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GEOLOGICAL ACOUSTICS

Seismoacoustic Emission of an Oil-Producing Bed

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Abstract—Results are presented from a study of seismoacoustic emission appearing in an oil-saturated porous geological medium under the acoustic force action in a borehole. It is shown that dynamic nonlinear processes in the producing bed are activated under the internal elastic action on the stratum, changing the energy state of the medium, and this change can be seen as a change in the acoustic emission pattern. The correlation between the high-frequency part of the acoustic emission spectrum and the low-frequency one is found, indicating the development of this process in space at different scale levels.

Keywords: seismoacoustic emission, acoustic action, oil-saturated porous medium, energy flux density, empirical modes, reservoir permeability

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The new and convincing data has recently been gained in developing methods to search for and refine the detection of hydrocarbons when developing oil and gas fields using nonlinear geophysical methods based on a change in the properties of a saturated porous medium under the action of physical fields,. These data were obtained as a result of industrial geophysical surveys by studying the induced energy activity of reservoir beds.

Elastic energy emission in a layer is caused by natural processes and different artificial action on it. Studying the properties of this energy under different geological conditions has made it possible to reveal the emission parameters unambiguously related to the presence of hydrocarbons and their recoverability.

In this case, the source of acoustic emission is the area of the producing layer subjected to irradiation by such an acoustic force field; the parameters of this acoustic field effectively influence the change in the filtering capacity properties. As the results of independent hydrodynamic tests have shown, these changes took place both in the near and far zones of the layer [1]. It follows that the acoustic emission source can be located in these zones, and this point is essential for estimating the true saturation of the producing bed.

Seismoacoustic emission (SAE) is the process of elastic wave radiation resulting from reversible or partially reversible changes in the structure of a solid body under the action of external and internal factors of different physical nature, such as local redistribution of stresses, fissuring, degassing, phase change, and a change in the chemical composition of rocks. The presence of SAE in crystalline massifs is related to new crack formation . In fluid-saturated media, hydrodynamic causes can take place in addition to elastic processes [2–10].

Much earlier, SAE was defined as a fundamental property of time-varying emission for rocks in situ [11, 12]. Some of the main distinctive features of emission are reflection of stress relaxation, high sensitivity to external actions, its common character, and broadband radiation. In particular, the cited works note the high sensitivity of seismic emission to a change in geostatic pressure during vibroseismic action on a deposit. Data has also been reported on SAE as a diagnostic feature of increased recovery of a layer when it is artificially acted upon, and an example presented on the different layer emission response of reservoirs and nonreservoirs, both in the background recording mode and after vibration action. The authors of the cited works also noted the heterogeneity of the SAE noise process in the form of pulses with a strong change in their parameters (flux density and amplitude), which take place against a background of a significant change in the mean noise level. Note that significant changes in these parameters were detected in the oil layer under triggering action of a ground-based vibrator.

The authors proposed the use of such "vibrosensitivity of a medium" as a parameter for calculating the intensity of artificial action performed in order to increase oil recovery by triggering SAE.

Thus, this is likely one of the first works to propose the method of analyzing the SAE dynamics to estimate the oil saturation and control the oil recovery of a deposit.

What is the basis for the concept of determining these important oil layer characteristics from SAE analysis?

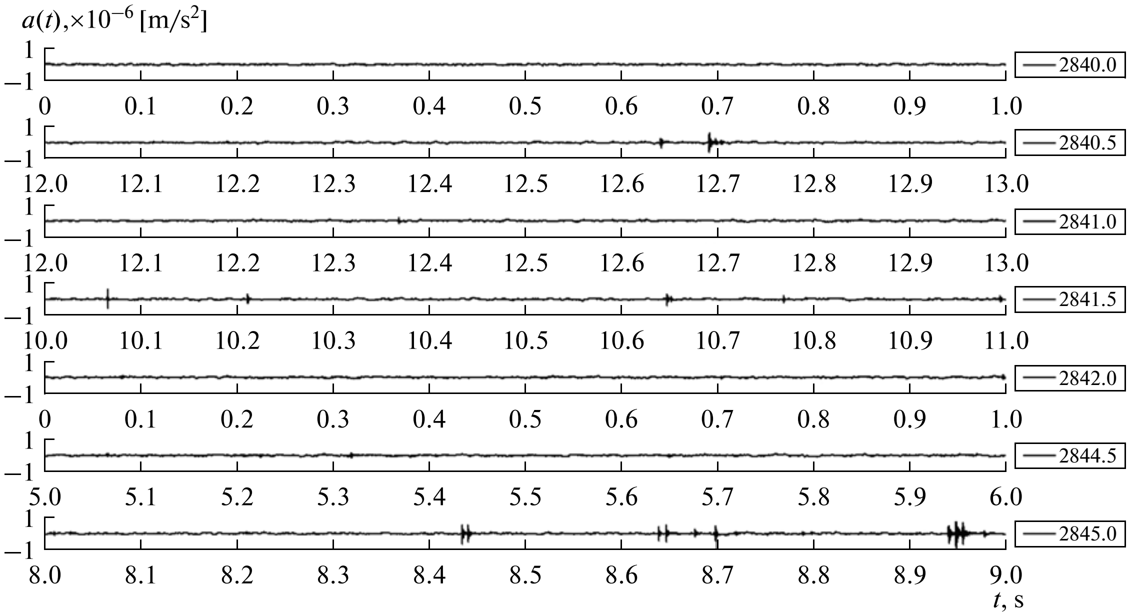

Fig. 1. Tevlinsko-Russkinskoye oil field, layer BS10(2–3), oil-saturated layer; fragments of background SAE record.

The conclusions in [11] indicate the complex character of the relationship between SAE spatial variations, on the one hand, and structural features of rocks, their rheological properties, and stressed state, on the other. It also indicates that oil reservoirs possessing a high seismic emission potential and temporal stability of the process create "the outlook on the development of oil exploration methods based on natural and induced SAE," which falls under the general heading of emission tomography.

Another feature of SAE mentioned in this work and verified in our works on the technology of studying SAE in wells, is related to the change in porosity and permeability properties of a saturated porous medium influenced by acoustic action in a well.

Here, two models of vibration action on the medium are suggested for the first time. The first is direct vibration action from a special source (the ways of this action is described in the literature), and the second one is the model of indirect action on medium. The latter implies that artificial vibrations induce SAE in the medium and SAE has a local action on the effective permeability and viscosity of oil in a small area of the medium via acoustic force field. Thus, the second mechanism explains a commonly observed technological effect of the action with time and in the layer space.

The results of field tests of acoustic action using an AAV-400 instrument at oil fields in Perm oblast showed an increase in the permeability coefficient PC (by 80–130% in the near region and by 4–145% in the far region of the layer) [1], with a corresponding increase in the debit of wells and a duration of the effect of six months on average. In these works, the emission was not studied, but in subsequent SAE studies, the acoustic sources were of the same type and with an analogous specific emission power.

Combination of two functions—powerful acoustic field emission and reception of weak emission signals—in a well within one technological cycle has allowed new qualitative information to be obtained on the energy processes in reservoirs and their relationships to the presence and extraction of oil [13, 14].

We obtained analogous results when studying induced acoustic emission at a number of oil fields in Russia to solve problems on determining the saturation of producing reservoirs. Figures 1 and 2 show fragments of SAE signals in several intervals of producing beds in a well at the Tevlinsko-Russkinskoye oil field, Western Siberia.

SAE signals were recorded over the entire interval of layer BS10(2–3). This interval includes seven isolated reservoirs (layers) of different saturation, which had be evaluated through a blank casing. The geological objective was to choose the perforation interval. Figure 1 presents an SAE recording in the background mode after which the near-borehole space was irradiated with a borehole acoustic emitter with an intensity of at least 8 W/cm^2. Immediately after this action, SAE was recorded again (Fig. 2).

Dynamic processes caused by acoustic action in the fluid-saturated rock medium reflect on the how SAE parameters change during action from the acoustic force field. Acoustic field emission and SAE reception were performed by the devices installed within one borehole-based geophysical instrument that could

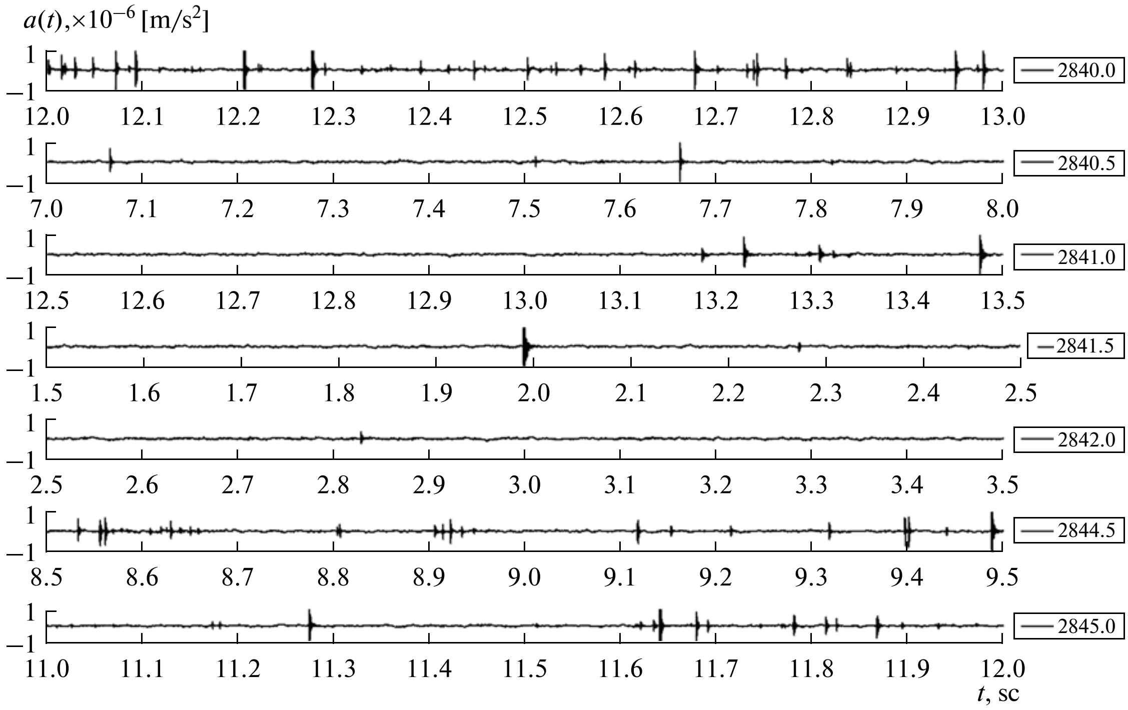

Fig. 2. Tevlinsko-Russkinskoye oil field, layer BS10(2–3), oil-saturated layer; fragments of SAE record after the acoustic action.

move along the borehole during the study. Emission and recording are spaced in time as repeated cycles with respect to the set operational algorithm.

For comparison, plots of signals are presented for the same depths, at the same time and amplitude scales. Visual examination of SAE signals suggests that the emission intensity and energy increased after the action: they are manifested as repeating pulses but differently at different depths. These fragments of signal records are extracted from the initial signal recording 15–60 s in length. The main signal parameters were analyzed in accordance with the GOST 27655-88 technique [15], as well as by Hilbert–Huang method.

Acoustic emission energy released in the studied recording interval was defined by the express method of calculating the energy spectral density in the entire recorded frequency band; it was recorded by a special geophysical station. The mean increase in the SAE signal was 12–42% of the background value. The SAE events in the form of singular actions from emission sources were random, but they possessed characteristic parameters of acoustic emission signal pulses with a finite duration of a certain shape with a certain peak energy value and carrier frequency. The presence of dominant frequencies in the acoustic emission was noted.

Comparison of the emission signal parameters with the geological features of oil fields has made it possible to determine the dependence of their spectral energy characteristics and dominant frequencies with a porous or cracked type of filtering properties of a reservoir. Thus, in a section of the Tevlinsko-Russkinskoye oil field, several producing beds were revealed—BS10(2+3) and BS11(1+2), occurring at depths of 2500–2900 m. The layers are composed by fine-grained sandstone with siltstone and argillite interbeds. Reservoirs are sandstones and siltstones, and nonreservoirs are argillites and clays. The porosity and permeability properties of reservoirs change in wide limits: porosity from 21.2 to 26.9%, and permeability is from 2 to 444 mD.

Based on the results of geological-geophysical information of field tests of oil flow from these layers and comparison with SAE logging data, it has been established that their recoverability is determined by porous and cracked reservoir types, which are detected by different dominant frequencies and energy dynamics after acoustic action. Reservoirs of 2–12 mD in permeability possess dominant frequencies of 6–9 kHz and their SAE energy increment is 30–40% with respect to the background; for tests at two boreholes, their debit was 34–40 t of oil per day (the water content of oil is no more than 2%).

Similar tests of a reservoir having a permeability of 221–444 mD showed a debit of 40 t per day; the SAE parameters were 10–12 kHz for the dominant frequency and 90–180% for an energy increment with respect to the background. The appearance of a second band of dominant frequencies (2–4 kHz) is typi-

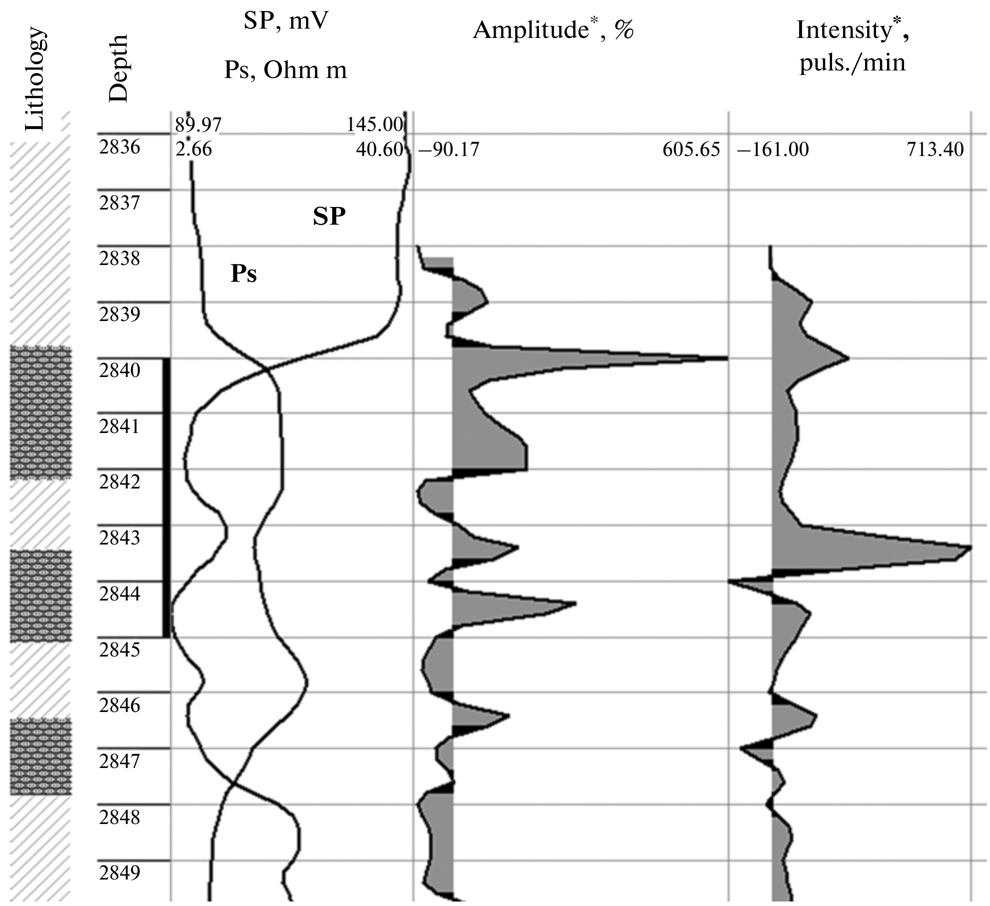

Fig. 3. Diagrams showing results of standard geophysical well logging and seismoacoustic emission measurements.

cal of these reservoirs, but with an increase of two to three times less than for the first frequency band.

The change in emission activity along the layer section is highly heterogeneous, indicating the corresponding heterogeneity of the reservoir in terms of porosity and permeability properties (Fig. 3). The "Lithology" column shows producing beds promising for oil based on geophysical studies in an uncased borehole. The "Depth" column shows the perforation zone made on the basis of data from SAE studies. The plots of spontaneous polarization and lateral logging (SP and Ps, respectively) illustrate the presence of a reservoir in the depth interval of 2840–2848 m with subdivision into three subintervals. The "Amplitude*" plot shows the change in relative amplitude of the SAE signal (relative to the background amplitude) after the acoustic action. The "Intensity*" plot shows the change in pulsed emission signals relative to the background after the acoustic action.

A high heterogeneity of the layer can be seen in these plots, as well as the tendency of emission activity growth in the upper two intervals, which produced oil after perforation. However, the lower interval demonstrated a weak (down to a negative) dynamics of emission, indicating the absence of oil. This interval was not included in the perforated part of the layer.

The most clearly seen relationship is the one between the SAE energy and the calculated permeability coefficient PC (Fig. 4), which was obtained in noncased borehole studies.

The SAE energy was determined, just like in the previous case, as the ratio between the energies before and after the acoustic action. The energy after the acoustic action was determined as the total energy of the high-frequency component of the SAE signal measured at a step of 0.5 m along the borehole depth.

The relative energy of the high-frequency part of the SAE is

$$E^* = 20\lg\left(\sum Eat(i)/E(fon)\right) \qquad (\text{дБ})$$

where $\sum Eat(i)$ is the total energy of the SAE signal, determined by the energy spectral density of the high-frequency spectral part, obtained after several ($i = 2$–4) instances of acoustic action;

$\sum E(fon)$ is the signal background energy in the same part of spectrum.

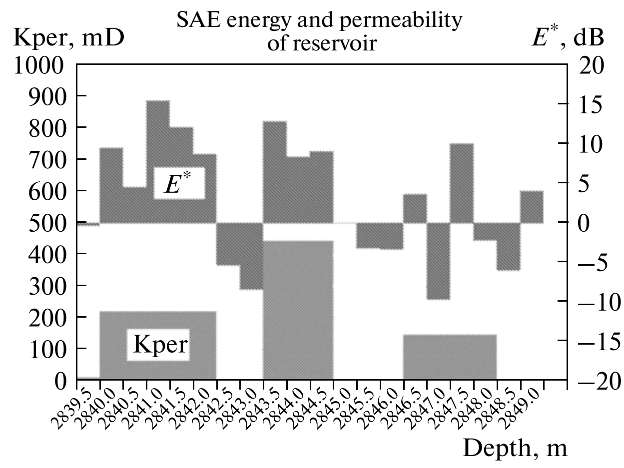

Fig. 4. Comparison of SAE-induced energy and reservoir permeability.

In the upper intervals of the layer (the permeability values are 220 and 444 mD), the SAE energy significantly increases after the acoustic action, and this is consistent with the plots shown in Fig. 4. In the lower interval of the layer, the energy changes in more complex way: it includes both an increase and decrease in energy after the acoustic action. In the impermeable intervals between the reservoirs, the energy changes in negative manner; this is likely related to development of mechanical stresses in the impermeable and unsaturated rock under acoustic action.

Thus, the conclusions made in [11] on the promising character of the development of oil exploration methods based on natural and induced SAE have been convincingly verified. The influence of wave or acoustic action on the layer described in this and many other works is attributed to an increase in oil extraction due to growth of the phase permeability of a reservoir. However, at this point, we should refer to [16] and emphasize two factors affecting the oil layer; these are the direct action of artificial vibrations on the medium and the indirect action of SAE itself, caused by these vibrations. As well, it has been noted that on the background of uniform vibration action, a second process occurs where a small volume of the medium is locally irradiated for a short time by the acoustic force field. This field is a more effective factor that affects the permeability of the oil-saturated medium than a periodic vibration field with the same power generated by an artificial source.

As to the parameters of SAE signals in the broader frequency band and their dynamics, the studies have shown a good coincidence with the results of borehole studies under the vibration action from a 50-t vibrator. Thus, according to estimates by Academician A.S. Alexeev, the power of a wave field in a producing bed at a depth of 2–3 km and a vibration source operating on the surface at a frequency of 7–11 Hz is about 10^{-7}–10^{-6} W/m^2 [17]. This author's works give the results of spectral density measurements of SAE in a borehole for the cases before and after the vibration action from the surface. Measurement points were located at depths of 1531 and 1000 m in porous sandstone of the P layer at the Mortymya-Teterevskoye oil field. The vibration frequency was 7.3 Hz, vibration amplitude of oil producing bed was estimated at about 3.8×10^{-9} m in a frequency band of 2–26 Hz. The energy flux of a monochromatic seismic wave traveling through the unit area had the above-mentioned value; the occurrence of autovibration processes in the oil-producing bed at frequencies differing from that of monochromatic action, the long-term character of layer sounding, and the occurrence of resonances in the sedimentary rock stratum homogeneous in terms of acoustic rigidity have also been noted. In addition, it was noted that the natural resonance frequencies of the layer were quantized and were at peak values in the mentioned frequency band, which was attributed by the authors to the concept of a partitioned blocked medium and the dominant frequencies of peak SAE intensification in rocks [18, 19, 20].

The results of studies on the "seismic luminescence" of the oil-producing layer given here have shown presence of two components in elastic energy emission by the producing layer: formation and relaxation. The parameters of this processes imply strengthening of emission at low dominant frequencies: up to 20 dB relative to the background level, and it takes from tens of minutes to two days for this process to develop. Special emphasis is placed on the influence of low intensity vibroseismic action on high-frequency SAE in the frequency band of 10.5–14.5 kHz; this SAE was observed for two days after the vibration action and it exceeded the background value twofold. A smaller peak was also observed at a frequency of 2.5 kHz.

As a result of our studies, the following SAE parameters were obtained within the technological cycle (recording–action–recording): the measured amplitude of acceleration in the borehole at depths of 2500–2900 m was $Am = (3.3–3.59) \times 10^{-3}$ m/s^2; the amplitude of the velocity, calculated at the peak acceleration frequency in the band of 8.52–11.2 kHz, was $Vm = 5.06 \times 10^{-9}–5.48 \times 10^{-8}$ m/s^2 . At an average rock density of 2200 kg/m^3 and sound velocity of 3000 m/s, we also able to estimate the specific SAE energy density ($W = 2.8 \times 10^{-14}–3.3 \times 10^{-12}$ J/m^3) and energy flux density ($I = 7.9 \times 10^{-11}–5.4 \times 10^{-8}$ W/m^2).

The peak acceleration frequency given in these calculations was determined based on spectral analysis of SAE signals, which have the character of high-frequency attenuating pulses (Figs. 1 and 2); these pulses can exist in an oil-saturated layer like in a background SAE measurement and appear or intensify after the acoustic action. An SAE usually manifests itself as pulses packet several seconds long.

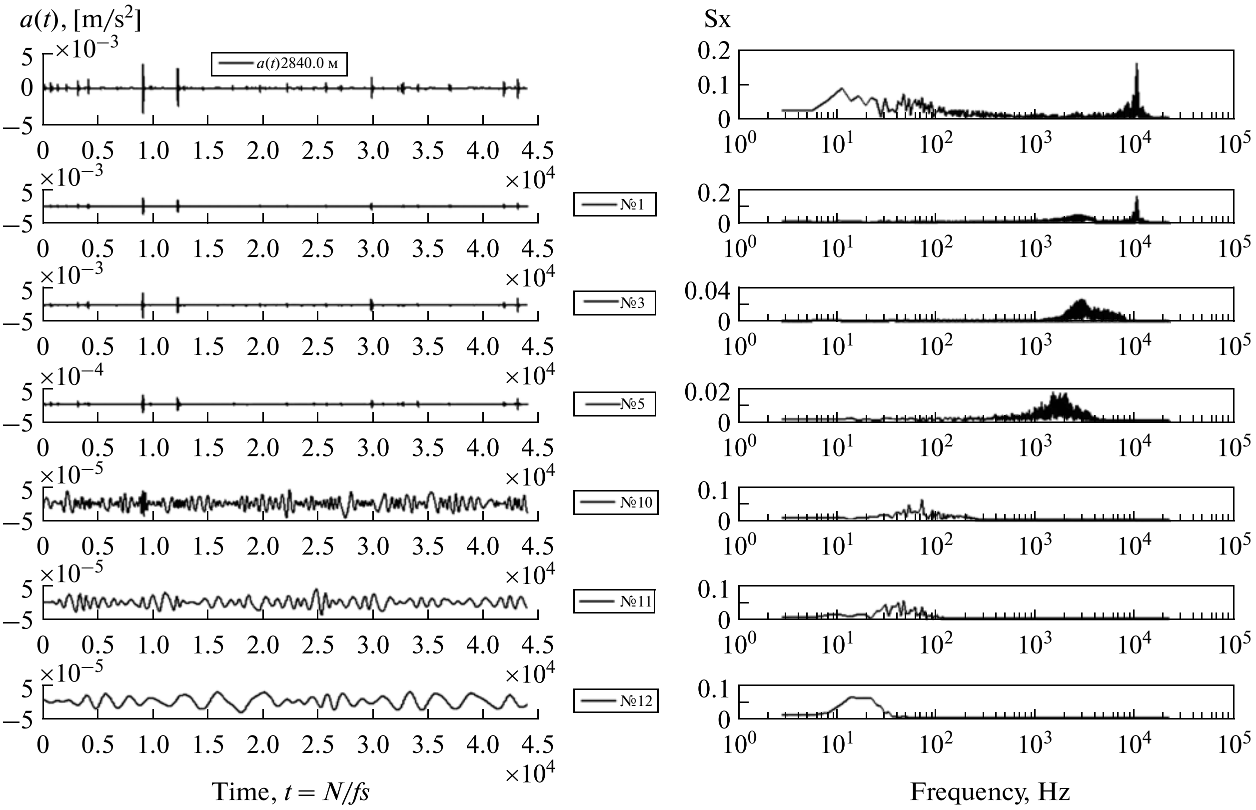

Fig. 5. Example of SAE signal (2-s fragment) decomposition into empirical modes and determination of dominant frequencies.

Further analysis of processes in the layer was carried out using decomposition of an SAE signal into empirical modes by the Hilbert–Huang method, with the subsequent application to the obtained components of the Hilbert transform. This method makes it possible to implement adaptive analysis of nonlinear and nonstationary signals and to obtain the set of empirical modes directly from time implementation of signal, making it possible to take all local peculiarities into account in real time [21].

Figure 5 shows an example of decomposition for an SAE signal 2 s long into empirical modes and determination of the dominant frequencies. This figure shows only the six main modes that made the largest contribution to the initial signal; a total of 16 modes were obtained in this decomposition. The upper plots show the initial signal (left) and its Fourier spectrum (right); the lower plots show the first mode and its Fourier spectrum, etc. The main harmonic frequency in the first two plots is 10.4 kHz and means that the largest contribution to the spectral density of SAE energy was made by the high-frequency component. However, the following decomposition modes demonstrate the presence of explicit components with main frequencies of 2793, 1477, 72, 48, and 16 Hz, which coincide with the dominant frequencies described in [17].

Figures 6 and 7 present plots of the dependence of the calculated amplitude and SAE energy flux density on frequency for the initial signal and its empirical components obtained in the decomposition of a 2-s signal from the mentioned time interval and recording point in the borehole.

The energy flux density for the empirical mode is defined as follows, based on the measured value of the SAE signal and calculated values of its empirical modes:

$I(N) = \frac{1}{2}\rho c \frac{A^2 m(N)}{\omega^2(N)}$, where c is the acoustic impedance of rock; $Am(N)$ is the acceleration amplitude of the N mode of the empirical decomposition of SAE; $\omega(N)$ is the average frequency of the N mode.

Despite the decrease in energy and amplitude in the low-frequency modes, their specific energy increases (Fig. 6) and coincides with the value obtained in [17] (i.e., it falls within the range $I(N) = (10^{-7}–10^{-6})$.

Successful application of techniques implying cyclical action on an oil layer by an elastic wave field was reported earlier [22, 23]. In these studies, primarily borehole sources of elastic energy were used and the study method was logging–action–logging. The

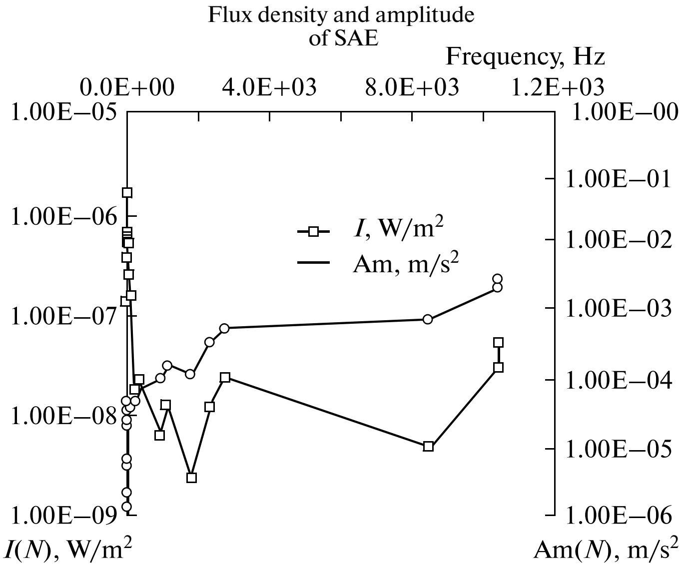

Fig. 6. Frequency dependence for energy flux density and amplitude of SAE field.

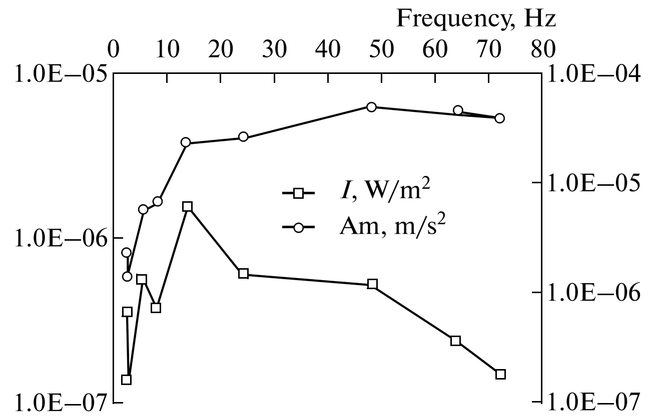

Fig. 7. Fragment of frequency dependence for energy flux density and amplitude of SAE field in the low-frequency part of spectrum.

task of obtaining data on the properties of a geological medium by nonlinear geophysical methods based on active elastic wave action on the geological medium has been posed for the first time, as well as studying how these properties change in real time.

CONCLUSIONS

Thus, SAE caused by acoustic force action in a borehole significantly exceeds the background emission of an oil-saturated layer and hence can be an informative factor of recoverability. This is primarily related to the high-frequency component of SAE.

Dynamic nonlinear processes in the producing bed are reflected in the constantly acting emission of elastic energy in the seismic and acoustic frequency bands, as indicated by analysis of background SAE recordings. Any external elastic action on a layer causes activation of the foundation and relaxation for states of a saturated porous medium. These states are, for example, filtering, degassing, phase permeability, etc., in the case of the presence of complex hydrocarbons and water. These processes inevitably change the energy state of the medium, and it can be seen in the change in acoustic emission. Correlation of the high-frequency part of SAE with the low-frequency one indicates that SAE develops in space at different scale levels. Such a combination of SAE frequency bands probably reflects the ability to involve the entire hydrocarbon reservoir in the case of a singular or periodically repeating trigger mechanism (vibration action).

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SPELL: 1. nonpenetration