DOCTORAL SCHOOL

DOCTORAL FIELD: MINES, OIL AND GAS

PhD THESIS

SUMMARY

ANALYSIS OF THE FATIGUE PHENOMENON OF THE BEARING STRUCTURE FOR EXTRACTION AND STORAGE EQUIPMENT

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PETROSANI
2024

CONTENT

Keywords: heavy mining equipment; fatigue phenomenon; mechanical degradation; linear elastic fracture mechanics; spectral analysis; finite element method; wavelets; Weibull analysis; S-N (Wöhler) and Miner-Palmgren curves; tensometers

However, coal will remain one of the only fossil energy sources that can play a particularly important role as a transitional energy source in the stages of transition to an economic system based on inexhaustible or renewable energy systems. Within the national energy system, the exploitation of coal deposits occupies a priority place in order to ensure from own resources, in as large a proportion as possible, the domestic electricity needs.

In the mining field, the extraction of deposits involves the continuous completion of specific technological operations, operations in which technologies and machines of great complexity and productivity are used, which aim, by increasing the degree of mechanization, to increase the efficiency of cutting, loading, and transport operations and implicitly to increase economic efficiency.

The objective of this PhD thesis consists in the analysis and evaluation of the fatigue phenomenon that manifests itself in the structural resistance elements (of the load-bearing structure) of the heavy mining equipment used in the extraction and storage in the lignite quarries. Depending on the place where they are used, these machines can be grouped as follows: machines, installations, and equipment specific to the underground exploitation of useful mineral substances; machines, installations, and equipment specific to the exploitation and handling of useful mineral substances on the surface.

The doctoral thesis is in the direction of the analysis of the metallic structure of the rotor excavators, as well as the assessment of their remaining safe operating life by non-destructive methods.

The structure of the PhD Thesis

In **chapter 1**, I made a presentation of: the technological flow for exploitation, transport, and loading of coal in the quarry; of heavy mobile machinery used in coal yards; and of the five successive functions that a combined depositing and loading machine performs; the combined destocking and stacking machines with rotor types T3855, KsS 5600/5600-40, and their main drive mechanisms; and the heavy mobile machines with rotors used in the extraction of lignite (bucket wheel excavators).

In **chapter 2,** I analysed, from a theoretical point of view, the phenomenon of fatigue manifested in heavy mining equipment. Initially, we carried out an analysis of the excavation mechanism of the mining equipment and the spatial components of the load at the cutting depth of the chipping force and analysed the influence of the variables that occur during the excavation by tensometric measurement of the specific deformations on the load-bearing structure of the mining equipment excavation. In order to highlight the distribution of the excavation force, we performed a cubic graphic interpolation of "cubic splines" of the specific deformation using tensometric stamps positioned on the machine. The fatigue phenomenon was approached from the perspective of variable stresses that influence the mechanical structure. The chapter also includes the analysis of durability under cyclic stresses by using Wöhler curves and Miner-Palmgren curves and Weibull analysis for modelling the temporal distribution of damage. Also, the problem of mechanical stresses that manifest themselves in the welded joints of the load-bearing structures of mining equipment is addressed, especially in the tie rods made of laminated sheet with different thicknesses (by the nominal stress method, by the structural stress method).

Chapter 3 presents the contributions to the analysis of the load-bearing metal structures of heavy mining machinery. The determination of the degree of structural and mechanical degradation was carried out by taking the material for the execution of the samples from the supporting metal structure of the machine type KSs5600/3800-40, having a number of 76,138 hours of operation since commissioning. The samples were subjected to destructive tests to determine the structural degradation of the material subjected to excavation forces, and the results were used to outline the behavioural profile of the materials used in the load-bearing structure of the extraction and storage equipment. In addition to these tests, I also carried out the chemical analysis of the material samples through spectrographic analysis. Weibull analysis was performed to evaluate the probability distribution of breakage and degradation of the material from which the specimens are made, taken from the KSa5600 machine. The fatigue evaluation for a mining machine operated by variable, non-periodic forces was performed using spectral analysis and the Dirlik method.

In **chapter 4**, I presented a solution for estimating the remaining service life of heavy mobile mining equipment used in lignite mining. For this, considering the fact that in the case of excavation and deposition machines, which have a service life of more than 105 cycles and an operating time of more than 115000 hours, a combined approach is necessary, in the doctoral thesis I used the method σ-N for structural elements and the fracture mechanics method, as some elements already show cracks or crack initiation. The static fracture analysis method was applied in the PhD thesis to determine the structural integrity and potential breaking points of a component under constant loading conditions. The originality consists in the application of the LEFM method for the analysis of crack development, the determination of the component material characteristics of the subassemblies of heavy mining machinery, but also the verification of the applicability of the method and the comparison of the modelling results, using the Fracture Mechanics Calculator software, with those obtained from the tests performed. This method was also applied to determine the mechanical characteristics of the samples made from the material taken from the sub-assemblies of two coal removal or deposition machines used in mining operations, namely machine type T2052, machine designed according to the German model KSa5600/5600. The applicability of the LEFM linear elastic fracture mechanics method to the analysed situation was also verified. In this chapter, the geometric scaling correction factor Y for the considered samples was also analysed.

Chapter 5 presents an analysis of instrumentation (apparatus) and structural modelling in mining machinery analysis, focussing on techniques such as ESR, accelerometer analysis, and the finite element method. Finite element analysis includes stress and strain analysis under various loads and operating conditions. A detailed approach based on spectral and Dirlik fatigue analysis is presented to investigate the behaviour of the Bucket Wheel Stacker - Reclaimer KsS 5600/3800x40 in its operational environment. The proposed methodology involves the evaluation of the dynamic responses of the machine in frequency using the data from in situ measurements obtained during the technological process of excavation. Wavelet analysis was used to understand the underlying mechanisms contributing to the deformation of the structure, as this method is particularly useful for investigating the local details of complex signals as a function of time and frequency, thus providing a finer and more detailed insight than other methods of spectral analysis. At the end of this chapter, the working methodology for determining the remaining life by applying the Dirlik method in fatigue analysis is established and exemplified.

The last part of the PhD thesis includes the **final coclusions** of the studies carried out, the **original contributions** regarding the analysis of the manifestation of the fatigue phenomenon in the load-bearing structure of heavy mobile mining equipment used in lignite quarries and the calculation of the remaining service life of these equipments, as well as some **recommendations and future research directions** to continue studying this issue.

Final conclusions

To answer the main objective of the thesis, the first stage in the research consisted of knowing the types of mining equipment used in the lignite quarries in the Oltenia basin. The analysis focused in particular on the combined depositing and loading machines, the combined machines for removing the material from the warehouse, and the type T3855, KsS 5600 rotor stacker and their main drive mechanisms, as well as on the heavy mobile rotor machines used in the extraction of lignite (in the present case, it is about bucket wheel excavators). In conclusion, the analysis of heavy bucket-wheel mobile machinery in mining pits and coal deposits reveals a number of essential aspects for the mining industry. The final personal conclusions to the analysis of these machines refer to: the characteristics and performances of the machines; the impact of external factors on the machines.

Chapter 2 of the PhD thesis presents a detailed analysis of the phenomenon of fatigue and mechanical degradation in the metal structures of mining equipment. In this chapter, I highlighted the importance of a detailed analysis and constant monitoring of the fatigue phenomenon in mining equipment, using advanced assessment methods and high-quality materials to ensure durability and safety in operation. Following the study, we formulated the following main conclusions regarding: mechanics of excavation forces; metallic materials used; analysis of the fatigue phenomenon; stress analysis at welded joints (nominal stress method, local stress method, use of electroresistive transducers); durability analysis (Weibull analysis).

Chapter 3 of the paper focusses on the analysis of the load-bearing metal structures of heavy mobile machinery used in mining, with an emphasis on the identification and evaluation of the loads acting on these structures, the mechanical characteristics of the component materials, and the analysis of the phenomenon of fatigue through random vibrations. This chapter emphasises the importance of a detailed and rigorous analysis of the load-bearing metal structures of heavy mobile machinery, using advanced methods to assess loads, mechanical characteristics, and fatigue phenomena. These analyses are essential to ensuring the safety and durability of structures under the demanding conditions of mining. The main conclusions are presented below:

1) *Loads on load-bearing metal structures;*
2) *The mechanical resistance characteristics of the component materials;*
3) *Determination of the degree of structural and mechanical degradation;*
4) *Analysis of the phenomenon of fatigue through random vibrations (Wohler's method and vibration analysis for evaluating the durability and performance of structures under repeated stresses);*
5) *The Dirlik method for fatigue assessment.*

In chapter 4, the remaining service life of heavy mobile machinery used in coal mining was estimated based on linear elastic fracture mechanics. From the research and analysis carried out, the following main conclusions can be mentioned:

1) *Crack growth according to the number of cycles (a-N);*
2) *Crack growth rate as a function of ΔK (da/dN - ΔK);*
3) *Stress intensity factor depending on crack length (K - a);*
4) *Lifetime, depending on the initial length of the crack (N - a_i);*
5) *Weibull analysis: calculation of Weibull parameters for the central and lateral crack;* analysis of Weibull distribution functions; the variability of the Weibull parameters;
6) *Crack behaviour:* crack growth according to the number of cycles (a-N) for lateral cracks compared to central ones; crack growth rate (da/dN - ΔK) according to the Paris-Erdogan law; 6) *Distribution of the stress intensity factor*;
7) *Estimating life span and highlighting areas of increased vulnerability.*
8) *The Weibull parameters* calculated for the central and lateral cracks provided detailed information on the probability of failure;

9) *Fracture mechanics analysis combined with Weibull failure probability* assessment provides a robust framework for understanding crack behaviour and material durability under cyclic stress;
10) *Evaluation and experimental considerations of the method.*

Chapter 5 presents a detailed approach based on spectral analysis and Dirlik fatigue to investigate the behaviour of the Bucket Wheel Stacker - Reclaimer KsS 5600/3800×40 in its operational environment. The main conclusions resulting from the experimental analyses carried out, I specify:

1) Importance of Metrology and Instrumentation (use of sensors and electroresistive transducers);
2) Electroresistive tensometry (tensions and deformations can be determined in the analysed structures, providing accurate data for evaluating the behaviour of materials under mechanical stress);
3) Analysis with accelerometers (for measuring vibrations and evaluating the dynamic behaviour of mining equipment);
4) The Finite Element Method (FEM) allows the evaluation of stresses, strains, and other relevant characteristics of mining machinery, providing a detailed picture of the structural behaviour under different loads and operating conditions;
5) Applying the Dirlik Method in Fatigue Analysis, establishing the working methodology for determining the remaining life:

- The Dirlik method is used to evaluate the fatigue behaviour of structures exposed to random loads.
- Spectral analysis and the use of PSD (Power Spectral Density) allow a detailed evaluation of the energy distribution as a function of frequency, providing essential information for estimating the lifetime of mining structures.

Detailing and interpreting graphs in lifetime analysis using the Dirlik method and wavelet analysis

Dominant frequency and spectral analysis

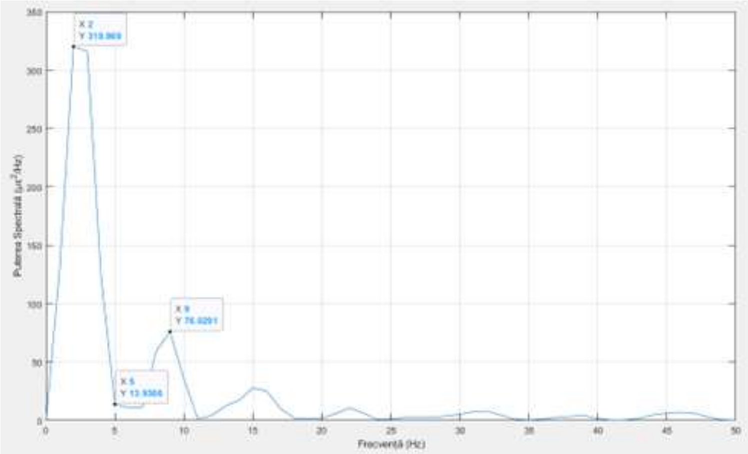

Figure 6.1 Power Spectral Density (PSD)

Frequency Spectral Power:

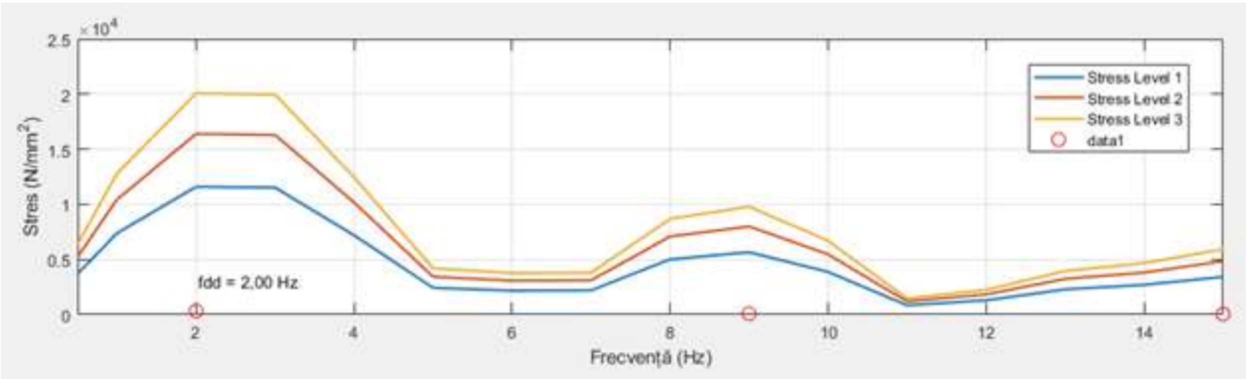

Figure 6.2. Energetics distribution as a function of frequency and associated voltage levels

Wavelet analysis

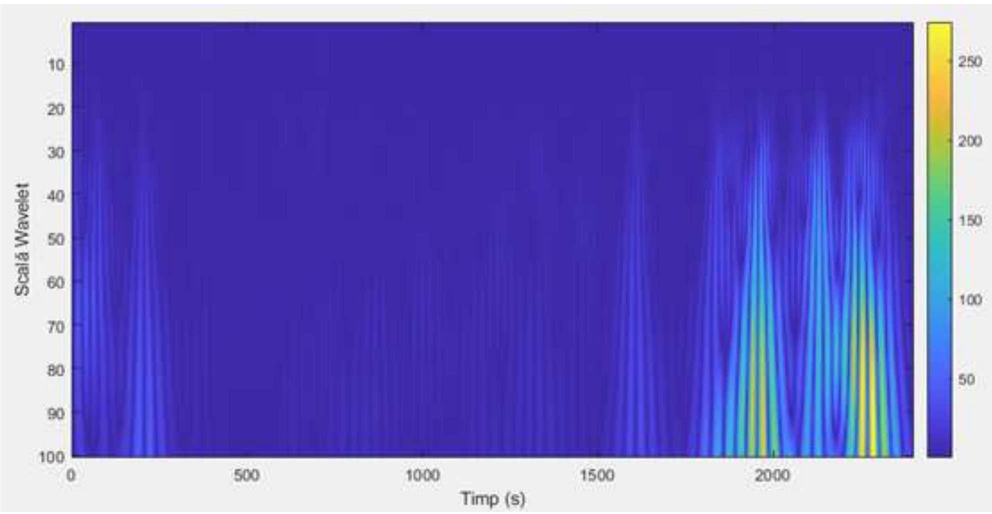

Figure 6.3. Wavelet scalogram

Dirlik Method and Fatigue Analysis

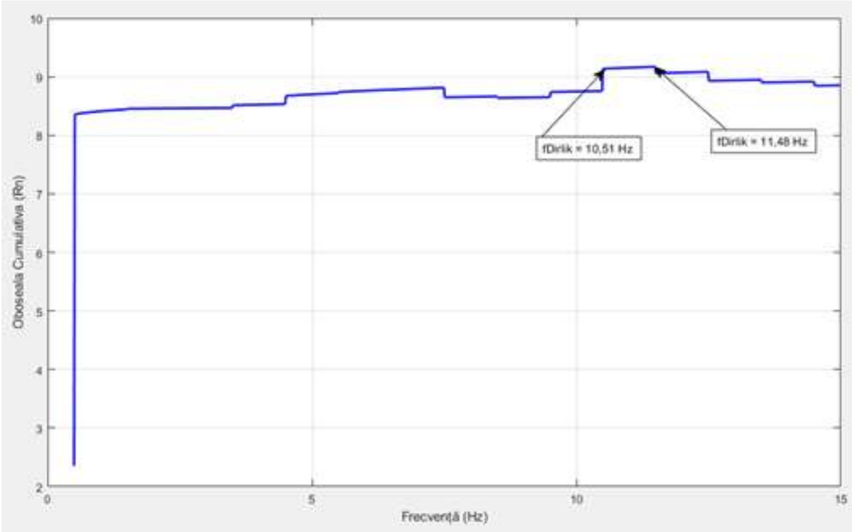

Figure 6.4. Cumulative fatigue as a function of frequency

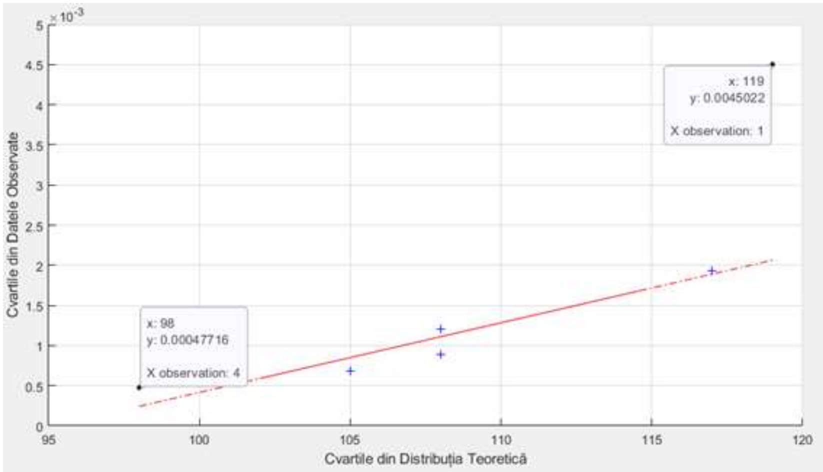

Figure 6.5. Q-Q Plot for Weibull distribution

Evaluation of the Distribution of Periods and Frequencies

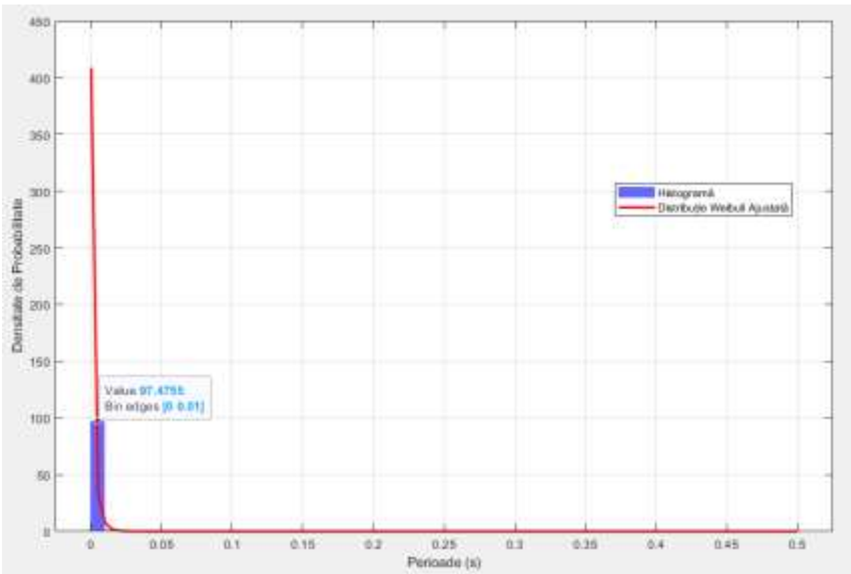

Figure 6.6. Histogram of frequencies of interest for the adjusted Weibull distribution

6) Research and in situ measurements:
   - Data collection through in situ measurements is crucial for validating theoretical models and getting a clear picture of the real behaviour of mining machinery.
   - The use of data acquisition systems such as Fastview and piezoelectric accelerometers allows continuous monitoring of critical parameters and evaluation of structural dynamics under real operating conditions.

General conclusions:

a) Integration of electroresistive strain measurement, accelerometer analysis, and MEF methods for evaluating the structural behaviour of mining machinery. These methods allow potential structural failures to be identified and prevented, thus ensuring safe and efficient operation.

b) Fatigue analysis using the Dirlik method and spectral analysis provides a detailed picture of the durability of mining structures under random loads, contributing to the optimisation of the design and maintenance of these machines.

c) The importance of in situ measurements: they are essential for validating theoretical models and obtaining accurate data about the real behaviour of mining structures under operating conditions; they allow the continuous monitoring of the health status of the structures and the adoption of appropriate preventive measures.

Original contributions

The main contributions of the PhD thesis are as follows:

1. Analysis of the characteristics and performance of mobile heavy machinery with bucket wheels used in lignite quarries in the Oltenia basin;
2. Analysis of the impact of external factors on heavy mobile mining equipment in order to develop a methodology for estimating the duration of operation of load-bearing metal structures in safe conditions;
3. Detailed study of the mechanics of excavation forces and the influence of these complex, non-uniform, and random forces on the load-bearing structure of mining equipment;
4. Analysis of the characteristics of the metallic materials used for bracing and load-bearing beams and their influence on the fatigue resistance of the structures;
5. Analysis of the fatigue phenomenon by means of the S-N (Wöhler) and Miner-Palmgren curves for evaluating the behaviour of materials and structures in the face of cyclical stresses; stress distribution and their variation according to material and operating conditions;

6. Analysis of stresses in welded joints by the method of nominal stresses, the method of local stress, and the use of electroresistive transducers (TER) to measure nominal stresses and local stresses in critical areas of welded joints;
7. Durability analysis by statistical methods—Weibull analysis, with obtaining results related to: the temporal distribution of failures and the probability of degradation of structural materials, the shape and scale parameters of the Weibull distribution, very important indicators in the evaluation of the life span, and the rate of degradation of machinery;
8. Taking samples from the load-bearing structures of the KSs5600/3800-40 machine and performing detailed analyses of the mechanical and chemical properties of the component materials and determining the degree of structural and mechanical degradation; chemical analysis of material samples through spectrographic analysis;
9. Analysis of the phenomenon of fatigue through random vibrations and fatigue calculation for a mining machine operated by variable, non-periodic forces using spectral analysis and the Dirlik method;
10. We proposed a solution to estimate the remaining service life of heavy mobile mining equipment used in lignite pit mining by the σ-N method for structural elements and the fracture mechanics method because some elements already show cracks or crack initiations. A significant contribution is the application of the LEFM method for the analysis of crack development, the determination of the characteristics of the component material of the subassemblies of heavy mining equipment, but also the verification of the applicability of the method and the comparison of the modelling results with those obtained from the tests performed.
11. I carried out the structural modelling in the analysis of mining equipment by applying electroresistive tensometry, analysis with accelerometers, and the finite element method;
12. Spectral and fatigue analysis by the Dirlik method to investigate the behaviour of the Bucket Wheel StackerReReclaimer KsS 5600/3800x40 machine in its operational environment. The proposed methodology involves the evaluation of the dynamic responses of the machine in frequency using the data from in situ measurements obtained during the technological process of excavation;
13. I proposed and exemplified in the content of the thesis the working methodology for assessment the remaining life by applying the Dirlik method in the fatigue analysis.

Recommendations and future research directions

1) *Improvement of analysis methods*: Further research is recommended to improve fatigue analysis methods, including the integration of more advanced material behaviour models and real-time monitoring techniques.
2) *Application of advanced technologies*: The use of high-precision sensors and IoT technologies to continuously monitor the condition of load-bearing structures can provide essential data for failure prevention and maintenance optimization.
3) *Extending the studies*: It is important to extend the studies to include a wider range of machines and operating conditions in order to validate and generalise the conclusions obtained in this work.
4) *Development of training programs*: Implementation of training programs for mining engineers and technicians focused on the use and interpretation of advanced fatigue analysis methods can contribute to increased operational safety and efficiency.
5) *Monitoring system*: The introduction of partial monitoring of the operation of the main sub-assemblies of the rotor excavator and its generalisation throughout the Oltenia basin.