Railway Load Analysis During the Operation of an Excavator Resting on the Railway Track

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Abstract: Mobile machines perform many functions in the development and maintenance of railway infrastructure. Among them, particular emphasis is on hydraulic excavators. The paper defines a mathematical model of a hydraulic excavator for determining the static and dynamic loads of the railway during the operation of an excavator resting on the railway track. Based on the mathematical model, an excavator simulation program was developed. As an example, using the developed program, the loads of the railway tracks were determined for the operation of an excavator of 17000 kg in mass, equipped with a manipulator with a backhoe bucket of 0.6 m^3 in volume.

Keywords: hydraulic excavators; railway transport; load analysis

1 Introduction

Rail transport, as a reliable and efficient means of transporting passengers and goods has been the subject of interest of numerous researchers. The research related to rail transport is quite broad and includes various investigations such as those related to locomotive engines [1], interaction of trains and railways [2], environment protection by reducing the noise emitted from the rails [3] [4], efficient inspection of railways [5], behavior of rails under different conditions [6] [6] [7], to name but a few research directions. There are numerous mobile machines (hydraulic excavators, loaders, graders, dumpers, cranes) (Figure 1a) that are used on railways in performing operational transport functions, but also in the operation and maintenance of railways and other railway infrastructure. Hydraulic excavators weighing from *10000 kg* to *25000 kg* with a support and movement mechanism on caterpillars and tires are the most common mobile machines for performing various functions on the railway. Hydraulic excavators move and rest on railway tracks using modular devices with one pair of rail wheels for narrow, standard or wide gauge railway track, installed on the supporting structure of standard support and movement mechanisms in the front and in the rear. According to drivetrains, motion modules can be divided into: a) motion modules with indirect drivetrain, and b) motion modules with direct drivetrain.

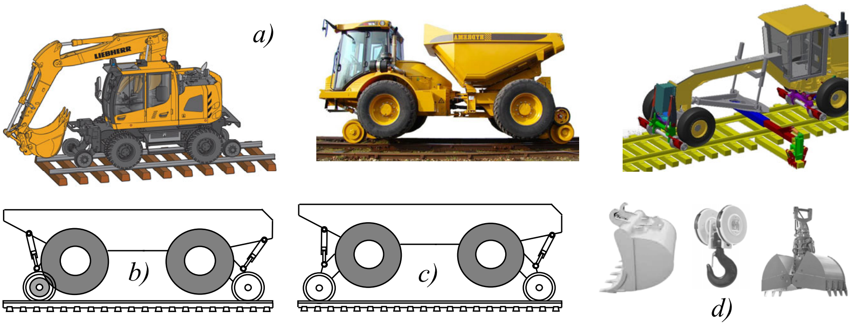

Figure 1
Mobile machines and tools which are used in railway transport

In motion modules with indirect drivetrain, the drive wheel (Figure 1b) in a friction pair transmits drive directly or indirectly to the rail wheel. In motion modules with direct drivetrain (Figure 1c) there are two concepts. The first achieves motion of the machine through the friction pair of the drive wheel and rail stripes. In the second, motion modules have their own hydrostatic transmission, which drives the rail wheels independently of the transmission of the machine movement. Motion modules have a brake system that is derived in the form of hydraulic disc brakes. During operation, resting on railway tracks, hydraulic excavators mostly have a backhoe manipulator, which is equipped with various executive tools in the form of a bucket, hook, or grabber (Figure 1c). Railway track loads are investigated by experimental measurements and theoretical analyses through the development of mathematical models and numerical simulation procedures [8] [9]. Research [10] into railway track loads refer to the experimental simulation of the spectrum of static and dynamic loads, which can occur during the lifetime, with the aim of optimizing and determining the capacity and service life of the elements of the railway track structure. In paper [11], the dynamic relationship between the railway track and the railway vehicle when moving in the curve of the railway track was analyzed using the developed mathematical model. The influence of crawler mobile machines on the moving surface was analyzed in [12] with the aim of determining the parameters of the movement mechanism of a machine, which enables comfortable driving when moving on different surface configurations. The load of a flat surface when a crawler support and movement mechanism of a hydraulic excavator is resting was analyzed in [13], on the basis of the developed dynamic mathematical model of an excavator with a backhoe manipulator. The analysis of the capacity of hydraulic excavators resting on railway tracks is given in [14], where the permissible capacity of the excavator with a backhoe manipulator, in the entire working space, is determined based on the static stability of the excavator and the hydraulic stability of manipulator drive mechanisms. In what follows, a general mathematical model of a hydraulic excavator is defined to determine the load of the railway track and the dynamic stability during the operation of the excavator resting on the railway track.

2 Mathematical Model

A mathematical model is developed for the general configuration of an excavator kinematic chain composed of: the support and movement mechanism L_1, (member by which the excavator rests or moves) (Figure 2a), the rotating platform L_2 and the three-plane manipulators with: boom L_3, stick L_4 and backhoe bucket L_5, which drives the hydraulic cylinder two-way action c_3,c_4,c_5. The support and movement member of the excavator is a conventional (standard) movable mechanism with integrated pneumatic modules, having a pair of railway wheels with a mechanism for raising and lowering without stabilizers.

The position of the members of the excavator kinematic chain is defined by the mathematical model in the absolute coordinate system $OXZY$ with the generalized coordinate θ_i (Figure 2a) determined by the set [15]:

$$\theta = \{\theta_1, \theta_2, \theta_3, \theta_4, \theta_5\} \tag{1}$$

where: θ_1 - the displacement of the support-movement member, θ_2 - the angle of the rotation platform, θ_3 - the angle of the boom position, θ_4 - the angle of the stick position and θ_5 - the angle of the backhoe bucket position.

The mathematical model of the member of the kinematic chain excavator L_i was defined in its local coordinate system $O_i\ x_i\ y_i\ z_i$, with geometric, kinematic and dynamic parameters covered with a set of quantities:

$$L_i = \{\boldsymbol{e}_i, \boldsymbol{s}_i, \boldsymbol{t}_i, m_i, J_i\} \tag{2}$$

where: $\boldsymbol{e}_i$ - the unit vector of joint axes O_i whose member L_i is linked to the previous member L_{i-1}, $\boldsymbol{s}_i$ - the position vector of the center joint O_{i+1}, which is the chain member L_i linked with the next member L_{i+1} (intensity vector is the length of the kinematic members) $\boldsymbol{t}_i$- the position vector of the center of mass of member L_i, m_i – the mass of member, J_i – the member moment of inertia. The parameters of the manipulator drive mechanism of the excavator are determined using a set of parameters:

$$P_i = \{ d_{i1}, d_{i2}, a_i, b_i, m_{ci} \} \tag{3}$$

where: d_{i1}, d_{i2} - the diameter of the piston/piston rod in the hydraulic cylinder, a_i, b_i - the vectors, i.e. coordinates, of the position of the centers of the joints in which the hydraulic cylinders are connected to the members of the drive mechanism kinematic pair, m_{ci} - the mass of the hydraulic cylinder.

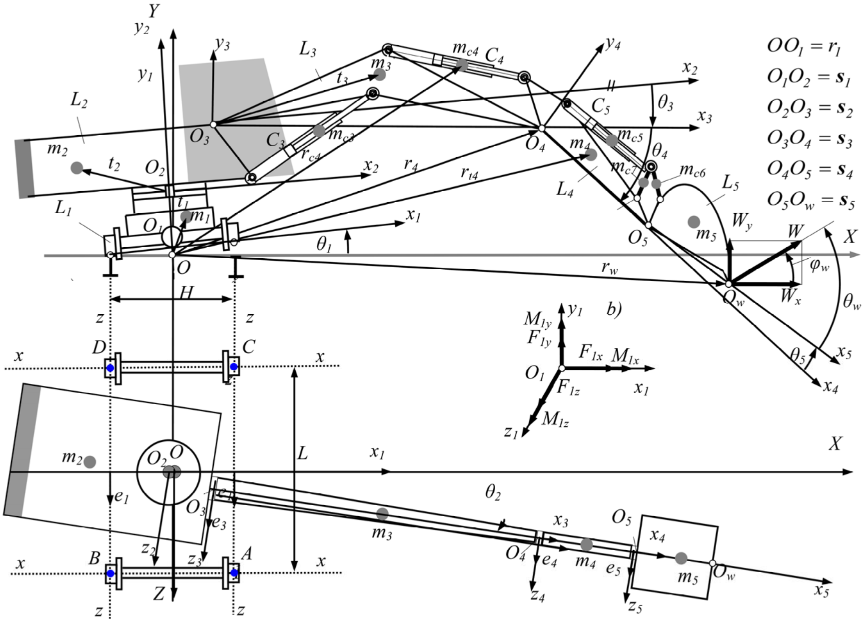

Figure 2
The mathematical model of the hydraulic excavator for determining reaction reliance

The mathematical model of the excavator is based on Newton-Eyler dynamic equations and the following assumptions:

- the support surface and kinematic chain members are modeled using rigid bodies,
- during the manipulation task, gravitational and inertial forces and digging resistance force *W* act on the members of the kinematic chain,
- the support surface of the excavator lies in the horizontal plane *OXZ* of the absolute coordinate system,
- the movement of the support-movement member of the excavator is neglected and it is accepted that the generalized coordinate is $\theta_1 = 0\,°$,
- all excavator loads are transferred to the support surface in the centers *A, B, C* and *D* of the contact surfaces of railway wheels and railway tracks,

- connecting lines (x-x and z-z) of the centers *A, B, C* and *D* of contact surfaces are potential lines of overturning of excavators, which form a supporting polygon with the center in the coordinate origin *O* of the absolute coordinate system *OXYZ* with unit vectors ***i, j, k***.

According to the introduced assumptions, by reducing all the loads of the excavator to the center of the support surface *O*, the resulting force F_1 and the resulting moment M_1, which load the support surface of the excavator, are obtained [15-17]:

$$\boldsymbol{F_1} = \boldsymbol{W} + \sum_{i=1}^{5} \boldsymbol{F_{ui}} - \boldsymbol{j} \sum_{i=3}^{5} g m_{ci} \tag{4}$$

$$\boldsymbol{M_1} = (\boldsymbol{r_w} \times \boldsymbol{W}) + \sum_{i=1}^{5} (\boldsymbol{r_{ti}} \times \boldsymbol{F_{ui}}) + \sum_{i=1}^{5} \boldsymbol{M_{ui}} - \sum_{i=3}^{5} (\boldsymbol{r_{ci}} \times \boldsymbol{j}) g m_{ci} \tag{5}$$

where: $\boldsymbol{W}$ *[kN]*- the vector of the digging resistance force, $\boldsymbol{F_{ui}}$ *[kN]*- the vector of the total force acting in the center of mass of the member of the excavator kinematic chain, $\boldsymbol{M_{ui}}$ *[kNm]*- the vector of inertial moment of the member of the excavator kinematic chain, $\boldsymbol{r_w}$ - the vector of position of the cutting-edge of the bucket, $\boldsymbol{r_{ti}}$ – the vector of the center of mass of the member of the excavator kinematic chain, m_{ci} – the mass of hydraulic cylinders of the excavator manipulator drive mechanisms, $\boldsymbol{r_{ci}}$ - the vector of the center mass of the hydraulic cylinder.

The vector of the total force $\boldsymbol{F_{ui}}$ acting in the center of mass of the member of the excavator kinematic chain is determined by the following equation:

$$\boldsymbol{F_{ui}} = m_i \boldsymbol{u}_i - g m_i \boldsymbol{j} \tag{6}$$

where: $\boldsymbol{u_i}$ - the vector of linear acceleration of the member.

Components of the vector of the resulting force $\boldsymbol{F_1}$ and the moment $\boldsymbol{M_1}$ in the absolute coordinate system are

$$F_{1x} = \boldsymbol{F_1} \cdot \boldsymbol{i}\,; \qquad F_{1y} = \boldsymbol{F_1} \cdot \boldsymbol{j}\,; \qquad F_{1z} = \boldsymbol{F_1} \cdot \boldsymbol{k} \tag{7}$$

$$M_{1x} = \boldsymbol{M_1} \cdot \boldsymbol{i}\,; \qquad M_{1y} = \boldsymbol{M_1} \cdot \boldsymbol{j}\,; \qquad M_{1z} = \boldsymbol{M_1} \cdot \boldsymbol{k} \tag{8}$$

Horizontal forces in the centers *A, B, C* and *D* of the support surface which load the railway track in the *OX* direction have the value:

$$F_{Ax} = \frac{F_{1x}}{2} - \frac{M_{1y}}{L} \ \wedge \ F_{Bx} = 0 \ \forall \frac{F_{1x}}{2} - \frac{M_{1y}}{L} > 0 \tag{9}$$

$$F_{Ax} = 0 \ \wedge \ F_{Bx} = \frac{F_{1x}}{2} - \frac{M_{1y}}{L} \ \forall \frac{F_{1x}}{2} - \frac{M_{1y}}{L} < 0 \tag{10}$$

$$F_{Cx} = \frac{F_{1x}}{2} + \frac{M_{1y}}{L} \;\wedge\; F_{Dx} = 0 \;\forall\; \frac{F_{1x}}{2} + \frac{M_{1y}}{L} > 0 \tag{11}$$

$$F_{Cx} = 0 \;\wedge\; F_{Dx} = \frac{F_{1x}}{2} + \frac{M_{1y}}{L} \;\forall\; \frac{F_{1y}}{2} + \frac{M_{1y}}{L} < 0 \tag{12}$$

where: L - the range of railway wheels of the excavator movement mechanism.

Vertical forces in the centers *A, B, C* and *D* of the support surface which load the railway track in the *OY* direction have the value:

$$F_{Ay} = \frac{F_{1y}}{4} - \frac{M_{1x}}{2L} + \frac{M_{1z}}{2H} \qquad F_{By} = \frac{F_{1y}}{4} - \frac{M_{1x}}{2L} - \frac{M_{1z}}{2H} \tag{13}$$

$$F_{Cy} = \frac{F_{1y}}{4} + \frac{M_{1x}}{2L} + \frac{M_{1z}}{2H} \qquad F_{Dy} = \frac{F_{1y}}{4} + \frac{M_{1x}}{2L} - \frac{M_{1z}}{2H} \tag{14}$$

where: H - the width of the railway track of railway wheels of the excavator movement mechanism.

Based on the set mathematical model, a program was developed for dynamic simulation of the excavator and, among other things, determination of dynamic loads of the railway during the operation of the excavator resting on the railway track. During the simulation, the conditions of movement of the kinematic chain of the excavator and technological resistances of movement during the manipulation task of the excavator were set.

3 Example

As an example, using the mathematical model and program, the railway load analysis was performed during the operation of an excavator, weighing *17000 kg,* resting on the railway track with a support and movement mechanism with railway wheels, longitudinal wheel range *L* (Table 1) and wheel width *H.* The numerical simulation procedure was used to analyze the configuration of a kinematic chain with a backhoe manipulator with a boom, stick and bucket with a volume of $0,6\ m^3$ (Table 1). The manipulation task of the excavator was simulated with the following operations: capturing (digging), transfer and unloading of material of specific mass $\gamma_z=1500\ kg/m^3$ and returning to the new digging position (Table 1). During the simulation, the conditions of movement of the members of the excavator kinematic chain during the manipulation task were given, as defined in the set of the following simulation parameters:

$$U = \{\theta_2, c_3, c_4, c_5, p_{21}, p_{22}, p_{31}, p_{32}, p_{41}, p_{42}, p_{51}, p_{52}\} \tag{17}$$

where: θ_2 *[°]*- the angle of the rotation platform (Figure 3), c_3 *[m]*– the length of the boom cylinder (Figure 3), c_4 *[m]*– the length of the stick cylinder, c_5 *[m]*– the length of the bucket cylinder, p_{21}, p_{22} *[MPa]*– the pressures in the hydraulic motor lines to turn the platform (Figure 4), p_{31}, p_{32} *[MPa]*- the pressures in the hydraulic cylinder lines of the boom (Figure 4), p_{41}, p_{42} *[MPa]*- the pressures in the hydraulic cylinder lines of the stick (Figure 5), p_{51}, p_{52} *[MPa]*- the pressures in the hydraulic cylinder lines of the bucket (Figure 5). The given parameters of simulation of the excavator were determined by measuring a physical model of the hydraulic excavator weighing *17000 kg* with a backhoe manipulator, when operating in exploitation conditions [18]. Based on the given simulation parameters, the developed program determined: the coordinates of the position of the members of the kinematic chain, the linear and angular velocities and accelerations, the gravitational and inertial forces and inertial moments of the members, the components of the resistance of the digging force and the static and dynamic loads of the railway.

Tabele 1
Parameters of kinematics chain of excavator (Figure 2)

Title	Symbol	Values [*m*]	Mass[*kg*]
Support and movement member L_1	*L/H*	*4,610 /1,435*	*7040*
Rotation platform L_2	-	-	*6765*
Boom L_3	s_3	*5,0*	*1270*
Stick L_4	s_4	*1,8*	*430*
Bucket L_5	s_5	*1,3*	*540*
Hydraulic motor of rotation platform $1xC_2$	d_{21}/d_{22}	*75/75* cm^3	*25*
Boom hydraulic cylinder $2xC_3$	d_{31}/d_{32}	*0,115/0,080*	*205*
Stick hydraulic cylinder $1xC_4$	d_{41}/d_{42}	*0,140/0,090*	*280*
Bucket hydraulic cylinder $1xC_5$	d_{51}/d_{52}	*0,115/0,080*	*190*

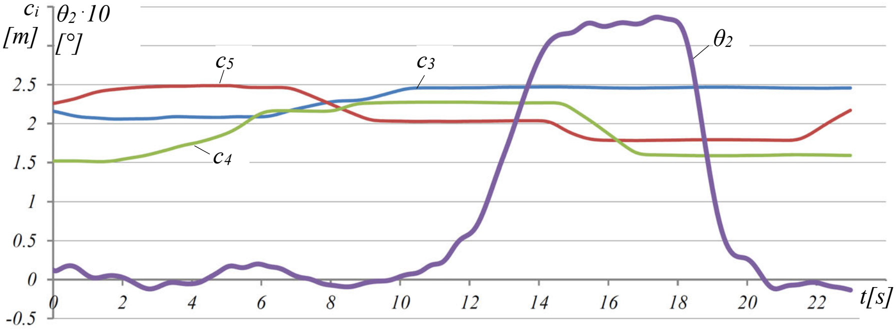

Figure 3
Given simulation parameters for the angle of the rotation platform θ_2, and the lengths (strokes) of the hydraulic cylinder of the boom c_3, stick c_4 and bucket c_5

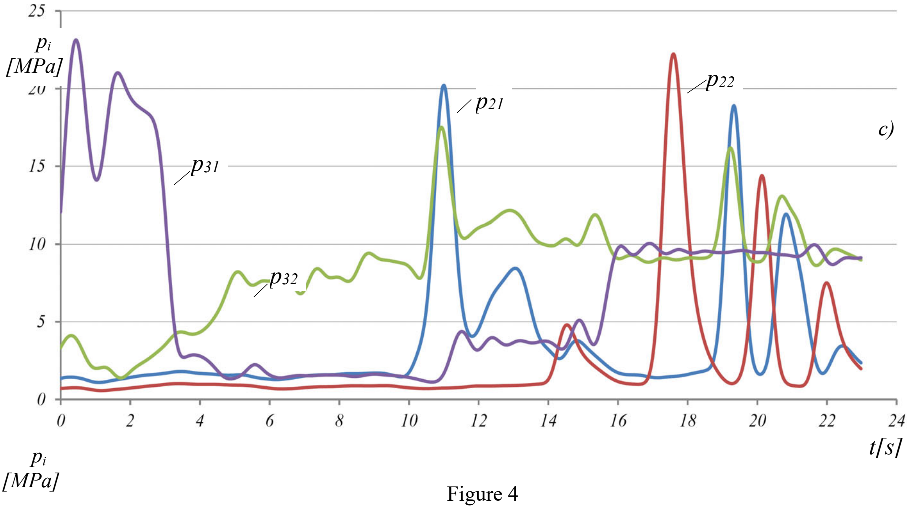

Figure 4

The parameters of simulation: pressures in the hydraulic motor lines to turn the platform p_{21}, p_{22} and pressures in the hydraulic cylinder lines of the boom p_{31}, p_{32}

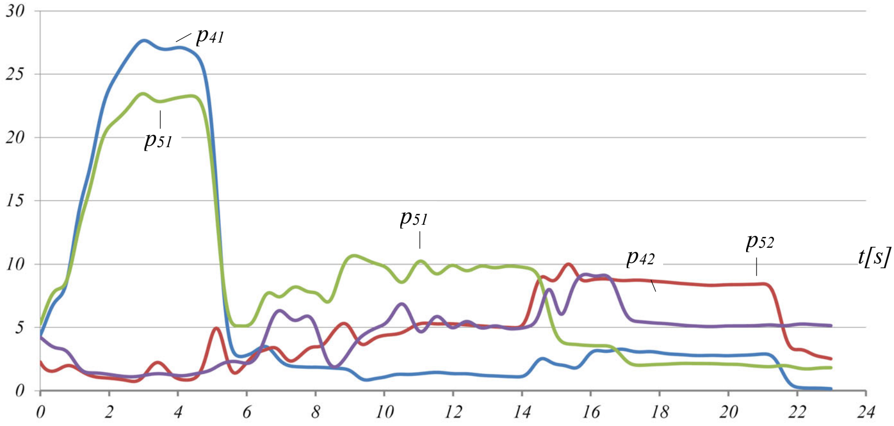

Figure 5

The parameters of simulation: pressures in the hydraulic cylinder lines of the stick p_{41}, p_{42} iand bucket p_{51}, p_{52}

4 Analysis

The obtained simulation results show that during the capture operation ($\theta_2 = 0^\circ$) the maximum digging depth is Y_w=*-1,5 m* (Figure 6a), and during the unloading operation ($\theta_2 = 30^\circ$) the maximum unloading height is around Y_w=*4m*.

During the capturing of materials (*t=0-5,8 s*), the components of vector *W* (Figure 6b) of the digging resistance force change differently.

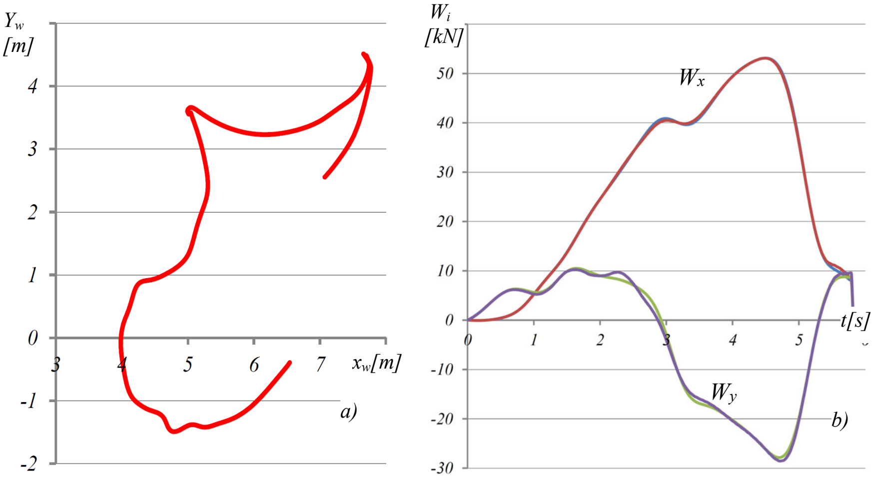

Figure 6

The parameters of the manipulation task of the excavator: a) the center path of the bucket cutting edge, b) the components of the digging resistance force *W* vector

The horizontal component W_x has a variable one-way action, while the vertical component W_y has a variable intensity and a variable direction of action. The lateral component is of insignificant intensity in relation to other components of the digging resistance force *W*.

It is characteristic that the magnitude of the total force F_1 (Figure 7a) and the total moment M_1 (Figure 7b) obtained by reducing all excavator loads to the center of the excavator support surface during the manipulation task possesses, in addition to gravitational forces, inertial loads of kinematic chain members. A comparison of total (F_1,M_1) with static loads (F_{1s},M_{1s}) shows that the highest inertial loads occur at the beginning (*t=6s*) of the material transfer operation, when the manipulator is abruptly lifted from the material capture channel.

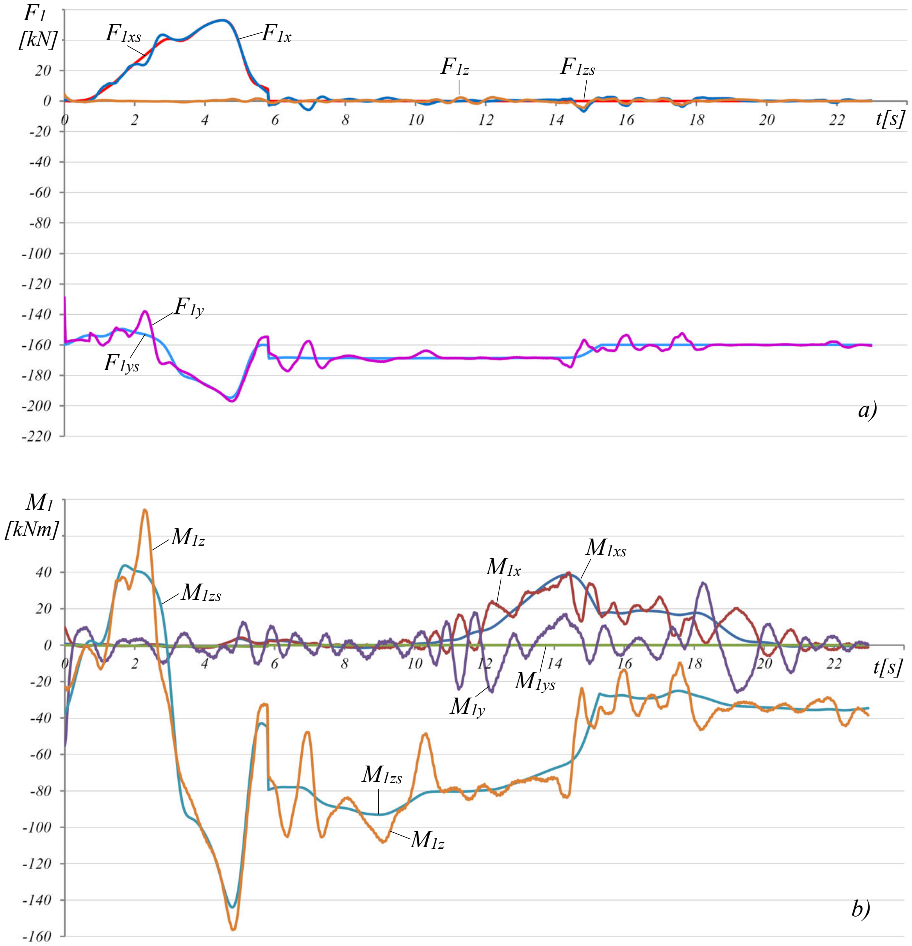

Figure 7

Load vector components: a) forces F_1 and b) moment M_1 in the center of the excavator support surface

Slightly smaller inertial loads occur (*t=5 s*) at the beginning of the accelerated rotation of the platform with the manipulator from the digging plane ($\theta_2 = 0^\circ$) to the unloading plane ($\theta_2 = 36^\circ$). The increase in inertial loads occurs again (*t=15 s*) due to abrupt stopping of the platform with the manipulator in the unloading plane of material. Inertial loads of lower intensity also occur during the unloading operation due to an abrupt change in the mass of the captured material when emptying the bucket.

The lowest intensity of inertial loads occurs during the operation of capturing (digging) the material due to the relatively slow and not so abruptly changing movement of the members of the kinematic chain of the excavator.

By decomposing the total force F_1 and the moment M_1, significantly variable loads of the railway track were obtained during the manipulation task in the centers *A, B* (Figure 8) *C, D* (Figure 9) of the support surface of the railway wheels of the support and movement mechanism of the excavator on the railway track.

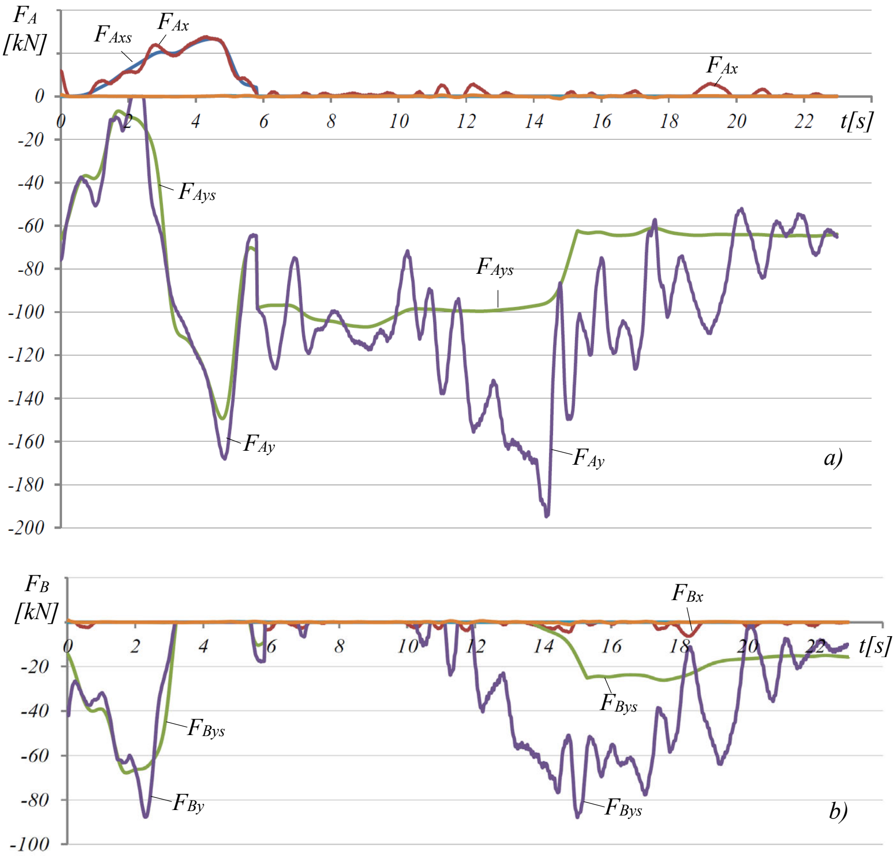

Figure 8

Forces loading the railway track in the *X* and *Y* directions in supports: a) *A*, b) *B*

According to the given conditions of the excavator simulation, the railway track is most loaded in supports *A* (Figure 8a) and *C* (Figure 9a), while in supports *B* (Figure 8b) and *D* (Figure 9b) minimal loads occur during the highest period of the manipulation task, especially in support D.

During the operation of capturing (digging) (t=0-5,8 s), the railway track is most loaded in supports *A* and *C* due to static loads - the resistance of digging and gravitational forces of the members of the kinematic chain of the excavator, while inertial loads are small. During the same operation, the horizontal railway track loads F_{Ax} and F_{Cx} (Figures 8, 9) occur due to the action of the horizontal component W_x of the digging resistance force, while the railway track is unloaded in the same direction $F_{Bx}=F_{Dx}=0$ (Figures 8, 9).

The vertical loads F_{Ay} and F_{Cy} of the railway track in supports *A* and *C*, at the beginning (t = *0-2,5 s*) of the digging operation, decrease due to the increase in the positive value of the vertical component W_y of the digging resistance force, up to (t = *2,5 s*) of unloading ($F_{Ay}=F_{Cy}=0$) of the railway track in that direction. In the same period, loads F_{By} and F_{Dy} (Figures 8b, 9b) of the railway track in supports *B* and *D* increase and reach the maximum value during the digging operation.

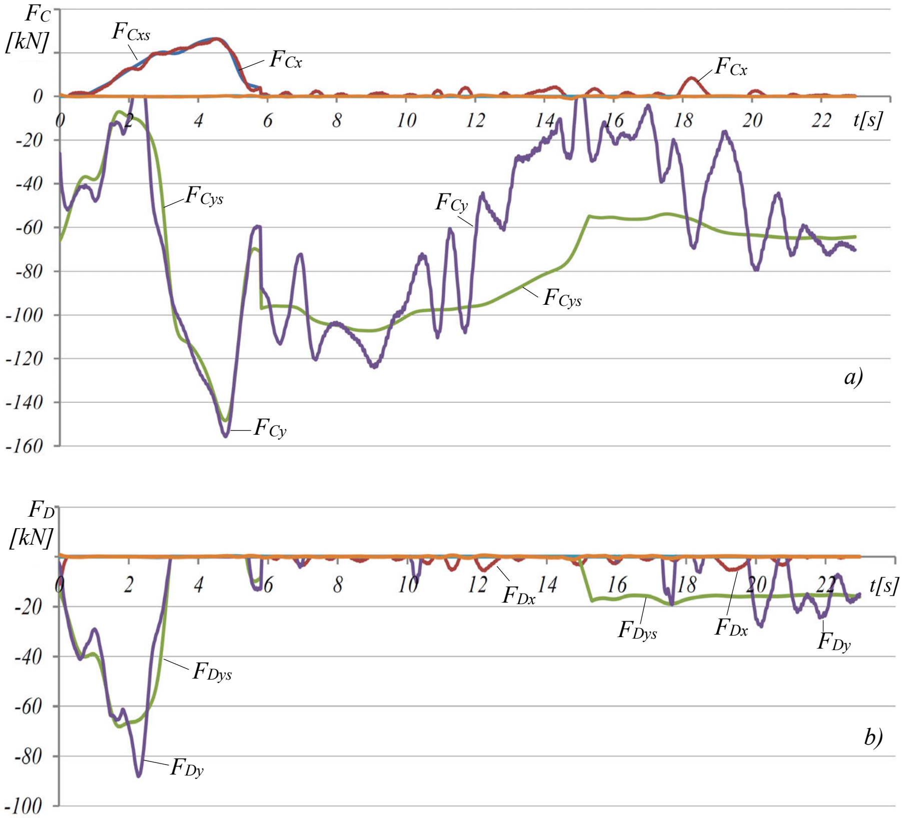

Figure 9

Forces loading the railway track in the X and Y directions in supports *: a) C, b) D*

In other operations of the manipulation task, the maximum vertical load of the F_{Ay} of the railway track occurs (t = *14s*) in support *A* due to the occurrence of the maximum inertial loads at the end of the material transfer operation due to abrupt stopping of the platform with the manipulator in the unloading plane.

In the same period (t = 12-15 s) there is an increase in the vertical load F_{By} (Figure 8b) of the railway track in support *B* and a decrease (*t = 10-15 s*) in the vertical load F_{Cy} to unload the railway track ($F_{Cy}=0$) in support *C*. The increase in vertical loads of the F_{Cy}, F_{Dy} railway track in supports *C* and *D* occur during the operation of returning the manipulator by turning the platform to a new digging plane (*t=18-23 s*). Slight horizontal loads F_{Ax} and F_{Cx} (Figure 8a, 9a) of the railway track, in relation to the same loads during the digging operation, occur at the beginning (*t = 13 s*) of the material transfer operation and at the beginning (*t = 18 s*) of the manipulator return operation to the new digging position.

The results of the analysis show that the vertical loads of the railway track in the supports are significantly higher than the horizontal loads. Comparing the static vertical loads of the railway track (F_{Asy}, F_{Bsy}, F_{Csy}, F_{Dsy}), caused by the action of the digging resistance force and gravitational forces of the kinematic chain of the excavator and material in the bucket, with the total vertical loads (F_{Ay}, F_{By}, F_{Cy}, F_{Dy}), indicates that the maximum inertial forces of the railway track occur due to lifting the manipulator with the captured material from the digging channel, then at the beginning and end of the operation of material transfer by turning the platform with the manipulator, and at the end of the operation of returning to a new digging plane.

Conclusion

Mobile machines (hydraulic excavators, loaders, cranes, …) have found great application on the railway in performing operational functions of transmission and transport, but also in the development and maintenance of infrastructure - especially railway tracks. For performing functions on the railway track, mobile machines are equipped with special support and movement mechanisms, with two - axle railway wheels, which enable them stable support and movement.

Hydraulic excavators weighing *10000-25000 kg*, equipped with various manipulators and tools (buckets, hooks, grapples, …) are used on the railway to perform various manipulative tasks. In the paper, a general mathematical model of a hydraulic excavator was developed for determining the dynamic loads of the railway during the operation of an excavator resting on the railway track.

The mathematical model includes the configuration of a kinematic chain of an excavator, weighing *17000 kg*, with a support and movement mechanism, with two - axle railway wheels and a backhoe manipulator. The numerical simulation procedure of the excavator yielded the results which show that during the operation of the excavator resting on the railway track, dynamic loads of the railway track occur.

Loads depend on the position and character of the change in the movement of the members of the kinematic chain of the excavator during the manipulation task. During the capture operation, the static loads of the railway track are primary due to the action of the digging resistance force and the gravitational forces of the members of the kinematic chain of the excavator.

During the material transfer operation, in addition to static forces, the railway track is significantly loaded by inertial forces occurring due to the abrupt movement and stopping of the rotating platform with the manipulator when moving from the digging plane to the material unloading plane. The obtained research results, in addition to the analysis of the railway track load, can be used to assess the dynamic stability of excavators.

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