IN SITU MEASUREMENTS REGARDING THE BWE BOOM USING ACCELEROMETERS AND STRAIN GAUGES AT BWEs OPERATING IN CEO OPEN PITS

POMIARY IN-SITU WYSIĘGNIKÓW WIELONACZYNIOWYCH KOPAREK KOŁOWYCH W KOPALNIACH CEO Z WYKORZYSTANIEM TENSOMETRÓW I AKCELEROMETRÓW

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The boom of BWE is a very complex structure, dictated by its functions in operation of the excavator. In the simplest approach, it can be considered as an arm of an R-R robotic manipulator, having at distal extremity the working element, i.e. the bucket wheel, being fixed at proximal extremity by a joint to the turret, which, at its turn is articulated to the infrastructure which includes the undercarriage (travelling mechanism). In order to reduce the weight/stiffness ratio and to include the on board conveyer, the boom is generally embodied as a lattice – truss structure. The constitutive elements i.e. the members and joints are subject to severe loads, which due to their cyclical variable character with a high random component, lead to failures which are caused by overloading and/or fatigue. The actual paper deals with the field measurements performed in past years on several BWEs from CEO open pits, including acceleration measurements and stress measurements using strain gauges. Both kind of sensors-accelerometers and strain gauges were mounted on several critical points of the boom, and the measurements were performed both in normal operation and in some loading-operating scenarios. The recorded data were postprocessed in order to obtain spectral graphs in order to obtain information about the influence of different excitation sources on the boom elements behaviour.

Keywords: bucket wheel excavator, boom, vibration, accelerometers, strain gauges

Wysięgnik wielonaczyniowej koparki kołowej jest złożoną strukturą definiowaną przez technologię pracy koparki. W celu zmniejszenia stosunku waga/sztywność oraz występowania przenośnika taśmowego wysięgnik jest zaprojektowany jako konstrukcja kratownicowa. Jej elementy są poddawane silnym obciążeniom, które ze względu na ich cykliczny charakter z wysoką składową losową prowadzą do awarii spowodowanych przeciążeniem lub zmęczeniem konstrukcji. Niniejszy artykuł przedstawia pomiary terenowe wykonane w ostatnich latach na wielonaczyniowych koparkach kołowych pracujących w kopalniach CEO za pomocą tensometrów oraz akcelerometrów. Pomiary te zostały zamontowane w krytycznych punktach wysięgnika, a pomiary zostały wykonane zarówno podczas normalnej pracy koparki jak i podczas realizacji scenariuszy obciążenia. Zarejestrowane dane zostały poddane obróbce w celu uzyskania wykresów widmowych.

Słowa kluczowe: koparka wielonaczyniowa, wysięgnik, wibracje, przyśpieszeniomierz, tensometr

FOREWORD

The bucket wheel supporting steel structure (boom) is the most responsible part of failures and damages on the bucket wheel excavator resulting from overloads during the excavation and fatigue due to the variable-cyclical character of loads.

It is actually the main part of the bucket wheel excavator that defines its lifetime. Condition and behaviour of the bucket wheel boom primarily depend on its geometry and its supports to the main structure of the BWE with higher levels of stiffness.

The specificity of this structure is in its lattice design and structure. This form should have a good condition and behaviour under load, especially during twisting. However, due to possible material fatigue and weakening of the structure, especially at the local level, as well as the occurrence of an extremely hard material that is excavated, failure of structure may be expected.

In order to have information about these both causes of failures, measured vibrations are used up or could have been used as decisive parameters for making the correct attitude on the future operation.

In addition, derived numerical model indicates issues of structural integrity of these types of bucket wheel excavators with possible failure locations of steel structure.

Diagnosis of the condition and behaviour by such complementary perception mode is gaining importance.

The specific design, i.e. the lattice -spatial truss structure make the superstructure disposed to vibrate, with very low frequencies, as a rigid body which is supported on the undercarriage that can be treated as the flexible support. Consequently, vibrations of higher frequencies represent the flexible modes.

The dynamics of the BWEs is one of the crucial elements in the design process, while the operation loads, in most cases are not stable and can have the impact character [1]. For the excavators, the major excavation energy is related to buckets discharge and superposition of alternating digging forces (or shocks in case of the non-mineable structures).

Common excitation sources are technological movements

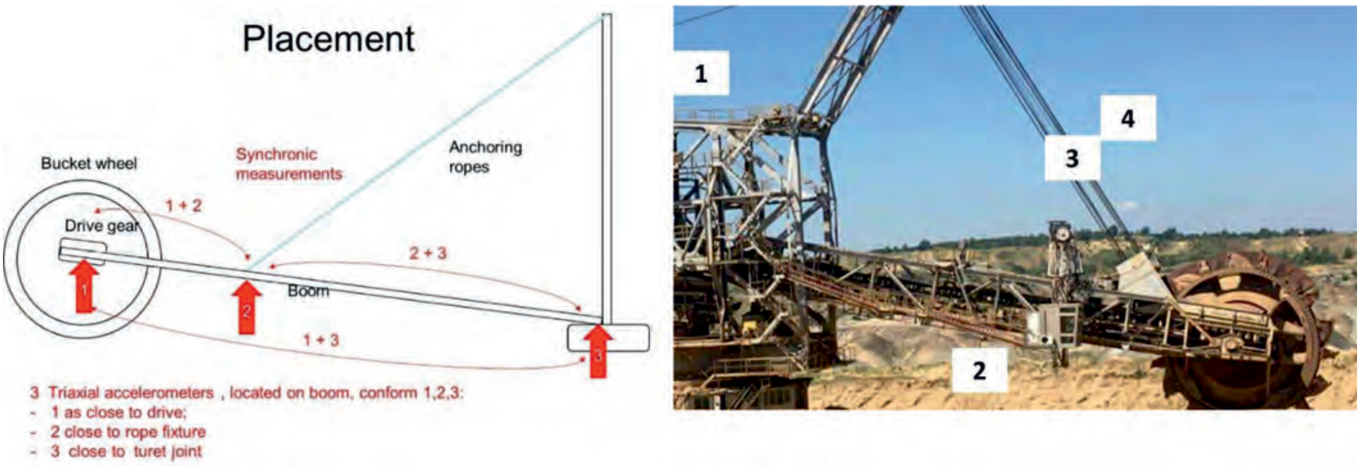


Fig. 1. Planned (left) and realized (right) location of the accelerometers on the BWE boom
Rys. 1. Planowane (po lewej) oraz rzeczywiste (po prawej) umiejscowienie akcelerometrów na wysięgniku koparki

(travel, slewing, hoisting) and the transportation system: belt conveyors idlers which are hit by the excavated material, material drop in chute points (change of the elevation between conveyors).

ACCELERATION MEASUREMENTS

The accelerometers are reliable devices for measuring strain (by further processing of acquired data) and could be complementary of strain gauges measurements.

A remote measurement system dedicated to investigation of Bucket Wheel Excavator boom Lattice Structure has been devised and tested in lab and real conditions, comprising sensors (accelerometers), transmission and storage components, data recovery and pre-processing.

The wireless transmission (including methods of avoidance the metal elements EM influence) in parallel with SD card storage has been tested and validated.

Measurements were made on ESRC -1400 BWE from Husnicioara open pit using accelerometers and wireless transmission of data and toward a data logger.

One measuring point is based on a devised and prototype sensor which is object to a future patent. It is able to detect: very low variations of accelerations produced by sudden changes in cutting forces, able to detect small displacements of the monitored site.

The parameters are measured in 3 axes. Some other auxiliary environment parameters (air temperature and humidity and pressure, soil humidity) can be integrated in the same measuring point.

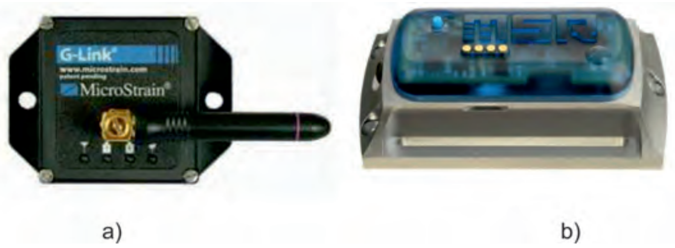


Fig. 2. Accelerometer (a) and data logger (b)
Rys. 2. Akcelerometr (a) i data logger (b)

At this moment, each measuring point is equipped with a wireless transceiver that create an ad-hoc network (Zigbee network) for covering large area of monitoring system.

The actual distance between any two measuring points must be below 50 meters.

The maximum tested number of measuring points is 200, but according with Zigbee protocol, the limit number is much higher. Through a network gateway, the monitoring system sends data to local software or can publish values into a web-based map.

Next approach will replace the Zigbee transceiver with a WiFi transceiver that make the system perfect integrable in Internet of Thinks.

Another real time measurement system is implemented with a wireless low rate data transmission, and the main target is to optimize the entire process from the energy consuming point of view. The next step is focused on local high processing data, with results forwarding to a dispatching system.

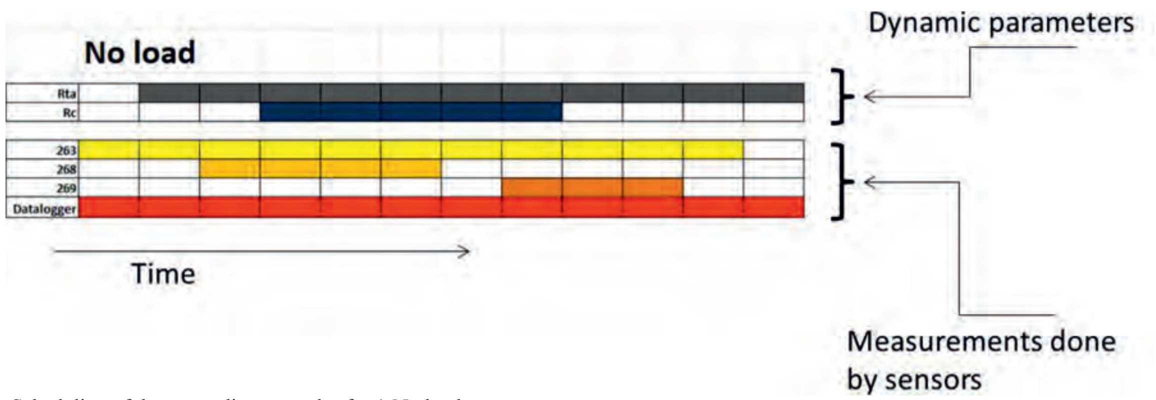


Fig. 3. Scheduling of data recording on nodes for 1-No load
Rys. 3. Harmonogram rejestracji danych w węzłach bez obciążenia -1

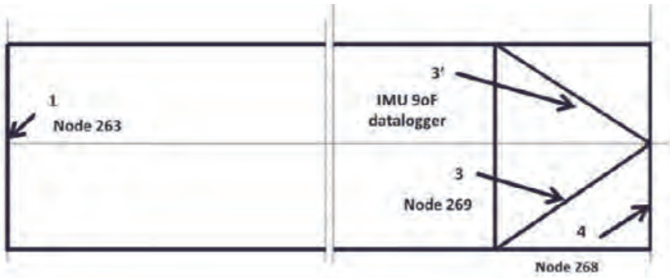


Fig. 4. Codification of nodes
Rys. 4. Kodyfikacja węzłów

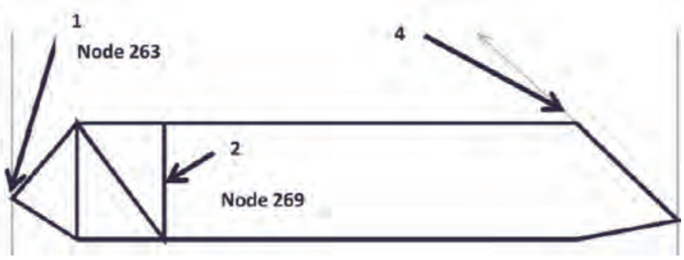


Fig. 7. Codification of nodes 3- load1
Rys. 7. Kodyfikacja węzłów 3

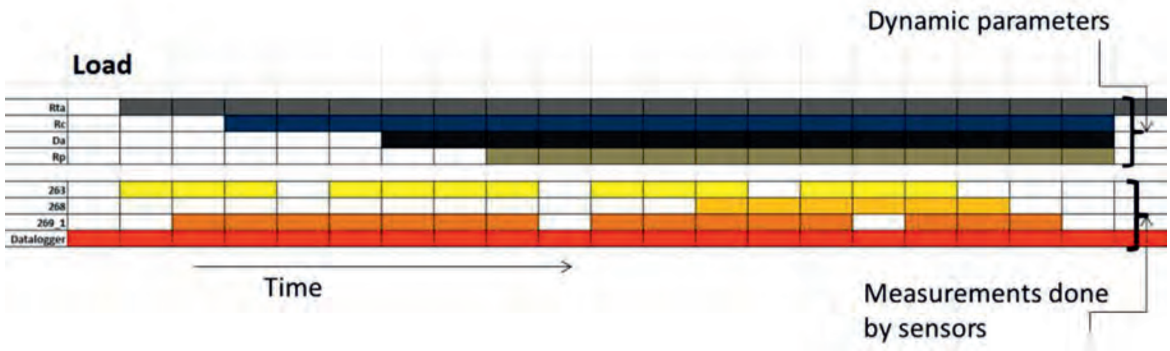


Fig. 5. Scheduling of data recording on nodes for 2- load
Rys. 5. Harmonogram rejestracji danych w węzłach pod obciążeniem -2

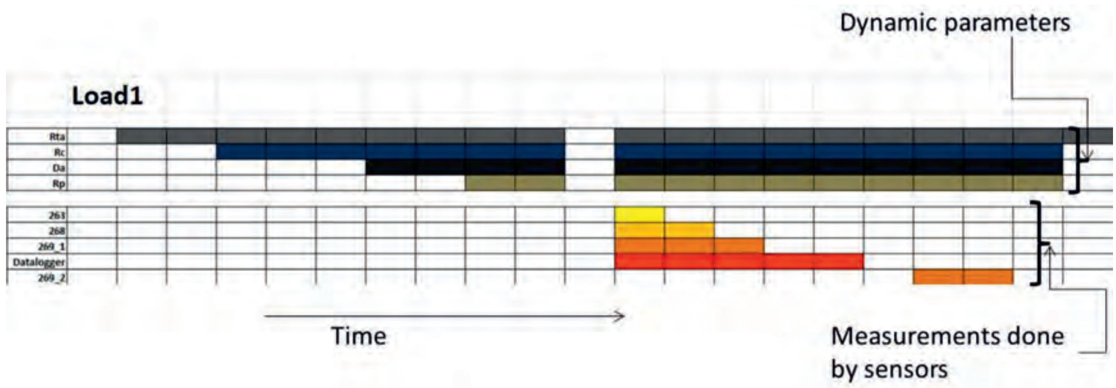


Fig. 6. Scheduling of data recording on nodes for 3- load1
Rys. 6. Harmonogram rejestracji danych w węzłach pod obciążeniem -3

Fig. 8. Preparatory works on nodes placement-details
Rys. 8. Prace przygotowawcze na węzłach

Tab. 1. Excitation frequency calculation
Tab. 1. Obliczanie częstotliwości wzbudzenia

Rotor type	Wheel rpm	No of buckets	Excitation frequency [Hz]	
			Cutting/Emptying	Rotation
Classic	4.32	9 precutters +9 buckets	1.037...1.555 0.518...0.778	**0.058-0.086**
Modernized Var. I	4.68	18 buckets	1.123...1.684	**0.062-0.094**
Modernized Var. 2	4.68	20 buckets	1.248....1.872	

Recorded data are in course of processing. Some sample data were processed and it has been possible to provide spectra graphs.

As a result the previously programmed testing program will be adjusted accordingly.

In continuation we show the prerequisite preparation for onsite acceleration measurements.

1. Placement of accelerometers

The accelerometers were planned to be located in three regions, i.e. in the proximity of drive gear, in the proximity of suspension points of the boom with boom-rising rope-pulley system and in vicinity of turret joint, as in fig. 1.

2. Accelerometers used

• We use three G-link fast wireless system (Measurement range: ± 2 g or ± 10 g standard; Accelerometer bandwidth: 0 Hz to 500 Hz; Accuracy: 10 mg; Resolution: 12 bit), fig. 2 a) , http://files.microstrain.com/G-Link_Datasheet_(8400-0077).pdf

• and a MSR 145 data logger (Waterproof IP 67), fig. 2 b)

3. Measurement conditions and schedule

- 1-No load
  - *Rta* (on board conveyer running)
  - *Rc* (bucket wheel rotation- without digging)
- 2-Load- load conditions (cutting, marching, spinning)
  1. *Rta* (conveyer running)
  2. *Rc* (wheel rotation)
  3. *Da* (advancing- entering into front for cutting)
  4. *Rp* (excavator boom swelling)
- 3-Load1- load conditions (cuttings, marching, spinning)-

1. Identic with upper; measurements are done by relocating sensor 269 according with placement diagram.

Before the measurement campaign, some preparatory works were necessary, i.e. fixing by welding the appropriate supports for the accelerometers on selected boom members (fig. 8).

In order to establish the frequency domain to calibrate the accelerometers and the DAQ system, the excitation frequency range of the bucket wheel has been established using the known formula for the excitation frequency due to cutting forces.

$$f_c = \frac{n_{rc}}{60} * z_c \pm 20\%$$

Where: n_{rc} the bucket wheel rotation speed (rpm) z_c the number of buckets in contact with the face. For wheels with cutting and cutting loading buckets, the frequency of emptying the buckets will be the half of the calculated value.

The excitation frequency of rotating wheel will be

$$f_r = \frac{n_{rc}}{60} \pm 20\%$$

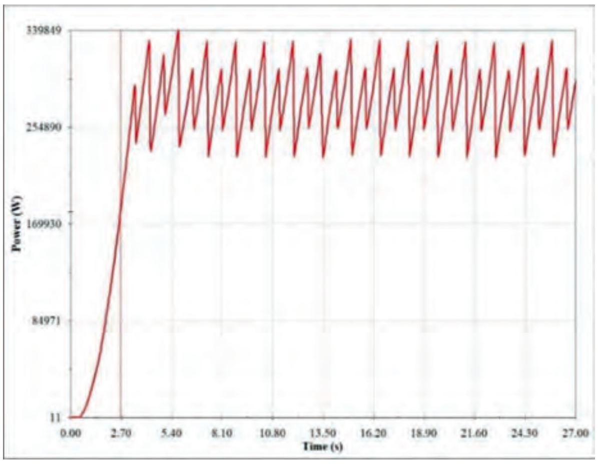


Fig.9. Variation of peripheral forces on bucket-wheel obtained by simulation
Rys. 9. Zmienność sił obwodowych na kole czerpakowym uzyskana za pomocą symulacji

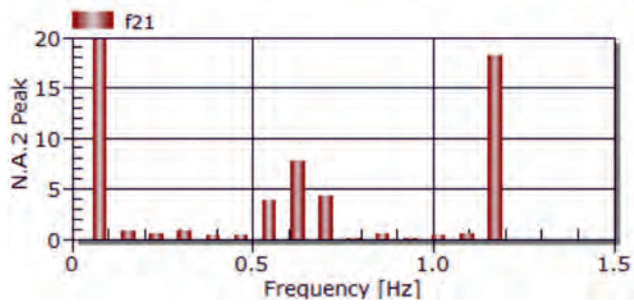


Fig. 10. Periodogram of the forces variation from fig.9
Rys. 10. Periodogram zmiany sił z rys. 9.

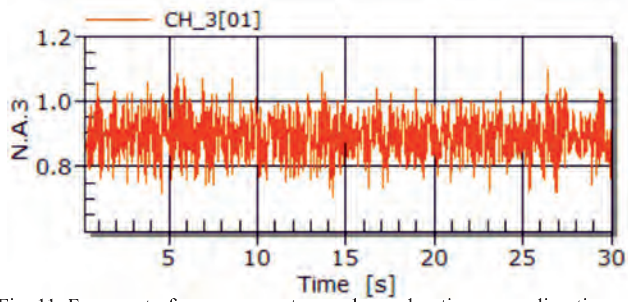


Fig. 11. Fragment of measurement record, accelerations on x direction, node 269, fig. 7
Rys. 11. Fragment zapisu pomiaru przyspieszenia w osi x, węzeł 269

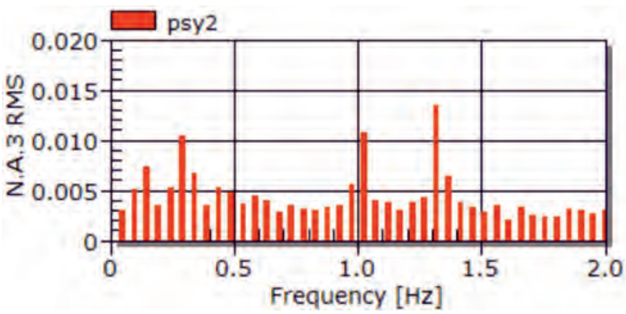


Fig. 12. Periodogram of the signal presented in fig. 11
Rys. 12. Periodogram sygnału z rys. 11

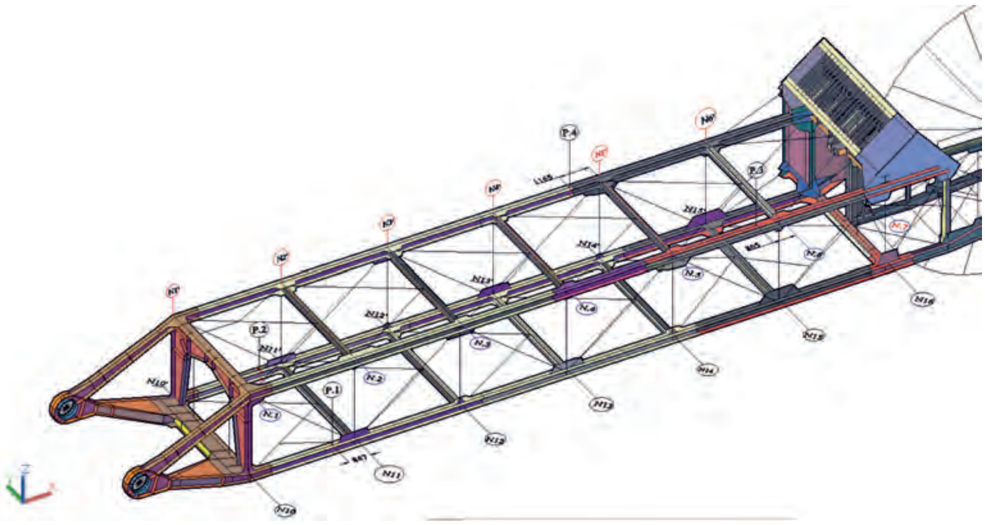


Fig. 13. Location of electro-resistive transducers (ERT) on the bucket wheel boom
Rys. 13. Rozmieszczenie przetworników elektro-rezystancyjnych (ERT) na wysięgniku koła czerpakowego

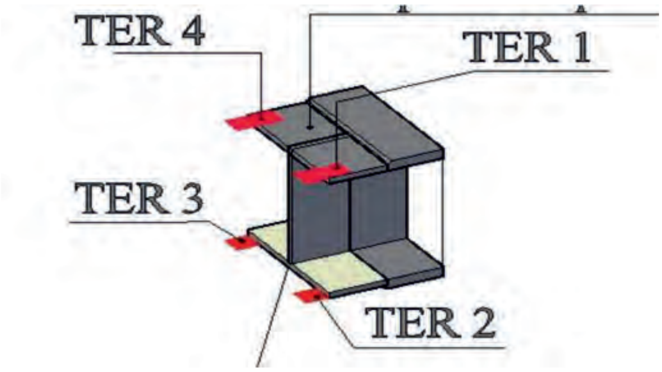


Fig. 14. Location of ERTs on the load carrying beam (detail)
Rys. 14. Lokalizacja ERT na belce nośnej

We established the following frequencies, shown in the table 1.

These values are in accordance with previous dynamic modelling of bucket wheel (fig. 9), when simulated different number of buckets, cutting-loading and cutting ones, we find the same range of proper frequency of exciting forces.

The main finding is that cutting buckets influences only the cutting forces and the others (cutting-loading influences also by inertial forces of loaded unloaded rock). This is why our graph is in detail different from those of the literature. However, the knowledge of fundamental frequency (fig. 10) is useful information to discriminate it from the spectra.

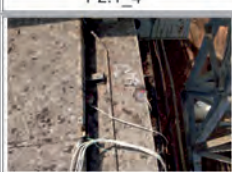
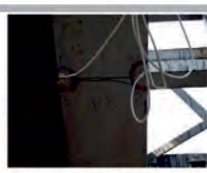
In fig. 11 an excerpt of measurement record is presented, according to item 269_2 from figs. 6 and 7. The according periodogram is presented in fig 12.

The similarity – existence of some common frequencies confirms the correctness of the simulation model. A large amount of data is in course of processing and identification, in order to confirm the critical areas and the future analyse of the propagation of exciting stresses along the boom in the 3 directions.

STRAIN MEASUREMENTS USING STRAIN GAUGES

The measurement of the mechanical stresses on the bucket wheel boom is made by placing the electro-resistive transducers (ERT, strain gauges) in the critical areas, which are determined by the finite element method or, in the technical experiments, by visual control, areas where the load carrying elements have been subjected to strong deformations or stresses, even cracks. The four nodes where the ERTs were placed are marked on fig. 13.

Tab. 2. Placement of the strain gauges
Tab. 2. Lokalizacja tensometrów

Point of measure according to fig. 13	Gauges on upper plate	Gauges on lower plate
P1	 P1.1_4	 P1.3_2
P2	 P2.1_4	 P2.3-2
P3	 P3.1_4	 P3.2_3
P4	 P4.1_4	 P4.2_3

The extreme values of the normal stresses for the bending sections, with simple or compound cross-section shapes, with the continuous link of the main elements (profiles I, U, Π) are in the corners of the profile, in which case four ERTs will be applied as close as possible to the corners of the profiles and symmetrically aligned with the axis of the profile.

Fig. 15. Wiring and performing measurements on the bucket wheel boom
Rys. 15. Okablowanie i pomiary na wysięgniku koła czerpakowego

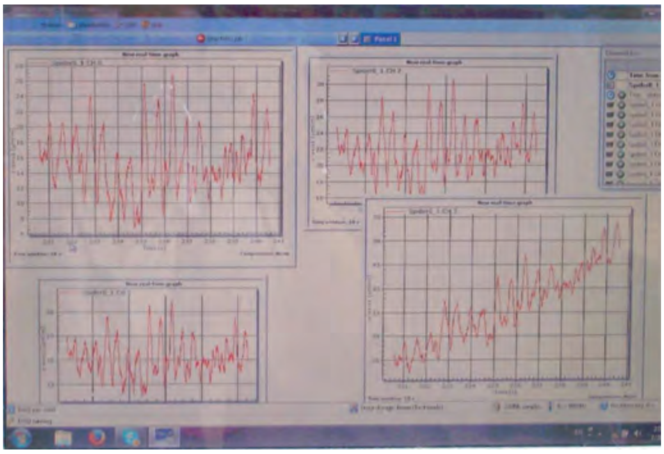
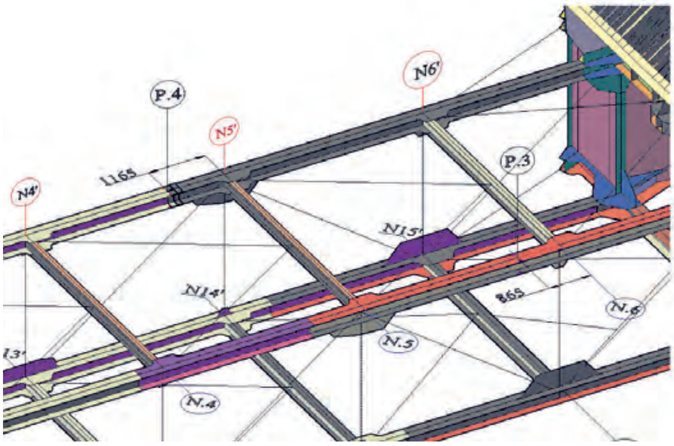


Fig. 16. Measurements at P1 recording point, channels: CH 0, CH 1, CH 2, CH 3
Rys. 16. Pomiary w punkcie P1, kanały CH 0, CH 1, CH 2, CH 3



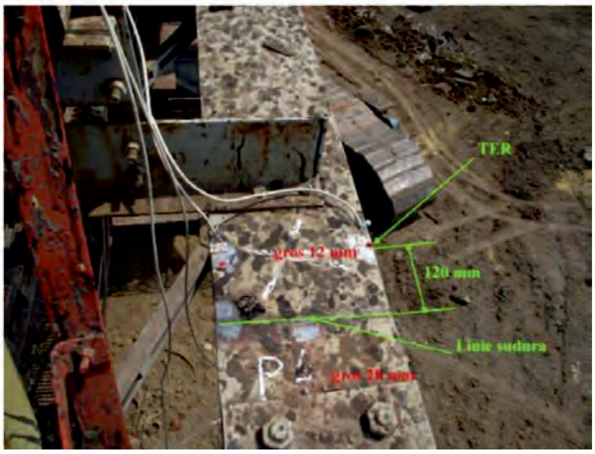


Fig. 17. Beam joint area 4` - 5`, point P4
Rys. 17. Obszar łączenia belek 4'-5'. punkt P4

As the load carrying beams of the bucket wheel boom are beams of profile I made in welded construction, we applied four ERTs positioned as in figure 14.

Taking into account these considerations, the strain gauges were placed on the bucket wheel boom at the points P1, P2, P3, and P4, according to table 2, to the outer part of the I profile, which forms the boom's load carrying beam.

After the ERT placement, they were wired to the measuring apparatus figure 3, and the measurements were performed the on cutting cycles, as illustrated in figure 15.

THE RESULTS OF NORMAL STRESS MEASUREMENTS ON THE BUCKET WHEEL BOOM

The measurements were made in the working face, by performing a complete working cycle, by turning the boom of the bucket wheel in the senses Left → Right and Right → Left.

An excerpt of the measurements results are presented in the screenshot shown in fig. 16.

After processing the data and analysing them we found that the highest values of the stresses are obtained at the measure point P4, the diagrams illustrated in table 3 and figure 17.

The corresponding periodogram is shown in fig. 18. We can notice the existence of the main spectral lines as in fig. 12.

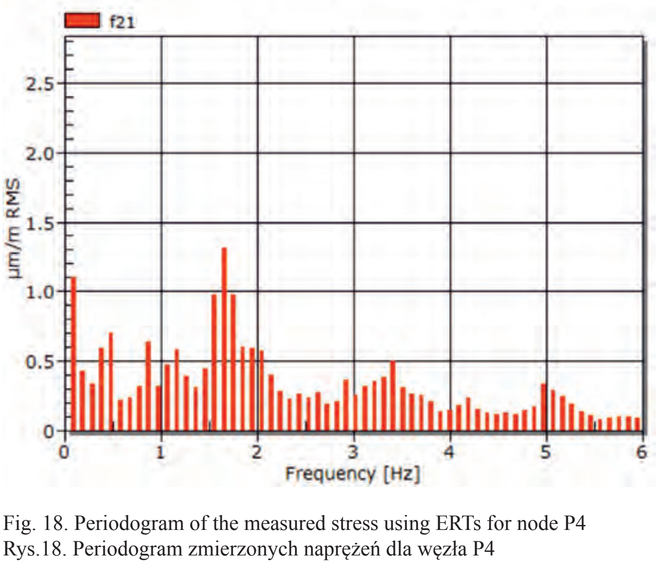
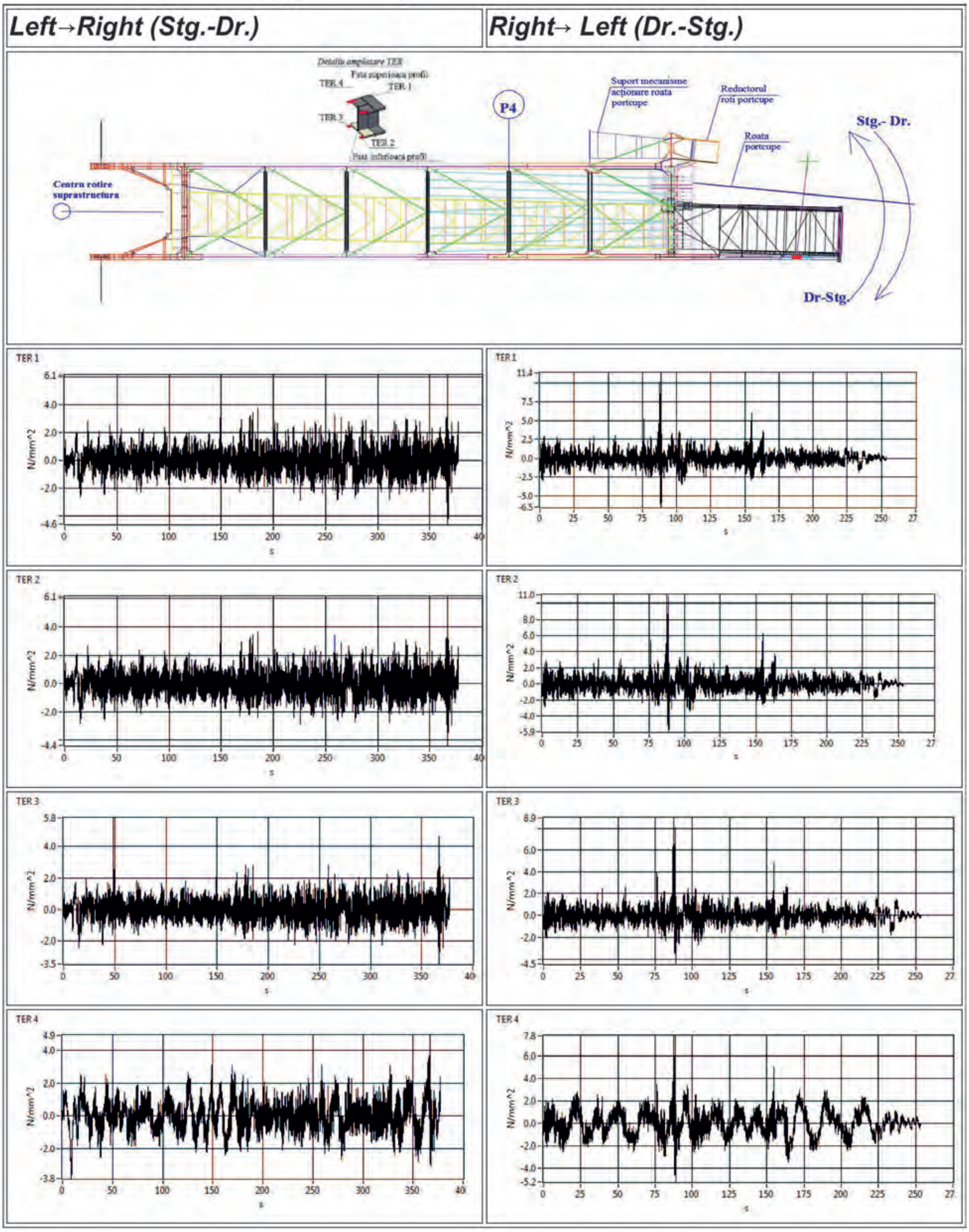


Fig. 18. Periodogram of the measured stress using ERTs for node P4
Rys.18. Periodogram zmierzonych naprężeń dla węzła P4

CONCLUDING REMARKS

Acceleration and strain gauge (extensometer) stress measurements were performed on BWEs operating in different open pits of CEO, in different working regimes. The measuring points, i.e. the sensors placement has been decided using visual inspection, operating and maintenance staff recommendations, and FEM analyses. For the two different excavators (of same type) working in dif-

Tab. 3. Stresses measured at point P4
Tab. 3. Naprężenia w punkcie P4



ferent open pits (in quit similar conditions) the sensor placement has been closely similar.

Analytical modelling has been utilized for obtaining a priori indications about the shape and spectral content of the exciting forces. The obtained results for both measurement systems are similar, complementary and coherent. The next step, after finishing the data processing will be the spatial variability of the measured items, by involving more sophisticated analysis tools in order to discriminate the components due to overload and deriving the spread of stresses from exciting source among the constitutive elements of the boom's truss structure. The presented methodology and the preliminary results could be information inputs to deliver the basis of a monitoring system which uses minimal number of sensors, optimally placed in order to obtain maximum of relevant information about the load state of the BWE boom.

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Architectural details of Wrocław