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The influence of vibroacoustic disturbances on the precision of analytical spectrometric measurements

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Abstract The accuracy of chemical measurements is crucial for the quality of research. One factor influencing the precision of measurement is the environment, which can be a source of vibration or sound. Microwaveinduced plasma optical emission spectrometry (MIP OES) is one of the most commonly used instrumental techniques in quantitative elemental analysis. This technique is used in numerous fields, such as geology, chemistry, and medicine. Mechanical vibrations of various nature can have a significant impact on the performance of such sensitive equipment. The influence of controlled vibrational disturbances using a modal hammer and vibroacoustic disturbances on the results of spectroscopic measurements was investigated.

Keywords: optical emission spectroscopy, vibration, impulse test, measurement interference.

1. Introduction

Paraseismic vibrations have a significant impact on the stability and repeatability of chemical instrumental measurements, such as those used in spectroscopic studies. Their impact on the accuracy of the measurement has been of interest to scientists for many years. The most common cause of paraseismic vibrations is the movement of means of transport such as cars, trams and trains, as well as the impact of construction machinery on the ground during construction work.

Analytical atomic spectrometry is commonly used in elemental quantitative analysis. The two most popular radiation sources used in optical emission spectrometry (OES) are Inductively Coupled Plasma (ICP) and Microwave Induced Plasma (MIP) [1-4]. The measurement is based on the detection of radiation intensity emitted by excited atoms, which is characteristic for elements determined (wavelength) [2].

Numerous studies have been conducted on this topic, including the analysis of selected aspects of the structure and properties of low-carbon steel laser remelting assisted by acoustic vibrations [5]. The effect of vibrations on Fourier transform spectrometers, devices highly sensitive to many types of interference, was also investigated. Interference related to mechanical vibrations of the PFS FTIR spectrometer was analyzed to demonstrate how the measured spectra may differ from the actual data [6].

The curve fitting of simulated optical reflectance spectroscopy data was also studied and used to assess the accuracy of parameters obtained from real data fittings. These factors were experimentally investigated and the authors of the concept aimed to achieve the best possible calibration within the target range [7].

The presence of mechanical vibrations also negatively affects the proper operation of analytical balances [8]. In addition to vibrations, microvibrations negatively impact the accuracy of the measurements, posing a challenge in predicting and controlling complex wave fields, potentially leading to measurement errors in sensitive instruments in high-precision laboratories and affecting the accuracy of experimental results. Therefore, researching effective methods for their control under passive conditions is crucial to solving many measurement inaccuracies [9]. Vibrations also affect the length and amplitude of the beam in measurement resolution in microresonator-based optical sensors [10].

2. Research methodology

In order to identify the parameters of the models related to the assessment of valve clearance in the combustion engine, tests were carried out based on the assumptions of the active experiment [11]. An active experiment involves deliberately changing input or interference parameters and observing the effect of these changes on the output parameters. The input parameters were the force driving the vibrations, and the output parameters were the vibration acceleration measured at various locations on the spectroscope, and the intensity of the emission signal.

A PLASMAQUANT 100 atomic emission spectrometer (Carl Zeiss, Jena, Germany) equipped with microwaveinduced plasma excitation source was used in the study. The device consists of a plasma cavity, an optical system, a detector and a control system.

An integrated microwave generator and resonator system (Plazmatronika, Wrocław) was used as the exciation source of the MIP OES spectrometer. The system consists of a rectangular resonant cavity with a basic TE_{101} field type, in which the electromagnetic field distribution is similar to that of a Beenakker TM_{010} resonant cavity. This cavity is directly coupled to a magnetron *via* a waveguide. The resonant cavity is integrated with a 2450 MHz microwave energy generator. The generator has two cooling systems: a water cooling system (cooling the magnetron) and an air cooling system (cooling the cavity's outer wall). The Czerny-Turner optical system of the spectrometer includes a high-resolution chelle polychromator equipped with twelve photomultipliers. Fiber optics are used to transmit signals between the diffraction grating and the detection system. The optical parameters of the PLASMAQUANT 100 spectrometer are presented in Table 1.

Table 1. Optical parameters of the PLASMAQUANT 100 spectrometer.

Physical quantity	Value
Optical System	Czerny - Turner
Focal Length	500 mm
Optical Aperture	1 : 10
Grating Cuts	75 lines/mm
Grating Size	115 mm x 55 mm
Focal Plane	55 mm x 50 mm
Entrance Slit	0.18 mm x 0.07 mm or 0.18 mm x 0.03 mm
Exit Slit	0.20 mm x 0.08 mm lor 0.20 mm x 0.04 mm
Inverse Linear Dispersion	0.11 nm/mm at 200nm; 0.22 nm/mm at 400nm
Resolution	100000
Spectral Width	0.008 nm or 0.005 nm at 200 nm
Wavelength Range	193 – 852 nm
Orders of Operation	28 - 123

A quartz burner (SiO_2, outer diameter 5 mm, inner diameter 3 mm, length 100 mm) was used in the study. The microwave discharge was generated in a mixture of gases of 99.999% purity (BOC Gazy, Poznań): argon (flow 1000 mL/min) and helium (flow 500 mL/min). Atomic emission signals were measured for two elements: calcium (Ca 393.366 (II) and copper (Cu 324.754 (I)) in order to observe the effect of vibrations on the level and stability of the obtained results.

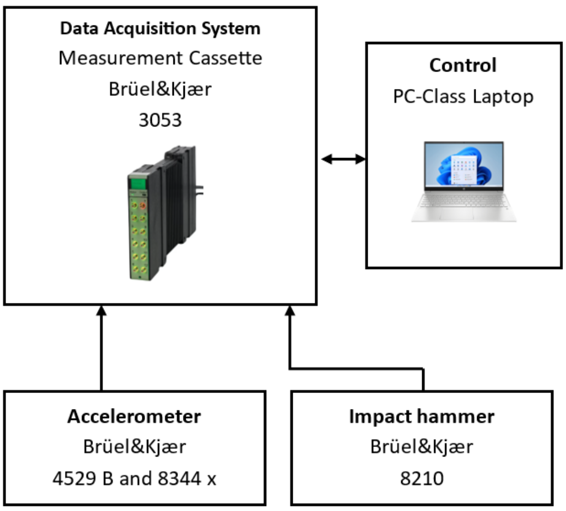

Figure 1. Diagram of the measurement system.

The vibrations were induced by hitting the floor on which the spectrometer is mounted with a hammer. Three measurements were taken, with impact forces of 1.7 kN, 2.8 kN, and 4.3 kN. The signals were continuously measured over a 30-second period, recording multiple hits with a modal hammer Brüel&Kjær 8210.

A Brüel&Kjær 3053 measuring cassette was used to record vibration and force signals. The sampling frequency during the measurements was set to 65536 Hz. A Brüel&Kjær 4529 B triaxial vibration accelerometer was used to measure vibrations of the spectroscope elements, and a Brüel&Kjær one axial accelerometer 8344 x was used to measure paraseismic vibrations of the floor. The directions of vibration measurements were as follows: horizontal plane - X along the burner, Y transverse to the burner; Z vertical direction. The diagram of the measurement system shows at Fig. 1.

The operating plasma torch is shown in Fig. 2a. and the mounting location of the vibration transducer on the plasma torch mounting support is shown in Fig. 2b.

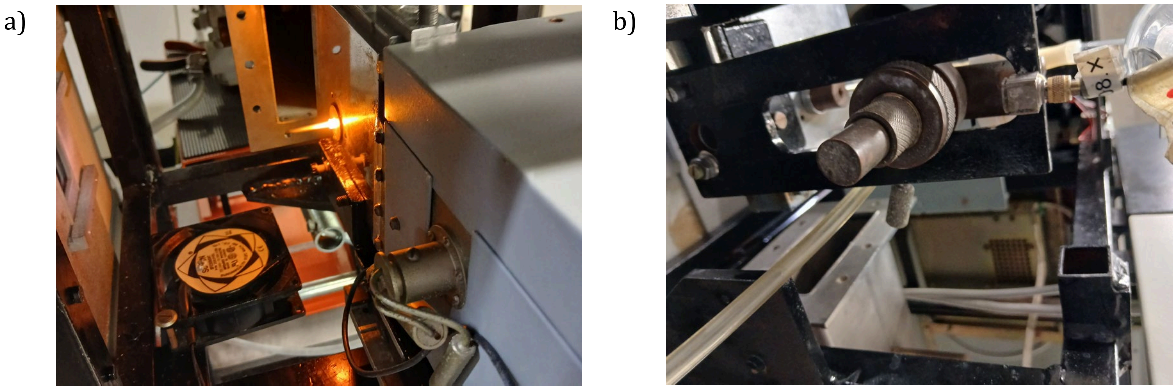

Figure 2. View of: a) microwave cavity with plasma torch, b) vibration transducer mounting location.

3. Research results

3.1. Time history analysis

Time-domain signal analysis was performed to identify the amplitudes of floor vibration displacements, the phase shift between the vibration excitation signal and the system response, and to check whether there is a time coincidence between the vibration signal and the emissivity signal.

Figure 3a shows the time history of floor vibration displacement for the maximum impact force (4.3 kN). Figure 3b shows the time histories of normalized extortion force and vibration acceleration. The normalization of the exciting force and vibration acceleration was performed with respect to the maximum value of each of these values.

Figure 3a shows that the maximum displacement of floor vibrations during the experiment was of the order of 70 µm, and the relaxation time was 44 ms. Based on the analysis of Figure 3b, it can be concluded that there is a relationship between the force driving the floor vibrations and the vibrations of the support mounting the plasma torch. It can also be stated that the time shift between the driving force and the system's response to impulse excitations is 10 ms.

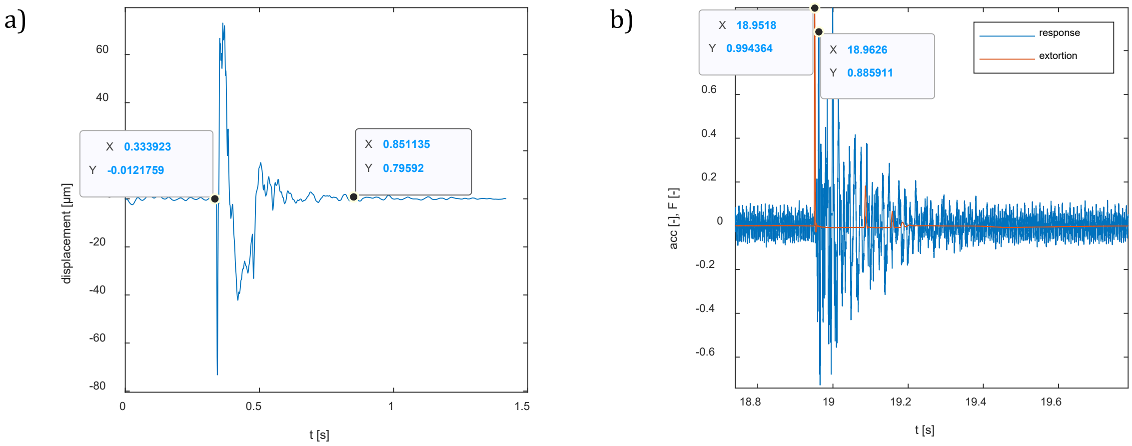

Figure 3. Time history: a) vibration displacement od floor, b) normalized vibration force and acceleration.

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The time history of the normalized signals: vibration and emissivity is shown in Figure 4. The normalization of the emissivity signal and vibration acceleration signal was performed with respect to the maximum value of each of these values.

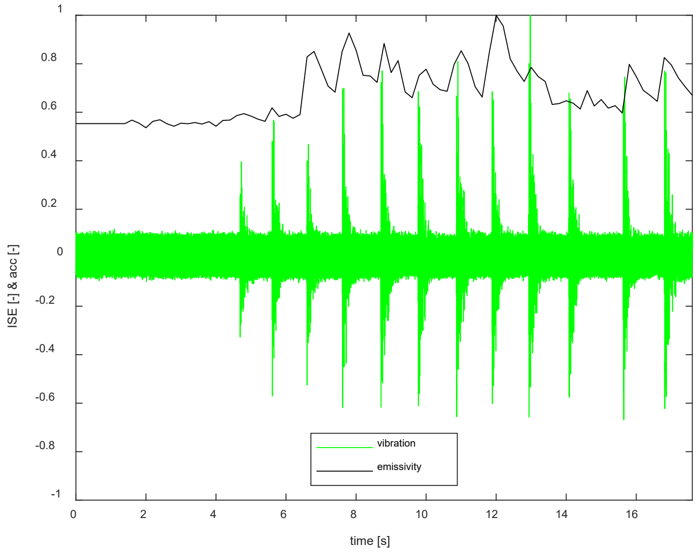

Figure 4. The time history of the normalized signals: vibration and emissivity calcium (Ca 393.366 (II)).

Based on the analysis of Figure 4, it was found that there is a temporal coincidence between the vibration and emissivity signals. Locally, the maximum values of the signals studied occur at the same time, but globally, there are differences, i.e., the maximum acceleration value does not correspond to the maximum emissivity value. This is related to the high inertia (mass) of the analytical equipment.

3.2. Damping of paraseismic vibrations by spectroscopic elements

Vibrations transmitted through the plasma torch mounting system in the spectroscope should be damped to minimize their impact on the accuracy of analytical tests. The vibration damping condition can be written as:

$$amlp\big(z(t)\big) \gg ampl\big(x(t)\big) \tag{1}$$

where $z(t)$ is the vibration of the ground, $x(t)$ is the vibrations of the burner mounting support.

The damping effectiveness of kinematically forced vibrations can be described by the damping coefficient described by the equation:

$$E = \frac{\max\big(z(t)\big)}{\max\big(x(t)\big)} \gg 1 \tag{2}$$

Figure 5 presents the measurement results of the maximum broadband vibration acceleration amplitudes measured on the floor and the support mounting the spectrometer's plasma torch, for various driving forces.

The determined vibration damping coefficients, depending on the exciting force, are presented in Table 2.

Table 2. Dependence of the vibration damping coefficient on the exciting force.

Force [N]	E [-]		
	X direction	Y direction	Z direction
1.8	7.15	5.75	1.97
2.7	7.73	6.24	2.41
4.3	8.03	4.89	2.43

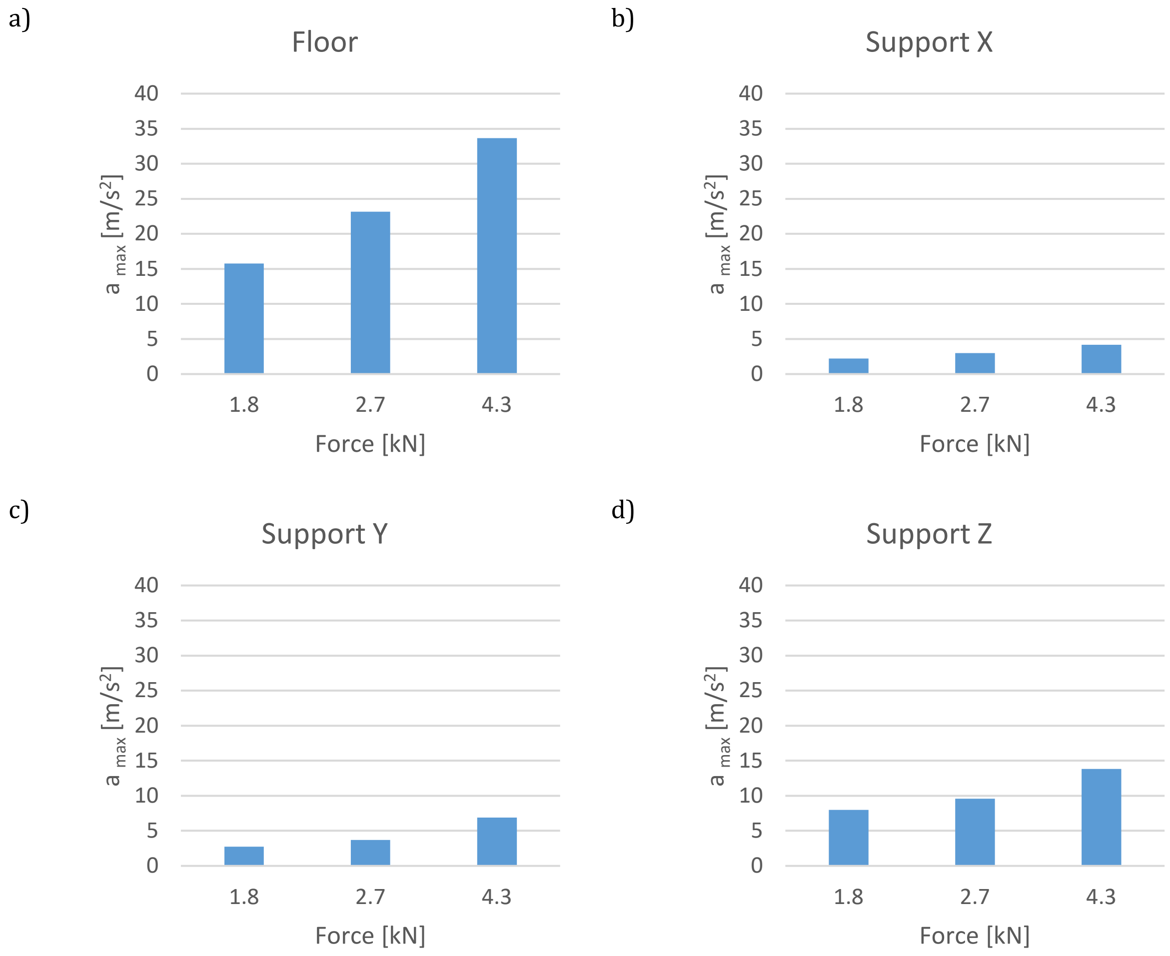

Figure 5. Peak value of vibration signals at different excitation forces for: a) floor, b) support in X direction, c) support in Y direction, d) support in Z direction.

Based on the analysis of the results presented in Fig. 5 and Table 2, it was found that the lowest vibration damping occurs in the Z direction. This is due to the fact that the exciting force was applied in the vertical direction, i.e. in line with the Z axis. The damping coefficient E in this direction is 2.0 – 2.4, which indicates low vibration damping. To more accurately describe the vibration damping of the tested system, a frequency-domain analysis was performed. The spectra were determined based on the assumptions of Fourier analysis [8,9]. The calculation results for various driving forces are presented in Figure 6.

Based on the analysis of the results presented in Figures 6, it was found that increasing the excitation force resulted in increased amplitudes in the spectrum for the entire frequency band analyzed, indicating that the system had a linear characteristic. For each vibration measurement direction, different vibration frequencies were observed on the plasma torch mounting support. The highest amplitudes were observed in the Z direction, because the direction of excitations using the modal hammer was vertical. For vibrations measured in the Z direction, the frequency ranges of 0-40 Hz and 80-120 Hz were characterized by amplified vibrations relative to the floor vibrations; in the remaining frequency range, the vibrations were damped by the system.

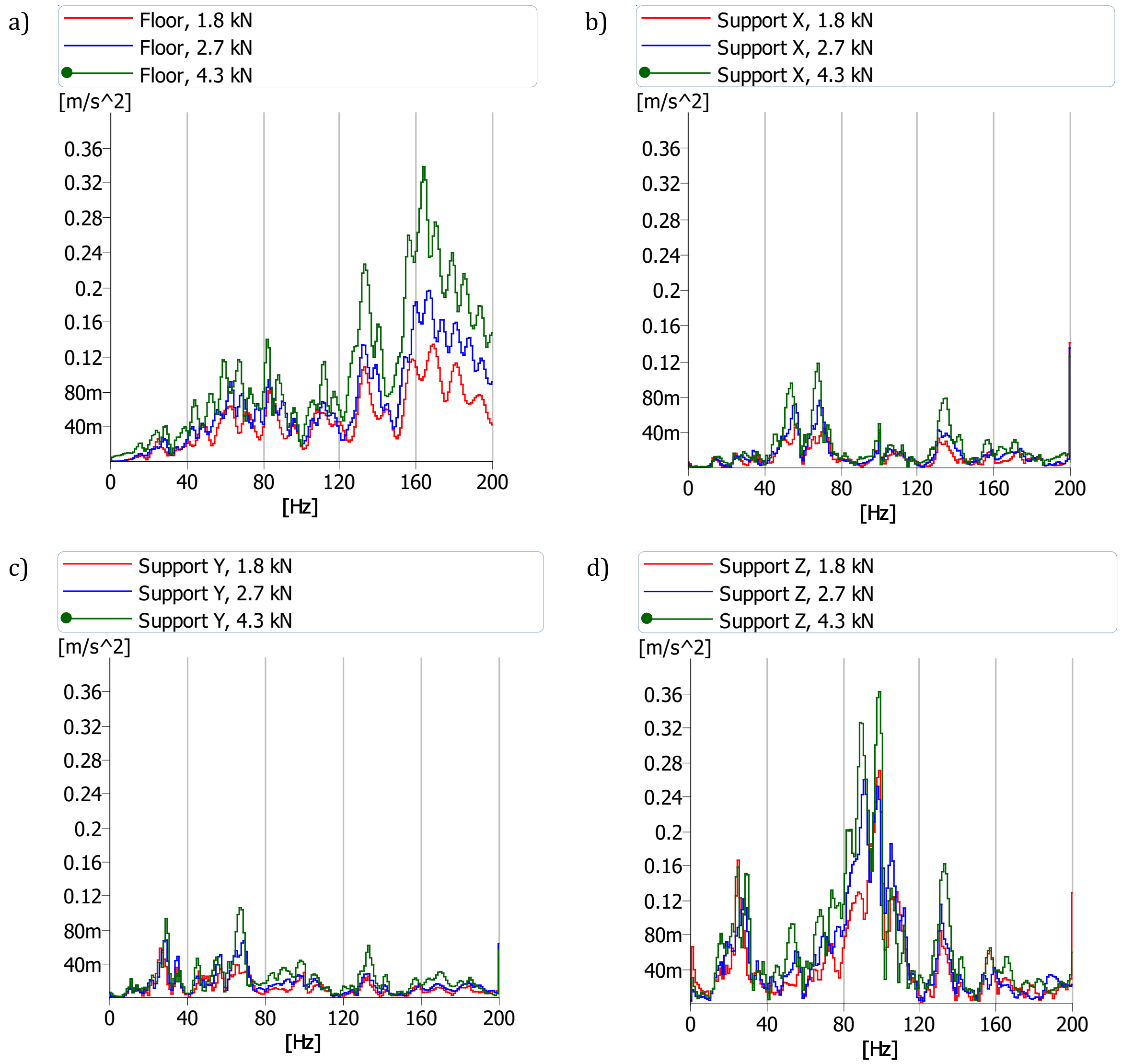

Figure 6. Spectra of vibration signals at different excitation forces for: a) floor, b) support in X direction c) support in Y direction, d) support in Z direction.

3.3. The influence of paraseismic vibrations on the results of emissivity measurements

The research on the influence of paraseismic vibrations on the results of spectroscopic chemical analyses consisted in determining the emissivity intensity of two elements: calcium (Ca 393.366 (II) and copper (Cu 324.754 (I)). The results of spectroscopic analyses are presented in Figure 8.

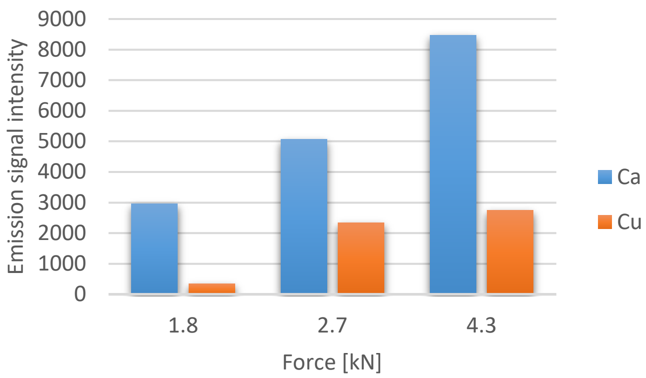

Figure 7. Dependence of the vibration damping coefficient on the exciting force.

Based on the analysis of the test results presented in Fig. 7, it can be concluded that paraseismic forcing affects the results of spectroscopic analyses. Increasing the impact force by 1.5 times resulted in a 1.7-fold increase in the emission signal intensity for calcium and a 6.8-fold increase for copper. Increasing the forcing force by 2.5 times resulted in a 3-fold increase in the emission signal intensity for calcium and an 8-fold increase for copper.

4. Conclusions

Based on the experimental results, the influence of paraseismic vibrations on the results recorded during the emission test was determined. As power increased, the values resulting from the emission for both elemental effects increased. A temporal coincidence between the emission signals and the emission test signals was demonstrated, indicating a cause-and-effect connection between the paraseismic vibrations and the frequency analysis results. It was found that the spectroscopic structure used for the tests was not used to enhance the paraseismic vibrations, and that in some frequency bands the plasma holder frequencies were amplified.

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Additional information

The authors declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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