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Sensitivity analysis on the vertical motion of heavy machine due to changing tires characteristics

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Abstract. *In this paper the author presents some aspects about the motion of a heavy machine with tires in moving on the irregular roads. Based on the spatial 3-DOF model of machine it was evaluated all eigen pulsations and simulated the tire-road interaction only for the vertical motion of a wheel loader. The influence of the tire characteristics to the dynamic behavior of the loader was studied.*

Keywords*: heavy machine, tire, irregular terrain, dynamics, simulation*

1. Introduction

The operational capability of heavy machine to ensure technological and functional performance is significantly influenced by perturbator actions that may occur during the working process [1]. For example, the wheel loaders are a type of heavy machinery used all over the world in construction for various tasks, such as: scooping, digging, dumping and carrying. They have sturdy tires equipping for better handling, traction and maneuverability that allow deliver the specific tasks under inappropriate roads. In this regard, a wheel loader moving on the uneven road, specific for construction site conditions, was proposed for studying its dynamic behavior under random perturbations induced by the terrain profile.

2. Theoretical considerations

The paper is focused on the aspect of the wheel-terrain interaction process for a loader modeled as a rigid body system (representing by the mass m), supported on four tires, having spatial motion characterized by three degrees of freedom. Is assumed that each tire has linear viscoelastic behavior (k_i, c_i), with identical characteristics and, preponderant elasticity on vertical direction.

The dynamic response of the machine, when it travels with speed *v* on uneven terrain, consists in analysis of vibrations generated by the all movements refers to the *Oxyz* coordinate (with origin in the mass center of the machine). Thus, it is interesting to know how to influence the viscoelastic characteristics of the tire over the angular oscillations about the x-axis (denoted by coordinate θ_2) and y-axis (denoted by coordinate θ_1), and, respectively, over the vertical translation motion (denoted by coordinate *z*) along the *Oz* axis, for the model described in Figure 1.

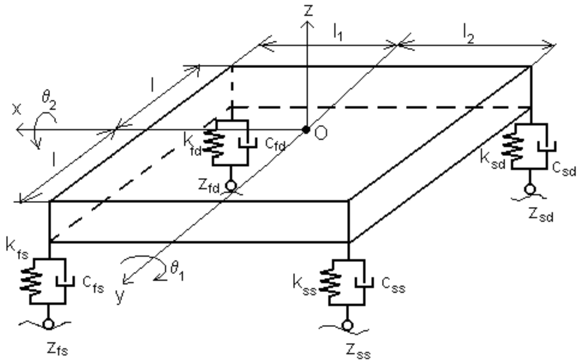

Figure 1. Dynamic model with 3-DOF for wheel-ground contact evaluation.

Many different roughness have been developed to parameterize terrain surfaces [2,3]. Usually, the uneven terrain profile (subjected to each tire *i* of heavy machine) can be modeled as following mathematic function:

$$z_i = A sin(\omega t + i\varphi / 12), i = \overline{1,4} \cdot \tag{1}$$

where *A* denotes profile magnitude, ω and φ are pulsation and phase of terrain irregularities, and index *i* indicates the effective tire - terrain interaction point.

The evaluation of vibrations that act to the wheel loader, modeled as a rigid body, is based on Lagrange equation of the second kind, so that, in advance will be required to express the kinetic and potential energies, respectively the dissipation functions of the rigid body [4].

The relative displacements of the machine wheels have following expressions:

$$\begin{aligned} &\delta_{fd} = z + \theta_2 l + \theta_1 l_1 - z_{fd}, \delta_{sd} = z + \theta_2 l - \theta_1 l_1 - z_{sd}. \\ &\delta_{fs} = z - \theta_2 l + \theta_1 l_1 - z_{fs}, \delta_{ss} = z - \theta_2 l - \theta_1 l_1 - z_{ss}. \end{aligned} \tag{2}$$

The total kinetic energy of the system is

$$E = \frac{1}{2} m (\dot{z})^2 + \frac{1}{2} J_1 \dot{\theta}_1^2 + \frac{1}{2} J_2 \dot{\theta}_2^2, \tag{3}$$

where J_1 is the moment of inertia of the rigid body about the *y*-axis, and J_2 the moment of inertia about the *x*-axis.

The potential energy of the system is

$$V = \frac{1}{2}k\delta_{fd}^2 + \frac{1}{2}k\delta_{fs}^2 + \frac{1}{2}k\delta_{sd}^2 + \frac{1}{2}k\delta_{ss}^2 \cdot \tag{4}$$

The dissipation function of the system is

$$D = \frac{1}{2}c\dot{\delta}_{fd}^2 + \frac{1}{2}c\dot{\delta}_{fs}^2 + \frac{1}{2}c\dot{\delta}_{sd}^2 + \frac{1}{2}c\dot{\delta}_{ss}^2 \cdot \tag{5}$$

After deriving the parameters involved in Lagrange equation, the second-order ordinary differential equations of motion result by the form:

$$\begin{cases} m\ddot{z} + 16\dot{z}c + 16zk - 8c\dot{\theta}_1(l_1 - l_2) - 8k\theta_1(l_1 - l_2) = 4c(\dot{z}_{fd} + \dot{z}_{fs} + \dot{z}_{sd} + \dot{z}_{ss}) + 4k(z_{fd} + z_{fs} + z_{sd} + z_{ss}) \\ -8\dot{z}c(l_1 - l_2) - 8zk(l_1 - l_2) + J_1\ddot{\theta}_1 + 8\dot{\theta}_1 c(l_1^2 + l_2^2) + 8\theta_1 k(l_1^2 + l_2^2) = \\ \qquad = 4k[l_1(z_{fd} + z_{fs}) - l_2(z_{sd} + z_{ss})] + 4c[l_1(\dot{z}_{fd} + \dot{z}_{fs}) + l_2(\dot{z}_{sd} + \dot{z}_{ss})] \\ J_2\ddot{\theta}_2 + 16\dot{\theta}_2 cl^2 + 16\theta_2 kl^2 = 4kl(z_{fd} + z_{fs} + z_{sd} + z_{ss}) + 4cl(\dot{z}_{fd} + \dot{z}_{fs} + \dot{z}_{sd} + \dot{z}_{ss}) \end{cases} \tag{6}$$

For similar characteristics of the tires, in the absence of damping and of the disturbing factors caused by the irregularities of the terrain, the eigenfrequencies of the system can be determined from the equation

$$\mathbf{M} \cdot \{\ddot{q}\} + \mathbf{C} \cdot \{\dot{q}\} + \mathbf{K} \cdot \{q\} = 0, \tag{7}$$

where

$$\{q\} = \begin{Bmatrix} z(t) \\ \theta_1(t) \\ \theta_2(t) \end{Bmatrix}, \quad \mathbf{M} = \begin{bmatrix} m & 0 & 0 \\ 0 & J_1 & 0 \\ 0 & 0 & J_2 \end{bmatrix}; \quad \mathbf{C} = \begin{bmatrix} 16c & -8(l_1 - l_2)c & 0 \\ -8(l_1 - l_2)c & 8(l_1^2 + l_2^2)c & 0 \\ 0 & 0 & 16cl^2 \end{bmatrix}, \quad \mathbf{K} = \begin{bmatrix} 16k & -8(l_1 - l_2)k & 0 \\ -8(l_1 - l_2)k & 8(l_1^2 + l_2^2)k & 0 \\ 0 & 0 & 16kl^2 \end{bmatrix}.$$

Thus, solving the equation (7) with the following solutions $q_i = A_i \sin(pt+\theta)$, we obtain the algebraic equations system

$$\begin{cases} (-mp^2 + 16k)z - 8k(l_1 - l_2)\theta_1 = 0 \\ -8k(l_1 - l_2)z + [-J_1 p^2 + 8k(l_1^2 + l_2^2)]\theta_1 = 0 \\ (-p^2 J_2 + 16kl^2)\theta_2 = 0 \end{cases}, \tag{8}$$

from where result the three natural eigenfrequencies (in term of p_z, $p_{\theta 1}$, $p_{\theta 2}$), corresponding with the 3-DOF of motions of mechanical system associated to heavy machine. The periodically wheel-road impacts generate higher amplitude of vertical vibrations if the resonance phenomena appear, and frequency analysis is required for avoid appearance of this situation, considering redesigning of the machine and repositioning the mass center [5].

3. Study case

The machine travelling with a constant velocity (v = 20 km/h), stressed by the road bumps that meets along its route in the areas of contact between tire and road profile, generates perturbations within the machine motion [6,7]. Finally, the numerical simulations have focused on the evaluation of dynamic loads transmitted to the machine by the terrain. Thus, it can evaluate the dynamic load coefficient, as a ratio between the dynamic load F_d and the static load G:

$$DLC = F_d/G = k(z-\delta)/mg. \tag{9}$$

The main parameters of the wheel loader (MMT 45, Romania) used for dynamic simulation are: heavy machine mass m=4000 kg, moments of inertia of the machine J_1=J_2=1000 kgm^2, vertical tire stiffness k=25x10^5 N/m, tire damping c=800 Ns/m, constructive dimensions l_1=l_2=2 m. Thus, for the initial conditions $z_0 = \theta_{10} = \theta_{20} = 0$, $\dot{z}_0 = 0.1$ m/s, $\dot{\theta}_{10} = 0.1$ rad/s, $\dot{\theta}_{20} = 0.1$ rad/s, results the free vibrations of the mechanical system, as temporal evolutions of z, θ_1, θ_2 (see Figure 2).

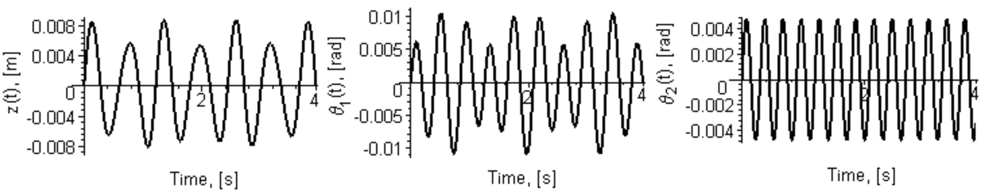

Figure 2. Wheel loader motion for each supposed 3-DOF

The equations of motion are implemented in the Matlab/Simulink environment. Thus, it was evaluating the natural frequencies (p_z, $p_{\theta 1}$, $p_{\theta 2}$) and the laws of motion corresponding to undamped vibrations of the machine (shown in fig.2).

4. Sensitivity analysis

When moving the machine on uneven roads, the tires have supplementary role of mitigating the vibrations that propagate to its structure. If only the vertical motion of the machine is important to study, then we assumed that a bump with the surface generated by expression $z_i = 0.2\sin(5{,}5t)$ encounters the front-axle wheels. In this way, the vertical motion of the mass center along z axis can be highlighted for low frequency excitations of ground surface. The sensitivity analysis of viscoelastic characteristics of tires gives a general view over the dynamic behavior of the heavy machine, as can be seen in Figures 3 and 4.

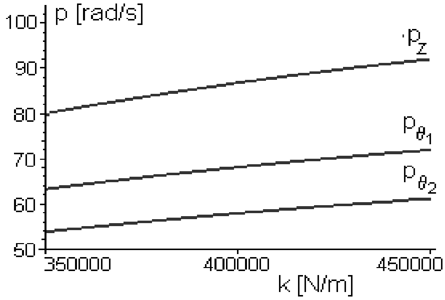

Figure 3. Variation of eigenpulsations versus stiffness tires

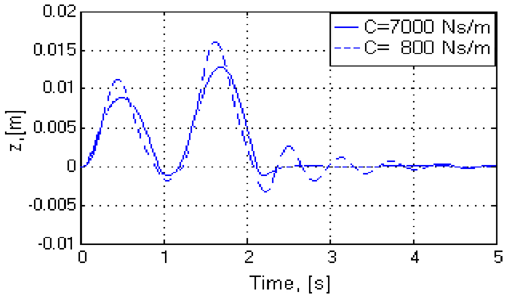

Figure 4. Vertical oscillations of machine versus damping tires

Thus, the tire stiffness range was varied between 3,5x10^5 - 4,5x10^5 N/m and the damping coefficient between 800 – 7000 Ns/m. All machine eigen pulsations have approximatively the same proportional variation in respect to stiffness tire increment. In addition, as the inflation pressure increases, the diagram shows higher amplitude of the vertical oscillation of the machine.

If the damping increases by more than eight times, the amplitude of motion decreases by only 128%. This fact highlights the nonlinear relationship between the vertical oscillation peaks and tires damping. In addition, for *c*=800 Ns/m results the dynamic loads coefficient DLC=1.6, which demonstrates the existence of overloads when machine traveling on uneven surface.

Next, for four simulation scenarios, in Figure 5 has been represented the vertical acceleration response of the proposed model to a singular terrain excitation, with the frequency increased twice, and defined as: $z_i = 0.2\sin(11t)$.

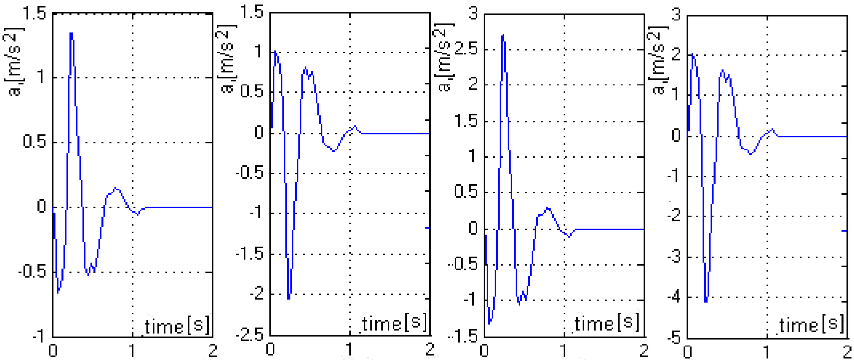

Figure 5. Vertical acceleration of the center of mass for motion over the bump with: a) front-right wheel; b) rear-right wheel; c) front-axle wheels; d) rear-axle wheels.

All kinematic excitations have inducing vertical oscillations into the machine frame, with different values of the peak amplitude depending on the position of the contact point between the wheel and the bump road.

5. Conclusion

Study of motion of a heavy machine, when this moves on irregular roads profiles, was approached in this paper. It was analyzed a free undamped (natural) vibration for a model assimilated with a 3-DOF mechanical system. The proposed mathematical model shows that the equation of rotation of the machine along the longitudinal axis *Ox* is decoupled from the other equations of motion.

Therefore, the influence of tire characteristics on the vertical movement of the machine, in the imposed road conditions, was highlighted in conditions of low frequency excitations generated by the terrain surface. Hereby, equipping with tires characterized by the high damping has the effect of reducing the amplitude of vibrations that are transmitted to the machine, a useful aspect both for the life of the structure and for the ride comfort of operator.

Possible directions for future work: finding technical solutions to reduce the vibrations caused by moving on irregular terrain through implementation of a device for controlling active suspensions.

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