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CONTRIBUTIONS TO THE ANALYSIS OF MINING EQUIPMENT FATIGUE THROUGH THE DIRLIK METHOD AND SPECTRAL ANALYSIS

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Abstract: *The paper analyses the phenomenon of mining machinery fatigue, focusing on the Bucket Wheel Stacker-Reclaimer KsS 5600/3800x40 machine. To evaluate fatigue cycles under variable and non-periodic force conditions specific to this type of machine, Dirlik method and spectral analysis are applied. Dirlik method provides an innovative approach to stress spectrum analysis, taking into account the complex distribution of stress amplitudes during coal stacking operations and their deposition on the conveyor belt. Spectral analysis provides detailed insight into the frequency distribution in the dynamic response of Bucket Wheel Stacker-Reclaimer. This analysis allows the identification of the dominant frequencies associated with the charging and discharging cycles. The results obtained have significant implications for the optimisation of operations and the effective management of fatigue within this specific equipment.*
Keywords: *Bucket Wheel Stacker - Reclaimer, Dirlik method, spectral analysis, fatigue, variable forces*

1. Introduction

One of the phenomena that can cause premature breakage of the structural components of mining equipment is the phenomenon of fatigue [1-4]. This phenomenon constitutes a challenge, a particularly important engineering problem that has been much studied by researchers in the field [5], [6]. Wenliang et al. (2024) [7] conduct a study of the fatigue characteristics of specific materials and analyse the relationship between fatigue loading and fatigue life by performing tests to obtain the traditional S-N curve. The use of these curves in the evaluation of structural fatigue life under the action of different loads requires the use of specific fatigue analysis methods, such as: time-domain methods [8-11], and frequency-domain methods [12-14] (spectral methods). The first methods do not use a large number of simplifying assumptions and offer the possibility of greater flexibility regarding the choice and selection of damage accumulation models caused by the fatigue phenomenon; this selection is much more realistic, but the calculation efficiency through these methods is low. On the other hand, the second category, namely, the spectral methods, allow the calculation of fatigue damage by means of the power spectral density (PSD) of the obtained stresses. Compared to the first methods, the spectral methods are based on a fairly large number of simplifying assumptions and have a higher degree of difficulty in simulating fatigue damage.

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Ashish Aeran et al. (2017) [15] propose a fatigue damage analysis model based on S-N curve parameters for C45 and 16 Mn steel. The authors find that a more accurate estimate of the fatigue life is obtained and apply the proposed model also in the case of welded joints.

The mining industry is a complex and demanding field where equipment has to cope with extreme working conditions and variable loads [16-19]. The phenomenon of fatigue becomes a critical aspect, having significant implications for the lifetime and efficiency of mining equipment. Bucket Wheel Stacker-Reclaimer KsS 5600/3800x40 is an example of multi-functional mining machinery involved in complex material handling and pile storage operations.

The importance of fatigue analysis in this context derives from the large requirement to understand the dynamic behaviour of equipment under various loads and to identify critical areas at risk of damage.

These types of machineries are generally used for the handling of coal (lignite) in the deposits of the thermoelectric power plants of the national system or in the deposits of the lignite quarries for loading or depositing the lignite extracted from the quarries, with the movement on the railway track type CF 49.

The main technological operations are: depositing the material in the pile (Figure 1), and loading the material from the coal stack on the conveyor in the coal deposit (Figure 2).

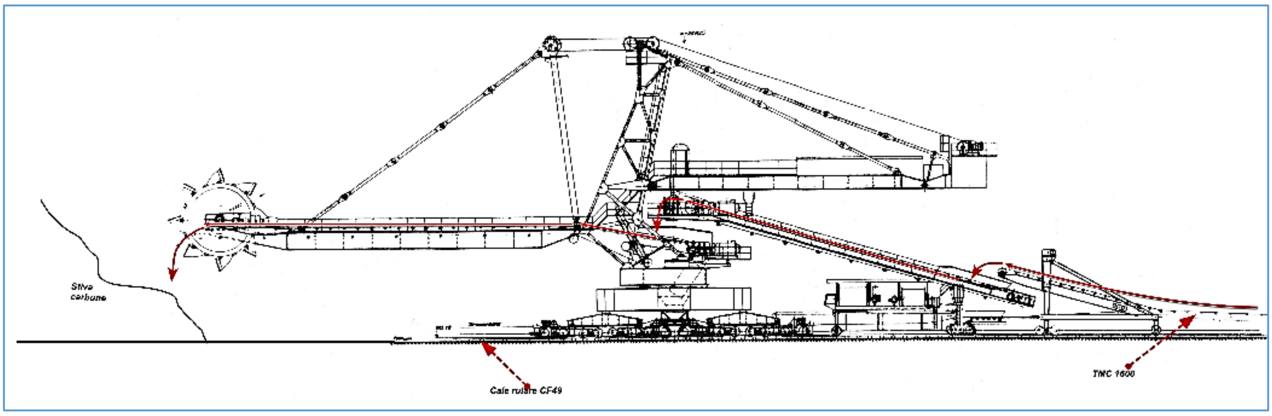

Fig. 1. The pile storage function of the machinery

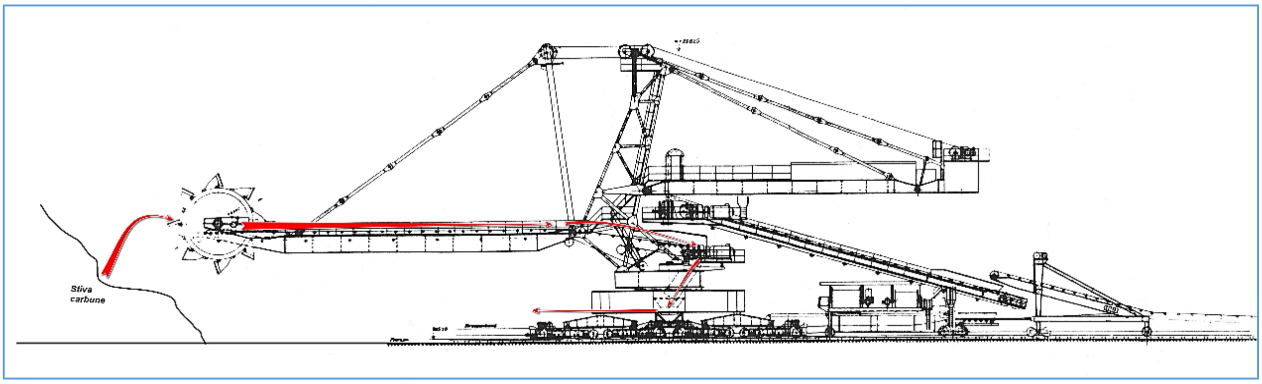

Fig. 2. The take-over function of the machinery

2. Methods for frequency-domain fatigue analysis

Common methods for frequency domain fatigue analysis developed to handle Gaussian random loadings are discussed in this section. For broadband loading processes [9], the following are included: Wirsching-Light method (WL), α0.75 method (AL), Gao-Moan method (GM), Dirlik method (DK), both Zhao-Baker methods (ZB1 and ZB2), Tovo-Benasciutti methods (TB1 and TB2), and Petrucci Zuccarello method (PZ). The narrowband (NB) approach refers to a situation where the frequency spectrum of the load is concentrated around a specific frequency or a narrow range of frequencies [20-22]. In other words, the loading is characterised by a narrow range of dominant frequencies. The NB method is suitable for such processes because it can provide an accurate approximation of the system's response under these conditions.

In contrast, broadband processes have a wider frequency spectrum, covering a larger range of frequencies. In these cases, methods that take into account this wider frequency distribution are better suited to obtain accurate results. So the statement that the narrowband approximation is only suitable for

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narrowband processes indicates that this method can only provide accurate results when the load has a frequency spectrum concentrated in a narrow range.

In the context of fatigue analysis, these patterns can vary depending on the spectral characteristics of the loads, such as: the width of the spectral bands, the Gaussian or non-Gaussian nature of the loads, and the stationarity or non-stationarity conditions of the loading processes. The method proposed by Dirlik, T., represents a specific model for evaluating loads and estimating fatigue under certain conditions [1], [5], [8], 17], [23].

Dirlik method (1985) is based on spectral analysis to estimate the distribution of stress cycles and to assess the fatigue of structures under a random load spectrum. Specific formulas for Dirlik method are based on parameters such as frequency, number of cycles, and the power spectral density (PSD) of the excavation forces.

The originally formulas developed by Dirlik (1985) [10], [11], and including Zalaznik and Nagode temperature effects, are given by the relations:

$$p_a\left(s\right)=\frac{1}{\sqrt{m_0}}\left[\frac{G_1}{Q}e^{\frac{-Z}{Q}}+\frac{G_2 Z}{R^2}e^{\frac{-Z^2}{2R^2}}+G_3 Z e^{\frac{-Z^2}{2}}\right] \tag{1}$$

where Z is the normalized amplitude and x_m is the mean frequency as defined by the author of the method [11]:

$$Z=\frac{s}{\sqrt{m_0}} \quad ; \quad x_m=\frac{m_1}{m_0}\left(\frac{m_2}{m_0}\right)^{\frac{1}{2}} \tag{2}$$

The parameters G_1, G_2, G_3 and Q are defined as follows:

$$G_1=\frac{2\left(x_m-\alpha_2^2\right)}{1+\alpha_2^2} \quad ; \quad G_2=\frac{1-\alpha_2-G_1+G_1^2}{1-R} \tag{3}$$

$$G_3=1-G_1-G_2 \quad ; \quad R=\frac{\alpha_2-x_m+G_1^2}{1-\alpha_2-G_1+G_1^2} \tag{4}$$

$$Q=\frac{1{,}25\left(\alpha_2-G_3-G_2 R\right)}{G_1} \tag{5}$$

To determine the value of the parameter α_2, we start from the premise that in the frequency domain, the random loading of a random process X, $S_{XX}(f)$, is defined by the power spectral density (PSD) (where f represents the frequency). It is common to use a one-sided power spectral density, $G_{XX}(f)$, defined only on the positive half-axis. The statistical properties of a stationary process can be described by the moments of the power spectral density. According to [10], the general form for the spectral moment (mi) is given by**:**

$$m_i=\int_0^\infty f^i G_{XX}\left(f\right)df \tag{6}$$

Moments up to m4 are normally used for fatigue analysis. The moments representing the variance σ_X^2 of the random process X and its derivatives are:

$$\sigma_X^2=m_0 \qquad\qquad \sigma_{\dot{X}}^2=m_2 \tag{7}$$

Variance is known to be a measure of dispersion, or the extent to which the values in a data set are spread out. In the aforementioned context, variance σ_X^2 refers to the dispersion or variability of the random process X or the associated data set. The larger the variance, the more dispersed the values in the data set are around the mean.

The process variability, or spectral width, is evaluated by means of the parameter (α_i), expressed in a general formulation:

$$\alpha_i=\frac{m_i}{\sqrt{m_0\, m_{2i}}} \tag{8}$$

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The most commonly used parameter (α_2) is the negative of the correlation between the process and its second derivative, as described by Tovo [12]. It takes values between 0 and 1. Let's analyse this parameter. In frequency domain fatigue analysis, the parameter α_2 is an indicator of the correlation between the random process (X) and its second derivative. This parameter is important in characterising the spectral width of the process. In the context of this parameter, a negative correlation indicates an inverse relationship between the process and its second derivative. Essentially, the closer α_2 is to 1, the narrower the process has a spectral width in the frequency domain, suggesting a concentration of energy in a narrower range of frequencies. Conversely, smaller values of α_2 indicate greater dispersion of spectral energy, with greater coverage in the frequency domain.

With the values of the parameter α_2 fixed, the closed-form expression for the fatigue life intensity was derived in the form:

$$\bar{D}^{DK} = C^{-1}\nu_p m_0^{\frac{k}{2}}\left[G_1 Q^k \Gamma(1+k) + \left(\sqrt{2}\right)^k \Gamma\left(1+\frac{k}{2}\right)\left(G_2\left|R\right|^k + G_3\right)\right] \tag{9}$$

Power Spectral Density (PSD) is an important measure in frequency domain signal analysis and provides information about the distribution of signal energy as a function of frequency. This mathematical function describes the amount of power (or energy) contained in a signal in different frequency ranges. By representing the PSD, the relative contribution of each frequency to the total signal is highlighted.

In the context of fatigue analysis, the PSD stress cycle counting method becomes particularly significant. This process involves estimating cycles of voltage variation as a function of the power spectral density of the signal, providing a detailed understanding of how voltages vary over time. Among the various methods of counting stress cycles in PSD, according to studies, the empirical formula developed by Dirlik stands out as the most accurate [13], [14], [19].

Dirlik's formula for cycle counting is based on an empirical closed expression derived through extensive computer simulations using the Monte Carlo technique. This formula allows the determination of the probability density function (PDF) of the stress variation cycle counts, providing essential data for fatigue analysis. Structural fatigue (D) is then calculated after counting cycles using Dirlik's method and is expressed by equations (10), [13], where m and A represent the material properties, respectively the fatigue resistance exponent obtained from the S-N curve of the material and the resistance coefficient to fatigue.

$$D = \left(\frac{1}{2^m \cdot A}\right) \cdot \int_0^{\infty} S^m \cdot N(S) \cdot dS \tag{10}$$

where: D – structural fatigue; m - the fatigue resistance exponent obtained from the S-N curve of the material; A - resistance coefficient to fatigue; S – power spectral density (PSD); $N(S)$ - distribution function of stress cycles for specific stress values.

This method proves to be particularly effective in accurately estimating structural fatigue in the context of random loadings in the frequency domain.

In Equation (10), the histogram formula N(S) for the range of stress cycles is given by Equation (11), where ν_p and τ are the spike rate (expected number of spikes per unit time) and the exposure time, respectively [13].

$$N(S) = \nu_p \cdot \tau \cdot p(S) \tag{11}$$

In this equation: $N(S)$ - the number of stress cycles in a certain stress range S; ν_p - peak rate, i.e., the expected number of peaks per unit time; τ - the exposure time or the total duration of the analysis; $p(S)$ - the probability of the stress power spectral density at the stress level S.

This equation highlights the influence of the peak rate (ν_p), the exposure time (τ), and the stress power spectral density at the specific stress level $p(S)$ on the number of stress cycles N(S).

Dirlik's proposed formula for the stress probability spectral density (p(S)) is given by equation (12), by rewriting equation (1):

$$p(S) = \frac{\frac{D_1}{Q} \cdot e^{\frac{-Z}{Q}} + \frac{D_2 \cdot Z}{R^2} \cdot e^{\frac{-Z^2}{2 \cdot R^2}} + D_3 \cdot Z \cdot e^{\frac{-Z^2}{2}}}{2 \cdot \sqrt{m_0}} \tag{12}$$

In equations (11) and (12), S represents the stress range, and the other parameters are defined according to the context of Dirlik method. Specifically, p(S) and N(S) are functions that describe the probabilistic distribution of stress cycles in a fatigue process. This new form of equation (1) involves parameters such as D_1, D_2, D_3, Q, R_2, and m_0, which must be adjusted or determined according to the characteristics of the loads and the properties of the studied material. Parameters of equations (11), and (12) are presented in Table 1 [13]. By means of these equations, the parameters and characteristics of the stress distribution can be estimated. Thus, it contributes to the analysis and prediction of fatigue phenomena in structures subjected to variable loads.

Table.1. Parameters of equations (11) and (12)

$D_1 = \frac{2(x_m - \gamma^2)}{1+\gamma^2}$	$D_2 = \frac{1-\gamma-D_1+D_1^2}{1-R}$	$D_3 = 1 - D_1 - D_2$	$Q = \frac{1.25\cdot(\gamma - D_3 - D_2 \cdot R)}{D_1}$
$R\frac{\gamma - x_m - D_1^2}{1-\gamma-D_1+D_1^2}$	$Z = \frac{S}{2\cdot\sqrt{m_0}}$	$x_m = \frac{m_1}{m_0}\sqrt{\frac{m_2}{m_4}}$	$\nu_p = \sqrt{\frac{m_4}{m_2}}$; $\gamma = \frac{m_2}{\sqrt{m_0 \cdot m_4}}$

3. Definition of spectral analysis in the context of the evaluation of the phenomenon of fatigue in mining equipment

Fatigue analysis can be approached and understood from two distinct perspectives, providing a complete picture of the behaviour of structures subjected to random forces.

Wöhler analysis (Wöhler curve) [22-28] usually focuses on fatigue life analysis of a single resistance element or a specific point on a structure. For this reason, the structural elements must be established, which, through degradation, can lead to the instability of the structure. This is a method used to evaluate the fatigue behaviour of a material or component based on the number of cycles of stress variation. It is a more localised approach, focusing on a specific location or element in the supporting structure of machinery.

On the other hand, spectral analysis, such as that performed with Dirlik method, is a technique that considers the entire spectrum of loads or strains and their influence on the entire structure. Dirlik method analyses how different frequencies contribute to the overall fatigue of the structure over time. It is based on the power spectral density (PSD) and estimates the number of cycles at different frequency levels.

Thus, while Wöhler analysis focuses on the behaviour of a single element or specific point, Dirlik method addresses the global impact of the entire spectrum of loads on the structure. This is important in situations where multiple frequencies contribute to the overall damage to the structure, given that the dominant frequency may vary in various areas of the structure and not just at a single point.

The role of spectral analysis in evaluating the dynamic responses of mining equipment leads to a detailed understanding of the dynamic behaviour of mining equipment. This allows the identification of the dominant frequency components of the movements and vibrations generated by the machinery during mining operations.

The process of performing a spectral analysis and frequency fatigue analysis for non-periodic random forces acting on the metal structure of a rotor mining machinery, with specific strains measured by strain gauges (TER) and frequencies measured by accelerometers (Acc) during the excavation process, can be divided into several distinct stages:

A. Collection of Data:
- Recording specific strain data using tensiometric stamps on the metal structure of the mining machinery during excavation activity.
- Measurement of structure frequencies with an accelerometer while the machinery is running.

B. Data processing:
- Data pre-processing to remove noise or other artefacts that may affect the quality of the analysis.
- Transformation of strain and accelerometric (frequency) data from the time domain to the frequency domain using Fourier analysis.

C. Identifying the dominant frequency:
- Using the results of Fourier analysis to identify the dominant frequency associated with the specific deformations measured on the metal structure.
- Dominant frequency: the frequency at which a particular component or mode of vibration of the structure has the largest amplitude. It is the frequency at which the frequency spectrum exhibits a peak or maximum. It provides information about the predominant vibration modes or the specific dynamic behaviour of the structure in a certain context or under certain loading conditions.

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- Correlating this dominant frequency with the measured frequencies of the structure to obtain a more accurate picture of the dynamic behaviour.

D. Spectral analysis:

- Performing the spectral analysis of non-periodic random forces acting on the structure. This may involve the use of methods such as spectrograms or waterfall analyses of spectral power.
- In this analysis, the power spectral density (PSD) plays a crucial role, providing detailed information about the frequency-dependent energy distribution in the analysed signal.

F. Fatigue analysis by frequency: In frequency fatigue analysis, a significant step is the integration of Dirlik method. This method provides a detailed insight into the distribution of stress cycles in relation to the power spectral density (PSD) and plays an essential role in assessing the fatigue level of the metal structure. By applying Dirlik method, the number of cycles and the fatigue intensity are accurately estimated, which provides essential information for assessing the lifetime of materials under a random loading spectrum. Comparing the results obtained with the strength and durability criteria helps identify potential requirements for improvement or adjustments in the mechanical design of the mining equipment.

In conclusion, it is worth emphasising that all these sophisticated frequency fatigue spectral analysis calculations, including the use of Dirlik method, Wohler method, or the other mentioned calculation methods, represent an advanced field that can only be explored and implemented successfully through computer technology.

The use of computing software such as Octave [29], Matlab [30], Python [31], or Scilab [32] becomes essential for efficient data manipulation, performing complex calculations, and generating accurate results. These software tools provide not only an accessible platform but also extensive functionality, facilitating advanced research in the field of fatigue analysis and helping to improve the reliability and durability of mining machinery. All these analyses are based on the collection of data by the method of resistive tensometry or frequencies with the help of accelerometers.

4. Study Case: Spectral and fatigue analysis of Bucket Wheel Stacker-Reclaimer KsS 5600/3800x40 machinery

In this analysis, we will use a detailed approach based on spectral and fatigue analysis to investigate the behaviour of Bucket Wheel Stacker-Reclaimer KsS 5600/3800x40 in its operational environment. The proposed methodology will involve the evaluation of the dynamic responses of the machinery in frequency using data from in situ measurements obtained during the technological excavation process.

We will apply Dirlik method, recognised for its precision in the analysis of stress cycles originating from random loads, such as those encountered in the mining field.

The machinery used is a Bucket Wheel Stacker-Reclaimer KsS 5600/3800x40, TAKRAF production; all the resistance elements, including the mechanisms (reducers, couplings, etc.), were executed in the German Democratic Republic and mounted in the coal deposit of the open pit (Figure 3).

Fig.3. Bucket Wheel Stacker-Reclaimer KsS 5600/3800x40 type machinery.

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The identification data of the machinery are presented in table 2.

Table 2. Identification data of KSs5600/3800x40 type machinery

Machinery name	**KSS 5600/5600.40**
Place of operation	Coal Quarry Deposit
Commissioning date	July1990
No. of working hours	55806
Machinery age [years]	33
Net weight [tonnes]	approx. 753
No. charging cups	8 pcs
Bucket wheel diameter [mm] / bucket wheel speed [rpm]	8860 .83

4.1. The work equipment used in the measurements. Their positioning on the machinery

The first stage, as presented in Section 3, is data collection. In our case, the specific deformations will be collected to determine the dominant frequency and the working frequency of the machine.

It should be mentioned as an important aspect during the technical measurements in situ [22], [36]: after the moment when the tool starts excavating in the massif, at certain moments of excavation, the main tie rods acquire an approximate deformed shape, as shown in figure 4. This shape manifests itself in the plane X\`O\`Y\`, a plane whose axis O\`Y\` is parallel to the edge of the coupling bar and O\`X\` is perpendicular to the inner plane of the coupling bar; it is the plane seen from A.

Fig. 4. The deformed shape (2) of the main coupling bars (1) on the KSs 5600/3800x40 type machine

The retrieval of non-electric quantities is done through data acquisition systems. These systems have the role of processing and transforming analogue input quantities into digital quantities and can generate analogue or digital control signals.

- The electric-resistive transducers (TER) used are manufactured in Kyowa, Japan, and have the following characteristics: KFGS-6-120-C 1-11 type [33]. The transducers were glued using an adhesive type CC-33A manufactured in Kyowa. The TER connection scheme is half-deck for each measuring point, with one of the transducers having the role of thermal compensator.
- The accelerometer KS48C model [34] is attached to the metal construction of the machine by means of a magnet attached to the accelerometer in the lower side.

The accelerometer is a type of piezoelectric sensor designed to measure vibrations at extremely low levels. These sensors are commonly referred to as seismic accelerometers due to their use in monitoring construction activity during earthquakes. Unlike other types of accelerometers with internal amplification, their high sensitivity is achieved through the sensing element itself. This results in the highest resolution and the lowest noise level.

The acquisition system, manufactured by National Instruments, consists of: cDAQ-9174, CompactDAQ Systems, 4 Slots, USB 2, -20°C to 55 °C; Strain / Bridge Input Module, C Series, NI-9237; Vibration Module, NI-9230, AC/DC Coupling, 3 Input Channel; Fastview, [35], is a specialised software in the

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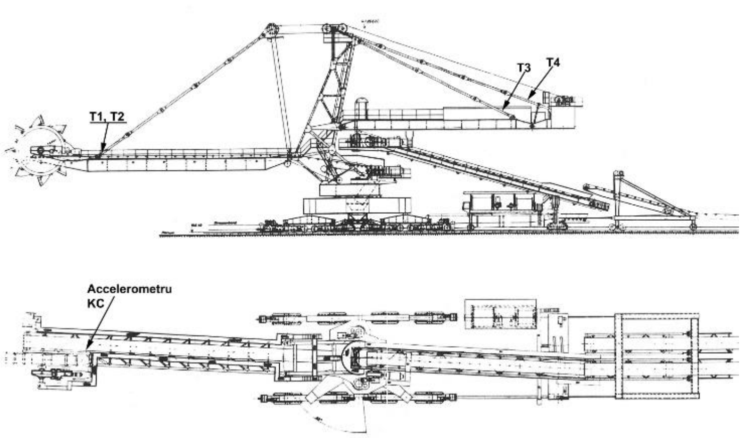
acquisition of data for the measurement of deformations and vibrations that consists of. It is software that can run the history of the recorded events after the field measurements are finished.

The positioning of the strain gauges T1 to T4 and the accelerometer on the machine is shown in fig. 5 [36].



T.1

T.2

T1, T2, positioning on the main coupling bars, in front
T3, T4, positioning on the coupling bars, supporting return-arm

T.3

T.4

Accelerometer positioning

Fig.5. Positioning (in situ) of the sensors on the machine

By applying the electric-resistive transducers (TER), the specific deformations on the resistance elements will be measured (Figure 4), and by applying the accelerometer, the working frequency will be determined.

The measurements were carried out according to the work plan, covering all the technological operations of excavation, deposition, and movement of the machine. The first part consisted of the movement of the superstructure, its rotation, lifting the bucket wheel arm, and moving the machine on the track without excavation, which is defined as a static component. The second part consisted of positioning the machine near the coal stack and rotating the superstructure, called technological preparation. The last stage that followed was the actual work of excavating, taking the coal, and depositing it on the deposit belt, called the dynamic component.

4.2. Application of spectral analysis to machine dynamics

All these steps, accompanied by detailed measurements of specific deformations, are exhaustively presented in figure 6, and the corresponding statistical results are detailed in table 3.

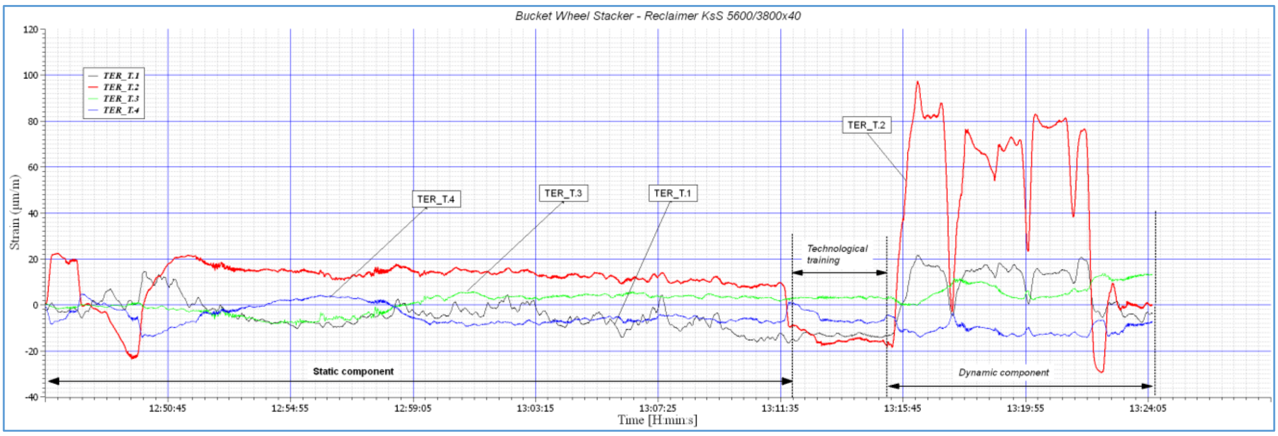


Fig.6. Specific deformations measured during the working trials

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This table provides a systematic perspective on the distribution and variability of deformations. The aim is to obtain relevant data for the analysis of the fatigue phenomenon of mining machinery by means of Dirlik method and spectral analysis.

Table 3. Statistical analysis of deformations

TER	**Mean**	**Standard Dev.**	**Variance**	**Max. Strain** [μm/m]	**Min. Strain** [μm/m]
T.1	-2.01	9.20	84.65	21.58	-16.39
T.2	**17.40**	**25.83**	**667.34**	**97.38**	**-29.54**
T.3	2.06	4.72	22.30	13.78	-8.74
T.2	-6.05	4.60	21.20	4.91	-14.30

In accordance with the details presented in figure 6 and table 3, which constitute the main values in the context of spectral analysis, we will turn our attention to the waveform generated by the tensometric stamp T.2, figure 7.

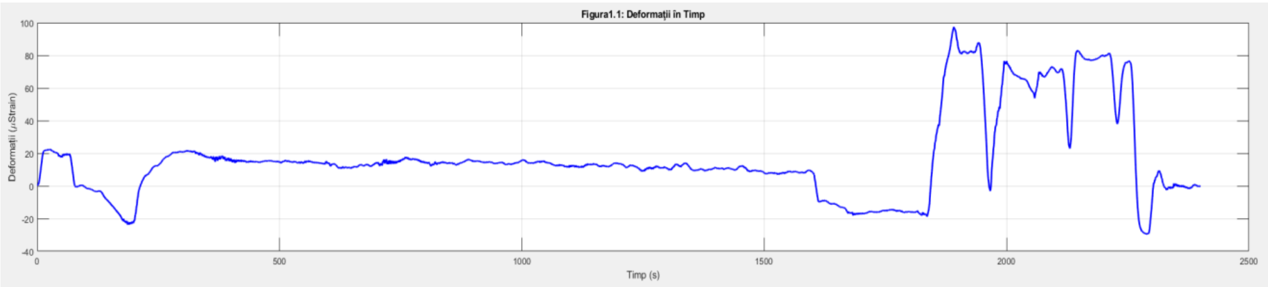

Fig. 7. The waveform of the T.2 tensometric stamp

This stamp, identified as generating the most significant specific strain amplitude, becomes the focus of our analysis.

First of all, from the classical fatigue analysis, based on the drawing of Wöhler curve, depending on the specific deformations and multiplication factors according to DIN 22261/2 [37] (figure 8), the number of operating cycles of a resistance element considered the most demanding from the load-bearing metallic structure of the machine can be determined. We will denote this as N_{TER} [cycles], which is equal to N_{TER} = 7.52×10^7 cycles. Applying the calculation methodology from the research works [10-17], [22], [23], [25], [26], [38], the operating time in years for the respective machine can be estimated.

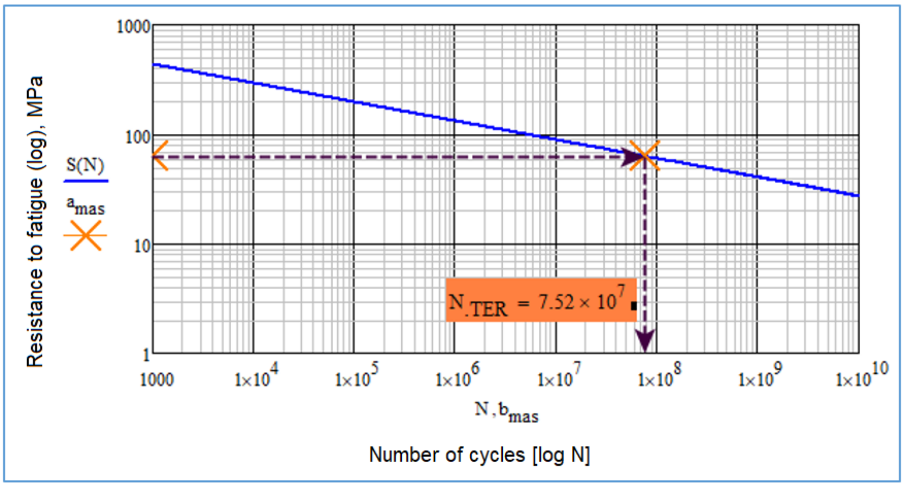

Fig.8. Wohler logarithmic curve

From the classical analysis, based on Wöhler curve, which provides an understanding of the fatigue strength as a function of the number of cycles, we move to the spectral analysis, taking a more detailed approach. At the centre of this analysis is the dominant frequency, a distinctive note of the dynamic behaviour of the metallic structure. The dominant frequency acts as a critical factor in generating the specific deformations leading to fatigue.

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Through spectral analysis, with an emphasis on power spectral density (PSD), we evaluate the energy distribution at different frequencies. This detailed approach allows us to identify and quantify the specific influence of frequencies on structural stresses.

In order to obtain an accurate assessment of the dynamics of the metal structure, we performed measurements of the frequency of vibration of the metal structure ($f_{CM,}$ in Hz) during the excavation in the coal pile. The measurements were carried out over a significant period of time, capturing the dynamic behaviour of the structure under various operating conditions.

This approach generated a data set, providing relevant information regarding the influence of specific work process loading conditions on vibration. For this, an accelerometer was mounted in the vicinity of the bucket wheel, according to figure 5, and through the acquisition system, the frequency spectrum was obtained in Fastview, according to figure 9.

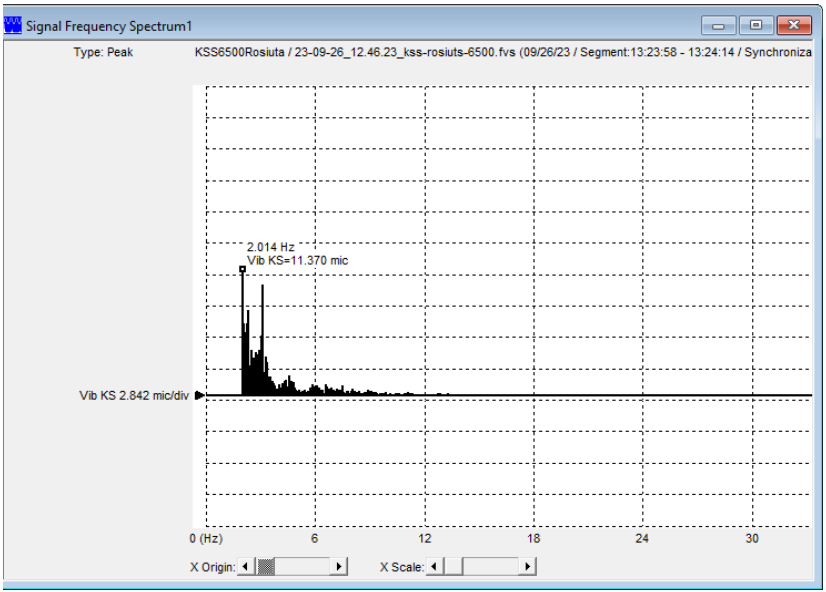

Fig. 9. Fastview: the frequency spectrum measured with the accelerometer

As shown in Section 3, the next step is to identify the dominant frequency. The dominant frequency is that which shows the greatest amplitude on the PSD plot. The identification of this dominant frequency is performed through a power spectral density (PSD) analysis, as exemplified in Figure 10: Frequency Spectral Power. In the analysis of the graph (Figure 10), the value of the dominant frequency (f_{dd}) generated by the specific deformations under the action of random forces is clearly highlighted, with a value of f_{dd} = 2 Hz.

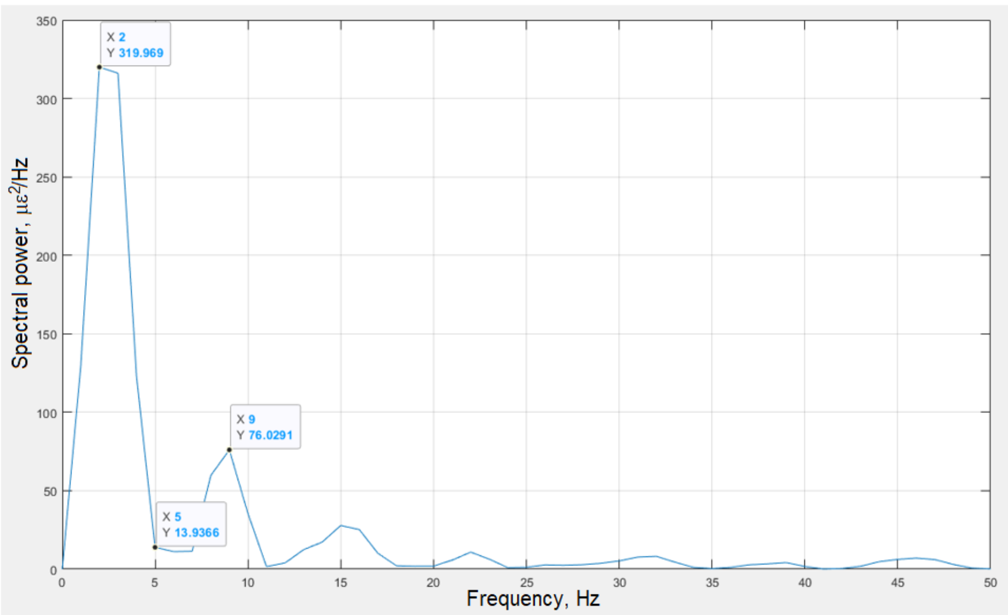

Fig.10. Spectral Power of the Frequency, the dominant frequency

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In the context of spectral analysis and power spectral density (PSD) as a function of frequency, stress levels represent the load or stress levels applied to the system or structure being analysed. These stress levels may reflect different operating conditions or loading situations for the equipment or structure. A detailed insight into the energy distribution as a function of frequency and the associated stress levels is shown in Figure 11: Spectral Power Density vs. Frequency for Stress Levels.

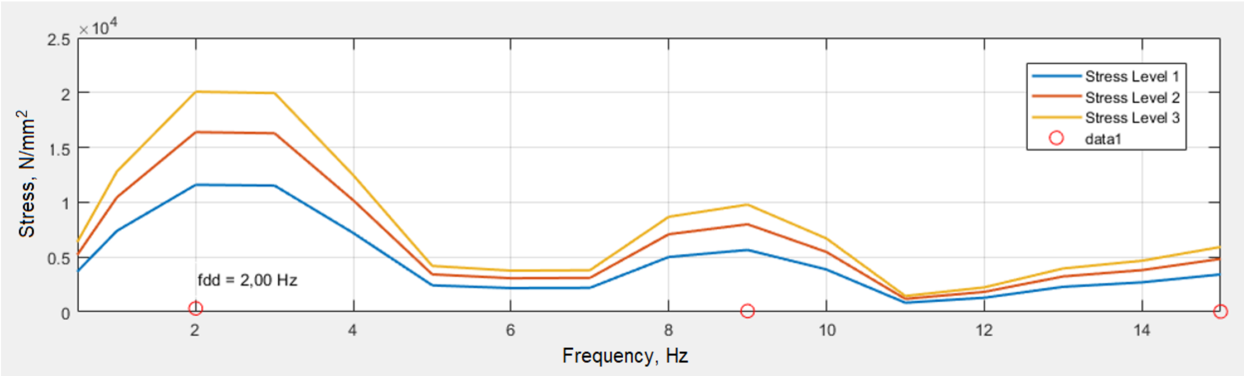

Fig. 11. Spectral Power Density vs. Frequency for Stress Levels

This graph, Figure 11, provides a deeper understanding of how energy is distributed across the various frequencies, with particular attention to the voltage levels involved at each specific frequency. For each voltage level, voltage versus frequency is calculated and plotted. This can provide insight into how voltage levels influence the energy distribution in the frequency spectrum, given the generated power spectral density.

To complete the picture of the dynamics of the structure, we will make a representation that shows us the intensity of the dominant frequency as a function of time and its size in intensity, namely the wavelet analysis of the deformations, which provides a detailed perspective on how the spectrum of the intensity of the dominant frequencies varies over time as a function of various wavelet scales.

Unlike other transforms, such as the Fourier transform, which only analyses the signal as a function of frequency, the wavelet transform allows detailed analysis of the signal in both time and frequency dimensions at the same time. During analysis using the wavelet transform, the wavelets can be scaled and positioned according to the original signal. Small scales are used to highlight fine details, while larger scales are used for general features.

Wavelet analysis is a mathematical and visual method used to analyse and represent complex signals, such as shock waves, seismic signals, or deformations of a metal structure under the action of random forces. This method is particularly useful for investigating the local details of complex signals as a function of time and frequency, thus providing finer and more detailed insight than other spectral analysis methods.

This detailed analysis is essential for understanding the underlying mechanisms contributing to the deformation of the structure (Figure 12).

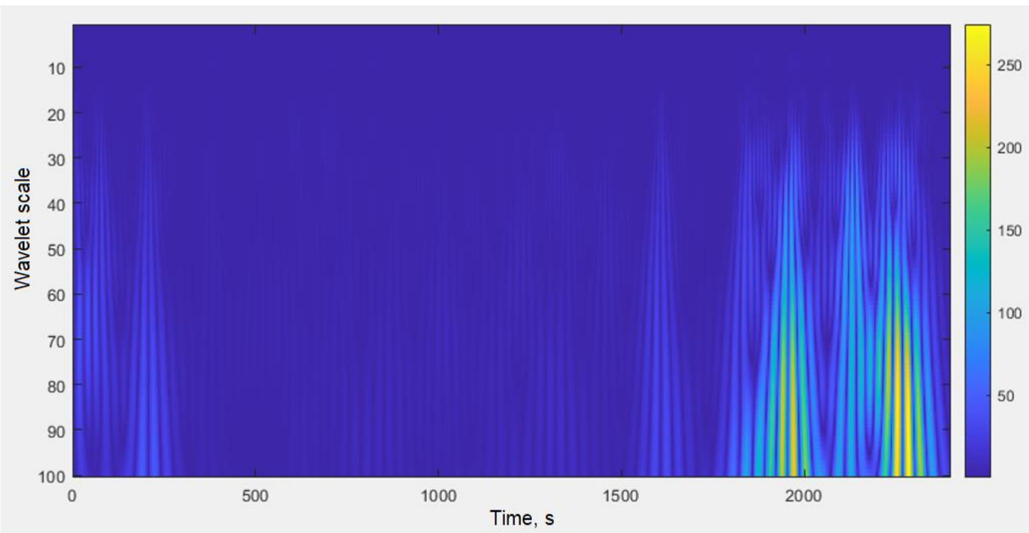

Fig. 12. Wavelet analysis of dominant frequency intensities

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Dirlik method is an essential tool in the lifetime analysis of structures subject to time-varying stresses. This method is based on the statistical analysis of the frequency spectrum and provides reliable estimates of the stochastic fatigue distribution, which is crucial in the lifetime assessment of structural components (Figure 13).

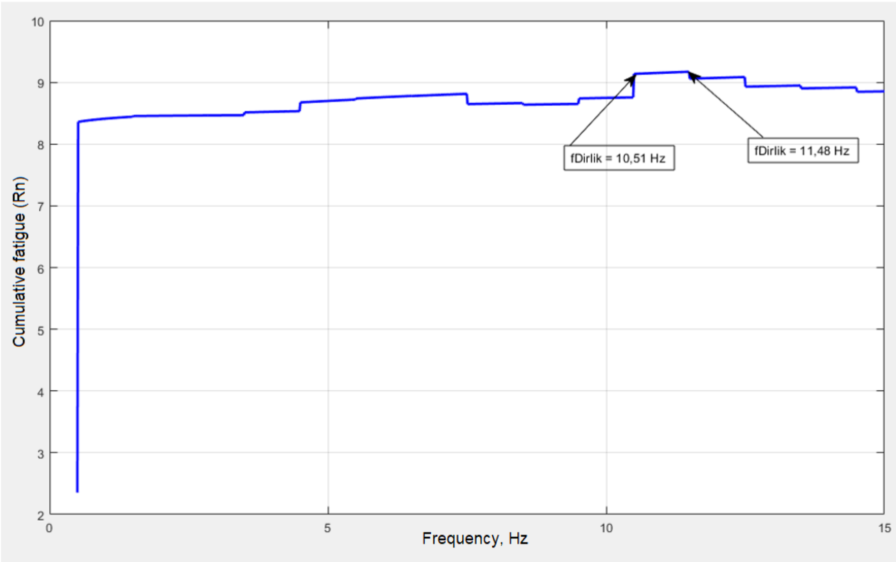

Fig. 13. Cumulative fatigue using the Dirlik method

The graph shows the relationship between frequency and cumulative fatigue (Rn), highlighting how fatigue accumulates in the structure under various frequencies. On the vertical (Y) axis is cumulative fatigue (Rn), and on the horizontal (X) axis is frequency, indicating how often certain frequencies occur in the system.

The results of Dirlik method are quantified in:

1. Frequency estimated using Dirlik method: 11.4875 Hz.
2. Maximum value of cumulative fatigue (Rn): 9.17.
3. Total Damage: approx. 1.46×10^7 cycles.

When the structure is subjected to the estimated frequency of 11.48 Hz, the graph indicates reaching the maximum cumulative fatigue value, Rn = 9.1712. This suggests that at this frequency, the structure suffers most from fatigue. Total Damage, TD = 1.46×10^7, indicates that, in total, the structure has been exposed to a significant number of loading cycles, resulting in damage and structural fatigue. In our case, the value "Total Damage: 14678379.5214 cycles" indicates that the structure has been subjected to this specific amount of load cycles, specifically around the frequency of [10…11] Hz. These cycles had a significant impact on the strength and integrity of the structure. Basically, this value is a way to quantify the level of wear or degradation of the structure as a result of repetitive loading and can be used to assess the remaining life or the need for maintenance interventions. It is important to understand that these values are not isolated but are the result of the statistical and stochastic analysis of the frequency spectrum made possible by Dirlik method. This method provides a more realistic insight into structural behaviour under time-varying stresses and allows a more accurate assessment of the lifetime of structural components.

To obtain a detailed assessment of the distribution of periods and frequencies involved in the analysis of structural fatigue by Dirlik method, we used two essential tools: a Q-Q plot for Weibull distribution (Figure 14) and a histogram of the frequencies of interest for adjusted Weibull distribution (Figure 15).

The Q-Q Plot is a graphical way to compare the distribution of our data to a theoretical distribution, in this case the Weibull. This plot allows us to assess how well the distribution of our data fits the theoretical model and to identify possible deviations. The diagonal dotted line represents the theoretical line of Weibull distribution. In a Q-Q plot, a diagonal line indicates a perfect fit between the theoretical distribution and the observed data. The solid red segment represents the linear regression or trend line to visually assess the fit between theoretical Weibull distribution and the observed data. A good fit is suggested when the points come as close as possible to this line. The histogram of frequencies of interest provides a visual representation of the frequencies in the load spectrum that are relevant to the structure. This helps identify the dominant frequencies contributing to structural fatigue and provides a basis for fitting Weibull distribution. Physically, this histogram reflects the intensity of stress on the structure as a function of frequency.

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The adjusted Weibull distribution is the result of fitting Weibull distribution to our specific data. This fitted distribution is essential in Dirlik method to estimate load cycle frequencies and amplitudes. Physically, it represents the mathematical model that best matches the actual behaviour of our structure in the face of variable loads.

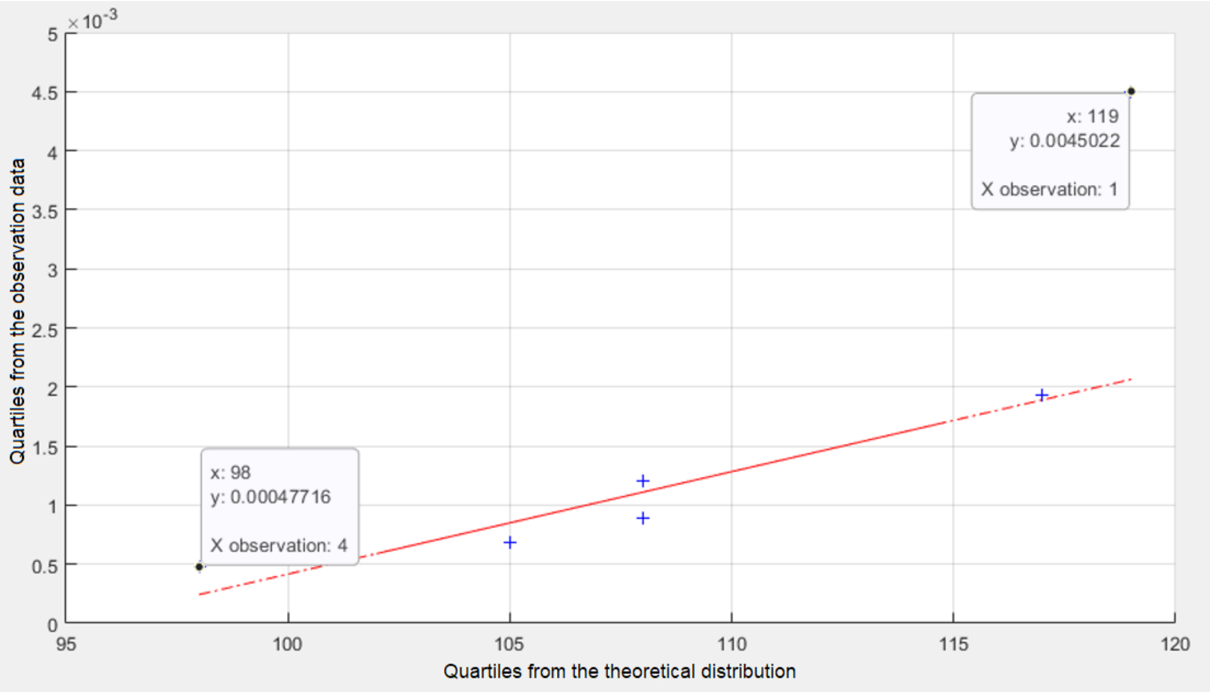

Fig. 14. Q-Q Plot for Weibull distribution

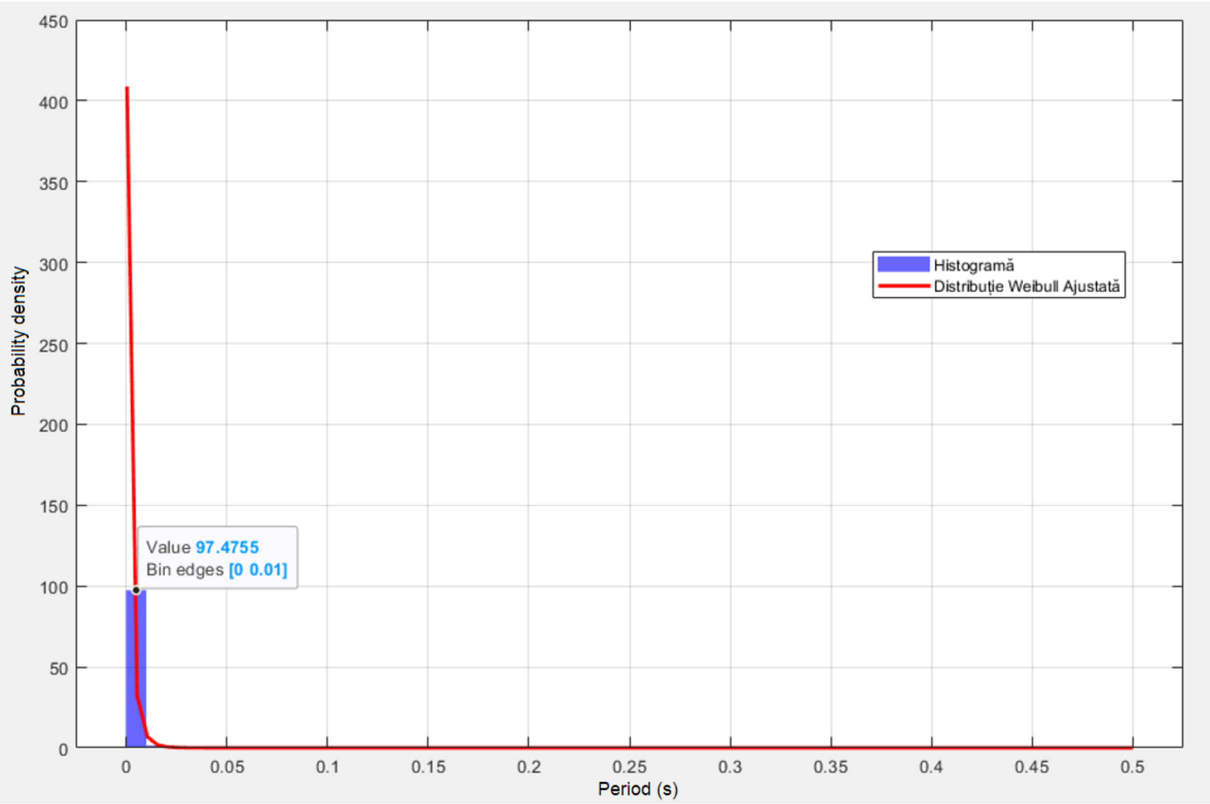

Fig. 15. Histogram of frequencies of interest and adjusted Weibull distribution

Together, these tools provide a detailed framework for Dirlik analysis. They allow an accurate assessment of dominant frequencies involved in structural fatigue and optimisation of lifetime estimates for structural components.

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5. Conclusions

1. The determination of the dominant frequency, the spectral analysis, focused on the power spectral density (PSD), allowed the identification of the dominant frequency of the metal structure during the excavation. The frequency estimated by Dirlik method (11.48 Hz) proved to be very important for understanding the dynamic behaviour of the structure.
2. By establishing the frequency dominated by f_{dd} = 2.0 Hz, an intrinsic property of the system, and measuring the frequency of the metallic construction f_{CM} = 2.014 Hz, it was established that at this frequency the system can enter resonance. This was observed through the deformations of the main tie rods, the cause of its generation being the bushing for attaching the cup wheel to the wheel shaft, which was loosened with a play greater than the tolerance limit imposed by the tightening on the shaft. The cause of resonance generation is excessive clearance.
3. Impact of Frequency on Structural Fatigue: at the frequency of 11.4875 Hz, the structure reached the maximum cumulative fatigue (Rn = 9.17). This indicates that at this frequency, the structure suffers most from repetitive stresses, resulting in significant structural damage and fatigue.
4. The Total Damage value (14678379.5214 cycles) reflects the total number of load cycles to which the structure was exposed in the frequency range between [24]-[29] Hz. This is an essential measure for quantifying the level of wear and degradation experienced by the structure under the specified frequency conditions. The Total Damage value can be used to assess remaining life or to determine the need for possible maintenance interventions, thus providing a valuable tool for maintaining structural integrity.
5. The importance of wavelet analysis is that deformations provide an essential visual representation, highlighting the intensity of dominant frequencies over time and at various wavelet scales. This completed the picture of the dynamics of the structure, contributing significantly to the understanding of its behaviour under dynamic loads.
6. Weibull Analysis and Frequency Distribution, Q-Q plot for Weibull distribution, and histogram of frequencies of interest provided detailed insight into the distribution of periods and frequencies involved in structural fatigue analysis. These tools have contributed to a more accurate assessment of the risks associated with the variability of loads over time and to the optimisation of the lifetime of structural components.
7. If we make a parallel between Wöhler analysis and Dirlik analysis, it is found that Wöhler analysis, based on Wöhler curve, and Dirlik analysis, focused on the spectral analysis, represent two distinct approaches to evaluating the behaviour of metallic structures under repeated loading. Both methods provide essential information about the performance and durability of the structure in the face of cyclic stresses. Wöhler analysis focuses on the resistance in relation to the number of cycles, while Dirlik analysis brings into question the influence of the dominant frequencies and their spectral distribution. Both approaches are complementary and can be used together for a comprehensive assessment of structural behaviour under dynamic loading conditions.
8. In the context of the average number of annual operating hours, we note that with T_Y = 2537 h (according to Table 3), the formula for calculating the total number of cycles of variation of the mechanical stress in the mechanical structure produced by the bucket wheel becomes [25]:

$$N_Y = 60 \times T_Y \times n_{BW} \times n_B \quad [cycles / year] \tag{13}$$

where: n_{BW} = 7.83 rpm – bucket wheel speed; n_B = 8 – number of bucket; T_Y = 2537 h – average operating hours of the bucket wheel machine per year.

Thus, the value of N_Y [cycles/year] is given by the formula:

$$N_Y = 9{,}53 \times 10^6 \text{ [cycles/year]} \tag{14}$$

This formula integrates the average annual operating time multiplied by the number of bucket wheel revolutions (nBW) and the number of buckets (n_B). The relationship thus provides an estimate of the total cycles of mechanical stress variation during one year of machine operation. Based on the relationships in [22] and the Miner-Palmgren criterion, the percentage structural depreciation factor (D_{MP}) can be estimated:

$$D_{MP} = \left(N_Y / N_{Dirik} \right) \times 100 \tag{15}$$

and the structural damage is:

$$T_{DF} = (9.53 \times 10^6 / 1.5 \times 10^7) \ \% = 63.58 \ \% \tag{16}$$

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Taking into account the standard DIN 22261/2 [37], it can be concluded that, under the action of random dynamic forces, more than 50 % of the operating time of the machine was consumed.

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