SOME ASPECTS OF SEISMO–ACOUSTIC PROCESSES AT THE INTERFACES OF MEDIA

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Some results of investigations of the behavior of seismo–acoustic resonators under the action of different processes occurring at the interface of the ocean, atmosphere, and land are given. Certain stable groups of frequencies are revealed in the oscillation spectra of envelopes of the signals received from these resonators. Possible relation between the behavior of these envelopes and the dynamics of recorded shearing strains is discussed. Some other results of signal recording in the neighboring media are also presented in this paper.

INTRODUCTION

Geophysical and seismo–acoustic processes of the coastal zone of the Japan Sea exhibit a number of peculiarities . Here there is an interface of three natural media: the ocean, atmosphere, and land. In addition, the earth crust in the ocean–land transient zone has irregular layered block structure.[1] The data presented in this paper were obtained by means of a laser strain gauge (LSG), or deformograph. It is characterized by high sensitivity and broad–band performance.[2]

These peculiarities of the device as well as the above–mentioned properties of the medium under investigation provided unique opportunity for studying various seismo–acoustic and geophysical processes. Nearby the LSG there were several concrete bunkers and apparently, small geoblocks, which served as the resonators. These resonators were excited by the arrival of seismo–acoustic waves including ones transformed under the action of the processes occurring in the boundary media. They reradiated the energy at natural frequencies. All the above–enumerated factors have special effect on the observed phenomena. A wide variety of signals recorded with the LSG were compiled in the almanac (see Ref. 3). But not all of them have been adequately explained yet. The present paper is devoted to the development of this subject. The emphasis is centred on the analysis of the dynamics of seismo–acoustic oscillators. Their investigation can shed light on some global and regional processes occurring in neighboring media. We have also touched the other questions arising in the course of discussion of these problems.

ON THE DYNAMICS OF THE SEISMO–ACOUSTIC RESONATORS

Over a period of years during operation with the deformograph it was noted that quite stable frequency components are present in the high–frequency region of the broad spectrum of seismo–acoustic oscillations (conditionally higher than 1 Hz). They were selected by means of an SK4–72 spectrum analyzer connected directly to the recording unit (RU) of the LSG. Their frequencies slightly varied during season and from measurement to measurement. Nevetherless, they were concentrated in a reasonably narrow interval. In particular, they belonged to the following frequency ranges: 7.1–7.3, 8.0–8.3, 13.8–14.0, 21.5, and 43.5 Hz. The amplitude of these components varied continuously, as was distinctly seen on the spectrum analyzer screen in the regime of following the current spectra.

In this connection the idea appeared to follow the dynamics of the amplitude envelopes in order to elucidate whether their behavior has any connection with ambient seismo–acoustic background and other trends. By tuning the analyzer to the given frequency and connecting the recording device to the corresponding output, one can record the variation in the amplitude envelope of this frequency component. Unfortunately, one can follow only one frequency at a time. The output signal from the RU was recorded simultaneously with its envelope and total meteorological background, i.e., wind, sea waves, precipitation, etc. The recorded signals were digitized with the step $\Delta t = 1$ s and processed on a computer. The number of readings in different realizations varied from 700 to 1000, i.e., the records were not long. The seismo–acoustic background could not essentially change for this short period of time, so we considered these processes to be more or less stationary. Time series were processed with the use of the Fast Fourier transform (FFT).

To increase the degree of certainty, Bartlett's spectral estimate was used. It is also called an averaging over the fragments of realization.[4] We used 6–8 averagings over partially overlapping periods. The data were first weighted with the bell–shaped cosine function thereby resulting in suppression of side lobes of the maxima by 30 dB, and then time series were padded with zeros to $N = 1024$. Of course, there are more powerful windows, for example, Keizer–Bessel or Blackman–Harris windows with the level of side lobe suppression varying from 70 to 90 dB, but with loss in 30–40% of readings in the time interval being processed and significant broadening of the principal lobe resulting in spreading of the spectral power density in the maximum and distortion of its amplitude.

During long–term observations we have succeeded in establishing the following. The resonators with frequencies lying in the ranges 8.0–8.3 and 13.8–14.0 Hz are most effectively excited by the local noise and pulsed sources. These sources can be easily identified. For example, the flight and landing of a helicopter in the region of location of the deformograph, the artillery fire during naval exercise in the neighboring water area (at a distance of about 50 km), and the special explosions at distances from 100 to 1000 m. In addition, these resonators–oscillators easily respond to excitation by the

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blows on supports of concrete structures, etc. Figures 1–3 show individual examples of such excitations. Data were recorded with an H–338 X–recorder directly from the RU of the LSG. The horizontal scale corresponds to the paper speed V, which is equal to 1 mm/s for these figures. Two large squares along the vertical correspond to half the wavelength λ of a He–Ne laser (λ = 0.63 μm) employed in the interferometer of the LSG.

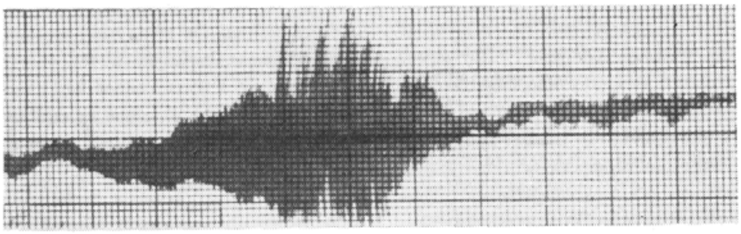

FIG. 1. Noise excitation of the resonators by a flying helicopter.

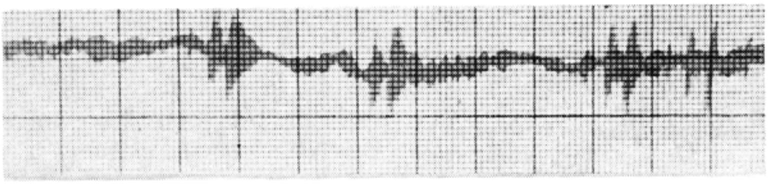

FIG. 2. Two–pulse excitation of the resonators by a remote source.

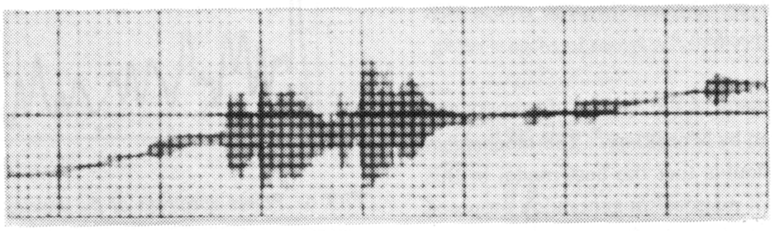

FIG. 3. Excitation of the resonators by blows on supports of concrete structures.

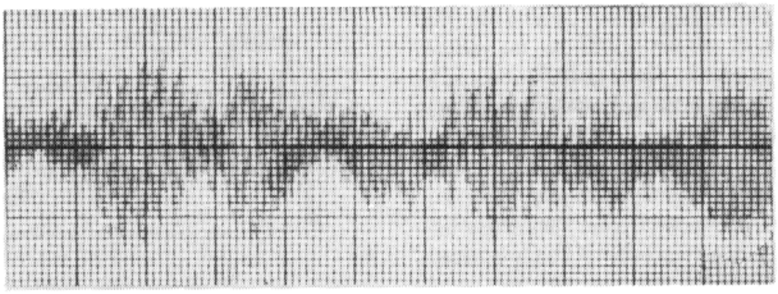

FIG. 4. Modulation of the high–frequency oscillations by the sea roughness after typhoon.

Figure 2 showing some pairs of pulsed excitations is especially characteristic. These excitations were recorded during the artillery fire from onboard the ships. The first overshoot in a pair is a shot, the second one is an explosion. The interesting example of the excitation of the above–mentioned oscillators is shown in Fig. 4. It was recorded at night on August 22, 1988 after the termination of typhoon when the wind practically died down, but the see roughness near the steep rocky seashore from the side of the open sea was still very large. Here the horizontal scale corresponds to V = 2.5 mm/s. The modulation by high–frequency oscillations of radiation of resonators with natural frequencies of 8.0 and 13.8 Hz is distinctly seen. It was revealed during recording with the spectrum analyzer. The signal envelope at a frequency of 13.8 Hz was simultaneously recorded and then its spectral analysis was made.

Figure 5 illustrates the power spectrum of oscillations of the signal envelope. Several discrete maxima are identified in two groups with periods 19–23 and 6.5–8.5 s, respectively. The principal peak from the second group is more powerful than that from the first one.

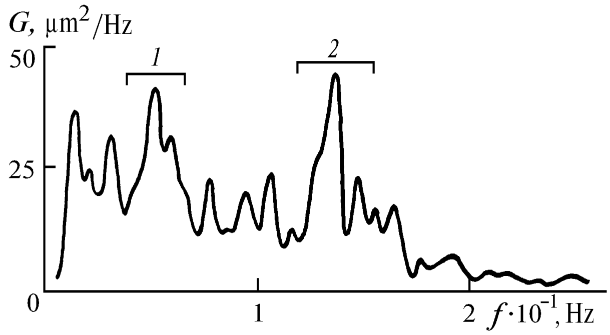

FIG. 5. Power spectrum of the envelope of 13.8–Hz *oscillations after typhoon. Horizontal brackets 1 and 2 mark the peak groups with periods* 19–23 *and* 6.5–8.5 s*, respectively.*

Such a shape is characteristic of the spectra of primary and secondary microseisms reported by Monakhov.[5] The mechanism of their formation leaves no doubts that the best model in this case is one of the first models of microseism generation proposed by Wichert (1903). The spectra of the 14–Hz signal envelope of the same oscillator are shown in Figs. 6 *a* and *b* for comparison. They were obtained from the records made 36 hours before and 2 hours apart, when the weather was quite calm. Two moments have engaged our attention. First, significant decrease of oscillation amplitude in the high–frequency region of the spectrum at $T < 30$ s is seen on two last spectra (see the vertical scale change) with sharp decrease of power in the second peak group. Second, the redistribution of the spectral energy over the larger number of maxima is observed as well as the appearance of the intermediate group of peaks with periods 9.5–13.5 s (it is veiled by more powerful neighboring groups in Fig. 5). The given spectra, as a whole, has similar shape. Figure 7 illustrates the spectrum of the resonator with a frequency of 8.0 Hz obtained from the record made on August 20, 1988 one and a half hours after recording of the signal envelope at a frequency of 14 Hz, whose spectrum is shown in Fig. 6. The meteorological and seismo–acoustic situation remained practically unchanged during this time. The shape of this spectrum is similar to the above–mentioned ones, testifying the similar mechanism of excitation of these resonators. Three groups of periods can be identified: 26–35, 11–15, and 7–9 s. Figures 8 *a* and *b* show the spectra of the amplitude envelopes of the resonators with frequencies of 21.5 and 43.5 Hz, respectively. These oscillations were recorded much later, on September 22 and 23, 1988, respectively. Nevertheless, the shape of these spectra is similar to the above–mentioned ones. Of course, not all the maxima in these spectra may be associated with the excitation of the oscillators under the action of the surf on the steep seashore in the region of the LSG. Several peaks, especially in the low–frequency region of the spectrum ($T > 30$ s) cannot be interpreted so simply. A comparison of the envelope spectra with the spectra obtained from the records made directly by the RU of the LSG does not indicate their direct connection. It may be supposed that the resonators are very sensitive to the noise produced in the upper part of the earth crust and are not intimately related with the shearing strain recorded by the deformograph.

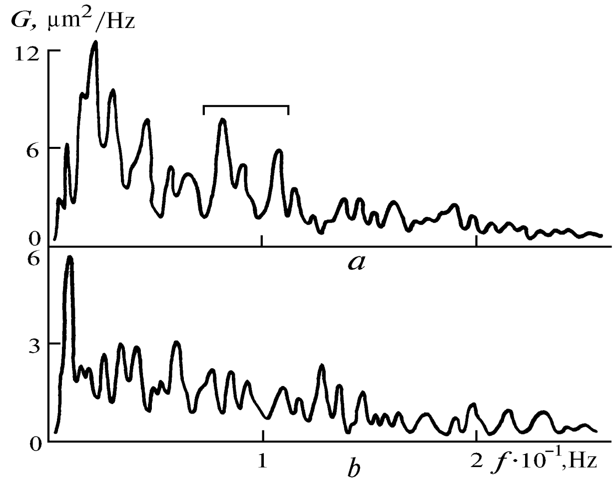

FIG. 6. Power spectrum of the envelope of the 13.8–Hz *oscillations under calm weather conditions. The bracket marks the peak group with periods* 19.5–13.5 s.

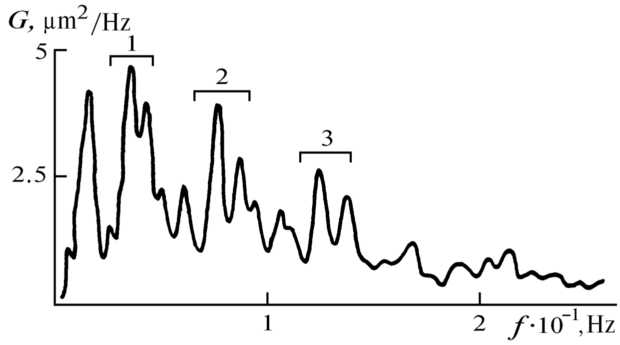

FIG. 7. Spectrum of the signal envelope at a frequency of 8.0 Hz. *Brackets 1, 2, and 3 mark the peak groups with periods* 26–35, 11–15, *and* 7–9 s.

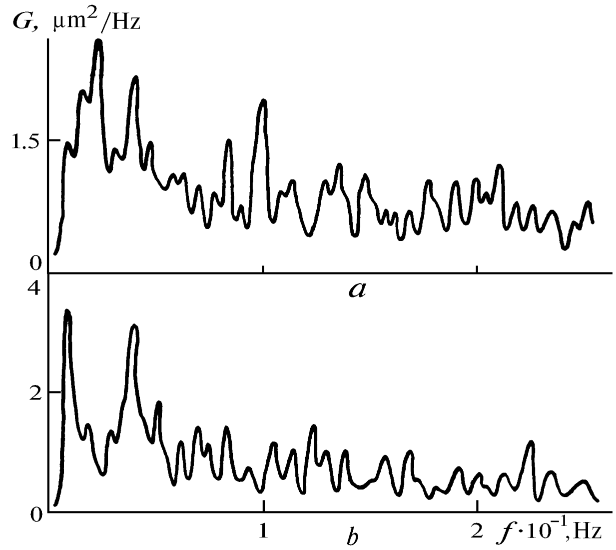

FIG. 8. Spectra of the signal envelopes at frequencies of 21.5 (*a*) *and* 43.5 Hz (*b*).

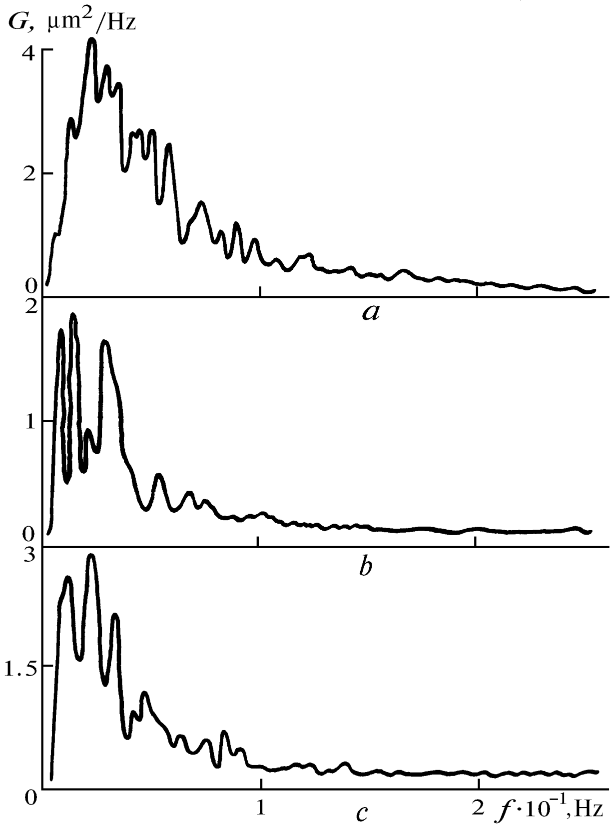

FIG. 9. Spectra of three consecutive records of the signal envelope of the resonator with the frequency 7.1–7.3 Hz.

Let us consider now the behavior of the resonator with natural frequency 7.1–7.3 Hz. Figure 9 shows the spectra obtained from three records of oscillations of the signal envelope. The shape of these spectra is essentially different from the above–mentioned ones. They decrease with increase of frequency without sharp overshoots in their middle parts. In such a form they more closely resemble the spectrum of the shearing strain, which is shown in Fig. 10. This spectrum was obtained directly from the record with the RU of the LSG and simultaneously with the record of the envelope of the signal at a frequency of 7.3 Hz made on September 21, 1988. These spectra are more similar in shape than that in the case of oscillators with frequencies 8.0–8.3, 13.8–14.0, and 21.5 Hz. This is apparently connected with the fact that the resonator with natural frequency 7.1–7.3 Hz is located not in the neighborhood of the deformograph and, probably, is divorced from the underground concrete bunkers. Most probably, this is a minigeoblock situated at a large distance from the LSG. This conclusion follows from the fact that this resonator practically does not respond to the local excitations of various character, the examples of which are shown in Figs. 1–3. Its excitation is apparently connected with internal processes proceeding in the earth crust. It characterizes the total seismo–acoustic background. In order to elucidate this possible relation, we calculated the coefficients of correlation between records of the shearing strain and envelope of the signal at a frequency of 7.1 Hz measured on October 13, 1988. It was made as follows. The samples containing 300 readings were taken from both realizations. They were delayed with a step of 20 s. The correlation coefficients were calculated for all possible combinations of these samples. One of such coefficients for zeroth time delay from the start of the shearing strain measurement is shown in Fig. 11. The time delay from the start of the frequency envelope measurement is plotted on the x axis. Quite unusual behavior of this function has engaged our attention. Its maxima occur at quite large time delays $\tau = 220$ and 440 s. It is difficult to consider that the interaction occurs with such a delay. The peak values of these maxima ($0.4 < r < 0.5$) are not large but statistically significant for the given lengths of samples.[6]

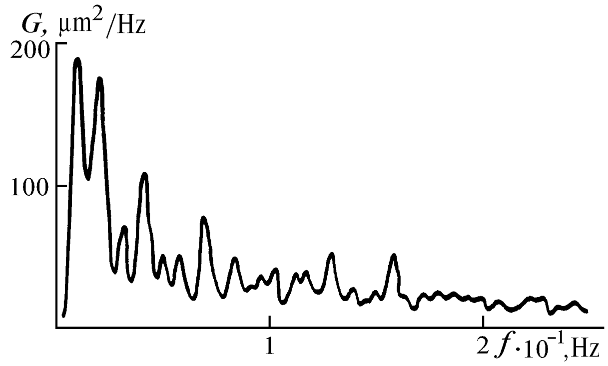

FIG. 10. Shearing strain spectrum obtained from the record performed simultaneously with the record of the signal envelope shown in Fig. 9a.

The behavior of r may be explained in the following way. Judging from the spectra, the powerful low–frequency components ($T > 100$ s) are present in both realizations. They cause the "macrobehavior" of both shearing strain and envelope. On the one hand, the function $r(\tau)$ describes the phase interrelations between them, on the other hand – the difference between these frequencies. The beats which can be seen in the function $r(\tau)$ confirm that. The small–scale oscillations are indicative of less powerful high–frequency harmonics in the examined time series. Thus, when analyzing the cross–correlation function of two processes, some preliminary conclusions about the spectral composition of the examined time series can be drawn.

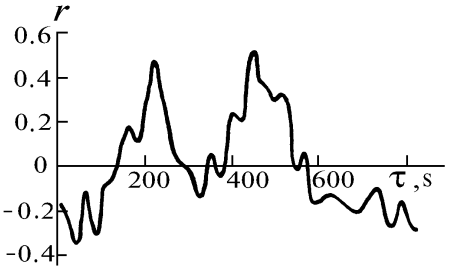

FIG. 11. The coefficients of correlation between the recorded shearing strain and the signal envelope of the resonator at a frequency of 7.1 Hz *with the zeroth time delay from the start of the shearing strain measurement. Here* τ *is the time delay counted off from the start of the signal envelope recording.*

SEVERAL COMMENTS ON RECORDING OF OTHER SIGNALS

In addition to the study of the behavior of the oscillators located in the region of the LSG, the experiments on the study of the interaction of the internal sea waves (ISW) with the deformations of the upper layer of the earth

crust were carried out in fall of 1988. The study of the dynamics of spectral components of pairwise realizations of thermocline oscillations and soil shearing strains suggests that there are definite frequencies as well as the spatial areas of the shelf in which the correlation between the above–indicated processes is most essential.[7] One more circumstance should be pointed out. The average spectra calculated for the entire length of realization in the examined pairs have the peaks, some of which can be identified with the Earth's free oscillations (EFO).[8] They may be related to the following spheroidal and torsion tones and overtones:
${}_0S_2(T = 53.2\text{ min})$, ${}_0T_2(T = 44.5\text{ min})$, ${}_0T_3(T = 28.8\text{ min})$, ${}_0S_4(T = 25.8\text{ min})$, ${}_2S_2(T = 15.3\text{ min})$, and some others. The presence of such harmonics in the thermocline oscillations is unexpected. It testifies that the above–indicated processes are interrelated. Although generally speaking, the theoretical consideration of the EFO took into account mainly the Earth's solid structure. Taking into account that 2/3 of its surface is covered with water, the Earth's oscillations certainly influence the water layer oscillations.

And finally, a few words about one more signal. On October 18, 1988 at 1:43 p.m., LT the signal from the underground nuclear explosion was recorded with the deformograph. As was reported in the TV program *Vremya*, this explosion was set off at 6:20 a.m., Moscow time in Semipalatinsk region. Taking into account the difference in seven time zones, it can be easily calculated that the signal has passed a distance of 4025 km in 23 min. Thus, judging from a speed of ~ 2.9 km/s, it may be assumed that mainly the Rayleigh surface wave reached the LSG. Although, taking into account the duration of the recorded signal (~1 min), the shock wave suffered from dispersion. Unfortunately, the author has lost the record of this signal. It was similar to the noise signal shown in Fig. 12.

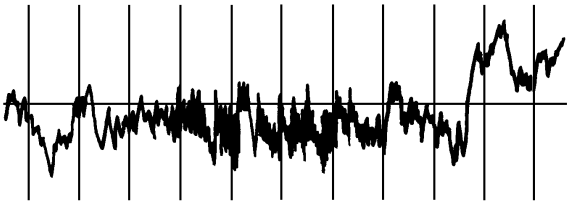

FIG. 12.

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