m
J_{tx}	48700 kgm^2	C_{t1}, C_{t2}, C_{t3}, C_{t4}	500000 N/m	c_3	0.8 m
J_{ty}	13819 kgm^2	K_{t11}, K_{t12}, K_{t21}, K_{t22}	4000 Ns/m	c_4	0.7 m
m_s	14310 kg	C_{s11},C_{s12}	401952 N/m	e_1	0.8 m
J_{sx}	64770 kgm^2	C_{s21}, C_{s22}	527042 N/m	e_2	0.8 m
J_{sy}	18852 kgm^2	C_{s31}, C_{s32}	527042 N/m	e_3	2.5 m
m_{u1}	1020 kg	K_{s11}, K_{s12}	3248 Ns/m	e_4	2.5 m
m_{u2}	1000 kg	C_{L11}, C_{L12}	569964 N/m	$2d$	1.5 m
m_{u3}	1000 kg	C_{L21}, C_{L22}	569964 N/m	$2B$	2.0 m
J_{u1}	1302 kgm^2	C_{L31}, C_{L32}	569964 N/m	l_1	2.538 m
J_{u2}	1277 kgm^2	K_{L11}, K_{L12}	6497 Ns/m	l_2	1.687 m
J_{u3}	1277 kgm^2	K_{L21}, K_{L22}	6497 Ns/m	l_3	1.847 m
m_4	800 kg	K_{L31}, K_{L32}	6497 Ns/m	l_4	1.9 m
J_4	1105 kgm^2	C_{21}, C_{22}	80000 N/m	l_5	0.55 m

The results of the survey when the wheel moves through a single slope is described in Fig. 5. The height of the bumpy is calculated as follows:

$$h(x)=\begin{cases}\dfrac{1}{2}H\left(1-\cos\left(2\pi\dfrac{x}{L}\right)\right) & when \quad 0<x<L\\ 0 \qquad when \quad x\le 0 \quad , \quad x\ge L\end{cases} \tag{20}$$

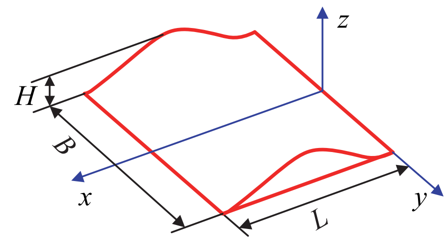


Fig. 5. A rough description of the road surface along the length

Due to the forest road with high roughness the maximum speed of vehicles is typically considered as 20 km/h. Therefore, when the wheels pass over the slope of L = 0.5m, the height of the bumping (H) is equal to 0.2 m. The velocity of the studied vehicle was considered constant at four speeds of 5km/h, 10km/h, 15km/h and 20km/h. Also it was assumed that the vehicle is moving straight and is not subjected to horizontal forces.

3. Results and discussion

3.1. The front wheel passing over the bump

In this case, the front wheel must face bumpy, the survey results will determine the movement of the body car vertically (Z_s), corner shaking vertical (θ_{sx}), and the angle of horizontal shaking (θ_{sy}) around the central body car. Figs. 6 to 11 describe the vertical displacement, roll and pitch angle value Z_s, θ_{sx}, and θ_{sy} for different speeds and height bump of 0.2 m.

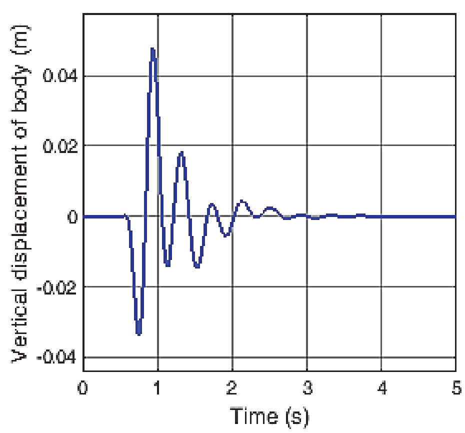


Fig. 6. Vertical displacement of body (Z_s, v = 20 km/h, h = 0.2m)

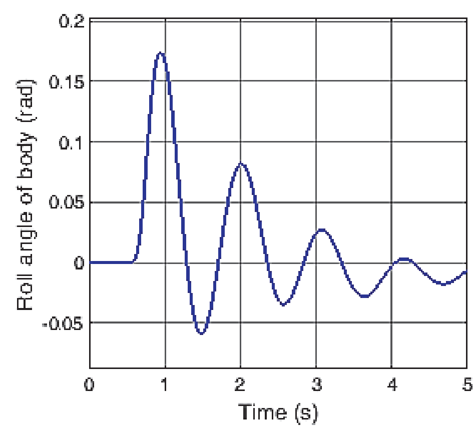


Fig. 7. Roll angle of body (θ_{sy}, v = 20 km/h, h = 0.2m)

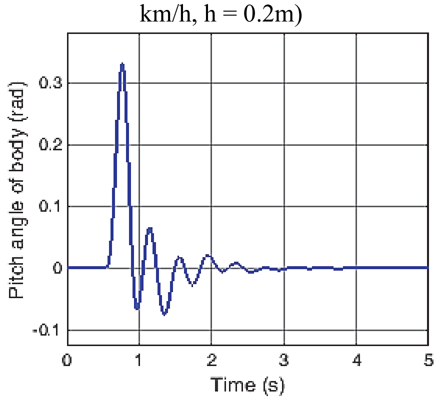


Fig. 8. Pitch angle of body (θ_{sx}, v = 20 km/h, h = 0.2m)

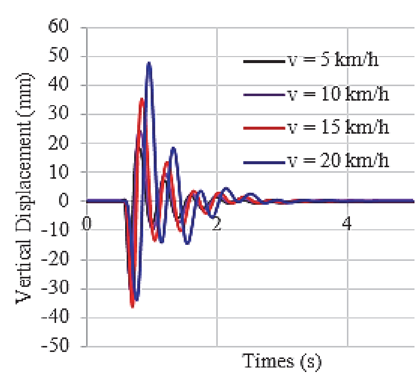


Fig. 9. Vertical displacement of body (Z_s, v = 5 - 20 km/h, h = 0.2m)

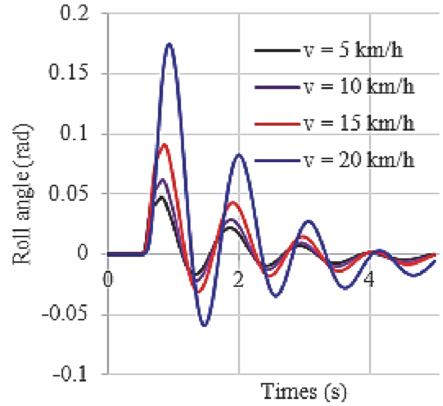


Fig. 10. Roll angle of body (θ_{sy}, v = 5-20 km/h, h = 0.2m)

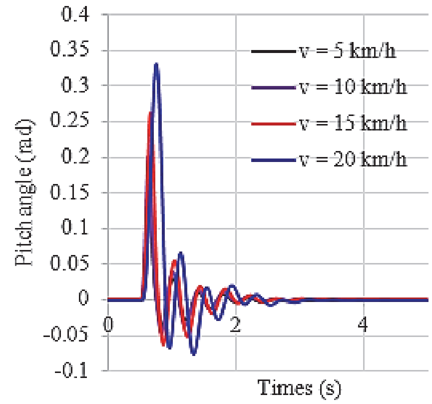


Fig. 11. Pitch angle of body (θ_{sx}, v = 5- 20 km/h, h = 0.2m)

3.2 . Disturbing the vibration of vehicle with two diagonally wheels

When moving at different speeds, the time in which the rear wheel is in contact with the pavement differs from the time that the front wheel comes into contact with the road. As the vehicle's movement speed increases, the body's displacement value in the vertical direction (Z_s), the vertical swing angle (θ_{sx}), and the horizontal swing angle (θ_{sy}) of the vehicle body are also increased. Figs. 12 to 17 show the results obtained for the vertical displacement, roll and pitch angle values under the acting two diagonally rear left and front right wheels of the vehicle. At the speed of 20 km/h, the maximum vertical movement of the body is 124 mm, the largest vertical swing angle is 0.33 rad, and the largest horizontal swing angle is 0.34 rad. Comparison of results of one and two wheels reveals that significantly increased amplitudes for the vehicle vibration parameters are obtained by passing two diagonal wheels over the bump.

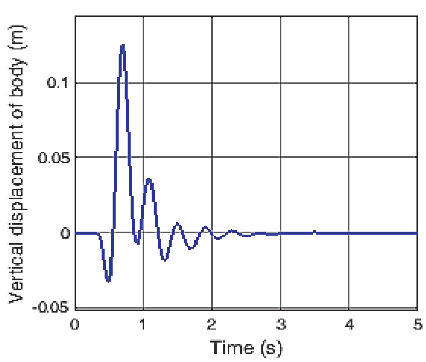


Fig. 12. Vertical displacement of body (Z_s, v = 20 km/h, h = 0.2m)

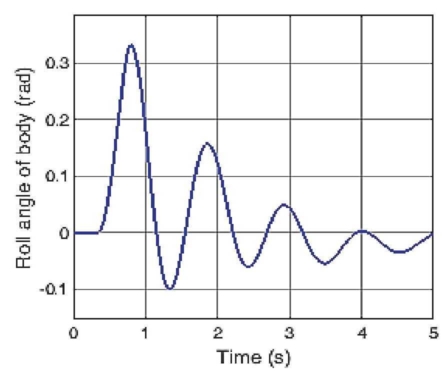


Fig. 13. Roll angle of body (θ_{sy}, v = 20 km/h, h = 0.2m)

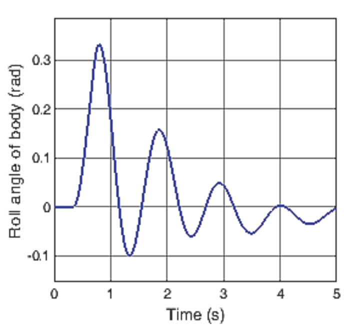


Fig. 14. Pitch angle of body (θ_{sx}, v = 20 km/h, h = 0,2m)

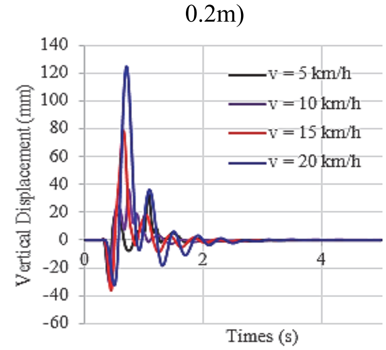


Fig. 15. Vertical displacement of body (Z_s, v = 5-20 km/h, h = 0.2m)

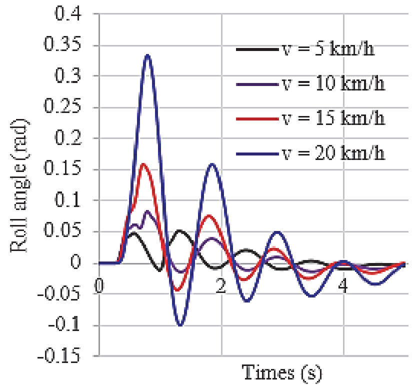


Fig. 16. Roll angle of body (θ_{sy}, v = 5-20 km/h, h = 0.2m)

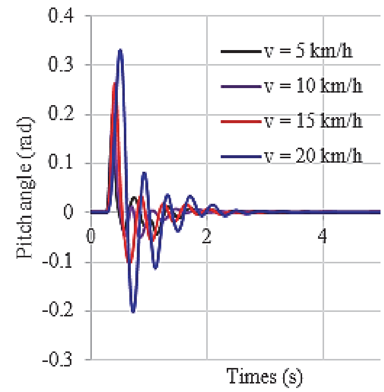


Fig. 17. Pitch angle of body (θ_{sx}, v = 5-20 km/h, h = 0.2m)

4. Conclusion

Based on the research of the structure of multi-purpose forest fire fighting vehicles, a vibration model of the vehicle was built. By applying the Newton-Euler equation, the system of differential equations of oscillators was established. Using Matlab - Simulink software the system of equations were solved to simulate the vibration of forest fire fighting vehicles. From the simulation analyses, it was concluded that the vertical movement, vertical shaking angle, and horizontal shaking angle of the vehicle body are proportional to the vehicle's movement speed. Furthermore, significantly increased amplitudes for the vibration of the vehicle are obtained by passing two diagonal wheels over the bump compared to one single wheel case.

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