Article citation info:
BRKIĆ A Đ, MANESKI T, IGNJATOVIĆ D, JOVANČIĆ P, SPASOJEVIĆ BRKIĆ V K. Diagnostics of bucket wheel excavator discharge boom dynamic performance and its reconstruction. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2014; 16 (2): 188–197.

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DIAGNOSTICS OF BUCKET WHEEL EXCAVATOR DISCHARGE BOOM DYNAMIC PERFORMANCE AND ITS RECONSTRUCTION

DIAGNOSTYKA WŁAŚCIWOŚCI DYNAMICZNYCH WYSIĘGNIKA ZRZUTOWEGO KOPARKI KOŁOWEJ ORAZ JEGO PRZEBUDOWA

The paper focuses on an investigation into the possible causes of the bad dynamic performance of bucket wheel excavator C7OOS (BWE) discharge boom in the Kolubara opencast mine, Serbia. A discharge boom load carrying structure model was produced and its static and dynamic calculations were made by the finite element method (FEM). The model was then validated by the experimental method – vibration analysis. The set goals were achieved by the FEM result analysis, which were further confirmed in the experiment. The causes for discharge boom weak performance were established. The main operation problems were found in the inadequate design of the discharge boom tie(s) and the subsequent installation of a steering cabin. Possible discharge boom reconstructions were considered with a view to improving its operation performance. The selection of the reconstruction approach was limited by the technical and financial resources available to the machine users. After the completed reconstruction, the discharge boom improved operation performance was demonstrated in practice.

Keywords: *Discharge boom, bucket wheel excavator, dynamic performance, vibration analysis.*

W artykule badano możliwe przyczyny złych własności dynamicznych wysięgnika zrzutowego koparki kołowej C7OOS (BWE) pracującej w kopalni odkrywkowej Kolubara w Serbii. Do stworzenia modelu konstrukcji nośnej wysięgnika zrzutowego oraz przeprowadzenia obliczeń statycznych i dynamicznych wykorzystano metodę elementów skończonych (MES). Model został następnie zweryfikowany przy użyciu metody eksperymentalnej – analizy drgań. Wyznaczone cele osiągnięto poprzez analizę wyników MES, które zostały następnie zweryfikowane w badaniach doświadczalnych. Ustalono przyczyny słabego działania wysięgnika. Głównymi problemami eksploatacyjnymi okazały się być nieodpowiednia konstrukcja cięgien wysięgnika oraz montaż kabiny kierowcy. Aby poprawić charakterystyki pracy wysięgnika, rozważono możliwe opcje jego przebudowy. Wybór metody przebudowy ograniczały zasoby techniczne i finansowe użytkownika maszyny. Przebudowa dała poprawę charakterystyk pracy wysięgnika, co wykazano w praktyce.

Słowa kluczowe: *Wysięgnik zrzutowy, koparka kołowa, właściwości dynamiczne, analiza drgań.*

1. Introduction

In terms of energy balance, open cast mines have the largest share in electrical power production in Serbia. The increasing price of electrical power compounded by the increasing social dependence on energy sources demand the close monitoring of machines and equipment in opencast mining operations, their regular maintenance, increased availability and efficiency. To achieve these goals – the maintenance of complex excavation, belt conveyor and dumping conveyor systems in opencast mines – ever greater significance is given to the diagnostics of the condition and performance of drive groups, steel constructions of excavation and transport machinery. The basic task of the condition analysis of each load carrying structure is to determine as accurately as possible its deformations, stress distribution and oscillation frequency. Carrying structures with bad dynamic behaviour can lead to undesirable occurrences in belt conveyor and dumping conveyor operations, such as: excessive construction deformations, entry into resonant oscillations, large dynamic response, the appearance of fatigue, the breakdown of connections between construction parts, long periods needed for construction oscillations to die out and similar [2, 3, 8, 16]. When modernizing the structure of the machine or modifying its operating parameters, it is necessary to establish the impact of changes on the behaviour of the machine undergoing modernization [17]. As a result a need arose to precisely determine the dynamic characteristics of the machine, which would help to establish its resonance range or to plan its modernization [4].

Such analyses are inherent in the design process of new belt conveyors and dumping conveyors and the correction and reconstruction of the existent ones. These machines operate in arduous conditions which additionally aggravates their operation performance. An engineer is expected to use accurate and quickly calculation methods to ensure reliable and cost effective construction. This can be achieved by using modern CAD/FEM calculation methods and calculation validation by means of experimental methods on the produced construction [18]. Nevertheless, Rusinski and others in [18, 19] point out some of the reasons leading to the breakdown of load carrying structures (faults in design, technology and operation). Faults in design are caused by the use of simplified calculation methods, the neglect of load influence and the existence of residual stresses, as well as the influence of construction element fits. Faults in technology occur in construction production and the most common causes are the use of inappropriate materials and the inappropriate production of joints. Faults in operation occur due to overloads, which may result from improper use or unforeseen circumstances. All of these can lead to weak static and dynamic performance of load carrying structures in ore excavation, conveyance and dumping machines.

Detecting the causes of weak performance and the breakdown of load carrying structure parts in the machines which make up the EBD system (excavator, belt conveyor, and dumping conveyor) is the subject of numerous studies, particularly in the light of some large scale accidents. In their research Rusinski and others [13, 14] analyse the causes of the breakdown of the dumping conveyor's steerable carriage in an opencast lignite mine during work in winter conditions. Using FEM analysis and the experimental (chemical analysis) method it was established that the accident was caused by faults in design and production, due to the use of the undercarriage half shafts systems. In paper [1] the structural failure of the bucket wheel stacker reclaimer was analysed by the computer structure analysis method and experimental methods of microstructure characterization. The conclusion of this research was that the main cause for breakdown was a high concentration of stress in the welded connection of the load carrying structure elements (tubular tie-rod and flange) combined with cleavage crack propagation in the direction of lower fracture toughness. In research [6] the causes of the failure of the stacker-cum-reclaimer in an ore handling plant in India were analysed by visual methods, metallographic studies, and finite element and experimental methods of establishing stress distribution on construction elements. The research conclusion was that the accident was due to faults in the operational conditions. Paper [7] deals with an evaluation of measuring of vibrations on a bucket wheel excavator (BWE) SchRs 1320 during mining and while analyzing its dynamical properties several measurements were made.

This paper analyses the bad static and dynamic performance of the BWE C700S O&K discharge boom in the opencast mine in Kolubara, Serbia. The static and dynamic FEM calculations of the discharge boom load carrying structure were made thus describing the physical problem and operation performance, which, in turn, allows the construction performance diagnostics. The analysis entails computer calculation by the FEM method. On the basis of the calculation results the cause of the weak performance of the discharge boom was established and several solutions for its reconstruction were offered. The selected manner of reconstruction was demonstrated and the reasons for the decision given. The validity of the FEM calculation was demonstrated on the reconstructed BWE discharge boom by experimental methods and its improved static and dynamic performance were then tested.

2. Methods

2.1. FEM analysis theoretical principles

Discharge boom weak dynamic performance is a common occurrence during the excavator operation. The discharge boom of the observed excavator C700S in figure 1, in the opencast mine in Kolubara, Serbia, was reported to have entered resonant conditions, with the oscillation amplitude reaching up to 600 mm. To find out the cause of this malfunction it is necessary to perform a detailed calculation. A dynamic performance analysis is very important for the evaluation of the selection parameters and the subsequent decision, especially in the case of constructions such as the discharge boom of a dumping conveyor system, whose operational performance and integrity depend largely on its dynamic characteristics.

Fig. 1 Discharge boom of C700S excavator in the Kolubara open cast mine

The static, dynamic and heat analysis of load carrying structures is most commonly performed by FEM (the Finite Element Method) [9, 10, 11, 12]. The basic static and dynamic (with damping) equations in matrix form and the global coordinate system can be expressed as follows (1), (2):

$$[K]\{\delta\}=\{F\} \tag{1}$$

$$[M]\{\ddot{\delta}(t)\}+[B]\{\dot{\delta}(t)\}+[K]\{\delta(t)\}=\{F(t)\} \tag{2}$$

In the above given expressions [M], [B], and [K] stand for the mass matrix, the damping matrix and the stiffness matrix, $\{\delta(t)\},\{\dot{\delta}(t)\}, and\{\ddot{\delta}(t)\}$ stands for the displacement, velocity and node acceleration vectors, $\{F(t)\}$ the dynamic load vector, and t – time.

The program used for the static and dynamic analysis of discharge boom performance was package KOMIPS [9] based on the FEM application, developed at the Faculty of Mechanical Engineering in Belgrade. For all kinds of final elements and the global node the equivalent stress is calculated according to the Huber-Hencky-Mises hypothesis. With the application of this program we will perform the discharge boom modelling and static and dynamic calculation, and determine the real model node movements and stress distribution on the construction model elements. On the basis of the obtained results we will define the causes of discharge boom weak performance and improve it through the direct modification of the model. Direct modification implies changes in the construction's design parameters (mass and stiffness of certain construction parts). In addition to the aforementioned, the KOMIPS program package also supports specific calculations of construction elements which allow the determination of the membrane and bending stress distribution, the deformation energy distribution and the kinetic and potential energy distribution per model element. The said distributions are expressed in percentages per element, or selected element groups, or graphically in the form of lines of equal potentials and energies per model. The energy deformation distribution per construction part defines their sensitivity to modification.

The equation of the deformation energy balance and external force work (3) is obtained by multiplying the basic static equation (1) by the transposed displacement vector.

$$\{\delta\}^T[K]\{\delta\}=\{\delta\}^T\{F\}\equiv 2E_d \tag{3}$$

The deformation energy of the final element ed is expressed in the form below (4):

$$e_d = \frac{1}{2}\{\delta_{sr}\}_e^T \left[\overline{k_{rs}}\right]_e \{\delta_{sr}\}_e \tag{4}$$

In the equation, (4) $\left[\overline{k_{rs}}\right]_e$ stands for the global matrix of stiffness of a given element, and $\{\delta_{sr}\}_e$ is the corresponding global displacement vector. The kinetic and potential energy distribution on the main modes of the vibrations per construction element allows an even more precise analysis of their performance. The equation of the potential and kinetic energy balance [12] is obtained by multiplying the basic dynamic equation without the damping effect by the eigenvectors transposed matrix [11]. The kinetic e_k^r and potential e_p^r energy of the finite element e and the whole system Er on the r main mode of the vibrations can be expressed by the equation below (5):

$$\begin{aligned} e_k^r &= \omega_r^2 \{\mu_{sr}\}_e^T [m]_e \{\mu_{sr}\}_e \\ e_p^r &= \{\mu_{sr}\}_e^T \left[\overline{k_{rs}}\right]_e \{\mu_{sr}\}_e \\ E^r &= E_k^r = E_p^r = \omega_r^2 \{\mu_r\}^T [M]\{\mu_r\} = \{\mu_r\}^T [K]\{\mu_r\} \end{aligned} \tag{5}$$

In the equations (5), ω_r stands for r eigenvalue (circular frequency of free undamped oscillations), $\{\mu_r\}$ stands for r eigenvector, and $\{\mu_{sr}\}$ stands for the corresponding r eigenvector of the finite element.

2.2. Modelling

Figure 1 shows the excavator discharge boom at the beginning of operation as it was designed and produced. After a certain time, the user installed a steering cabin on the discharge boom, as shown in figure 2. As already said, the dynamic performance of the discharge boom in operation became very bad (large deformations, large vibration amplitudes which took a long time to decay, construction vibrations). To find out the cause of the described performance of the discharge boom it is necessary to carry out calculations with the reduced model and to draw appropriate conclusions, which then need to be verified by calculations on a discharge boom spatial model.

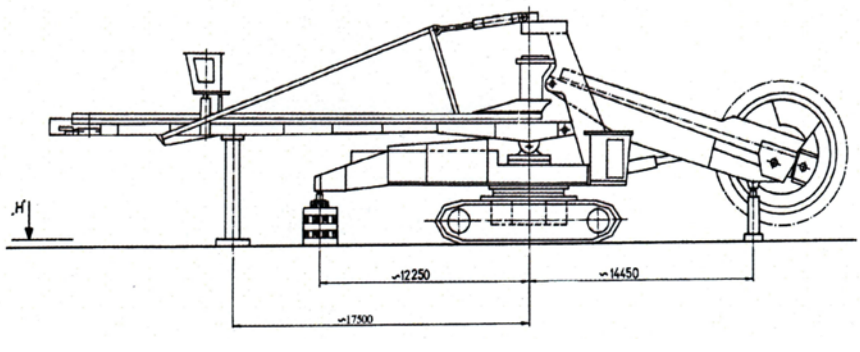

Fig. 2. The discharge boom of the C700S excavator with a steering cabin

The reduced model for the static and dynamic calculation of the discharge boom load carrying structure shown in figure 3 presents a plane model obtained by the reduction of the spatial linear model of the discharge boom structure. The calculation plane model will

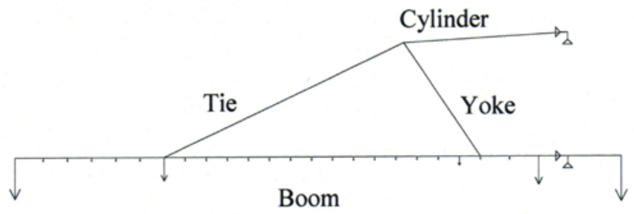

Fig. 3. Discharge boom reduced plane model

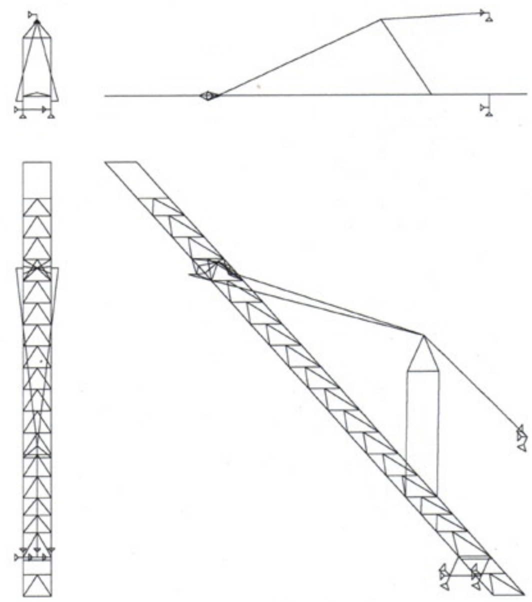

Fig. 4. Spatial model of discharge boom

be used for the analysis of the discharge boom performance in the plane.

The load acting on the model comprises the discharge boom weight itself, the load weight, the belt weight, the drive station weight, and the cabin weight [16]. The discharge boom supports on the excavator are modelled as two joints. The hydro cylinder is modelled by the linear element with a joint connection at both its ends. The yoke is also jointly connected to the discharge boom carrier and the connection point between the cylinder and tie. The reduced plane model comprises 25 linear elements of beam type which perform the discretization of the boom carrier construction, and three linear truss elements (tie, yoke and cylinder).

The results of the FEM calculation of the static and dynamic performance obtained from the boom construction reduced model need to be verified and confirmed on a more realistic and precise model which will demonstrate the real construction performance in operation more faithfully. The new model represents a spatial-linear model of the discharge boom. The number of nodes in the spatial model is 364, and the number of linear finite elements of beam and truss type 438. The discharge boom new spatial model is shown in figure 4. The methods of connecting the boom to the excavator, the yoke and hydro cylinder to the boom structure, and how the load acts on the model are the same as in the reduced model.

2.3. Results and discussion

2.3.1. Static and dynamic calculation of the reduced plane model

The deformed structure of the discharge boom plane model is shown in figure 5.

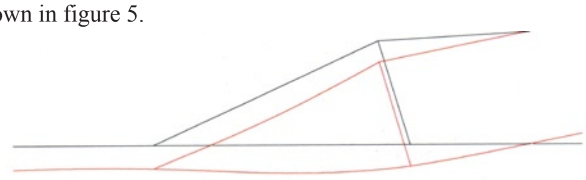

Fig. 5. Plane model deformation

Table 1. Load distribution and deformation energy distribution per element group

Model element	Axial force [kN]	Bending moment [kNmm]	Deformation energy [%]
Carrier	350/450	535000	72.2: cantilever=9.6, 1/3L= 3.5, 2/3L=17.6, 3/3L=41.5
Tie	380	-	16.8
Cylinder	450	-	10.5
Yoke	180	-	0.5

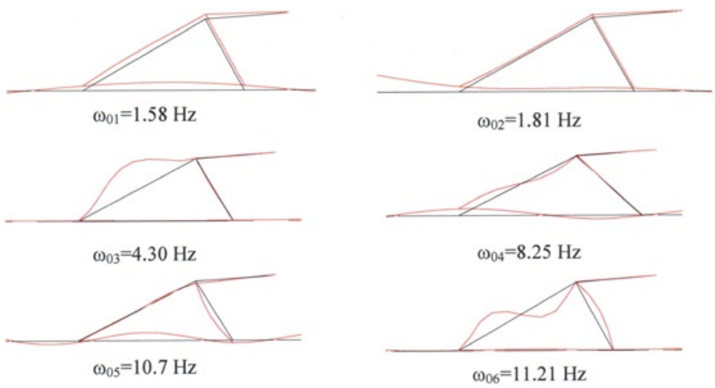

Fig. 6. Main modes of plane model vibrations

Table 2. Potential and kinetic energy distribution in the first two modes of vibrations

Model elements	Potential / kinetic energy distribution for the first two modes of vibrations [%]	
	ω_{01}=1.58 Hz	ω_{02}=1.81 Hz
Carrier	80 / 35	90 / 16
Tie	12 / 3	6 / 1
Cylinder	8 / 0	4 / 0
Yoke	0 / 0	0 / 0
External masses	0 / 62	0 / 73

The maximum deformation of the model points on the boom left end amounts to 104 mm. For a more precise definition of the discharge boom static performance and optimization elements it is necessary to analyse the load and energy deformation distribution per model element as shown in table 1.

An analysis of the static calculation results leads to the following conclusions about model performance:

- The boom deformation between the joint support of the boom structure and the yoke is significant due to the inaccurate positioning of the yoke connection.
- Additional deformation of the left boom cantilever is caused by the installed steering cabin.
- The axial force in the tie and hydro cylinder is considerable, while insignificant in the yoke.
- The bending moment of the boom carrier is large in the connection point between the boom structure and the yoke.
- The deformation energy distribution on the boom structure is dominant over the other elements (72.2% goes to the boom structure element group), while within the boom structure itself it is dominant between the joint and the yoke.

The first dynamic calculation is made for free undamped vibrations. The first six main modes of vibrations are shown in figure 6. They also demonstrate the boom deformation mode in resonance (overlapping) with actuation. The first two main modes represent the vibration of the discharge boom, the third represents the vibration of the tie, the fourth is the joint vibration of the tie and the discharge boom, the fifth is that of the boom and the yoke, while the sixth is the vibration of the tie and the yoke. In this case, the first three main modes of vibrations are sufficient for dynamic performance analysis.

After the calculation of free undamped oscillation, a dynamic calculation of forced damped oscillations in the frequency domain was made; these can produce the frequency characteristics of the structure. This is how we obtain the structure performance for simulated combinations of actuation and response; the simplest way to express this is through dynamic amplification in the observed frequency domain. The discharge boom frequency characteristics for vertical actuation acting on the connection point between the tie, yoke and hydro cylinder and the vertical response on the left end of the boom carrier are shown in figure 7.

An example of discharge boom time response for displacement and stress in the selected connection point between the tie, yoke and hydro cylinder is shown in figure 8.

By analysing the results of dynamic calculation the following conclusions about model performance can be made:

- The first two eigenfrequencies are very low, very close to each other and they overlap with static deformation.
- The factor of dynamic amplification with 5% damping equals around 38 for the first and 30 for the second modes of vibrations, which are rather significant values. The dynamic stability system diagram also shows a high imaginary part of characteristics; i.e. high system instability.
- The potential energy distribution on the boom structure is dominant in relation to other elements, while kinetic energy distribution is dominant on the external load (external masses) and on the boom structure elements.

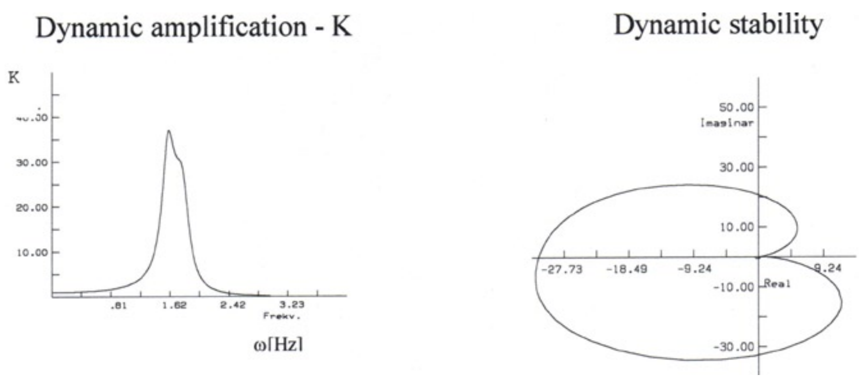

Fig. 7. Discharge boom frequency characteristics

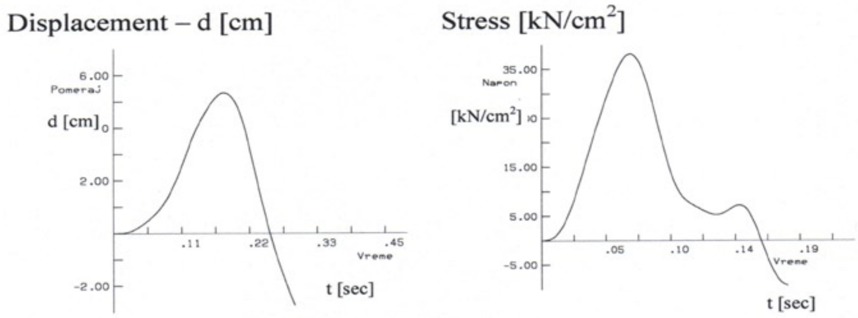

Fig. 8. Time response of discharge boom

2.3.2. Dynamic Calculation of the Discharge Boom Spatial Model

The results of the reduced plane model calculation were verified by means of the dynamic calculation of the more realistic and precise discharge boom structure spatial model. The dynamic calculations of the first eight main modes of vibrations are shown in figure 9. As expected, due to a more accurate stiffness and mass distribution, a change in frequencies and modes of vibrations occurred compared to those of the plane model. New modes of vibrations (6, 7 and 8) appeared as a result of the spatial model due to the introduction of 3 added degrees of freedom of nodes. The first three modes of vibrations are largely identical whereby the first two main modes swapped places. The fifth and ninth eigenvalues of the spatial model correspond to the fourth and fifth of the plane model.

The forced damped response of the spatial model in the frequency domain for vertical actuation acting on the connection point between the tie, yoke and hydro cylinder and the vertical response on the left end of the boom structure are shown in figure 10.

Based on the performed dynamic calculations of the spatial model we can conclude that the first two eigen values of the spatial model are very close (the conclusion of the plane model confirmed by dynamic calculation), whereby the second is insignificantly larger than the corresponding one in the plane model. Smaller values of dynamic amplification factor can be noted, as well as reduced system dynamic instability in relation to the corresponding values of the plane model. These results were also expected due to greater accuracy in the distribution of mass and stiffness in the spatial model.

The dynamic calculation carried out on the discharge boom spatial model completely confirms its bad performance. The actuation to the discharge boom comes from the bucket wheel on the bucket wheel excavator. The bucket wheel turns with 6 RPM. Since there are 12 buckets on the bucket wheel, it follows that the bucket wheelcauses the actuation frequency of 1.2 Hz. The actuation frequency is close to the first eigen frequency. The dynamic calculation results for the spatial model are more accurate and show the more favourable behaviour of the boom than the plane model. Due to the simpler determination of the structural parameters the modification influences its dynamic behaviour. We will analyse the plane model below.

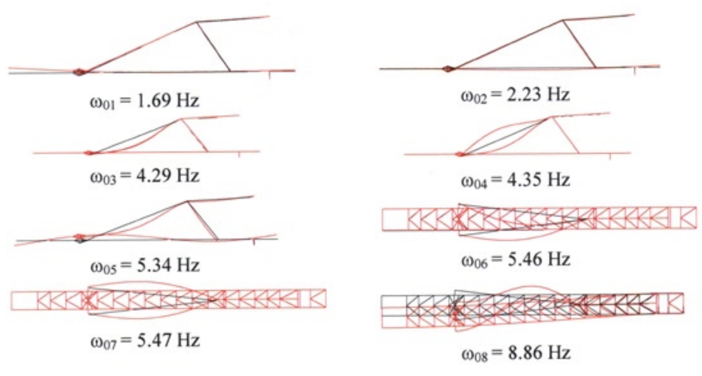

Fig. 9. Main modes of vibrations of the spatial model

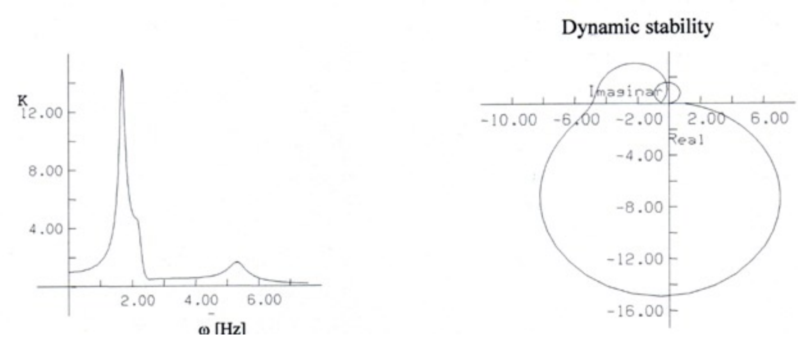

Fig. 10. Frequency characteristics of the discharge boom spatial model

2.4. Reanalysis of boom discharge construction performance and its reconstruction

Reanalysis or structural dynamic modification presents a set of methods which can improve the dynamic performance of the discharge boom structure. The dynamic response of the system is primarily characterized by relevant eigenvalues and main modes of vibrations. Dynamic characteristic modification entails changes to the relevant structural parameters in order to achieve the desired dynamic performance in the changed eigenfrequencies and main modes of vibrations.

The dynamic calculation results of the discharge boom plane model define the parameters for model optimization; i.e. the boom reconstruction method for the improved dynamic performance of its load carrying structure. The main course of dynamic model optimization is an increase in the value of the eigenfrequencies, as well as an increase in their value difference.

On the basis of the above said we will consider the following modification models which may lead to an improvement in the dynamic performance of the discharge boom:

- boom model without the subsequent installation of a steering cabin;
- boom model with increased stiffness on the bending boom carrier by introducing additional ties;
- boom model with a changed connection point between the yoke and boom cantilever.

To determine which dynamic model satisfies these demands to the highest extent, it is necessary to perform static and dynamic calculations of different model variants. The analysed discharge boom modified models have XYij markings, with the following meanings:

- X = S – static calculation;
- X = D – dynamic calculation;
- Y = A - model with a subsequently installed steering cabin;
- Y = B - model without a subsequently installed steering cabin;
- i = 0 – the existing model;
- i = 1 – model modified with the addition of two new ties;
- i = 2 – model modified with the addition of two new ties and their infill;
- j = 0 – the existing model;

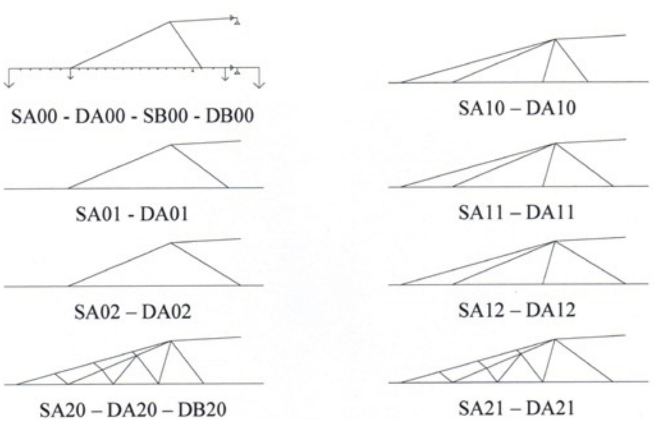

Fig. 11. Variants of analysed modified models of discharge boom

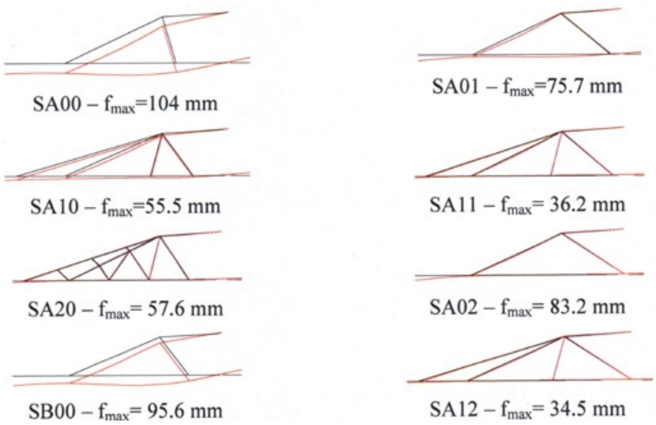

Fig. 12. Deformations of discharge boom modified models

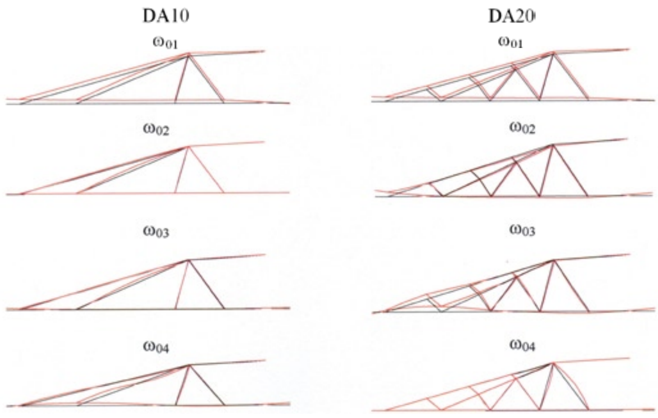

Fig. 13. Main modes of vibrations of the modified model with additional ties and infills

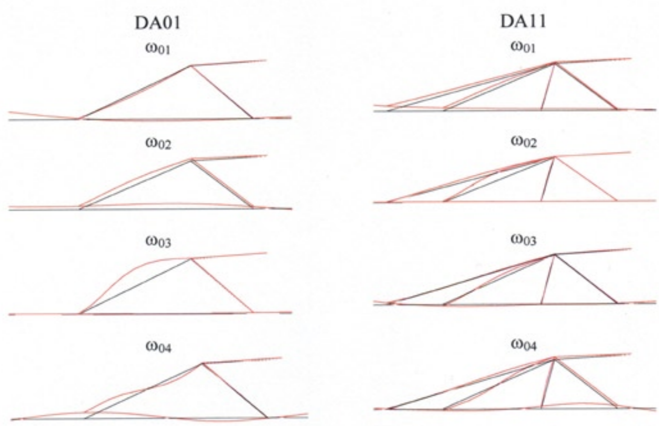

Fig. 14. Main vibration modes in the modified model with changed yoke-boom connection position

– j = 1 – model modified by moving the connection between the yoke and boom structure to the middle distance from the joint rest;
– j = 2 – model modified by moving the connection between the yoke and boom structure to the boom structure joint support.

Table 3. The values of axial force in [kN] per element group of discharge boom modified models

Model elements	SA00	SA10	SA20	SA01	SA11	SA02	SA12	SB00
Carrier	350	280	280	300	250	280	260	260
Tie	380	110	120	330	120	310	130	280
Cylinder	450	450	470	450	450	450	450	330
Yoke	180	300	320	190	240	200	230	130
Additional tie	-	180	200	-	140	-	140	-
Additional infill	-	-	0	-	-	-	-	-

Table 4. Deformation energy [kNcm] distribution per element group in the discharge boom modified models

Model elements	SA00	SA10	SA20	SA01	SA11	SA02	SA12
Beam	72.2	59.3	60.4	49.2	21.3	41.8	15.3
Tie	16.8	3.4	2.6	26.8	8.3	28.5	10.2
Cylinder	10.5	23.0	22.9	22.3	48.1	27.1	51.9
Yoke	0.5	3.3	3.4	1.7	5.6	2.6	6
Additional tie	-	11.0	10.7	-	16.7	-	16.5
Additional infill	-	-	0	-	-	-	-
Σ E_d [kNcm]	1418	647	709	669	310	551	287

The variants of the analysed modified models are shown in figure 11.

An analysis of the values of the modified model deformations enables the following conclusions:

- the steering cabin increases the deformation of the left boom cantilever;
- the introduction of new ties drastically reduces the deformation of all boom structure elements;
- the optimum position of the yoke-boom structure connection is between its current position and the boom structure joint support in the case of the model without ties, and at the joint-support in the case of the model modified with two new ties;
- the introduction of a tie infill insignificantly increases boom structure deformation, but it should have a positive influence on discharge boom dynamic performance.

Models SA12 and SA11 demonstrate the best performance as regards deformation values. Bearing in mind the difficulties involved in boom reconstruction by changing the yoke-boom structure connection point, the boom reconstruction according to modified models SA10 and SA20 is both technically and economically the most effective.

Axial force distribution on the boom structure for the considered model variants is given in Table 3. The optimum solution in view of this criterion is again model SA12 or SA11. The proposed solution (SA10 and SA20) has increased force in the yoke which does not pose a technical problem. The steering cabin contributes to the increase in axial force.

The deformation energy distribution in percentages per element of the analysed models is shown in Table 4. The total deformation energy is minimal on models SA12 and SA11. The deformation energy was transposed from the boom structure elements to the cylinder.

Keeping the steering cabin, and the current position of the yoke, the effect of additional ties (DA10) and their infills (DA20) on boom dynamic behaviour in the first four modes of vibrations is shown in figure 13. Analysing the given results we can conclude that the introduction of the addition of new ties and their infills favourably influences the dynamic behaviour of the basic model.

Table 5. Values of circular frequencies of free undamped vibrations [Hz] in the modified models

ω	DA00	DA10	DA20	DA01	DA11	DB00	DB10	DB20
ω_{01}	1.58	2.03	2.23	1.62	3.04	1.61	2.10	2.58
ω_{02}	1.81	2.38	4.64	2.33	3.92	3.22	4.11	6.94
ω_{03}	4.30	4.19	9.43	3.08	6.03	8.52	4.65	12.27
ω_{04}	8.25	4.74	13.16	7.11	7.83	9.31	8.93	13.31
ω_{05}	10.7	5.86	17.67	9.93	11.1	10.97	11.42	18.46
ω_{06}	11.21	8.30	21.77	11.05	14.53	12.20	13.81	21.98
ω_{07}	13.56	10.85	22.82	18.37	21.85	13.56	15.30	25.50
ω_{08}	18.43	11.98	24.16	20.55	22.24	19.83	20.30	28.22
ω_{09}	23.09	13.85	24.57	24.07	25.85	23.46	23.34	30.21
ω_{010}	24.53	15.02	26.57	25.60	26.48	28.15	23.62	31.81

The effect of the changed yoke-boom structure connection position (DA01) and the addition of new ties without infills (DA11) on discharge boom dynamic behaviour in the first four modes of vibrations is shown in figure 14. Analysing the given results we can conclude that only moving the connection between the yoke and boom structure insufficiently influences the improvement of the dynamic behaviour of the basic model, making it necessary to introduce the addition of new ties.

The values of the first ten circular frequencies in the considered model are shown in Table.5.

Based on the calculation results of free undamped vibration we can conclude that the introduction of new ties is fully justified. The presence of additional mass (steering cabin) has an adverse effect on discharge boom dynamic performance. The most advisable position for the yoke-boom structure connection is in the joint support. In the case of all the modified models there is an increase in the vibration frequency values, as well as their distance, which removes the basic cause of discharge boom weak performance. The dynamic behaviour of the modified model without a steering cabin and with additional new ties (DB10), and their infill (DB20), in the first four vibration modes is shown in figure 15.

The potential and kinetic energy distribution in the main modes of vibrations leads to the same conclusions as deformation energy distribution. The improved model variants have reduced energy in the boom structure and increased energy in the hydro cylinder.

The results of forced damped vibration calculations in the frequency domain which can produce the frequency characteristics of the modified models are shown in figure 16. Vertical actuation acts on the cylinder-tie-yoke connection point, while the vertical response is observed on the boom structure left end.

The frequency characteristics indicate the weak performance of the model with additional mass (steering cabin) on the boom structure left end, as well as the model without ties. Weak performance is observable in the high factor of dynamic amplification, the large imaginary part of characteristics, the low vibration frequencies and their short distances.

The demonstrated procedure for static and discharge boom dynamic performance analysis allows a highly ef-

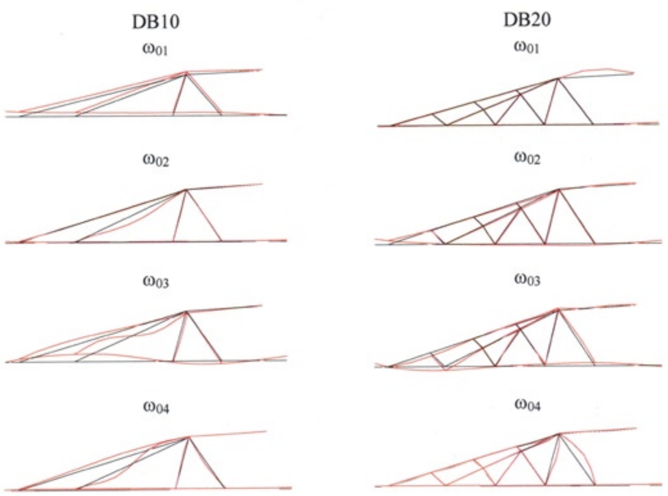

Fig. 15. Main modes of vibrations without a cabin and additional ties

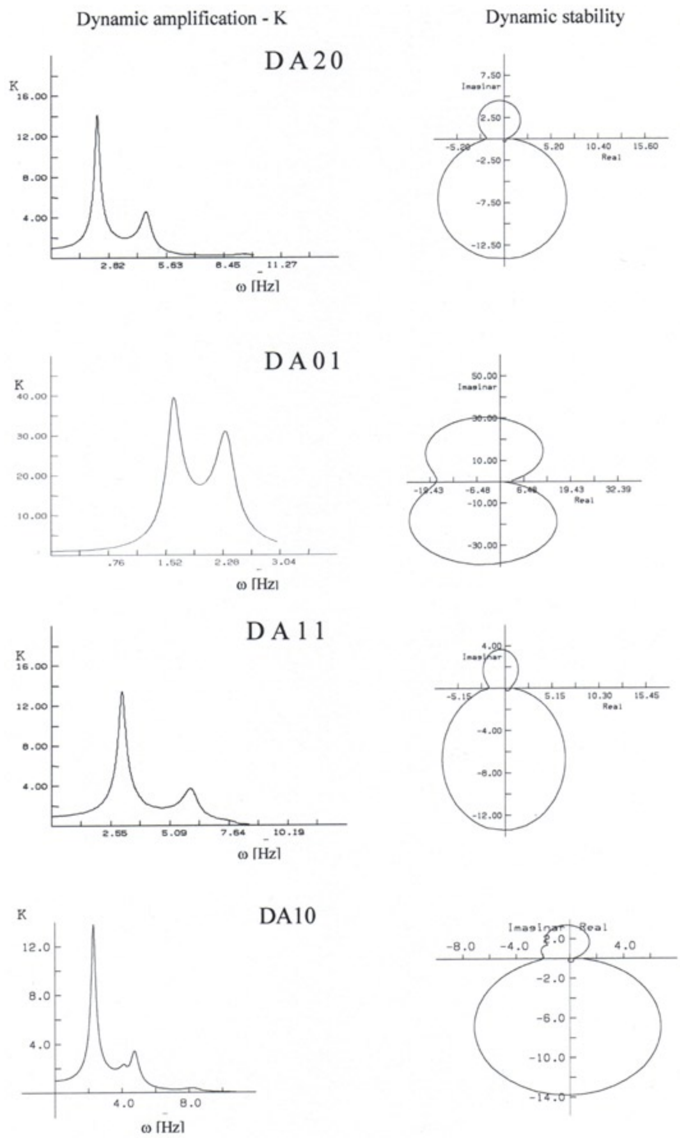

Fig. 16. Frequency characteristics of the discharge boom construction modified models

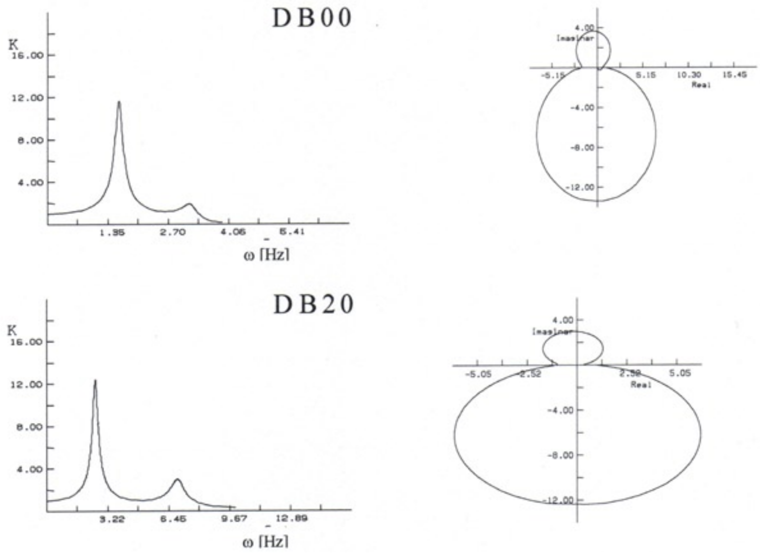

Fig. 16. Frequency characteristics of the discharge boom construction modified models (continued)

Fig. 17. Reconstructed BWE C700S discharge boom on the Kolubara open-cast mine

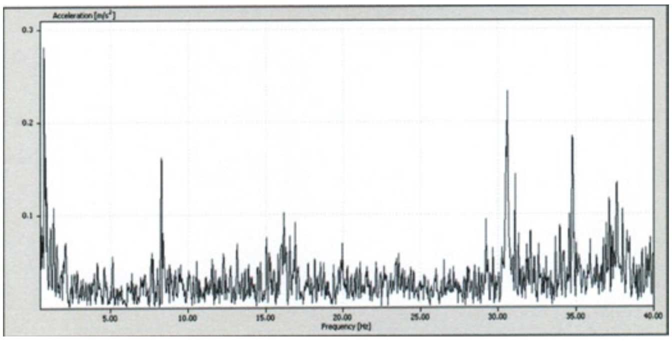

Fig. 18. Acceleration of additional tie-boom structure connection points in the vertical direction

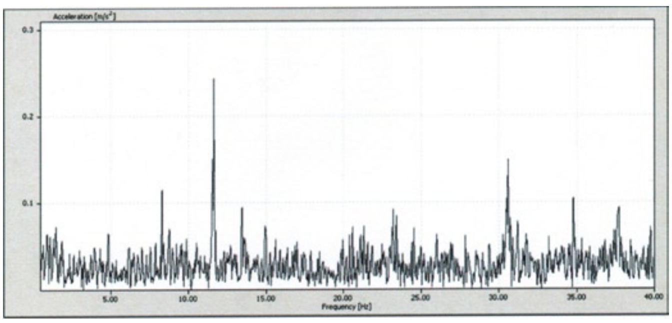

Fig. 19. Acceleration of additional tie and boom structure connection point in the lateral direction

ficient and quality assessment of construction exploitation performance, the detection of poor performance cause, the degree of impact of the construction's dynamic parameter on exploitation performance and allows for decision making on the selection of a reconstruction solution. The limitations present in the solution selection lie in the staff, and both the technical and financial capacities of the excavator users for the implementation of the optimal solution. According to all of the above, the selected solution for the discharge boom reconstruction comprises the following improvements on the present one: the steering cabin is removed (a camera is attached instead), two new ties without infills are added, while the yoke-boom structure connection remains in the same position (modified models SB10 and DB10).

The reconstructed BWE discharge boom is shown in figure 17. The performed reconstruction of the discharge boom solves the basic cause of previous poor performance.

Dynamic parameter values were experimentally determined for the reconstructed boom so as to describe its behaviour in operation. Location of the measuring sensors and directions in which accelerations will be measured is very important[15]. Accelerometer placement is shown on the fig.17. Selected place has the most inconvenient boom`s dynamic behaviour. Carrying structure vibrations were measured from the position of the last added tie-boom structure connection in the vertical direction and in two horizontal directions (axis and lateral). Vibration measurement was performed with equipment consisting of a three-component acceleration gauge sensor, an analogue-digital converter and USB computer communication. The software package supports the analysis of the time and frequency acceleration signal. The frequency signal was received by the application of the FFT analysis. Figures 18 and 19 show the measured accelerations within the frequency domain.

The performed experimental measurement is aimed at establishing the presence of local or global structure response close to the actuation frequency, and the verification of the FEM calculation model. The eigenfrequencies of FEM model DB10 given in table 5 largely overlap with the measurements shown in figure 18, hence the conclusion that

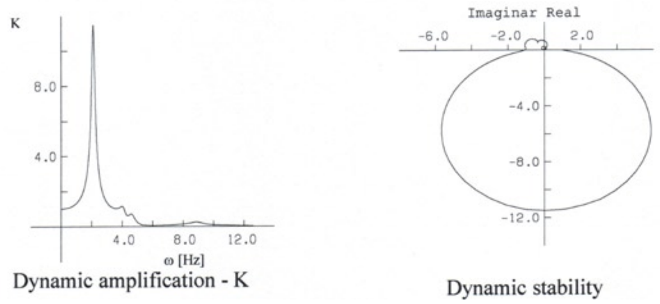

Fig. 20. Frequency characteristics of DB10 plane model of reconstructed discharge boom

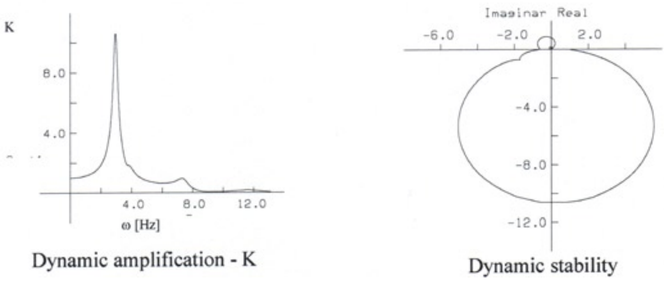

Fig. 21. Frequency characteristics of DB10 spatial model of reconstructed discharge boom

the FEM calculation model is validated. We also conclude that the measured acceleration values of the additional tie connection point on the boom structure in the vertical and lateral direction are within the limits of permissible values for this type of construction as prescribed in [5]. All of the above serves to prove that the dynamic behaviour of BWE C700S operation performance is significantly improved after the implemented reconstruction. This conclusion is further confirmed by the results of dynamic calculations of forced damped vibrations in the frequency domain of model DB10 according to which the boom reconstruction was carried out. The frequency characteristics of the reconstructed boom plane model are shown in figure 20, while figure 21 shows those for the reconstructed boom spatial model.

The numerical calculation of the spatial model show higher values of eigenfrequencies compared to those of the plane model. The experimental measurements were carried out on the BWE C700S reconstructed discharge boom in operating conditions. Although calculations were not done on the whole BWE model, the results of the measurements are in correlation with the calculation results on the discharge boom model. Correlation is related to the identification of the presence of the boom vibration close to its eigenfrequencies. The spatial model gives more accurate results, but for the investigation in this paper the plane model was accurate enough.

3. Conclusion

The diagnostics of the load carrying construction condition shown in this paper are performed by the FEM and experimental method in order to detect the cause of the BWE C700S discharge boom operation problem in the Kolubara opencast mine, Serbia. The cause of the exploitation problem was established – insufficient stiffness of the boom ties as defined in the design, as well as the subsequently attached steering cabin which does not form part of the original design. Numerical analysis (FEM) showed that the deformation energy distribution was dominant in the elements of the boom structure(72%), that the boom deformations were very high (104 mm), that the first two vibration frequencies were very low and at high proximity, and that the dynamic performance factors for the first two vibrations were considerable, all of which contribute to weak boom operation performance and point to possible courses of action in boom redesign. The paper analysed the dynamic performance of several possible dynamic behaviour improvement models.The selected model is optimal when taking into account the technical, financial and staffing capacities of the user for the reconstruction implementation. The boom reconstruction was implemented by removing the steering cabin and introducing two new boom ties.

The BWE discharge boom dynamic behaviour improvement was verified by the experimental method on the reconstructed boom. The experiment results prove a good match with the FEM analysis results, which validate the numerical model. The major advantages of the reconstructed discharge boom over the original comprise the following:

(1) Maximum boom deformation is reduced from 104 mm to 51.5 mm.
(2) The first two eigenfrequencies are increased as is their distance as shown in table 5.
(3) A more even deformation energy distribution on the construction elements is achieved.
(4) The dynamic amplification factor for the first vibration mode is reduced from 38 to 12, and a significantly higher system dynamic stability is secured due to a considerable reduction in the imaginary part of characteristics (figure 20).
(5) All accelerations of structure modes are reduced within the limits of permissible values [5] (up to 2 m/s^2).

The application of the described diagnostics methodology of load carrying structure performance is justified and necessary in the engineering analysis of exploitation problems since it produces good results and is cost effective.

Acknowledgement:
This work is partially supported by the Ministry of Education and Science of Serbia grants nos. TR35040, TR35030 and E!6761.

References

1. Araujo LS, De Almeida LH, Batista EM. Analysis of a Bucketwheel Stacker Reclaimer Structural Failure, Proceedings of the conference Materials science & technology, Charles R. Morin Memorial symposium on failure analysis and prevention, 2009, Pittsburg, Proceedings on CD, http://www.matscitech.org.
2. Arsić M, Bošnjak S, Zrnić N, Sedmak A, and Gnjatović N. Bucket wheel failure caused by residual stresses in welded joints. Engineering Failure Analysis 2011; 18: 700-712.
3. Bošnjak SM, Arsić MA, Zrnić NĐ, Rakin MP, Pantelić MP. Bucket wheel excavator: Integrity assessment of the bucket wheel boom tie-rod welded joint. Engineering Failure Analysis 2011; 18: 212-222.
4. Bošnjak SM, Zrnić ND. Dynamics, failures, redesigning and enviromentally friendly technologies in surface mining systems. Archives of Civil and Mechanical Engineering 2012; 12: 348-359.
5. DIN 22261-1 and DIN 22261-2, Excavators, spreaders and auxiliary equipment in opencast lignite mines. Part 1: construction, commissioning and monitoring, Part 2: calculation principles, Berlin: German Institute for Standardization, 1998.
6. Ghosal S, Misra D, Saha TK, Chakravorty D, and Chaudhuri B. Failure Analysis of Stacker-cum-Reclaimer in Ore Handling Plant. J Fail. Anal. And Preven.2008; 8: 564-571.
7. Gottvald J. Analysis of vibrations of bucket wheel excavators Schrs1320 during mining process. FME Transactions 2012; 40: 165-170.
8. Jovančić PD, Ignjatović D, Tanasijević M, Maneski T. Load-bearing steel structure diagnostics on bucket wheel excavator, for the purpose of failure prevention. Engineering Failure Analysis 2011; 18: 1203-1211.
9. Maneski T. Monography computer modelling and structures calculation (in Serbian), 1st ed., Belgrade: Faculty of Mechanical Engineering, 1998.
10. Maneski T, Ignjatović D. Repair and reconstruction of bucket wheel excavators. Structural Integrity and Life 2004; 1: 9-28.
11. Maneski T, Ignjatović D. Structural performance diagnostics. Structural Integrity and Life 2004; 1: 3-7.
12. Markowski T, Mucha J, Witkowski W. FEM analysis of clinching joint machine's C-frame rigidity. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2013; 15 (1): 51-57.
13. Rusinski E, Czmochowski J, and Moczko P. Failure reason investigations of dumping conveyor breakdown. J. of Achievements in Materials and Manufacturing Engineering 2007; 23: 75-78.
14. Rusinski E, Czmochowski J, Moczko P. Investigations of causes of dumping conveyor breakdown. J. of Achievements in Materials and Manufacturing Engineering 2007; 24: 267-274.

15. Rusinski E, Czmochowski J, Pietrusiak D. Problems of steel construction modal models identification. Eksploatacja i Niezawodnosc-Maintenance and Reliability 2012; 14 (1): 54-61.
16. Rusinski E, Czmochowski J, Iluk A, Kowalczyk M. An analysis of the causes of a BWE counterweight boom support fracture. Engineering Failure Analysis2010; 17: 179-191.
17. Rusinski E, Dragan S, Moczko P, Pietrusiak D. Implementation of experimental method of determining modal characteristics of surfface mining machinery in the modernization of the excavating unit. Archives of Civil and Mechanical Engineering 2012; 12 (4): 471-476.
18. Rusinski E, Moczko P, Czmochowski J. Numerical and experimental analysis of a mine's loader boom crack. Automation in Construction 2008; 17: 271-277.
19. Rusinski E, Moczko P, Kaczynski. Structural modifications of excavator's bucket wheel by the use of numerical methods. Solid State phenomena 2010; 165: 330-335.

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