Identification of soils, grounds and lands strata using the acoustic spectral analysis

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Abstract. One of the important tasks of computer technology for the dispersed systems' analysis of soils, grounds and lands strata is the determination of their qualitative (elemental) composition and quantitative ratio. Due to the complexity and cumbersomeness of traditional methods of chemical analysis, to solve such problems, modern technologies for the express analysis of the disperse systems under study, based on indirect measurements and computer calculation methods, are required.

The developed computer technology for determining the elemental composition of the studied disperse systems is based on the acoustic emission signal (AE) Fourier spectrum analysis emitted by these systems as a result of vibro-acoustic exposure. The (AE) signal of the studied systems is recorded in the form of phonograms, which are converted to digital form and processed using the fast Fourier transform. The result of this transformation is the total (AE) signal spectrum, which is a superposition of the spectra belonging to the elements of the studied system.

To determine the qualitative (elemental) composition of the studied system, signs are taken that uniquely identify the elements of the system. In the study of dispersed systems, the eigenfrequencies of the particle particles are taken as such signs. These frequencies make it possible to distinguish frequency sub-spectra corresponding to one or another element in the general signal spectrum (AE). Based on the sub-spectra analysis, the presence degree of these elements is considered. Thus, the task of determining the elemental composition is reduced to the selection and analysis in the (AE) total spectrum of the studied sub-spectra system corresponding to each element.

Introduction

Many tasks of environmental safety, soil condition monitoring of urban landscapes, engineering geology and construction are difficult to solve without attracting the new methods and technical means, which, along with high economic indicators, have a number of fundamental advantages. The most important of them are: 1) the ability to study soil masses remotely without disturbing their structure and the nature of the occurrence of natural processes in them; 2) the ability to study arrays with varying degrees of detail, which is necessary when studying heterogeneous media; 3) the ability to take measurements continuously in space and time [1, 2]. So, for example, the impedance method is the most sensitive, simple and convenient for operational and long-term registration of the soil state possible deviations
from the nominal values. These deviations can be caused by vibration exposure, leading to loss of soil stability and technical disasters. The disadvantage of this method is the shallow depth of the soil state control, which narrows the class of problems solved with its help [3, 4].

One of the promising methods for recognizing the dispersed objects in their natural occurrence is the timbre-acoustic method for analyzing the dispersion and concentration of constituent particles with assigning the presented object to a certain class. The essence of the method lies in the fact that the sounding acoustic signal with the help of an electromechanical transducer (vibrator) transmits mechanical sound vibrations to the analyzed sample’s characteristic structures. Part of the energy transferred to the vibrator by the structure is dissipated due to the viscous and dry friction forces in the mass, and only part of the supplied vibrational signal reaches the sensor installed on the object, which responds to the material particles’ acceleration in the diagnosed sample. From the decrease in the vibrational signal kinetic energy, with a precisely known frequency and amplitude of the impact, the average total number of structural components that are the characteristic of each “reference” samples’ class is determined.

There is a need to select the parameters of the probing signal so that the identification process is the most reliable. These parameters of the signal include: the frequencies of the probing signals, the pulse shape of the probing pulses’ amplitude, the range of the frequencies used, the exposure time of the signal, the ambient temperature and the analyzed object. A significant role is played by: a method for recording signals, responses of a dispersed object, methods for preserving the investigated reaction for further hardware and software analysis.

Materials and methods
Operational monitoring of soil conditions in urban landscapes, determination of their elemental composition and the pollution level are an important element of the environmental safety system and environmental monitoring. When organizing this control for designing devices and systems for its implementation, it is necessary to solve the following tasks: search for a set of quickly identifiable indirect features that allow to quickly evaluate the elemental composition of the soil and the percentage of impurities; development of a facility for rapid analysis of the soil component composition; development of algorithms and programs for processing measurement results [5]. To build the systems for express analysis of the soil component composition - soil mixtures, algorithms based on a statistical analysis of test results are traditionally used. In this case, the results are used to evaluate the physicochemical parameters of soils and the electrical characteristics of the signals generated by the measuring instruments. One of the promising and dynamically developing methods of soils’ physicochemical composition express analysis is considered to be a method based on the stimulated acoustic emission phenomenon [6]. In this case, acoustic emission is called the wave processes of the sound range generated by changing the mechanical, physical or chemical parameters of the soil - soil mixture. Acoustic emission is natural, arising in the process of free (due to internal properties and forces) movement of the mixture particles or forced, arising from the action of external disturbing forces on the mixture. To study the soils’ properties, the second type of acoustic emission is of most interest, for example, the development of wave processes in different soil horizons depends on their physicochemical properties [7]. The sources of acoustic emission signals in the soil-soil mixtures study - by the external disturbance are:

- shifts of the layers and particles of the mixture as a result of the actuating signals action;
- particle collisions during movement;
- the excitation of the tank walls in which the test soil is contained at the resonant frequency of the material or surface vibrations of the objects located in the soil in the area under consideration.

The response of a dispersed object to probing vibrational effects by normalized vibrations is recorded on a magnetic carrier with a frequency response sufficient for research in the field of acoustics. The probe signal supplied to the array under study uniquely provides the boundary conditions for the probe oscillations’ transmission to the sample volume under analysis. Similar requirements are imposed on the acoustic vibrations’ receiver conditionally referred to hereinafter as the microphone. The parameters
of the probing and recorded oscillations, as well as the distance between the vibrator and the microphone, should be maintained within the established optimal framework in order to obtain an unambiguous result of the structural analysis after its mathematical processing on a computer.

To ensure the highest resolution of the method, probe pulses should be recorded in those local conditions in which the layers’ reactions phonograms to be analyzed are recorded. Test recordings are carried out in order to establish the absence of acoustic noise in the selected range of sounding signals. If acoustic noise is detected, it is necessary: either to suppress it with electric filters, or switch to a different range of sounding signals.

Each experiment (recorded phonogram) should be performed at least three times, start and end strictly on the magnetic medium counter to ensure metrological reliability in the initial phase of the experiment. Repetitions of each experiment are necessary so that the segments of the reactive signal selected from the phonogram can be considered as the consistent samples from the general population, as well as to establish an estimate of the phonogram pulses’ random sequence and the normal distribution hypothesis.

It is assumed that both sounding oscillations and recorded formation reactions during the experiment were maintained at the optimal levels and frequencies.

The analyzes of magnetic recording (phonograms) were carried out according to the programs using a personal computer or an analog spectrum analyzer, which made it possible to perform the Fourier spectral transformation decomposing the analyzed signal into its elementary, physically real, components that ensure additivity by the superposition criterion, corrected for the frequency response of the signal. When processing a signal on a digital computer, the signal should be decomposed using the fast Fourier transform algorithm. Analog spectrograms are used for monitoring and give an opportunity to select all the periodic components in the form of harmonics, since they are not the distributed densities on the spectrogram, but have the form of thin columns. Analog spectrograms make it possible to establish the spectral components’ finiteness range and reasonably indicate the duration of the experiment necessary for approximating the recorded random process by the finite duration phonograms segments [8].

The proposed developed methodology includes two stages:
1. Recording phonograms, which is made in the “field” conditions;
2. Laboratory processing for digital and analog instrumentation.

Methods for the implementation of the first stage should provide for uniform distribution of the acoustic field to all morphological structures of the analyzed object. If the probing signal is transmitted using a simple stamp with sharp angles, then, as is known from the theory of elasticity, stress concentrations, and hence the acoustic field, will arise in the array along the contact profile perimeter of the stamp. Therefore, the proposed method provides the transmission of a sounding acoustic signal, for example, using a mechanical pilot, which has smooth curves along the perimeter and the contact surfaces of the pilot with an array with a roughness class not lower than 0.8. The polished pilot surface reduces friction between the pilot and the array. For even more equalization of the acoustic field, the pilot should be made, for example, of fluoroplastic, which contributes to an even more uniform distribution of the acoustic field and its resistance to chemical and temperature influences. These measures allow recording responses phonograms of the analyzed object with the greatest repeatability.

The actuating effect direction and its orientation along the installed microphones are also significant, since their non-standard location can change by 20, 30 or more% of the recorded phonogram amplitude.

**Discussions and Results**

To determine the qualitative (elemental) composition of the studied system, the signs that uniquely identify the elements of the system are taken [9]. In the dispersed systems’ study, the eigenfrequencies of the particles are taken as such signs. These frequencies make it possible to distinguish sub-spectra frequency corresponding to one or another element in the general signal spectrum (AE). Based on the sub-spectra analysis, the degree of presence of these elements is estimated. Thus, the task of determining the elemental composition is reduced to the selection and analysis in the total spectrum (AE) of the
studied sub-spectra system corresponding to each element.

To solve such problems, a database of reference features is created, which is filled as a result of the phonograms analysis (AE) of dispersed systems with a predominant presence of identifiable elements [10].

The following features are used as reference features:

- $f_{0j}$ - is the frequency of the fundamental (generatrix) sub-spectrum harmonic belonging to the $j^{th}$ element;
- $a_{0j}$ - is the fundamental amplitude of the $j^{th}$ element;
- $f_{ij}, a_{ij}, (i = 1,2,...,n)$ - are the frequencies and amplitudes of higher (timbre) sub-spectrum harmonics $j^{th}$ element, respectively; $f_{ij} = k \cdot f_{0j}$, ($k$ – is the coefficient of multiplicity).

To linearize the system, the weights are introduced into the database:

$$F_j = \frac{S_j}{\sum_{i=1}^{n} a_{ij}},$$

where $S_j$ – is the percentage of test element in the reference mixture,

- $a_{ij}$ - defines the $i^{th}$ timbral harmonics amplitude of the $j^{th}$ sub-spectrum.

Then the element identification function can be found in the form $S = \varphi(f_{0}, F, a_0)$, and the corresponding database tuples can be written as $\langle S_j, f_{0j}, a_{0j}, F_j \rangle, j = 1,...,m$, where $m$ – is the total number of reference elements making up the dispersed systems under study.

When analyzing the signal of a controlled system, the sub-spectra of known frequencies are distinguished $f_{0j}, j = 1,...,m$. Using the reference systems’ database, the quality of the controlled system can be determined by the presence of fundamental harmonics $f_{0j}$, for which $a_{0j} > a_n$ (where $a_n$ – is the noise spectrum amplitude). The quantitative composition, i.e. the $j^{th}$ percentage element is determined by the formula:

$$S_j = \frac{\sum_{i=1}^{n} a_{ij} F_j}{\sum_{j=1}^{m} \sum_{i=1}^{n} a_{ij} F_j}.$$

Figure 1 shows in digital form the Fourier spectrogram of the first sample and a sub-spectrum of significant fundamental harmonics.
If we take one of the spectrograms as the reference, and take the elemental composition according to the characteristic main five harmonics, then from the sub-spectra of the main and timbral harmonics, it is possible to determine the quantitative characteristic of each element in the system.

The results of processing phonograms by elemental composition and their percentage in the analyzed eight disperse systems are summarized in Table 1.

Figure 1. Fourier spectrogram and the sub-spectrum of significant harmonics
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### Table 1.

| Element (frequency Hz) | 1   | 2    | 3    | 4    | 5    | 6    | 7    | 8    |
|------------------------|-----|------|------|------|------|------|------|------|
| A (61)                 | 29.048 | 46.469 | 43.926 | 59.00 | 23.367 | 48.51 | 47.74 | 43.765 |
|                        | 7.88 | 8.13 | 5.73 | 7.98 | 2.15 | 7.34 | 3.05 | 3.04 |
| B (55)                 | 12.092 | 18.035 | 18.364 | 5.411 | 16.466 | 10.648 | 10.546 | 18.133 |
|                        | 4.06 | 3.16 | 2.39 | 0.73 | 1.52 | 1.61 | 0.67 | 1.26 |
| C (49)                 | 31.08 | 18.764 | 14.241 | 17.63 | 19.323 | 18.618 | 27.593 | 10.893 |
|                        | 8.44 | 3.28 | 1.86 | 2.39 | 1.78 | 2.82 | 1.76 | 0.76 |
| D (43)                 | 14.569 | 8.586 | 6.236 | 10.78 | 13.684 | 9.193 | -- | -- |
|                        | 3.39 | 1.5 | 0.81 | 1.46 | 1.39 | -- | -- | -- |
| E (37)                 | 12.815 | 8.147 | 17.232 | 7.165 | 27.159 | 13.032 | 14.116 | 27.209 |
|                        | 3.48 | 1.42 | 2.25 | 0.97 | 2.5 | 1.97 | 0.9 | 1.89 |

Note: the element percentage over the sum of five significant sub-spectra is given above the line; under the line is the element percentage in the entire noise field.

### Summary

At this stage, computer decoding of phonograms has been worked out:

1. A mechanism for converting phonograms to digital Fourier spectrum has been found;
2. The criteria for the indirect assessment of the conditional elements’ content in the disperse systems under study are determined;
3. Formation identification is more successful for the discrete distributions of statistical properties.

For the reliable phonogram analysis, the response signals recorded in the experiment should be selected in the range of no interference and the recorded on equipment with a sufficiently high amplitude-frequency response. It is recommended for audio signals to use a bandwidth of 10 Hz to 25 kHz with unevenness in a range not exceeding 3-4 dB.

4. The mechanism for determining the percentage in selected conditional elements in the whole spectrum, as well as the significant sub-spectra percentage has been adjusted.

5. For identification, taking into account the chemical properties, it is necessary to use the signals in the electromagnetic frequency range, respectively applying the electromagnetic and chemical sensors instead of acoustic ones. The refinement of this technique requires additional research.

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Table 1.

| Spectrograms |
|--------------|
| 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
| A  | 29.048 | 46.469 | 43.926 | 59.00 | 23.367 | 48.51 | 47.74 | 43.765 |
| B  | 12.092 | 18.035 | 18.364 | 5.411 | 16.466 | 10.648 | 10.546 | 18.133 |
| C  | 31.08 | 18.764 | 14.241 | 17.63 | 19.323 | 18.618 | 27.593 | 10.893 |
| D  | 14.569 | 8.586 | 6.236 | 10.78 | 13.684 | 9.193 | -- | -- |
| E  | 12.815 | 8.147 | 17.232 | 7.165 | 27.159 | 13.032 | 14.116 | 27.209 |
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