# CONTRIBUTIONS TO THE DYNAMIC STUDY OF ROTOR EXCAVATORS BY RESISTIVE TENSOMETRY AND SPECTRAL ANALYSIS

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**Abstract:** Frequency spectral analysis and resistive tensometry are two fundamental techniques in engineering, used to monitor and evaluate the durability of structures and mechanical equipment. Spectral analysis in the context of rotary excavators is a method of evaluating the dynamic characteristics of these machines, using the decomposition of signals into their spectral components. This approach is essential for understanding the dynamic behavior of rotary excavators and identifying structural elements or machine parts that can produce resonant frequencies. For the work methodology has been considered the excavator with rotor type ERc 1400-30/7M, for which in the first stage the specific deformations were measured on certain structural elements, and in the second stage they been determined by the finite element method the first natural frequencies to be able to compare them with the dominant frequency determined from the measurement of the specific strains.

**Keywords:** Spectral analysis, Power Spectral Density (PSD), Bucket wheel excavators, Tensometry.

## 1. INTRODUCTION

Electrical resistive tensometry and frequency spectral analysis are two engineering techniques used for dynamic evaluation of excavators. This method provides a detailed understanding of how excavation forces influence the structural behavior of rotary excavators. In parallel, spectral analysis, particularly Power Spectral Density (PSD), is proving to be a valuable tool in exploring how forces vary with

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frequency. By applying spectral analysis, we can identify dominant frequencies and assess how they may affect system performance and stability.

This paper focuses on the integration of resistive strainometry in the dynamic study of rotary excavators and the use of spectral analysis, especially PSD, to gain a comprehensive insight into the behavior of these equipments under various working conditions. By combining these methods, together with related software, we aim to highlight the benefits of real-time monitoring technologies for optimizing the performance and safety of excavators in their specific operating environment.

## 2. WORK METHODOLOGY

Although the state of stress is low, from the tensometric measurements, the yield limit of the material is not exceeded, in this case OL52.3, nevertheless cracks or microcracks appear in the load-bearing elements of the machines after a period of time, figure 1. On the other hand part, according to the definition given by ASTM E 1150-87, fatigue is "the process of permanent, localized and progressive structural change that occurs in a material subjected to conditions that produce specific deformations and fluctuating stresses in one or more points and that can culminate in cracks or complete rupture after a sufficient number of fluctuations".

(a) (b)

**Fig.1** Cracks produced at (a) pillar base, (b) turntable

The state of tension (deformation) in the bearing structure of the machine is produced under the dynamic action of the vibrations generated by the excavation forces, forces which, due to the inhomogeneous and anisotropic material, are variable forces and thus generate random vibrations.

Frequency spectral analysis for variable excavation forces is a method used to decompose signals given by variable forces into spectral components, thus allowing the identification of dominant frequencies and the characterization of the dynamic behavior of the excavation system. Dominant frequencies indicate the frequencies at which mechanical systems or metallic structures exhibit maximum response or the most pronounced sensitivity to external forces or disturbances. These frequencies basically represent the frequencies at which systems have a natural tendency to react with increased amplitudes to external actions.

If the external forces or disturbances have a component that matches the dominant frequency of the system, it can enter into resonance, which can lead to vibration amplification and undesirable effects on structural integrity. Thus, identifying and understanding the dominant frequencies is essential to prevent unwanted resonance situations and optimize the behavior of mechanical systems.

The most used method for signal analysis is the Fourier transform for random signals. It was developed by the French mathematician Joseph Fourier and is fundamental to the field of signal theory and signal processing. It should be noted that in the case of periodic signals, the transition from the time domain to the frequency domain is achieved by means of Fourier series, in the case of non-periodic signals, the connection between the two domains is achieved by means of the Fourier transform.

This transformation allows the decomposition of a continuous signal into an (integral) sum of sines and cosines of different frequencies, known as spectral components or spectrum. This is useful for analyzing the frequency content of a signal and obtaining information about its fundamental components.

In order to perform the frequency spectral analysis on the data obtained by resistive tensiometry, we have implemented the following work methodology:

*2.1. Placement of Electroresistive Stamps (TER):* Placement of resistive elements in critical areas of the excavator to measure specific strain variations associated with stresses produced by excavation forces.

*2.2. Recording of Tensometric Data:* Specific deformations must be processed and recorded over a significant period of operation of the excavator. We will consider the data set of specific deformations over a time interval *t(s)*, for which *x(t)* is considered the deformation signal

*2.3. Application of the Fourier transform (TF):* Passing the acquired data from the time domain to the frequency domain, interpreting and establishing the dominant frequency that can produce large specific deformations in the structure. The Fourier transform of a signal is given by the formula [1], [2], [3]

$$X(f)=\int_{-\infty}^{+\infty} x(t)e^{-j2\pi ft}dt \tag{1}$$

where, *X(f)* represents the frequency spectrum of the signal, *x(t)* is the signal in the time domain, *f* is the frequency, and *j* is the imaginary unit (*j* = -1), the integral is performed over the entire time interval , from $-\infty$ to $+\infty$. Identifying the dominant frequencies is done by examining the frequency spectrum, we can identify the frequencies with the highest magnitude. These are the dominant frequencies that contribute significantly to the total deformation of the resistance elements or can lead to a dramatic situation, namely the production of microcracks.

*2.4. Calculation of PSD (Power Spectral Density)* for frequency f.dom: To obtain the PSD, the squared modulus of the frequency spectrum is divided by the frequency interval (usually the sampling frequency). This is done to obtain the power spectral density, which shows the power per unit frequency. Power Spectral Density is plotted against frequency to visualize how the signal power is distributed across the frequency spectrum of these strains. After obtaining the frequency spectrum *X(f)*, one can calculate the PSD by multiplying the spectrum by its conjugate. PSD represents power per unit frequency and is calculated as follows[4],[5][6][7]:

$$S_X(f) = \lim_{T\to\infty} \frac{1}{T} \left| X(f) \right|^2 \tag{2}$$

where, $S_X(f)$ represents the power spectral density of the signal *X(t)* at frequency *f*; *X(f)* is the Fourier transform of the signal *X(t)* in the frequency domain, and *T* is the length of the time interval over which the PSD is calculated.

Power Spectral Density, PSD [$\mu\varepsilon^2$/Hz] is a measure of the power density at a certain frequency in the frequency spectrum of unit distortions [$\mu\varepsilon$]. To obtain an absolute value of the deformation $\varepsilon_{PSD}$ in unit [$\mu\varepsilon$], the power spectral density must be integrated over the entire frequency spectrum considered active.

$$\varepsilon_{PSD}[\mu\varepsilon] = \sqrt{(f_2 - f_1)\int_{f_1}^{f_2} PSD(f)df} \tag{3}$$

This relationship is used to calculate the microstrain ($\mu\varepsilon$) from a given power spectral density (PSD) for a given frequency range.

## 3. CASE STUDY

To highlight the above, we will do the dynamic analysis of the ERc1400-30/7M bucket wheel excavator, with the excavation system consisting of a cellular bucket wheel on which 20 loading/cutting buckets are arranged.

The measurement of the specific deformations will be carried out in situ, in the case of excavation in a working front composed of successive layers of earth-marl-coal, figure 2, with normal excavation kinematic parameters.

### 3.1.Measurement of specific deformations by resistive tensometry

The following steps will be taken:

*3.1.1.Placement of the electroresistive stamps* – It starts by gluing the electroresistive stamps, on the supporting metal structure according to the stress state established by the finite element method. So that for the bucket excavator analyzed, tensometric stamps from number 1 to 8 TER were arranged, figure 3.After the positioning of the stamps, the measurements were carried out in dynamic mode, namely the excavation in the working front.

*3.1.2.Registration of Tensometric Data.* All strain gauges were connected to a data acquisition system consisting of: NI9237 acquisition modules, FastView acquisition software[8]. The strain gauges are connected in half-bridge with a thermal compensation element. Their value is 120 **Ω**, made by the Japanese company Kyowa [9].

**Fig. 2** Earth-marl-coal excavation front

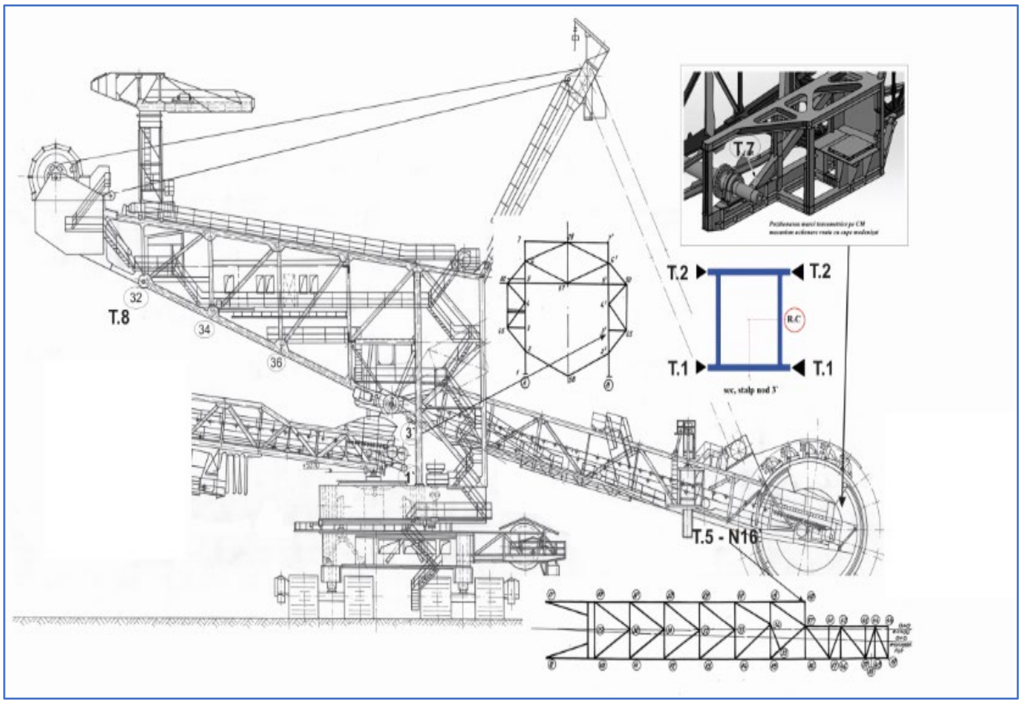



**Fig. 3** Positioning TER on the supporting metal structure of the machines

Spectra of specific deformations for the ERc 1400-30/7M rotor excavator generated in the metal structure of the machine during in-situ excavation are presented in figure 4.

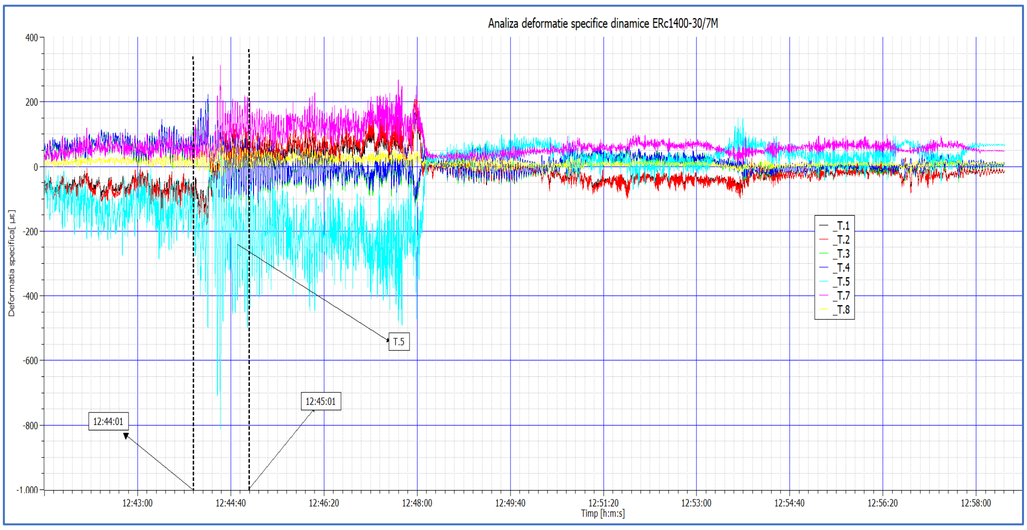



**Fig.4.** Dynamic spectra of specific deformations

The value of deformations on the tensiometric stamp T.5 (see fig.3) positioned on the eaves for the time interval 12.44.01-12.45.01 (see fig.3) the values of dynamic deformations reaching ε = approx. 800 μm/m in bending. Values of approx. 200 μm/m, on the T7 stamp located on the metal construction of the cup wheel drive mechanism.

If these values which have a repeatability with a certain frequency can lead to the appearance of microcracks in non-technologically executed bores or welds, figure 5.

For these situations different technological devices are made to stop microcracks by making stop bores (fig. 5a) of cracks or the arrangement of gouges (fig. 5b).

(a) (b)

**Fig. 5** Cracks at cup wheel reducer torque arm

The specific deformation values for the machine are presented in table 1. The deformation values are the highest when bending the metal structure T.5, (fig. 3), where the metal construction of the gear wheel drive mechanism is attached.

*3.1.3.Applying the Fourier transform (TF)* - Passing the acquired data from the time domain to the frequency domain. It is found that the values that produce the largest deformations in the resistance elements are the values obtained by the tensometric stamp T5, approx. 800 mμ/m. For this reason, the Fourier transform is applied for the values resulting from the measurements given by T5. To apply the Fourier transform on a string of 5153 samples, over a time interval of approximately 40 minutes, you can use programs such as: SciLab, Octave, MatLab or Python.

**Table 1**. *Specific Deformations ERc1400-30/7M*

| **TER** | **Mean** [μm/m] | **Standard Dev** [μm/m] | **Streching** [μm/m] | **Bending** [μm/m] |
|---|---|---|---|---|
| T.1 | -13.612 | 43.398 | 178.976 | -154.977 |
| T.2 | -12.84 | 53.293 | 228.784 | -201.254 |
| T.3 | 11.322 | 38.693 | 209.679 | -137.758 |
| T.4 | 14.86 | 37.763 | 222.561 | -121.405 |
| **T.5** | **-50.48** | **123.635** | **151.94** | **-812.047** |
| T.7 | 71.252 | 38.486 | 313.28 | 3.701 |
| T.8 | 11.311 | 12.073 | 84.28 | -32.011 |

Following the analysis, the graph in figure 6 is drawn, the evolution of the specific deformation over time for the stamp T5, under the action of the excavation forces.

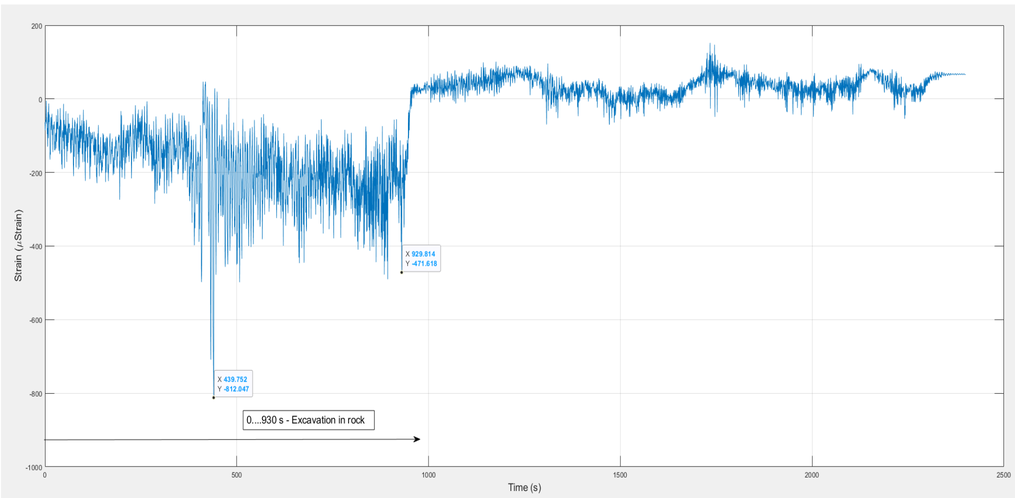



**Fig.6**. Evolution of the specific strain over time

In the interval (0 ... approx. 930s), figure 6, the machine enters the excavation of lignite from the working front, having a maximum point of - 812 με after which the excavation cycle resumes.

The transition of the acquired data from the time domain to the frequency domain is done through the Fourier transform. In the context of excavation forces, the time domain signal represents the forces acting on the excavator as a function of time.

The Fourier transform can decompose these forces into a sum of frequency components, showing how much each frequency contributes to the behavior of the force. The frequency spectrum obtained by the Fourier Transform can provide information about the predominant frequencies of the excavation forces. Higher frequencies may indicate rapid changes in forces, while lower frequencies may reflect slower variations. In figure 7, you can see the Fourier transform for the specific deformations of the machine, and the dominated frequency is denoted by $f_{.dom}$ = 1.00 Hz.

Most mining equipment for excavation or deposition works in the low frequency range, in the range of 0.5 ... approx. max. 2.2 Hz, frequencies determined by measurements with accelerometers, on various machines, their variation depending on the mass of material deposited on the elind or on the discharge hopper on lane 1 of the machine.

*3.1.4.PSD (Power Spectral Density) calculation for the dominant frequency* - in the dynamic study of rotary excavators is essential to understand how the system reacts to external forces as a function of frequency. Through PSD analysis, the frequencies at which the signal strength (excavation forces) is maximum are identified. These critical frequencies are essential to anticipate potential situations of resonance or vibration amplification, which can affect the integrity and performance of the excavator.

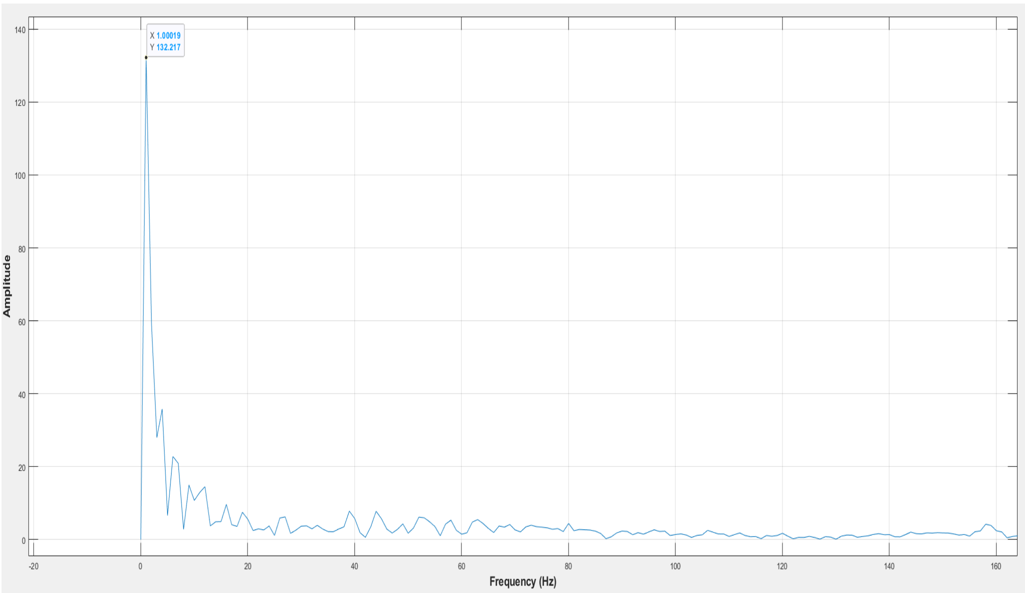



**Fig. 7.** Fourier Transform of the signal

In figure 8 you can see the PSD graph [$\mu\varepsilon^2$/Hz], resulting in a value of $PSD._{f.dom}$ = 17481 [$\mu\varepsilon^2$/Hz], for a dominant frequency of 1 Hz, which has a spectral power in unity microstrain ($\mu\varepsilon$) of approximately $PSD._{f.dom}$ = 186.98 $\mu\varepsilon$. We expand the calculation relations of Hooke's law, consider for steel according to EN 1993-1-1/3.2.6, the modulus of elasticity E = 2.1x$10^5$ N/mm$^2$; Poisson's constant $\nu$=0.3, considering the specific deformation $\varepsilon_{PSD}$ = 187 $\mu\varepsilon$ in this case, the voltage produced at the frequency of 1 Hz, by the random forces in the metallic structure can be :

$$\sigma_f = (187)\cdot 10^{-6} x 2{,}1\cdot 10^5 = 39{,}27 N/mm^2 \tag{4}$$

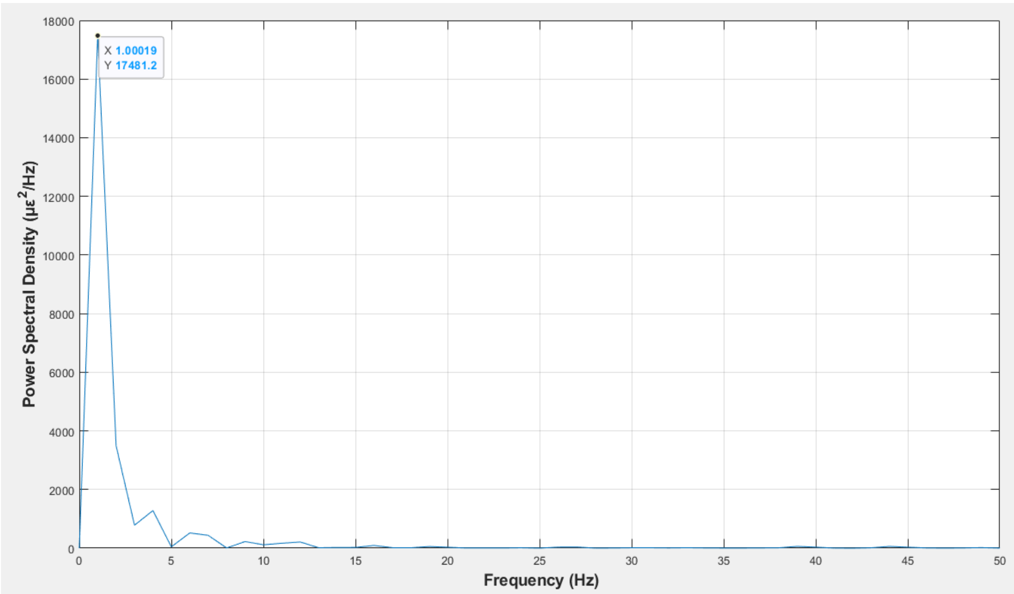



**Fig. 8.** Power of Spectral Frequency

**3.2.Natural frequency analysis by the finite element method**

There are two terms that can analyze a metal structure of a mining machine, or another type of dynamic machine, terms that are often confused but interact in the dynamics of the machine:

a) *The natural (proper) frequency* refers to an intrinsic property of a system or structure and is related to the way it vibrates or oscillates in the absence of an external force, when it is taken out of equilibrium. It is a specific frequency of the system that depends on the physical properties of the system, such as stiffness, mass, and length;

b) *The resonant frequency* is the frequency at which a system or structure reacts most strongly to an external force or disturbance. It is the frequency at which the amplification of the system response is maximum.

Natural frequency is important in the analysis of vibration and dynamic behavior of systems because it influences how the system responds to external forces or disturbances. The resonant frequency is not an intrinsic property of the system, but depends on the combination of the natural frequency of the system and external factors such as the frequency of the applied force or the frequency of the disturbance. In the case of small damping the natural frequency becomes the resonance frequency.

To determine the natural frequency of the machine, we will apply the finite element method by amplifying the bar/plate finite elements to discretize the structure.

In the application of this method for such machines [12], the stages in figure 9 can be distinguished.

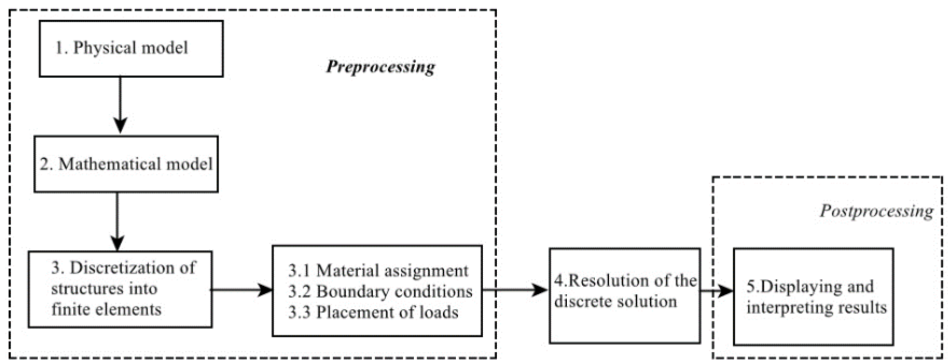



**Fig.9.** The stages of the analysis by the finite element method

The establishment of natural frequencies based on the stages described in fig. 9, are presented in stages in figure 10, only the superstructure is analyzed, fig. 10.a, where in point 3, the fastening of the poles to the superstructure will be considered a rigid fastening.

After performing the calculations, the natural frequency values for the machine superstructure were determined, table 2, figure 11.

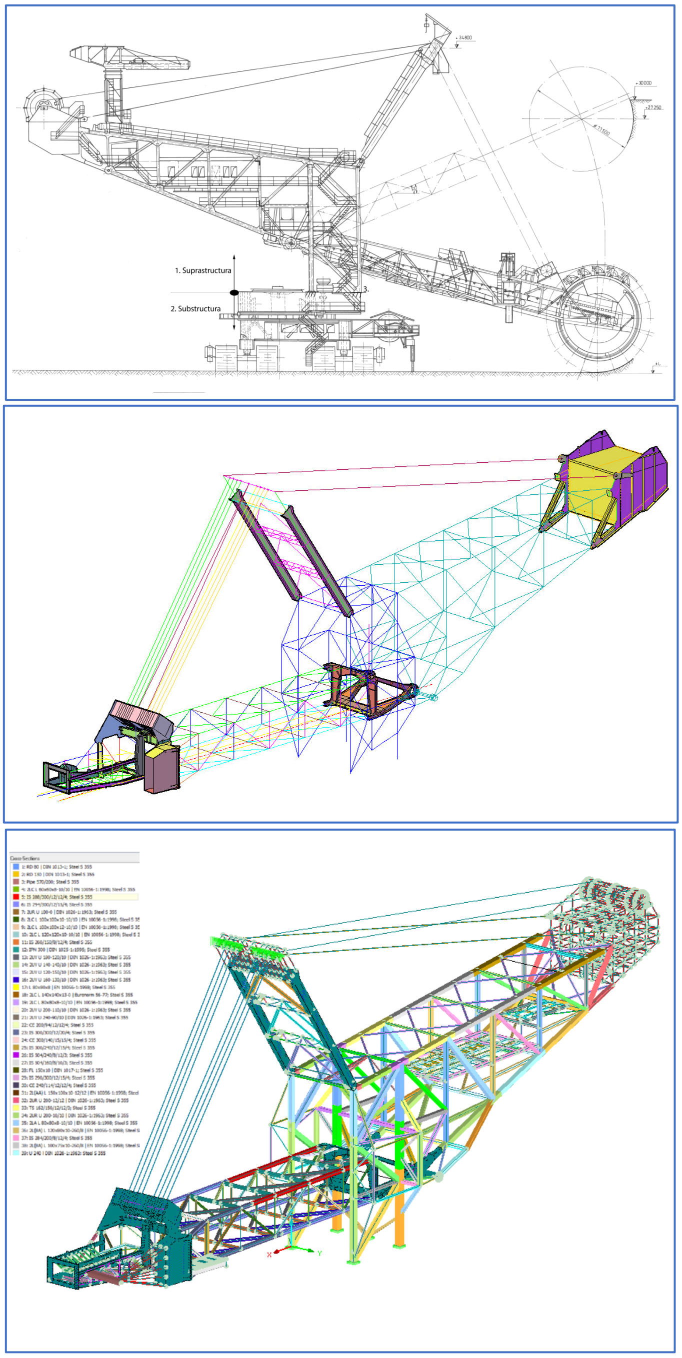
**Table 2**. *Frequency analysis ERc 1400-30/7M- superstructure*

| **Mod** | **Angular Frequency ω̃ [rad/s]** | **Natural Frequency f [Hz]** | **Natural Period T [s]** |
|---|---|---|---|
| **1** | 6.007 | **0.956** | 1.046 |
| **2** | 15.145 | 2.410 | 0.415 |
| **3** | 29.500 | 4.695 | 0.213 |
| **4** | 32.880 | 5.233 | 0.191 |

The first natural frequency or natural frequency of the rotary excavator is

$$fn._{E14} = \ aprox.\ 0{,}956\ Hz, \tag{5}$$

calculated on the simplified bar-plate finite element model.

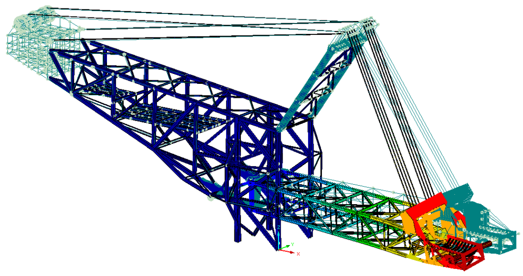



(1)Phisical model

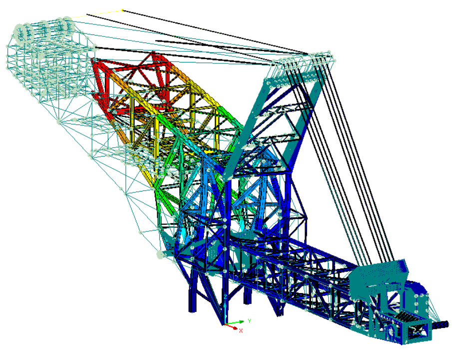
(2)Mathematical model

(3) Discretization of structures

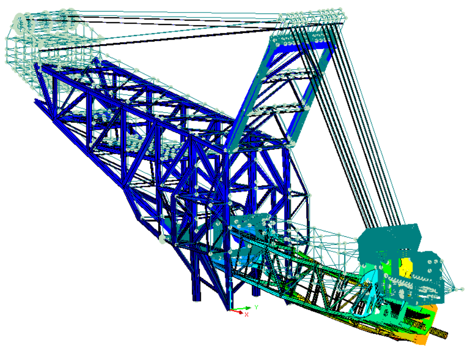
**Fig.10.** Stages of FEA model of type ERc 1400-30/7M



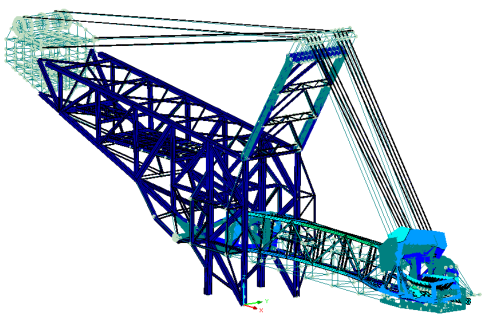
**Modul I** - $f_1 = 0.956$ [Hz]



**Modul II** – $f_2 = 2.410$ [Hz]



**Modul III** – $f_3 = 4.695$ [Hz]



**Modul IV** – $f_4 = 5.233$ [Hz]

**Fig.11** The natural frequencies of the excavator type ERc1400-30/7M

## 4.CORRELATION OF RESULTS

Comparing the values of the natural frequency and the value of the first dominant frequency, respectively all their characteristics can be written, table 3.

**Table 3.** *Comparative data of dynamic analyses*

| Mod | Natural Frequency $f_n$ [Hz] | Dominant Frequency $f_{dom}$ [Hz] | Tension s [N/mm$^2$] |
|---|---|---|---|
| **1** | **0.956** | **1.00** | **39.27** |

In other words, PSD shows which frequencies contribute the most to specific excavator deformations. Examining the graph (fig.8) the peak (maximum) corresponding to the resonance frequency can be identified and the main voltage that can generate degradations can be calculated.

It follows that the resonance frequency that can produce maximum deformations in the structure leading to cracks, damage to the structural elements is the resonance frequency that we note milling cutter $f_{rez}$ = approx. 1.00 Hz.

Correlating deformation/time, figure 12.a, with the location of the markings, figure 12.b, which represents the period in which the dominant frequency appears, two areas can be see.

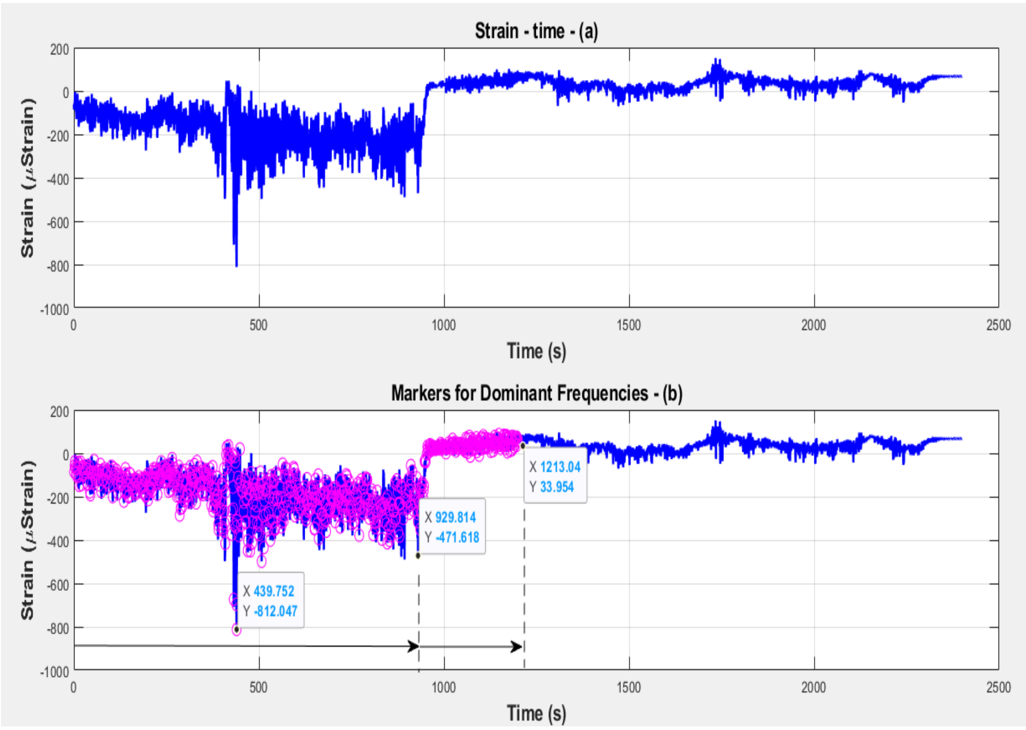



**Fig.12.** Correlation of dominant frequency with specific strain over time

Zone I – dynamic zone – 0 (s) .... approx. 939 (s) – during the excavation process, the frequency dominated by almost every specific deformation generated by the variable intensity of the excavation forces may appear;

Zone II – damping zone – 939 (s) ....1213 (s) – is the zone where the excavation forces disappear but due to the inertial forces generated by the moving masses and the impulses given by the excavation forces on the metal structure, the frequency dominant is preserved in the metallic structure even though the exciting part no longer exists.

## 5. CONCLUSIONS

Following the study of the dynamics of rotary excavators through the spectral analysis of specific deformations, the following conclusions can be drawn:

*1.Spectral Analysis of Specific Deformations:*

The study of the dynamic behavior of rotary excavators by spectral analysis of specific deformations provided a detailed insight into their variability as a function of frequency and intensity. This analysis highlighted not only the influence of frequencies on the metallic structure, but also the periods in which these specific deformations are dominated.

*2.Dominant Frequency:*

The identification of the dominant frequency is essential for understanding the prevailing vibration phenomena, having an impact on the behavior and safety of excavators, especially during the time interval in which they dominate.

*3.Power Spectral Density (PSD):*

The PSD calculation provided a measure of the power distribution of the specific strains as a function of the identified dominant frequency. This aspect is crucial for detecting critical frequencies and possible resonances that can affect the behavior and integrity of the machine. By determining the PSD in units of microstrain, one can roughly estimate the voltage level generated by the determined frequency.

*4.Determination of Natural Frequency:*

In this study, the determination of the natural frequency was imperative to evaluate the relationship between the dominant and the natural frequency of the system. The comparative analysis of the values in Table 3 suggests that the numerical differences are relatively small, indicating a possible approach in the I time interval to the appearance of the resonance phenomena. It should also be emphasized that a more robust comparative approach can be achieved by using accelerometers in direct measurements, thus eliminating the potential errors and approximations involved in the analytical model.

It is important to note that the identification of the natural frequency is a crucial aspect in the anticipation and prevention of resonance phenomena. As the analytical model involves some simplifications, direct measurements contribute significantly to the accuracy and detailed understanding of the dynamic behavior of rotary excavators.

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