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EKSPLOATACJA ZBROJENIA SZYBU GÓRNICZEGO W OPARCIU O GLOBALNY WSPÓŁCZYNNIK TŁUMIENIA

MAINTENANCE OF MINING SHAFT REINFORCEMENT BASED ON GLOBAL DAMPING COEFFICIENT

W eksploatacji urządzeń górniczych bardzo istotnym czynnikiem jest zachowanie równowagi pomiędzy ekonomią a bezpieczeństwem. Użytkowanie szybu górniczego według stanu związane jest z oceną jego stanu oraz oceną oddziaływań pomiędzy zbrojeniem szybowym a naczyniami wyciągowymi. W ocenie stanu technicznego zbrojenia szybowego wykorzystuje się heurystyczne metody wizyjne, ultradźwiękowy pomiar grubości elementów, pomiar „spokoju jazdy" itp. Nową, proponowaną metodą jest pomiar globalnego współczynnika tłumienia. Ponieważ metoda ta jest metodą selekcyjną, wymaga dodatkowych procedur diagnostycznych. Dobór tych procedur ukierunkowany jest na zmniejszenie niepewności otrzymanych wyników.
W artykule przedstawiono opis metody globalnego współczynnika tłumienia. Algorytm ten został zaimplementowany w przyrządzie pomiarowym. Przedstawiono sposób implementacji z zastosowaniem środowiska LabView oraz metody wirtualnych instrumentów Wyniki pomiarów importowane są do systemu bazodanowego. Na podstawie zebranych informacji podejmowane są decyzje dotyczące dalszej diagnostyki oraz dalszej eksploatacji zbrojenia szybowego. Prezentowany algorytm jest wdrażany w jednej z kopalni, oraz trwają prace nad jego udoskonaleniem.

***Słowa kluczowe**: analiza sygnałów, dekompozycjia falkowa, dekrement tłumienia.*

In mining equipment exploitation it is very important to keep balance between payoff and safety. Usage of shaft is related to its state assessment and the evaluation of interactions between shaft reinforcements and transportation vessels. In the reinforcement state assessment heuristic vision methods are used, ultrasonic thickness measurements, run stability measurement etc. Attenuation rate measurement is a proposed new method. Since this method is a selection method it needs additional diagnostic procedures. The choice of procedures is directed towards reduction of results uncertainty. The article presents the method of global attenuation rate. The algorithm was implemented into the measurement device. The method of implementation by means of LabView environment was presented as well as methods of virtual instruments. The measurement results are imported into database system. Based on the gathered information the decisions are made regarding future diagnostics and exploitation of the shaft reinforcement. The presented algorithm is being introduced in one of the mines and is constantly perfected.

***Keywords:** signal analysis, wavelet decomposition, attenuation decrement.*

1. Origin of the problem

One of the problems with determining the technical condition of a mining shaft is diagnostics of shaft reinforcement, operating under severe conditions and in aggressive, corrosion-inducing environment. The diagnostics may be even more difficult owing to the loss of the linearity of the track of mining vessels caused by tectonic shift.

The primary legal act dealing with the safe operation of mining machines is Ministry of Economy Decree from the 28th of June 2002 regarding health and safety at work and specialist fire precautions in underground mining plants (Dz.U. nr 139 poz.1169). This decree also covers requirements for lift devices, including guidance on the acceptable wear of shaft reinforcement. According to § 460, the elements of steel structure of the reinforcement are to be replaced if the wear exceeds the maximum permissible wear or 50% of primary nominal measure specified in technical documentation. This act has been extended by Minister of Economy Decree form the day 09-06-2006r enabling to specify another permissible wear of reinforcement elements [5]. Thus formed regulation unambiguously determines the assessment criteria, yet the problem remains of how to identify the elements showing the greatest wear. The main reason of this state of the issue is the fact that shaft reinforcement is a complex structure composed of, depending on the mine depth, from several hundred to several thousand elements. Given such numbers, it is difficult to select the elements of the greatest wear.

In maintenance practice it is accepted that the indicator of wear of steel elements of reinforcement is element wall thickness measured by means of various techniques, mainly with the application of ultrasound methods. Such measurements are beset by a number of limitations, including:

- Pointed character of measurement,
- Problems with measurements in case of corroded surfaces cavities etc.,
- No information about the stiffness of the beam being under dynamic excitation,
- Necessity of the proper preparation of the surface.

Examining of each structure element is very time-consuming and virtually impossible within the time expanse of routine controls and maintenance services. Hence, based on maintenance expertise or other circumstances, a limited set of elements is being established. Those elements are subject to periodical controls.

Other elements are assumed to feature similar wear. However, it is plausible that this selection could exclude the most worn out elements, which implies impossible to evaluate errors of the control [4].

Considering the safety measures of vertical transportation and economical aspects, as well as coalmine needs, for several years the Mechanics and Vibroacoustics Department of M&M Academy in Kraków conducted theoretical research and experiments intent on improving the reliability of diagnosis about technical state of shaft reinforcement. One of the objectives of the research is developing the method of quick selection of reinforcement elements and assigning them to the specified usability state. The assumption had been made that the new method should be simple to carry out, possible to apply under different environmental conditions, and the interpretation of the results should be easy. One of the main requirements was also the reduction of examination time as compared to the one in contemporary methods, and the possibility of conducting the method without the necessity of special preparations of the elements examined.

2. Applied methods

At present, knowledge about technical state of shaft reinforcement is gained through the results of the three manners of control [1,2]:

- The first is associated with visual inspection of the state of corrosion advancement. This method provides only simplified information.
- The second one is associated with non-destructive ultrasound tests. In these control procedures a point thickness measurement is carried out on structural elements of shaft reinforcement by means of ultra-sound defectoscope. An appropriate preparation of the installment surface of the transmitting head, onto an examined structural element, plays a very important role in these tests. Surface preparation involves removing contaminations and removing cavities and roughness mechanically. Apart from that, necessary requirement in these examinations is considering the appropriate acoustic feedback between the ultra-sound head and the examined element, which comes down to the application of suitable feedback means.
- Another control procedure providing information on mining-shaft state is examination associated with measurements of acceleration of mining vessels, or measurements of dynamic forces of the influence of mining vessels on shaft reinforcement during their movement. These testes include the evaluation of ride smoothness of lift vessels. The results of horizontal acceleration measurements of moving mining vessels provide data for this evaluation.

The results of acceleration measurements make allowance for both the influence of roughness of guiding rails and the setting of rolls installed into the vessels. Hence in the process of measurements of ride smoothness the setting of rolls is to be controlled and, if need be, adjusted as these rolls significantly affect the result of acceleration measurements of mining vessel.

3. Identification of damping coefficient

Review of articles devoted to the evaluation of structural degradation points to the existing specified areas of analysis, enabling to recognize changes in elements' states, among which the methods of modal analysis are of vast usage. However, in case of degradation of stiff elements of shaft reinforcement, the sensitivity of eigen-frequency changes for their occurrence is relatively low. Better symptom is the analysis of eigen-frequency forms under given circumstances, which generally is very troublesome.

In the analysis of general dynamic equation of diagnosed structural element:

$$M\ddot{x} + C\dot{x} + Kx = f(t) \tag{1}$$

where: *M, C, K* – are respectively matrices of masses, damping and stiffness of modeled element, $\ddot{x}, \dot{x}, x$ - vectors of acceleration, speed and replacement respectively, f - vector of exciting force.

It cannot be overlooked that the changes in one matrix are connected to the parameters' change in another one. For example, change in mass of the system caused by the corrosion affects not only to the mass matrix, but also damping and stiffness matrix

In modal analysis estimating parameters of the equation (1), one of the assumptions concerning its carrying out is the requirement of low dumping in the system. In case of examining elements of mining-shaft structure this assumption is not justified and can induce some reservations. So the question arises of the possibility of applying changes of state of shaft reinforcement, as information medium associated with damping occurred in the system, into diagnostics process.

The assessment of possible application of this property into examining elements of shaft structure is the subject of the conducted research. It required estimating the selected measures of vibration damping for diagnosed elements in the process of testing excitations or exploitation excitations.

The application of damping characteristic as a carrier of information regarding technical state of reinforcement is limited by non-stationary character of measurement signal. Good solution in the process of its estimation is the analysis (in time domain) of the response of an examined system for pulse excitation. To explain this issue let us look into the case of free damped vibrations of a point described by equation:

$$m\ddot{x} + c\dot{x} + kx = 0 \tag{2}$$

where: *m, c, k* – are parameters determining mass, damping coefficient and stiffness of the point given.

Introducing symbols:

$$\omega_0^2 = \frac{k}{m} \qquad 2n = \frac{c}{m} \tag{3}$$

we bring the equation (6.2) to the form of :

$$\ddot{x} + 2n\dot{x} + \omega_0^2 x = 0 \tag{4}$$

characteristic equation determining it:

$$r^2 + 2nr + \omega_0^2 = 0; \tag{5}$$

allows calculating equation roots:

$$r_{1,2} = -n \pm \sqrt{n^2 - \omega_0^2} = -n \pm i\sqrt{\omega_0^2 - n^2} \qquad i = \sqrt{-1} \tag{6}$$

which for subcritical damping brings the general solution of the equation (6) in the form:

$$x = e^{-nt}\left[c_1 \cos\sqrt{\omega_0^2 - n^2}\,t + c_2 \sin\sqrt{\omega_0^2 - n^2}\,t\right] \tag{7}$$

It determines behaviour of the system, which is illustrated in a figure below (Fig. 1).

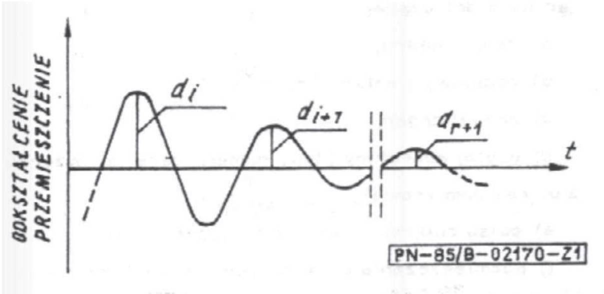


Fig. 1. Method of determining the damping of sinusoidal vibrations

The phenomenon of vibration fading, associated with damping occurring in the system, can be described by various measures. One of them is a logarithm of the consecutive maximum amplitudes. Their average value for r – number of periods (or half-periods) enables to determine the logarithmic decrement:

$$\delta = ln\left(\frac{1}{r}\sum_{i=1}^{r}\frac{d_i}{d_{i+1}}\right) \tag{8}$$

Such evaluations of vibration damping can be generalized and affiliated with the problem of evaluating of energy dissipation in a diagnosed structural element. However, careful attention should be paid to their correctness, in case of mono-harmonic signals' analysis. In the occurrence of exploitation excitation, various vibration frequencies are excited. Additionally, frequencies coming from the excitation could appear in the signal. Therefore the application of this procedure, in the evaluation of vibration damping of elements being examined, requires filtering the individual eigenfrequencies out of mono-harmonic signals. The main difficulty in such analyses could be questions of the requirement of considering phases of individual frequencies in the analyses of diagnostic signals, or conditions associated with non-stationary states [1].

Having the before-mentioned reservations in mind, in the search of method of reinforcement-structure damage detection based upon monitoring of variations in vibration damping in tits elements, authors needed to design algorithms of estimation of damping measure free of those limitations.

One of the best mathematical tools, useful in the estimation of damping in elements of steel construction executed in pulse test, could be new tools of analysis of non-stationary signals, including procedures of transformation measurement signals based on wavelet transformation. Wavelet-function group of given parameters is he core defining this transformation.

In case of estimation of damping coefficient, essential procedure of signal analysis is the process of separation monoharmonic parts. If a wavelet of concise, one-stripe spectrum is used in wavelet transformation, we could obtain information about measurement signal being convergent to a wavelet of known frequency characteristics. Exploiting this mechanism we can manufacture a wavelet filter, featuring no information loss and zero phase displacement in an analyzed signal.

By experimental selection of sequence of a coefficients of its wavelet function applied in the filter, an appropriate frequency range with the assigned resolution could be resulted

In this selection the analysis of PSD (Power Spectral Density) is very helpful. Based on this, number and range of frequencies occurring in a measurement signal.

Covariance method can be applied to the estimation of spectral density. Its application in reference to measurement signals in the discussed research problem brings a result illustrated in charts below (Fig. 2).

For the assessment of degradation of structural elements of reinforcement a critical-damping fraction can be applied. It is used in the assessments of building constructions, as calculated by the formula:

$$\xi = \frac{1}{N}\sum_{N}^{n=1}\frac{\delta_n}{2\cdot\pi} \tag{9}$$

Its estimation is possible after separating monoharmonic components out of diagnostical signal. In this process procedures of wavelet extensions could be exploited, as referring to measurement signals resulted from pulse test. Necessary preliminary stage in the process is determining the required resolution for executed analyses of decomposition of measurement signal. Its carrying out is associated with preliminary identification of eigenfrequencies of a diagnosed structural element.

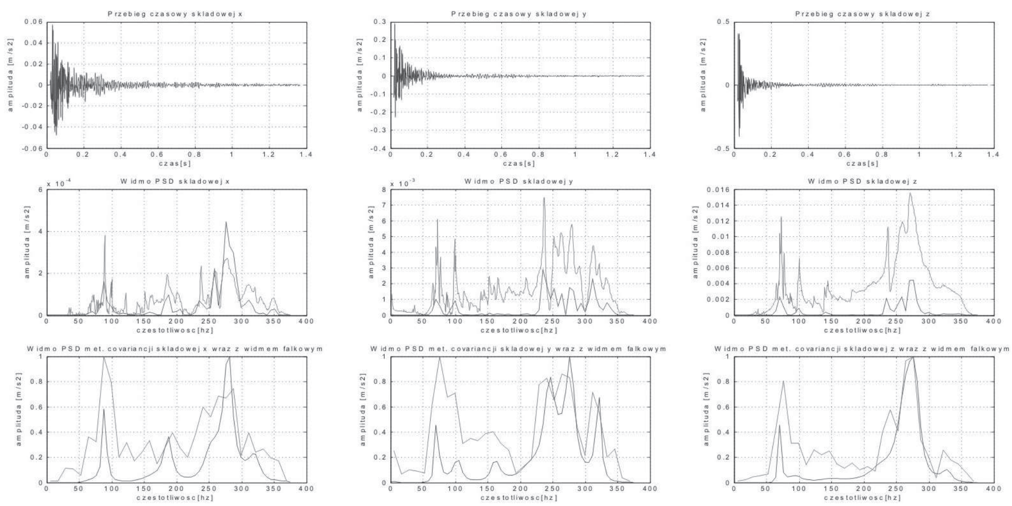
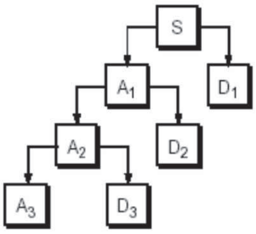


Fig. 2. Characteristic of spectral density of signal power

Based on the analyses, the level of wavelet decomposition for measurement signals has been established on the level 7. Its been stated that, for the process of estimation of damping of the analyzed shaft construction element, this decomposition level would secure the presence of significant frequency components in systems response for pulse excitation. Its been concluded that thus accepted decomposition level would not obstruct the frequencies, significant for calculations of frequency damping measure, reducing the time of their calculations.

The basis of the estimation of damping coefficients is the method of package wavelet decomposition. This method offers vast range of possibilities in signal analysis [3].

In wavelet analysis signal is divided into approximations and details. The approximations are again divided into approximations and details of level II. This process is repeated until reaching a priori assumed decomposition level. For n^{th} analysis level there exist n+1 viable paths of signal decomposition (Fig. 3).



$$S = A_1 + D_1$$
$$= A_2 + D_2 + D_1$$
$$= A_3 + D_3 + D_2 + D_1$$

Fig. 3. Diagram of wavelet decomposition of signal

Wavelet decomposition contains properties of square filter of stabile characteristic in the pass band. A single decomposition level divides the signal into equal parts in the frequency domain. Approximations occupy the frequency band from constant component to the half of frequency band, whereas details take the remaining band section. In a package wavelet decomposition details are also divided into approximations and details of the next level (Fig. 4)

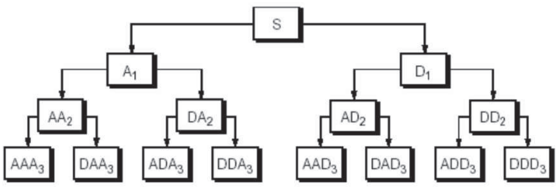


Fig. 4. Diagram of package wavelet decomposition

As a result of package wavelet decomposition of n^{th} level, a signal is decomposed into 2^n components. Symmetric division of the frequency band of an examined signal is being secured in each detail decomposition and approximation. So the bandwidth in the components of the lowest level is $1/2^n$ of Nequist frequency. It provides a possibility of controlling the approximation level and analysis accuracy.

In the case being discussed a package decomposition of 7^{th} level has been applied. For the signal of sampling frequency of 1 kHz the bandwidth of 3,9 Hz was obtained. Analyses STFT and PSD proved that this bandwidth provides monoharmonic property of individual components with assumed accuracy.

In vibrations with eigenfrequencies the energy fluctuates between the individual forms. This effect causes that in the time of vibrations of individual forms there occurs the energy transferring from another vibration form, hence the vibration amplitude increases. In order to eliminate this effect from time characteristic, only those time compartments are accepted in damping analysis, of which the entropy of isolated system is rising. It has been achieved by the examination of individual local extreme values. For those values a logarithmic damping decrement is approximated (Fig. 5).

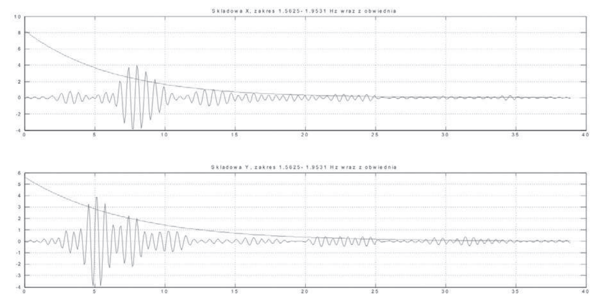


Fig. 5. Time characteristics of selected realization of decomposition (blue) and approximated logarithmic damping decrement (green)

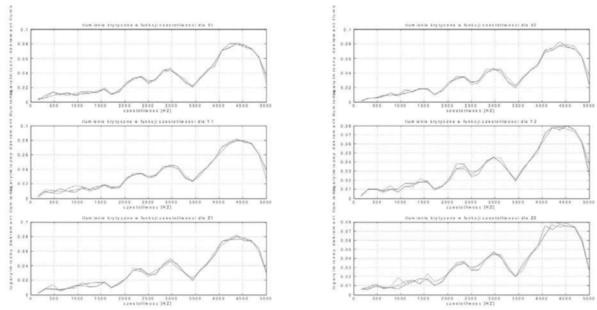


Fig. 6. Logarithmic damping coefficient as a frequency function

After calculating damping coefficient for individual realizations of decomposition we yield vector of size 2^n. It is connected with frequency, therefore it is possible to present damping in the spectral form. In order t obtain one-number damping value, square of spectral damping form is considered.

Package decompositions of individual measurement signals were carried out, with the assumptions settled before. Then for those signals a logarithmic damping decrement was determined. The results of executed calculations of damping decrement characteristic as frequency function, for the pulse-test carried out on one of the elements of shaft construction, are presented below.

It can be regarded as a diagnostical symptom for monitoring changes of condition of diagnosed shaft structure and procedure of detection of damages in reinforcement elements.

4. Analysis of results

Presented algorithm of estimation of global damping coefficient was implemented in portable measurement device. Measurements were carried out in several mining shafts copper ores and hard coal. The analysis assumed the proper condition of the whole reinforcement, and the examinations are to prove the departure from this rule. Confirmation of this assumption was, in a great majority of shafts, the distribution of normal global damping coefficients in a given category of reinforcement element (Fig. 7). Such a statistical distribution offers the possibility of the

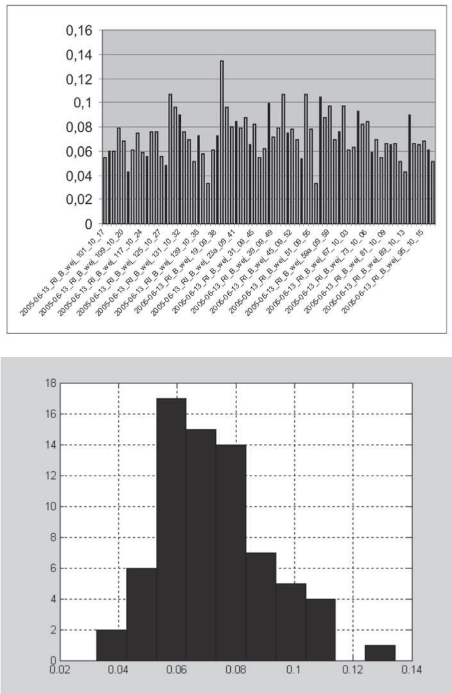


Fig. 7. Results of examination of shaft guide-rails and statistic distribution of the obtained results

application of model 3σ for determining decision compartments. The elements, whose global damping coefficient does not fit into specified standard deviation, are classified as elements intended to be tested by other methods.

Further research and comparing the results with the model ones, indicated high accuracy of diagnosis of shaft reinforcement condition. In many cases the method of global damping coefficient pointed to damages of elements, which were not detected by comparative methods. Check-up examinations confirmed that they were unserviceable.

5. Conclusions

Experimental exploitation of mining shaft based on the method of global damping coefficient revealed a number of positive properties. The most important include reducing the global time of shaft examination. Initially applied method of global damping coefficient as a selection method reduces the number of elements left to be examined by other methods – for example by ultrasonic method. The important advantage of the presented method is determining of dynamic properties not only of the examined object itself but also of its attachment and the surrounding. Thanks to that it is possible to evaluate the quality of screw-joints in shaft reinforcement.

Maintenance of mining shaft with the application of the examination of global damping coefficient significantly improved the operating safety of the shaft. Lowering maintenance cost resulted from both safety improvement and efficient usage of reinforcement elements, as well as repair of only those structure elements that are needed to be repaired.

6. References

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