THE CONCEPT OF THE NUMERICAL COMPUTING METHODS FOR ANALYSIS OF OPERATIONAL CONDITIONS OF BUCKET WHEEL EXCAVATORS

KONCEPCJA NUMERYCZNYCH METOD OBLICZENIOWYCH DO ANALIZY WARUNKÓW PRACY KOPAREK WIELONACZYNIOWYCH

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Modernisation of bucket wheel excavators, used in opencast mines, requires identifying their operational condition and analysis of the impact of bucket wheel loads to individual structure nod's load. Possibilities to apply state-of-the-art numerical computing methods to analyse the load to individual subassemblies of the excavator as well as to analyse their vibrations are presented. The use of numerical simulations enables analysis, both in normal operation and in emergency conditions. In addition, co-simulation technique allows simulation of the excavator operation with any load characteristic of individual buckets, as well as the associated load method for electric driven motors. Another advantage of using numerical methods is the ability to simulate the operation of control systems of individual excavator components. Selected results of numerical simulations using a simplified spatial geometric model built as part of the BEWEXMIN project are also presented.

Keywords: numerical analysis, MultiBody System, mining industry, bucket wheel excavators

Modernizacja i rozwój wielonaczyniowych koparek, stosowanych w kopalniach odkrywkowych, wymaga identyfikacji ich stanów pracy oraz analizy wpływu obciążeń koła czerpakowego na obciążenia poszczególnych węzłów konstrukcji. W artykule przedstawiono możliwości zastosowania nowoczesnych metod obliczeniowych w celu analizy obciążenia poszczególnych podzespołów nadwozia koparki, a także do analizy ich drgań. Zastosowanie symulacji numerycznych umożliwia przeprowadzenie analizy zarówno w stanach normatywnej pracy jak i w stanach awaryjnych. Dodatkowo technika symulacji równoległych umożliwia przeprowadzenie symulacji pracy koparki przy dowolnej charakterystyce obciążenia poszczególnych czerpaków, oraz związanego z tym sposobu obciążenia elektrycznych silników napędowych. Kolejną korzyścią zastosowania metod numerycznych jest możliwość przeprowadzenia symulacji sposobu działania układów sterowania poszczególnymi podzespołami koparki. Zaprezentowano także wybrane wyniki symulacji numerycznych przeprowadzonych z zastosowaniem uproszczonego przestrzennego modelu geometrycznego zbudowanego w ramach projektu BEWEXMIN.

Słowa kluczowe: analizy numeryczne, analiza układów wieloczłonowych (MBS), górnictwo, koparki wielonaczyniowe

INTRODUCTION

The MBS (Multibody System) method is a method used to simulate kinematics and dynamics of multibody systems. The use of this method allows to calculate forces and torques in individual nodes of the model, as well as calculations of displacement, speed and acceleration of cooperating elements [4,8]. The concept and possibilities of using state-of-the-art numerical calculation methods to support modernization of the bucket wheel excavator's body structure, is presented. The simplified geometric model of the excavator body, presented in the article, was developed for the needs of the BEWEXMIN project, at KOMAG Institute of Mining Technology [1]. The use of numerical calculations in the analysis of the operation of bucket wheel excavators allows for a comprehensive analysis of the kinematics and dynamics of the body structure. The results of these analyses facilitate and speed up work related to the modernization of these structures, affecting the increase of their durability and improving the working conditions by reinforcing the most strenuous components, expansion with new components or testing new control systems [1, 3, 5, 6].

COMPUTATIONAL MODEL

In order to build a bucket wheel excavator's computational model, it is necessary to have a 3D model. If the 3D model of the machine is not available, its manufacturing takes place on the basis of available technical documentation in the form of 2D drawings, pictures of the machine and measurements made on the existing object. Geometric model intended for numerical simulations is usually a very simplified model, in which the selected components of the structure and the additional equipment found on it (does not affect the way the excavator operates), have been omitted. Components of the excavator's additional equipment, affecting the physical phenomena occurring during the movement are often replaced by concentrated mass or substituting elements that reflect the physical properties of simplified components. As part of the BEWEXMIN project at the KOMAG Institute of Mining Technology, a very simplified geometric model of the bucket wheel excavator's body was built, which is shown in Figure 1 [1].

Based on the presented geometric model, the physical

Fig. 1. Geometric model of the bucket wheel excavator's body [1]
Rys. 1 Model geometryczny korpusu wielonaczyniowej koparki kołowej [1]

model of the excavator was built by linking individual blocks with geometric constraints, elastic-damping components and elements such as ropes. In this model, individual blocks were assigned the mass and moment of inertia. The physical model of the excavator's body is devoid of equipment located on the real object. The equipment includes: electric motors, belt conveyors, operator's cabins, etc. The mass of the elements omitted in the model was taken into consideration by adding it to the mass of one of the structure solids. So, the correct mass of the complete body of the excavator was maintained. The physical model of the excavator's body is shown in Figure 2. Additionally, in this model the bucket wheel boom, the counterweight boom and both masts (fixed and mobile) was discretized, therefore in the simulations they will be treated as deformable part. The bucket wheel was assumed to be a rigid body. The model also uses elements replacing structural strands and hoist ropes of the bucket wheel boom.

The method of modelling the hoist ropes for the bucket wheel boom and the drums on which ropes are winded when lifting the boom, is shown in Fig.4. The cylinders to which the ends of boom hoisting rope are attached were modeled by means of elastic-attenuating components with properly selected characteristics.

Additional simulation possibilities are provided by applying the co-simulation techniques that enable integrating the different computing environments. As a result of using this technology, it is possible to model the driving motors or control algorithms, as well as the method of measuring the load to the bucket wheel using a separate software. This allows to carry out load analysis of electric motors, check the correct functioning of the developed control algorithms or change the character of the load of individual buckets during the simulation. In order to carry out simulation in the physical model of the bucket wheel excavator's body, the vectors of forces loading the bucket wheel and the torque vector, setting the bucket wheel into a rotational motion were defined.

Electric motors that drive the bucket wheel can be modelled in various ways and at various levels of simplification. The best results are achieved when modelling the engine by implementation of all characteristic features of the components delivered by a manufacturer in dedicated modules for modelling electric motors. However, if there is no access to the required data, the engine operation method can also be described in a simplified manner by means of the torque relationship generated by a given engine as a function of its rotational speed. A sample

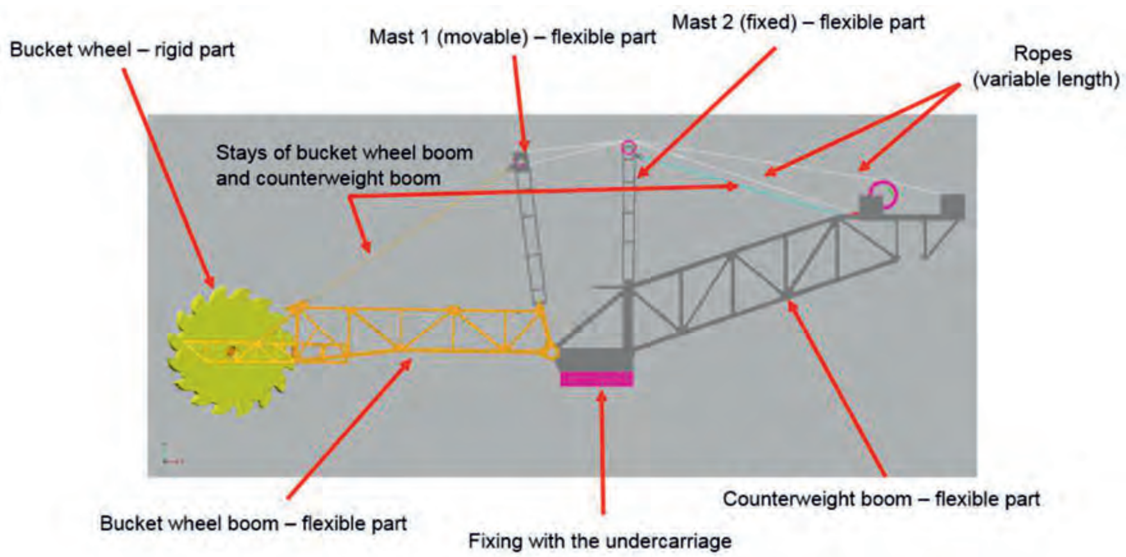

Fig. 2. Physical model of the bucket wheel excavator's body [1]
Rys. 2. Model fizyczny korpusu wielonaczyniowej koparki kołowej [1]

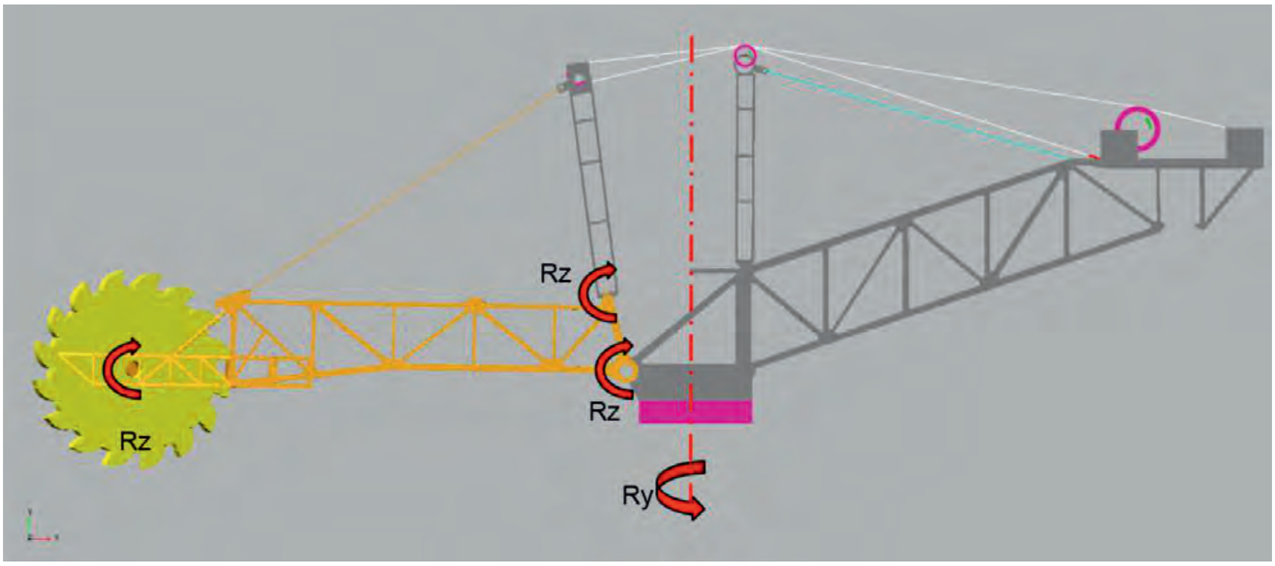

Fig. 3. Physical model of the bucket wheel excavator's superstructure [1]
Rys. 3. Model fizyczny struktury nośnej wielonaczyniowej koparki kołowej [1]

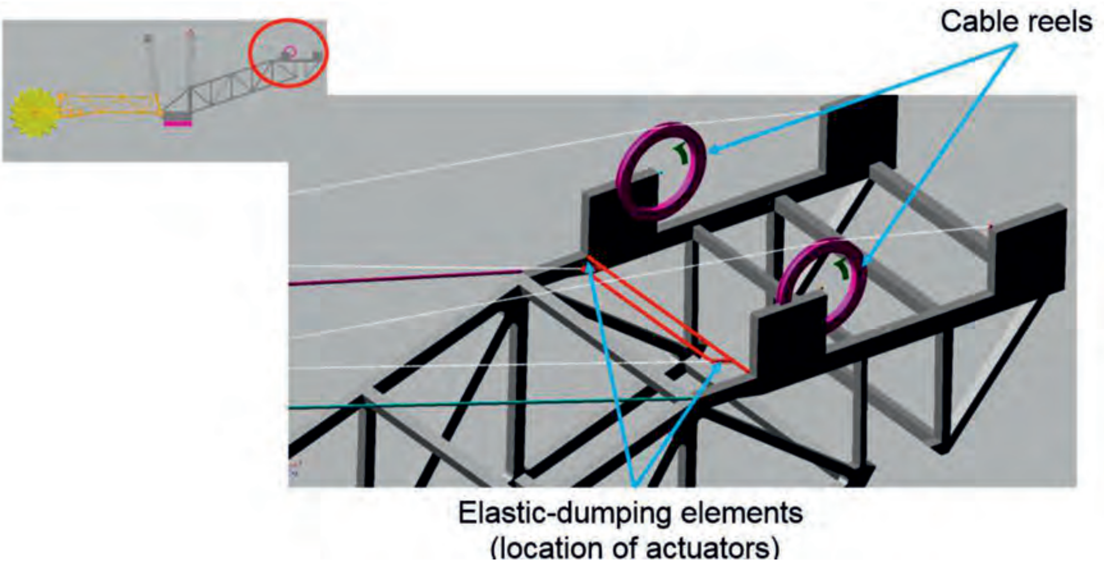

Fig. 4. The method of attaching the bucket wheel hoisting ropes [1]
Rys. 4. Metoda mocowania liny podnoszenia wysięgnika [1]

relationship of the torque value expressed in the function of the rotational speed of the bucket wheel (including reducers) is shown in Fig. 5. The value determined on the basis of this relationship was the value of the torque vector driving the bucket wheel in the physical model.

The load to bucket wheel can also be modelled in various ways. One of the methods of modelling the load of the bucket wheel is to define the vector that will „brake" the bucket wheel. This moment can be calculated in accordance with the accepted mathematical correlation. However, it is also possible to define any number of vectors loading the individual wheel dumps. The vectors of these forces can have different operational directions, thus, it becomes possible to distinguish the load from the run--of-mine weight or forces from the bucket wheel cutting into the rock mass, connected with e.g.: the gravitational acceleration of the Earth, friction forces or forces resulting from the rotation of the excavator's body in relation to the wall. Additionally, the consideration of the direction of loading forces can be related to the rotation angle of the bucket wheel.

In the presented example, the load of one fourth of the bucket wheel weight was assumed by defining a series of vectors of both vertical and horizontal forces, by means of which the external load, resulting from the process of mining and transportation of the run-of-mine was simulated. Dependences describing the ratio of vertical force to horizontal force constituting the components of the resultant loading force of the bucket is shown in Fig. 6.

A sample computational model of the excavator body consisted of a physical model of a multi-bucket excavator body and a model of mapping the operation of driving motors of the bucket wheel and the excavator's control. In order to carry out the simulation, co-simulation technology was used to integrate individual components of the computational model developed in various software environments [4,7]. Structure of the computational model is shown in Fig. 7.

The presented computational model of the multi-bucket excavator body after the validation, can be subjected to any loads, and then basing on the results of numerical simulations, one can draw conclusions about the behaviour of the structure body. The next section will present the ability to conduct the simulation.

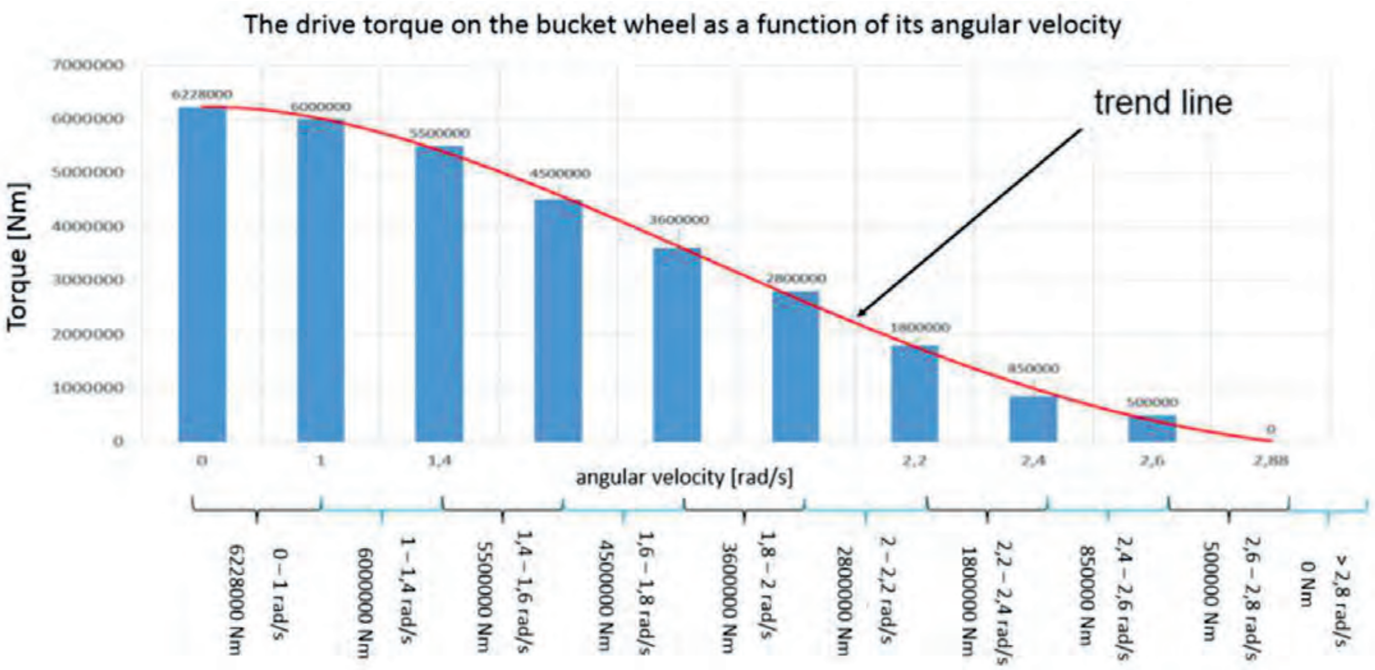

Fig. 5. Value of the driving torque of the bucket wheel as a function of its rotational speed [1]
Rys. 5. Wartość momentu napędowego koła czerpakowego w funkcji jego prędkości obrotowej [1]

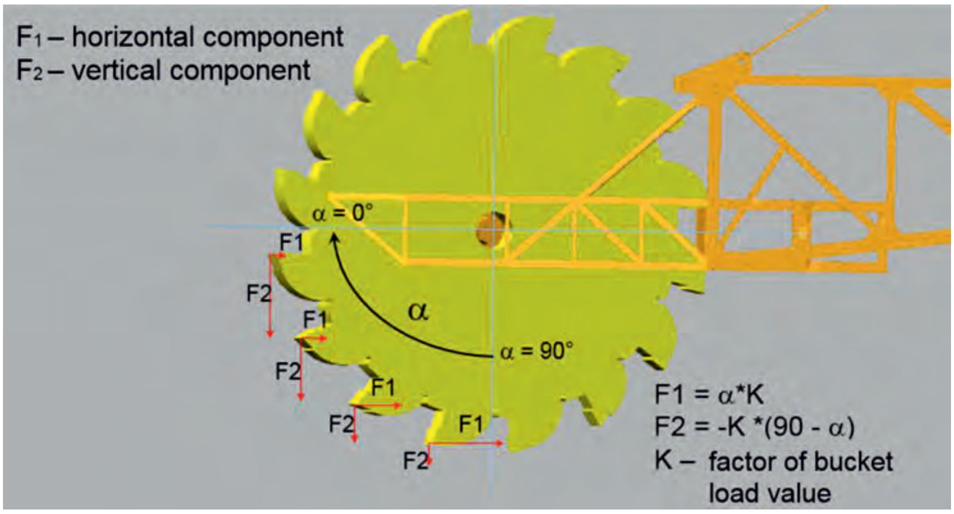

Fig. 6 The method of loading the bucket wheel [1]
Rys. 6 Modelowanie obciążenia działającego na koło czerpakowe [1]

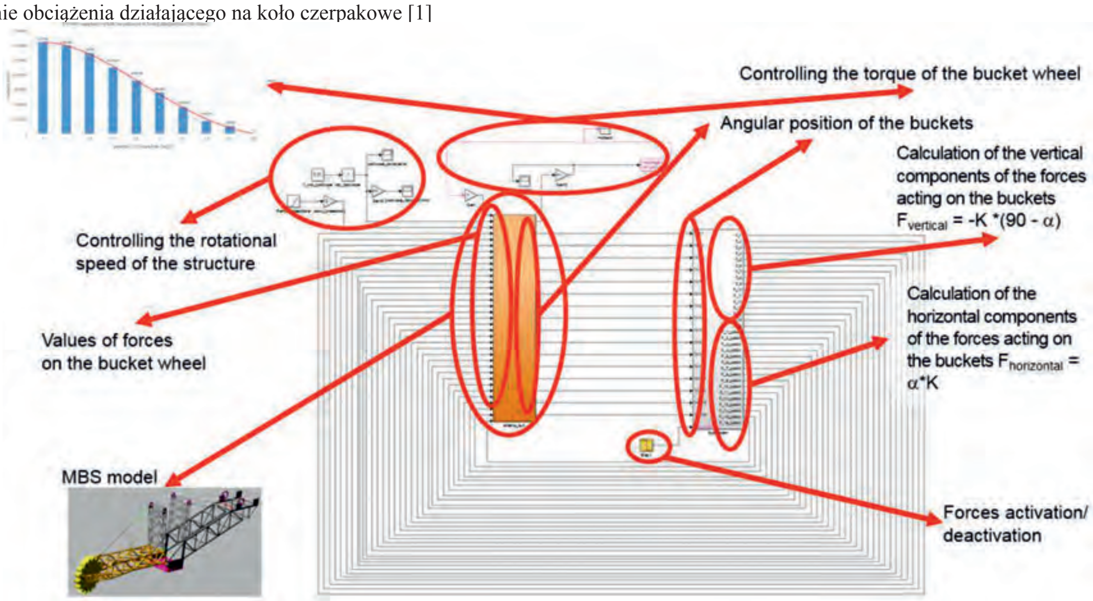

Fig. 7. Computational model of a multi-bucket excavator [1]
Rys. 7 Model obliczeniowy wielonaczyniowej koparki kołowej [1]

SIMULATION AND NUMERICAL ANALYSIS POSSIBILITY

Using the presented calculation model, it is possible to carry out a series of simulations enabling the analysis of cooperation of individual structure nodes, as well as the distribution of forces and identification of the most strained parts of the structure.

Vibration tests – natural vibration frequency analysis

The presented computational model can be used to analyse the vibrations of the multi-body excavator body structure resulting from the mining process, excavator torques, as well as caused by external factors such as wind. In order to analyse the vibrations of individual subassemblies of the body at specific locations of the structure, it is possible to add to the model virtual accelerometers measuring the acceleration at a given point in a given direction. Fig. 8 presents an example of acceleration measurements in the Z axis at the indicated point, along with their Fast Fourier Transform (FFT), recorded during numerical simulations. The Fast Fourier Transform (FFT) allowed the presentation of accelerations in the frequency domain, recorded during simulations.

Comparison of the acceleration results recorded from accelerometers on the real object, and virtual accelerometers in the computational model can be one of the validation points of this model [2, 3, 5, 6]. Then, any number of virtual accelerometers can be built in the computational model to analyse vibrations in any place on the structure and in any criterion states, e.g.: during lifting and lowering of the bucket wheel boom, during mining when the buckets are loaded or during the excavator travel.

In addition, in the case of deformable bodies, the natural

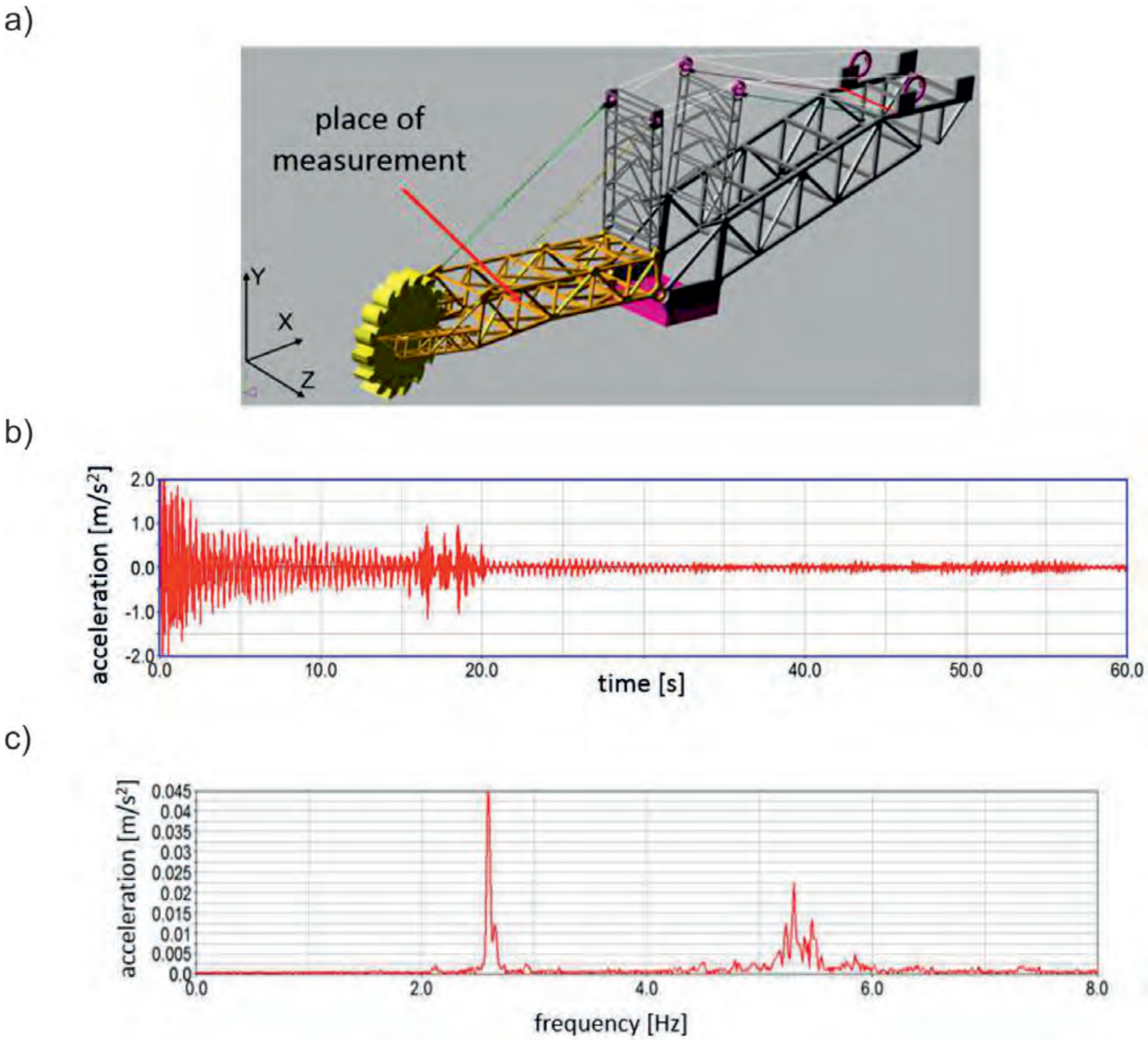

Fig. 8. Measurement of vibrations by numerical simulations
a) place of measurement,
b) recorded accelerations in time domain,
c) fast Fourier transform of registered vibrations [1]

Rys. 8. Pomiar drgań za pomocą symulacji numerycznych
a) miejsce pomiaru,
b) zarejestrowane przyspieszenia w dziedzinie czasu,
c) szybka transformata Fouriera zarejestrowanych drgań [1]

frequency and deformation form are calculated for each of these frequencies. Fig. 9 shows samples of deformations at four natural frequencies in relation to mast 1.

In the same way, one can determine and present the natural frequencies and deformation form of all deformable bodies in the computational model.

Analysis of the forces distribution within the structure

During simulation of the excavator's operations, the forces and torques are calculated in all nodes of the body structure. Recording these forces allows the analysis of force distribution through the structure during operation and identification of the most strained places in the body structure. Fig. 10 presents the forces recorded during a sample simulation at the point of fixing the rope, that supports and lifts the bucket wheel boom and in an elastic-attenuating element representing the actuator holding the rope.

Determination of boundary conditions for MES type strength analyses is another application of numerical simulations, in which forces are determined at given nodes of the structure. Such conditions can be determined with any setting of the bucket wheel boom and with any method of loading this wheel. On this basis, strength calculations may be carried out in relation to the most unfavourable operatinonal conditions of the entire structure.

Simulation of emergency criterial states

Another possibility of using a computational model is to perform simulations in emergency criterial states. During such situation, significant dynamic overloads are often observed, resulting in danger of structural damage

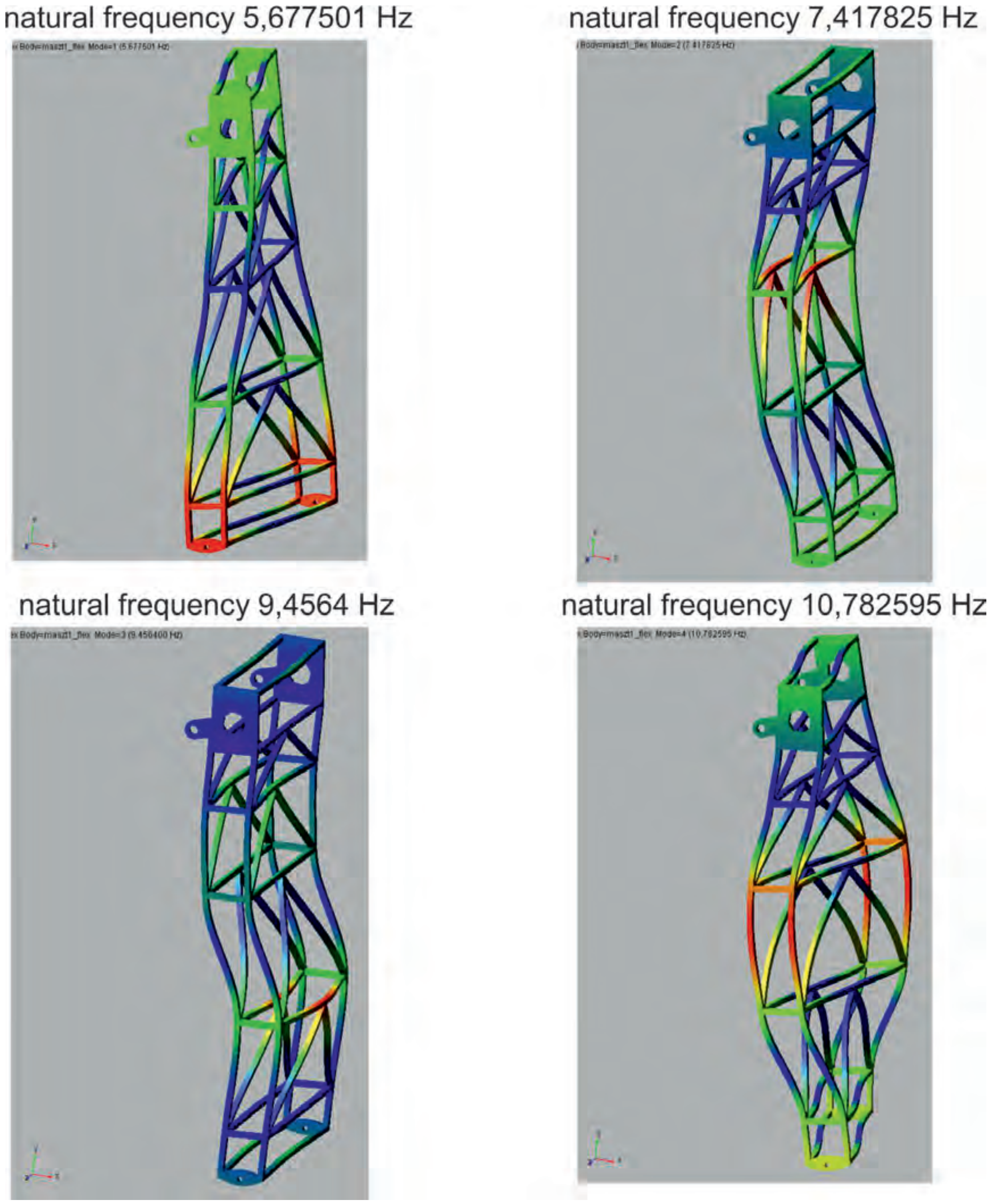

Fig. 9. Mast 1 deformation forms in relation to selected natural frequencies
Rys. 9. Formy deformacji masztu 1 w odniesieniu do wybranych częstotliwości drgań własnych

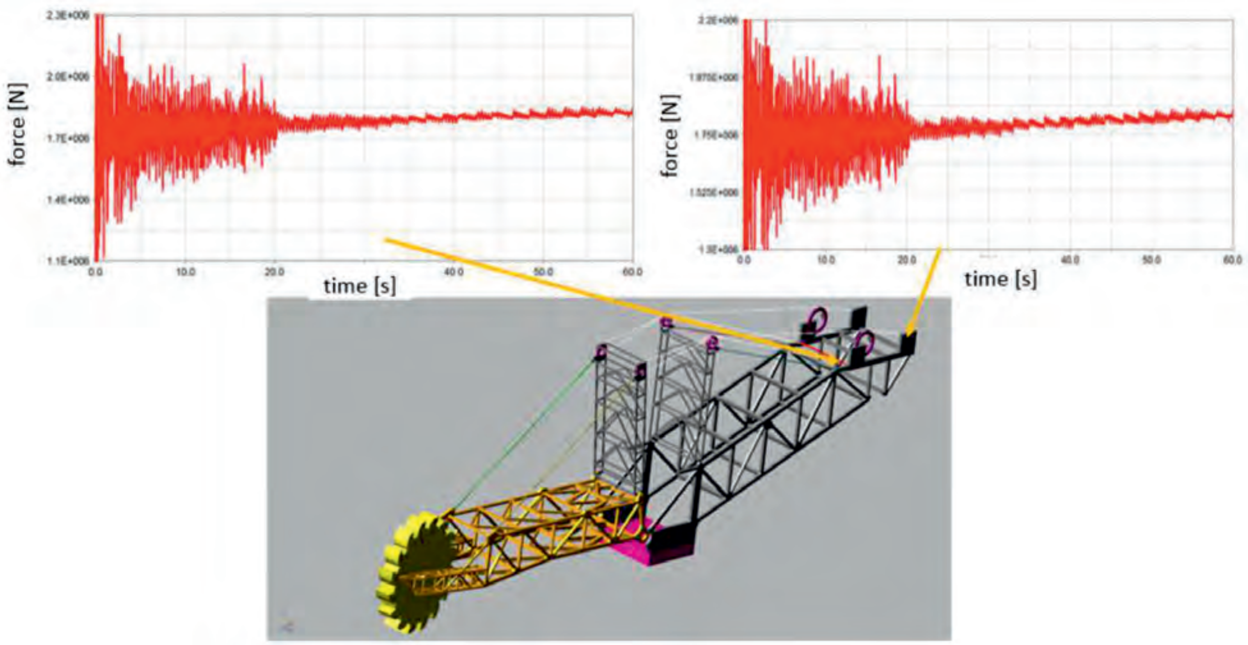

Fig. 10. Forces at the point of fixing the rope, that supports and lifts the bucket wheel boom [1]
Rys. 10. Siły w miejscu mocowania liny, która podpiera i podnosi ramię wysięgnika koparki z kołem wielonaczyniowym [1]

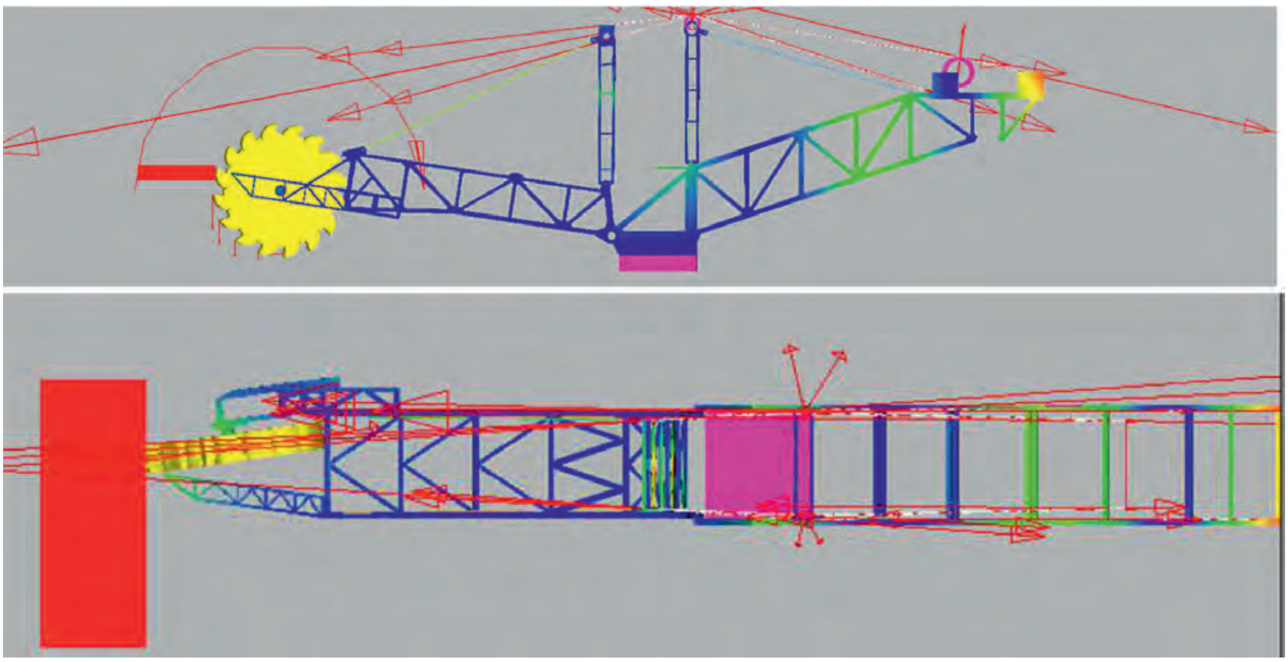

Fig. 11. Visualization of the collision situation of the bucket wheel hitting an obstacle [1]
Rys. 11. Wizualizacja sytuacji uderzenia koła wielonaczyniowego w przeszkodę [1]

[3,5,6]. An example of emergency condition simulation is the simulation of the bucket wheel hitting an obstacle during mining, this situation can take place in the case of a bucket wheel collision with the inclusion in the excavated deposit. Fig. 11 presents the simulation of a dangerous collision situation, where the bucket wheel hits an obstacle. The red element in front of the bucket wheel is an obstacle which was hit by one of the wheel buckets, while lifting the boom.

During the simulation, just like in the previous case, forces and accelerations are recorded in individual construction nodes, which may be the starting point for strength analyses in emergency situations.

Analysis of the correctness of the control system operation

The advantage of using the co-simulation technique is that it allows simulation of the correctness of the operation of the newly developed machine control algorithms [4, 7]. After the control algorithm is implemented, a virtual controller is built to change the parameters of the computational model during simulations. The force and torque vectors, the speed and rotation of the excavator body or the degree of lowering the bucket wheel boom may be the subject to changes and adjustment. This approach allows to detect imperfections of new algorithms and their maximum refinement before their implementation on the real object.

CONCLUSIONS

The method of building computational models of a very simplified nature that are used in the numerical analyses carried out to improve and modernize the design of multi-bucket excavators was presented. On the basis of a developed simplified computational model, possibilities of conducting numerical analyses and possibility of obtaining results useful in analysing the design of various types of excavators were presented. The application of the presented concept to utilise numerical calculations for the purpose of development and modernization of multi-bucket excavator's body design consists in the possibility of carrying out many analyses of already existing structures and then the structures with newly designed elements. The simulation of a design in which a bucket wheel boom is equipped with an additional element for fixing the ground-penetrating radar (GPR), which should be located near the bucket wheel, is an example. The use of numerical methods makes it possible to analyse several alternative solutions of new elements, and then by performing subsequent iterations of the optimization simulation of the selected solution. Such approach can be justified both economically and in the context of speeding up the project work.

It should be noted that the computational model presented in the paper is to a large extent simplified and the results presented are illustrative and showing the possibility of conducting a given type of numerical analyses. In order to verify the presented results and possibilities of referring to specific forces, torques or vibration frequencies, the presented model should be subjected to the process of validation and possible adustment to a specific real object.

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