Computer Modelling of Roadheader's Body Vibration Generated by the Working Process

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Abstract

Boom–type roadheaders represent heavy working machines used in underground mines for the drilling of dog headings, for tunnelling and – to a certain extent – for surface mining. The key working process carried out by such roadheaders is rock mining. This process, especially when cutting rocks with low workability, causes strong vibration excitations and dynamic loads not only in a roadheader cutting system, but within its entire construction. The article presents a dynamic model of a boom–type roadheader body. Four vibrating masses, representing the key subassemblies of the studied object and a seat together with a roadheader operator, are distinguished in a spatial physical model with a discrete structure. They are subject to the activity of an excitation from the loads generated in the cutting process. A mathematical model is comprised of 19 non-linear ordinary differential quotations of the second order. The model was implemented in the MATLAB/Simulink environment, in which a simulation model was created. The article presents the examples of results of numerical simulations using the established model.

Keywords: roadheader, dynamic model, dynamic loads, vibrations

1. Introduction

Roadheaders are working machines used in mechanised technologies for drilling dog headings and chamber headings in underground mines and tunnels in civil engineering. Roadheaders are multi–functional machines designed for the mechanisation of the basic activities connected with the drilling of mine headings, namely tunnels. The activities encompass, in particular, rock cutting, loading the mined rock into the means of transport, transporting the mined rock from the heading face, as well as mechanised erection of a dog heading support. For this reason, such machines are subject to the activity of vibration excitations originating from different sources, with their varied intensity. As the key process carried out by such type of machine is the mechanical cutting of rock, the vibrations they are susceptible to and the dynamic loads of their construction are basically caused by interactions taking place in the machine–mined rock configuration. Such an activity is not limited here only to a drive of the working units directly performing the cutting process, but is transmitted by such working units' load-carrying structure onto the roadheaders' other subassemblies. The vibrations excited by and the dynamic loads generated by the cutting process of rocks with especially low workability, are having the greatest effect on the durability and reliability of not only the roadheader cutting system, but also its other subassemblies and systems.

The dynamic state of the group of heavy working machines discussed is analysed here not only to draw conclusions concerning the improvement of their construction. The investigations of roadheaders' dynamics are of high significance also for ensuring the operational safety and ergonomics of such type of mining machines. Such investigations include, notably, those aimed at identifying the magnitude and character of the excited vibrations transferred onto an operator's station for evaluating the impact of mechanical vibrations on a human organism and an operator's vibration isolation [1,7], or examining the stability of the discussed machines. A roadheader may lose its stability as a result of the vibrations generated in a working process, and a serious hazard may be posed for people working in the confined space of dog headings or tunnels (this concern also applies to numerous mobile machinery, for instance cranes [4]). The vibrations excited by roadheader operation, transferred through a substrate (the floor plane of a heading being driven) to the environment may also be a source of paraseismic vibrations (tremors) [5]. Such vibrations are propagated in rock mass, in the surrounding of a place where mining works are carried out. Such vibrations may affect the environment adversely.

This article touches upon the issue of modelling of vibrations and dynamic loads of boom–type roadheaders. Such machines are a sub–group of mining roadheaders, used for excavation of dog headings, equipped with working units in the form of cutting heads with small dimensions, in relation to the cross section area of the headings excavated with them. The heads are mounted at the end of a boom which is inclined in two mutually perpendicular planes. Cuttings heads can be moved this way along the heading face surface along any track. Rock mining is carried out in this case by way of cutting – by means of picks mounted on a cutting head, where the rotary motion of a cutting head is caused by a drive system.

The research works pursued until now have been related to the dynamics of selected subassemblies of a roadheader or its components – mainly the cutting system: cutting heads, their drive and a load–carrying structure (e.g. [2,3,6,9]). The reasons given above allow to conclude, however, that the entire object should be treated as a whole – as a complex dynamic system, taking into account the dynamic impact onto its substrate. The article presents a dynamic model of a boom–type roadheader body. For the purpose of numerical investigations of the roadheader's dynamics, the mathematical model created was implemented in the MATLAB/Simulink environment, in which a simulation model was created. The article presents the examples of computer simulations accompanying the execution of a working process of cutting the heading face surface of the dog heading being drilled.

2. Physical model

The construction of a boom–type roadheader body supports the creation of discrete physical models. Four rigid bodies connected with each other with weightless viscoelastic elements are distinguished in a physical model of the studied object (Fig.1).

The bodies represent the key parts of a roadheader boom, i.e.: roadheader casing (1), movable part of the turntable (2) and a boom with cutting heads (3), and a seat together with an operator seating on it (4). A movable part of the turntable with a vertical axis of rotation is fitted rotationally to the roadheader casing (body). In case of the considered roadheader construction, the movable part of the turntable is provided with a bearing relative to the fixed part (of the roadheader casing) by means of two bearings – a axial and radial bearing. The rotary motion of a movable part of the turntable is carried out here with an actuating–rack–and–pinion mechanism. The activity of such a mechanism is modelled in the form of the concentrated force $P_{SO} = f(\dot{\varphi}_{OZ})$ applied to point 13. The direction in which the force is acting is parallel to the axis X_O of the system of coordinates $X_OY_OZ_O$. A roadheader boom is mounted to the movable part of the turntable by means of two slide bearings and is supported with two hydraulic lifting actuators – a right one (SPP) and left one (SPL).

The roadheader components mentioned above are considered as rigid bodies with the mass of, respectively, m_K, m_O, m_W and m_{FO}, concentrated in their centres of gravity (in the points: S_{CK}, S_{CO}, S_{CW} and S_{CFO}) and with the moments of inertia of, respectively: I_{KX}, I_{KY} and I_{KZ}, (roadheader casing) I_{OX}, I_{OY} and I_{OZ} (movable part of the turntable) and I_{WX}, I_{WY} and I_{WZ} (boom). The values of moments of inertia of the turntable and boom were determined in relation to the axis of the system of coordinates $X_OY_OZ_O$.

The activity of the roadheader casing on the substrate was modelled as six viscoelastic constraints with the specific rigidity k_i and the damping coefficient c_i (for i=1,…,4) applied in the points marked with numbers from 1 to 4. Four of them (nominated with index Z) are transmitting loads perpendicular to the substrate. Two of them (nominated with index X and Y) – are transmitting loads in the plane parallel to the substrate, in the direction of the axis X_K and Y_K of the system of coordinates $X_KY_KZ_K$ connected with the roadheader body.

The susceptible mounting of the movable part of the turntable in relation to its fixed part was modelled as six viscoelastic constraints applied in the points numbered 5 to 10. They represent the considered way of its bearing. Out of six viscoelastic elements, fours are situated in the vertical direction and arranged at the pitch diameter of the axial slide bearing raceway (located in the upper part of the turntable). The activity of a radial bearing situated in the lower part of the turntable is modelled by means of other two constraints (situated horizontally, perpendicular to each other). The bearing of the boom on the turntable is presented as five viscoelastic elements applied in points 11 and 12. The constraints are representing reactions acting in the place where a boom is fitted to a turntable in slide bearings. As already mentioned, the boom is supported with two hydraulic actuators. The actuators' dynamics is shown as indicated in the work [8]. The mounting of the operator's seat to the roadheader casing is modelled by means of a single viscoelastic element with the rigidity k_{FO} and the damping factor c_{FO}. It was assumed that the seat–operator system has only a single degree of freedom (this results from the mounting construction).

The physical spatial model created has nineteen degrees of freedom. The temporary location of a roadheader casing modelling solid is described with the six coordinates:

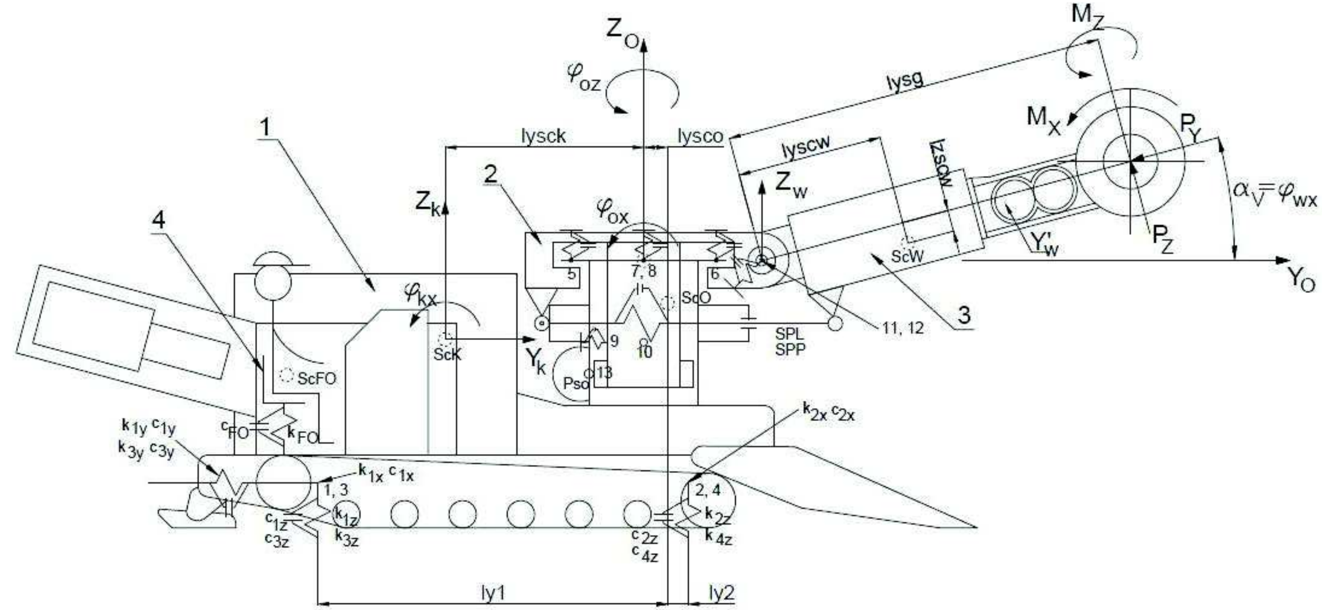

Figure 1. Physical model of roadheader body (view of the YZ plane): 1 – roadheader casing, 2 – movable part of the turntable, 3 – boom with cutting heads, 4 – seat together with roadheader operator

three translation coordinates – x_K, y_K and z_K, and three rotation coordinates – φ_{KX}, φ_{KY}, and φ_{KZ} (six degrees of freedom). The following designations for coordinates were used for the movable part of the turntable: x_O, y_O, z_O (for translation movement) and φ_{OX}, φ_{OY}, φ_{OZ} (for rotational movement). The following translation coordinates are describing the situation of the boom: x_W, y_W, z_W and the rotation coordinates: φ_{WX}, φ_{WY}, φ_{WZ}. The vibrating motion of the seat together with the operator is described by the translation coordinate z_{FO} measured in the direction of the axis Z_K of the system of coordinates connected with the roadheader body.

Vibration excitations are acting on the masses distinguished in the physical model in the form of an external load, which are the result of carrying out the working process (cutting the heading face of the drilled dog heading). This load was reduced to the intersection point of the boom longitudinal axis with an axis of rotation of the cutting heads and was described with six components – three concentrated forces (P_X, P_Y and P_Z) and three moments of forces (M_X, M_Y and M_Z). The time curves of this excitation are generated in a separate computer programme for the set values of parameters for the execution of this cutting process.

3. Mathematical model

The motion equations in the developed physical model were entered using the Lagrange second degree equation:

$$\frac{d}{dt}\left(\frac{\partial E_K}{\partial \dot{q}_j}\right)+\frac{\partial E_P}{\partial q_j}=Q_j-R_j \qquad \text{, for } j=1,2,\ldots,19 \tag{1}$$

where: E_K – kinetic energy of the system; E_P – potential energy of the system; Q_j – the external generalised force corresponding to the coordinate q_j; R_j – the generalised resistance force corresponding to the coordinate q_j; q_j and $\dot{q}_j$ – the generalised (translation or rotation) coordinate and its first derivative

A mathematical model describing motion in the established physical model of the studied object consists of a system of 19 ordinary nonlinear second–order differential equations, which have the following form in the matrix–vector form:

$$\mathbf{M}\cdot\ddot{\mathbf{q}}+\mathbf{C}\cdot\dot{\mathbf{q}}+\mathbf{K}\cdot\mathbf{q}=\mathbf{Q} \tag{2}$$

where: **M**, **C**, **K** – mean, respectively, the matrix of: inertia, damping and rigidity; **Q** – vector of external forces; whereas $\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}$ – vectors of generalised coordinates and their subsequent derivatives. The vector of generalised coordinates **q** has the following form here:

$$\mathbf{q}=\left[x_K, y_K, z_K, \varphi_{KX}, \varphi_{KY}, \varphi_{KZ}, x_O, y_O, z_O, \varphi_{OX}, \varphi_{OY}, \varphi_{OZ}, x_W, y_W, z_W, \varphi_{WX}, \varphi_{WY}, \varphi_{WZ}, z_{FO}\right]^T \tag{3}$$

The motion equations were entered into MATLAB/Simulink software after executing relevant conversions. Three layers can be distinguished in a hierarchy structure of the so obtained simulation model. Functionally interrelated sub-systems are situated in the master layer (Fig.2), which are representing the vibrating elements distinguished in a physical model (roadheader casing, turntable, boom and seat with an operator), a block responsible for recording calculations results (to workspace) and blocks responsible for calculating, in successive steps, numerical integration of motion equations of temporary values of dynamic parameters of actuators lifting the boom (Lsp, P_SP) and the force developed by a boom rotation mechanism actuator (Pso). The second layer of the simulation model consists of blocks in which motion equations are implemented for each of vibrating masses (Fig.3). Motion equations are integrated numerically in the lowest (third) layer by means of appropriate function blocks (integrators) (Fig.4). The values of coordinates of each of the masses are established in successive integration steps as a result of solving a motion equation iteratively. Motion equations are integrated numerically by means of a fourth order Runge–Kutta algorithm with a constant integration step.

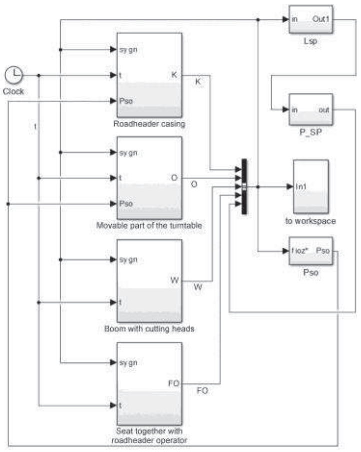

Figure 2. Master layer of simulation model in MATLAB/Simulink environment

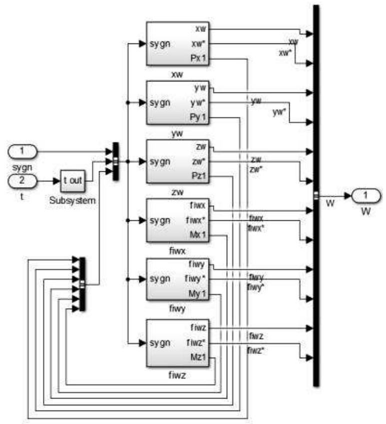

Figure 3. Second layer of simulation model

4. The examples of simulation results

Figures 5 and 6 show the selected results of computer simulations of roadheader body dynamics using the developed simulation model. The motion of the boom together with a movable part of the turntable was started in the right direction in the considered time interval, after the lapse of 0.5 s of the simulation. The cutting heads performed 3 revolutions over the next 2.5 s of the simulation. During this motion, the roadheader body was loaded with forces exciting vibrations generated by a cutting process. The cutting of the rock with the compressive strength of R_C=80 MPa with the web of z=0.13 m was simulated here. As seen, the working process carried out by the roadheader is a source of strong vibrations of its components, in particular – a boom. The angular speed of boom deflection was established at the average level of 0.033 rad/s, whereas the amplitude of such speed vibrations (understood as the variability range) was 0.05 rad/s. During this time interval the boom turned about the axis of rotation of the turntable through an angle of ~5 deg.

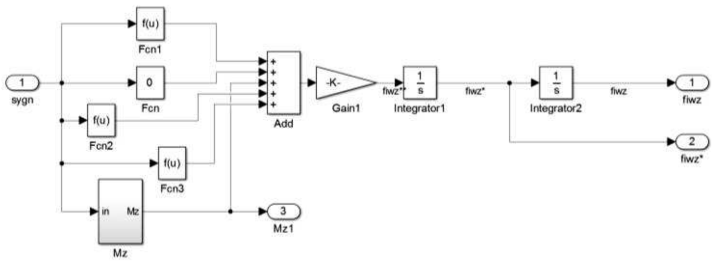

Figure 4. Structure of the lowest (third) layer of simulation model with the example of equation describing the rotation motion of the boom along the axis Z

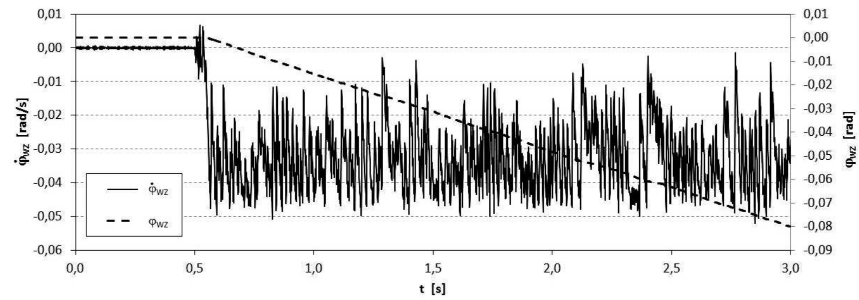

Figure 5. Boom angular speed and its angular displacement curve relative to the axis Z

Due to the dynamic properties of the studied object resulting from its construction (especially with the use of hydraulic actuators), the boom subjected to the activity of a variable external load is performing intensive lateral vibrations (Fig.6). This is important considering the dynamic state of the studied machine as well as the working process it performs. The roadheader body's vibrations result in periodical changes in parameters for which this process is performed. Changes in cutting conditions have, on the other hand, influence of the character and magnitude of excitation of vibrations of the roadheader body. This is because strong feedback exists in the system of the roadheader and the working process carried out by it.

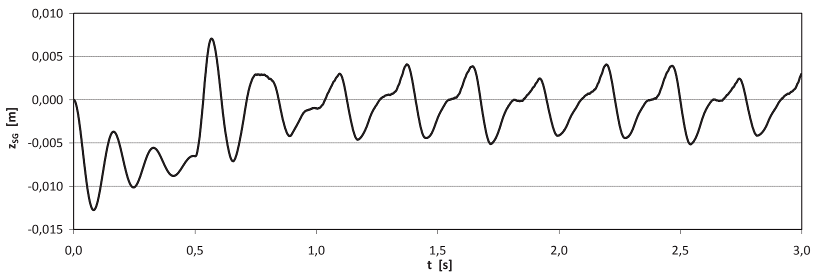

Figure 6. Curve of the coordinate of the boom axis intersection point with the axis of rotation of cutting heads in the direction of the axis Z

5. Conclusions

The dynamic model created allows to perform simulation investigations in order to determine dynamic loads in the selected constructional nodes of a boom–type roadheader body and to analyse its vibrations generated in a working process. Experimental verification is necessary, however, to be able to use it practically for research purposes. The conformity of the results obtained by way of a computer simulation with the actual dynamic characteristics of the modelled object will be established based on the outcomes of experimental investigations. Dynamic characteristics will be measured with an experimental station developed for this aim by the Institute of Mining Mechanisation, Faculty of Mining and Geology, Silesian University of Technology. The R–130 roadheader (manufactured by FAMUR S.A.) will be the object of investigations. Vibrations will be excited in the body of the machine as a result of the cutting process of a block made of equivalent materials.

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