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Experimental investigations of nonlinear seismic effects

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Special experimental investigation using seismic vibrators allowed the propagation of periodic seismic signals accompanied by strong nonlinear effects to be demonstrated. These effects are caused by the physical nonlinearity of a real geological medium. The effects of higher harmonic generation and self-demodulation of signals are studied over a large range of distances from a source. A conclusion is that nonlinear properties of the medium should be taken into account in corresponding physical models used in seismology and seismic prospecting.

1. Introduction

The problem of nonlinear effects accompanying seismic wave propagation was considered to be completely hypothetical until recent years. Even though nonlinear effects had been analysed theoretically they were ignored in practical seismics.

Nevertheless, a direct check of the hypothesis of linear propagation of seismic waves was apparently never carried out. This became possible only recently after the appearance of seismic vibrators able to emit quasimonochromatic waves.

According to the principles of nonlinear acoustics, the propagation of a harmonic signal in a nonlinear medium is accompanied by several characteristic effects, e.g. the generation of higher harmonics and wave interaction (Rudenko and Soluyan, 1975). The propagation of modulated signals is accompanied by self-demodulation effects. All these phenomena have been studied in detail in the acoustics of strong sound.

Our idea is to use seismic vibrators to observe analogous phenomena in seismics.

2. Methods, techniques and area description

We have used 10- and 50-t surface seismic earth vibrators (1 t = $9.80665 \cdot 10^3$ N). Our experiments have been carried out in a region geologically characterized by a thick sediment cover with total thickness of ~ 3–4 km. We shall describe the phenomena observed when the vibrators emit monochromatic and modulated signals and the source power is varied.

3. Results

In the first series of experiments we used vibrators with a total force of 10 t emitting long monochromatic signals at frequencies of 19 and 20 Hz. The idea of these experiments is to study the spatial alteration of the spectra of these signals which may result from a gradual accumulation of nonlinear distortion.

The measurement of the signals was carried out on the surface of the medium by a series of seismographs placed at distances in the range 0–5 km from the vibrator. The surface wave velocity at the experimental site was ~ 200 m s^{-1}; the velocity of strong P-waves propagating in the upper layer of the medium was 1500–2000 m s^{-1}.

We established that the propagation of monochromatic seismic signals is accompanied by their substantial nonlinear distortion caused by the high physical nonlinearity of the medium in its upper layer of 1 km thickness.

Figure 1 features the evolution of a monochromatic signal with frequency of 20 Hz. Figures 1a, 1b, 1c correspond to the spectra of this signal recorded at distances of 120, 500 and 1700 m from the source. The signal shape at each recording point is shown in the top right-hand corner of each figure. The scale of the spectra is logarithmic. Here and henceforth, the spectral amplitude A is given in arbitrary units.

The level of the harmonics of the signal recorded near the source does not exceed a few percent (see Fig. 1a). During the propagation of the signal through the medium one can observe the gradual enrichment of its spectrum by higher

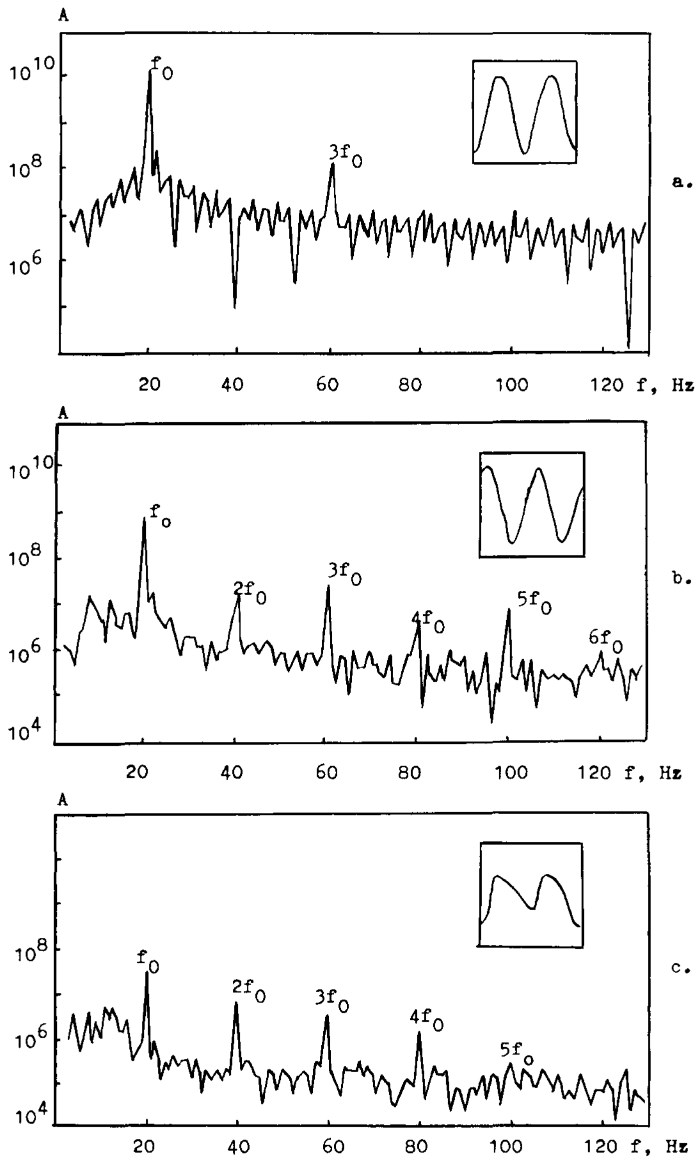

Fig. 1. Amplitude Fourier spectra of a monochromatic seismic signal with frequency of 20 Hz at different distances from the source: a–120 m, b–500 m, c–1700 m.

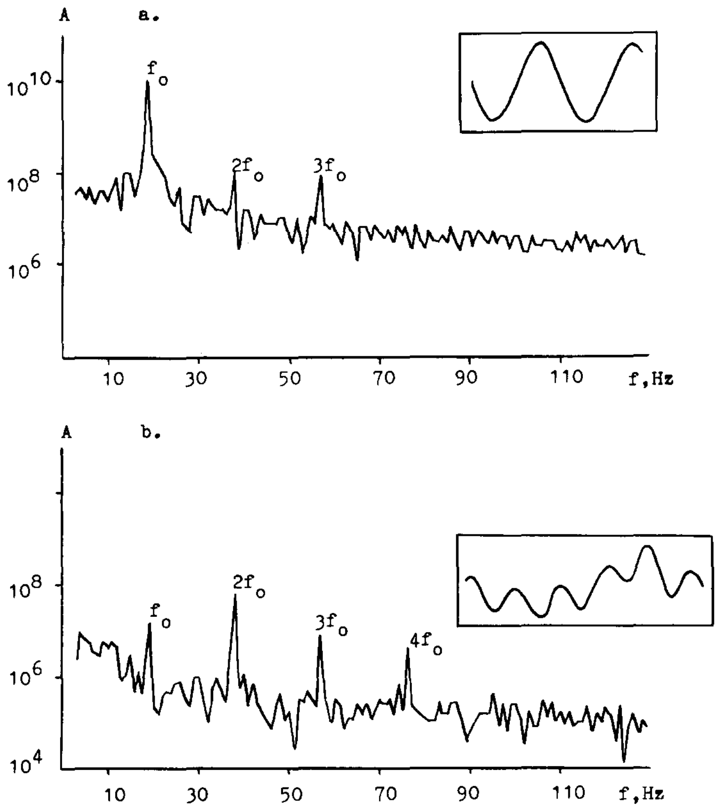

Fig. 2. Amplitude spectra showing the nonlinear doubling of the seismic field frequency at different distances from the vibrator: a–100m, b–1500 m.

harmonics the relative values of which increase up to distances of ~ 2 km from the vibrator, where the Mach number characterizing the field intensity is less than 10^{-8}–10^{-9}. The average level of harmonics at this distance from the source is evaluated as several tens of percent. The signal shape is substantially distorted and has a quasi-sawtooth form, as can be seen from Fig. 1c.

Under some conditions we observed the effect of a substantial transfer of energy from the fundamental wave to its second harmonic which then energetically exceeded the level of the fundamental. This process is illustrated in Fig. 2. The spectrum of Fig. 2a corresponds to the signal with frequency of 19 Hz recorded near the vibrator. The spectrum in Fig. 2b has been recorded at a distance of 1.5 km. The high level of the second

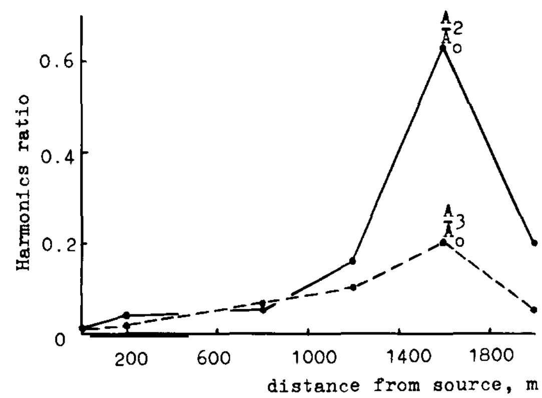

Fig. 3. Dependence of the ratios of the second and the third harmonics to the fundamental on distance from a source. $A_{0,2,3}$–the spectral amplitudes of the fundamental, second and third harmonics, respectively.

harmonic may be observed; the shape of the seismogram also shows the apparent doubling of the seismic field frequency.

The increase of the ratios of the second and the third harmonics to the fundamental one caused by nonlinearity for the signal with the frequency of 19 Hz is shown in Fig. 3. We observe that the second and the third harmonics have maximum contribution to the field at distances of 1.5–2 km.

We studied the dependence of the size of the nonlinear effects on the source power. Figure 4 features the spectra of the signal with frequency of 30 Hz recorded at a distance of 750 m from a vibrator. The spectrum in Fig. 4a corresponds to a vibrational force of 10 t and in Fig. 4b to one-tenth of this value. We see that the decrease of source power causes a decrease in the rate of generation of the higher harmonics. But even at the smallest vibrational forces used (~ 1 t) we measured the appearance of harmonics.

In the next series of experiments, we carried out the study of the evolution of amplitude-modulated signal. The signals were emitted by a vibrator with a force amplitude ~ 50 t. Observations using the same technique allow us to establish that amplitude-modulated signals with an envelope of sinusoidal form at the same characteristic distances are substantially influenced by self-demodulation processes. They lead to the detection of a strong envelope signal which does not exist in the initially emitted spectra. Figure 5 shows the alteration with distance of the spectrum of an amplitude-modulated signal with carrier frequency of 19 Hz and modulating frequency of 4 Hz. Figure 5a shows the spectrum of this signal recorded near the source. In the spectrum of Fig. 5b corresponding to a distance of 1.5 km from the vibrator the envelope signal with frequency of 4 Hz is found dominant in the field. The same result was repeated with other modulating and carrier frequencies.

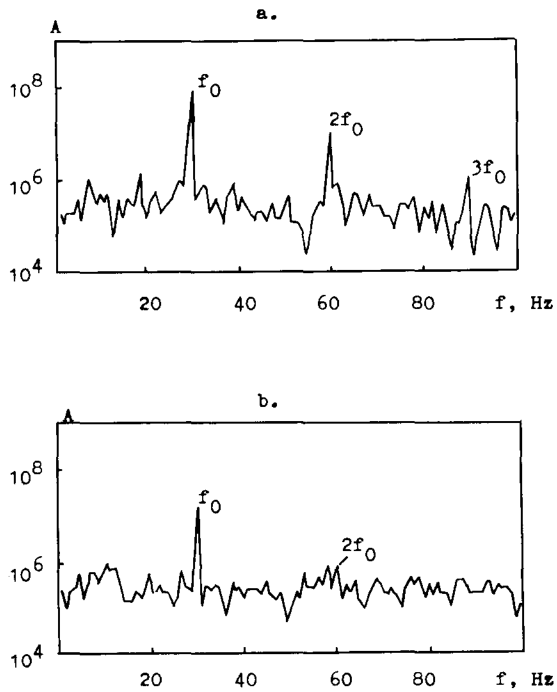

Fig. 4. Amplitude spectra of a monochromatic seismic signal with the frequency of 30 Hz at a distance of 750 m from a source corresponding to different source forces: a–maximum force level produced by a vibrator, b–minimum force level.

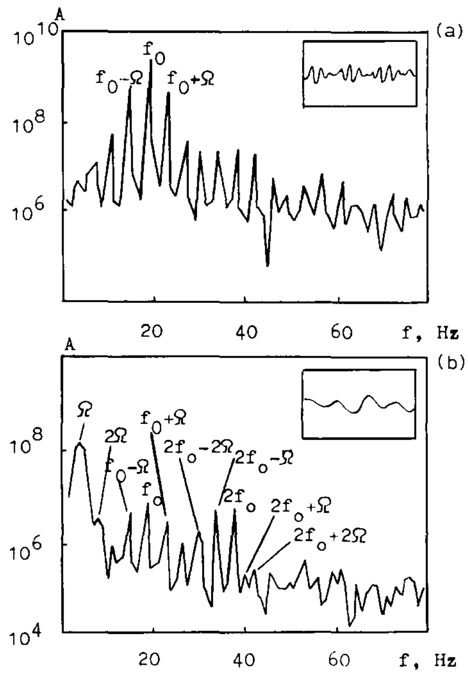

Fig. 5. Amplitude spectra of an amplitude-modulated seismic signal at different distances from a vibrator: a–70 m, b–1500 m; f_0 is the carrier frequency, Ω is the modulating frequency.

4. Conclusions

Our experimental data permit us to come to the following general conclusions.

(1) The evolution of long periodic seismic signals is accompanied by intensive nonlinear effects caused by physical nonlinearity of a medium. The nonlinearity of geological media is a major property resulting from the intricate rheological state of rocks.

(2) The effects of energy transfer of sinusoidal signals to the higher harmonics may cause substantial decay of the fundamental.

(3) The effects of transfer of seismic energy to lower frequencies (e.g. the self-demodulation of amplitude-modulated signals) may be used for creating new types of low-frequency seismic vibrators (e.g. parametric arrays known in nonlinear acoustics).

Acknowledgement

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