Luxemburg-Gorky effect in a granular medium: probing perturbations of the material state via cross-modulation of elastic waves

V. Zaitsev[1], V. Nazarov[1], V. Tournat[2], V. Gusev[2], B. Castagnede[2]
[1]*Institute of Applied Physics, R ussian Academy of Science, Russia, Email: vyuzai@hydro.appl.sci-nnov.ru*
[2]*Université du Maine, France, Email: Vitali.Goussev@univ-lemans.fr*

Introduction

The nonlinear effect of amplitude modulation of a weaker sinusoidal seismo-acoustic wave under the action of another stronger AM-modulated wave propagating in a sandy soil exhibiting dissipative nonlinearity was reported in [1]. In that experiment surface vibrators operating at 20 Hz ("pump" wave) and 44 Hz (probe wave) frequencies were used. The pump modulation had the form of bursts with duration of several seconds, which produced synchronous variation in the probe-wave amplitude of about 20%. Recently a related effect of transfer of the modulation spectrum from an intensive elastic wave to another probe one with different carrier frequency was observed in resonant-type experiments in solid samples containing cracks [2]. In the latter case the transfer of modulation manifested itself in appearance of sidelobes in the spectrum of the probe wave. This nonlinear effect is a close elastic-wave analog of the similar phenomenon known as the Luxemburg-Gorky (LG) effect for cross-modulation of radio-waves in ionosphere.

In this presentation, we report the observation of the acoustic nonlinear cross-modulation effect in significantly different conditions, in a granular medium, which demonstrates the universality of the phenomenon. The interaction of two traveling elastic waves of different frequencies (a strong amplitude-modulated and a weaker initially non-modulated) was observed. Amplitude dependencies of the induced modulation sidelobes of the probe wave have been studied. Furthermore, we observed complementary variability of the sidelobes and the probe wave amplitude at the fundamental (carrier) frequency under the action on the medium of short bursts produced by an additional shaker. This third impulsive source was buried in the media bulk and modeled "seismic events". The resultant transient variations in the amplitude of the modulation sidelobes exceeded normally by an order of magnitude the complementary variations in the signal amplitude at the fundamental frequency (the latter variations being often hardly noticeable).

Experimental setup

We observed the cross-modulation for longitudinal (L) and shear (S) elastic waves in glass beads 2 mm in diameter packed in a plastic cylindrical container, 40 cm in diameter and 50 cm in height (Figure 1). The vertical loading via a rigid plastic cover was controlled by a force cell (static stress and strain ranges were 10–50 kPa and $(1–5)\times10^{-4}$, respectively). Two of the L and S transducers (respectively, 4 and 3.5 cm in diameter) simultaneously radiated CW - waves with carrier frequency of 7 kHz ("pump") and 10 kHz (probe), the pump wave being 100% AM-modulated at frequency 30-40 Hz. An additional small electromagnetic shaker buried near the container bottom could produce "seismic events", bursts of 4-10 periods at 1 kHz frequency. Pump and probe path orientations could be either parallel or orthogonal, the resultant effect being roughly the same.

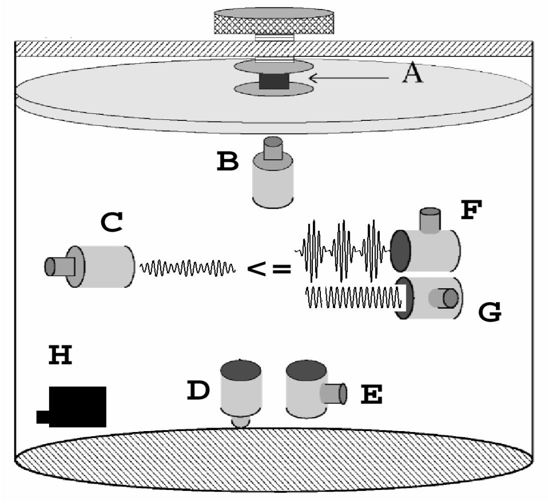

Figure 1: Sketch of the experimental setup and the cross-modulation process. A – force cell; B, C – receivers; D, E and F, G – sources of the pump and probe waves; H – shaker.

Observation results

Granular media have proven to possess strong acoustic nonlinearity [3-5], and such traditionally studied nonlinear effects as higher harmonics generation or demodulation can be very pronounced in granular materials compared to homogeneous solids. The nonlinear effects are very sensitive to presence of weakest contacts which hardly manifest themselves in the linear elasticity of the material. Consequently, the variations of the material strain and re-arrangements of the packing, which affects first of all the weakest contacts, are difficult to evaluate based on observations of the linear sound propagation. Such nonlinear effect as higher harmonics generation, in contrast, could exhibit high structure-sensitivity [3-5], but practical use of this effect for monitoring of the material state is complicated by stronger dissipation, the rather low level of the nonlinearity-induced harmonics and thus the necessity to provide highly-linear radiation of the primary elastic wave. In this aspect, the exploitations of the cross-modulation effect of the LG-type may be rather advantageous. The presence of parasite higher harmonics in the initial spectra of

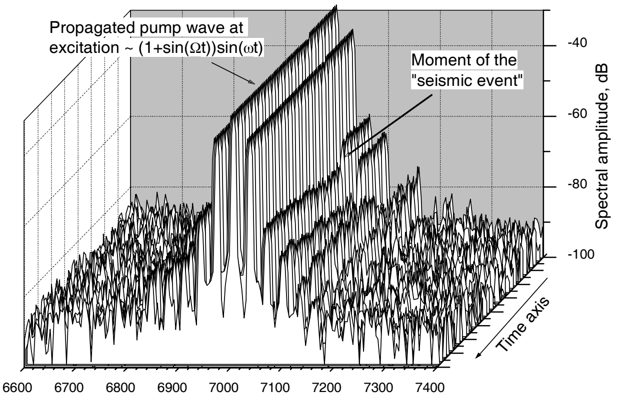

Figure 2: Spectral waterfall of the AM-modulated pump wave propagating in the material.

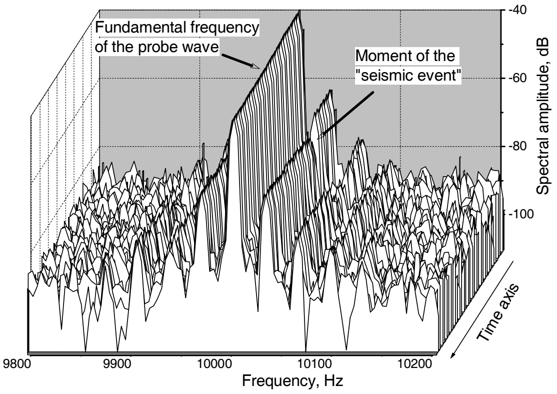

Figure 3: Spectral waterfall of the induced modulation of the probe wave.

both pump and probe waves does not prevent easy observation of the modulation transfer. The collinearity of the interacting waves is also not necessary, since the effect is related to the amplitude-dependent dissipation rather that to the amplitude-dependence of the elasticity.

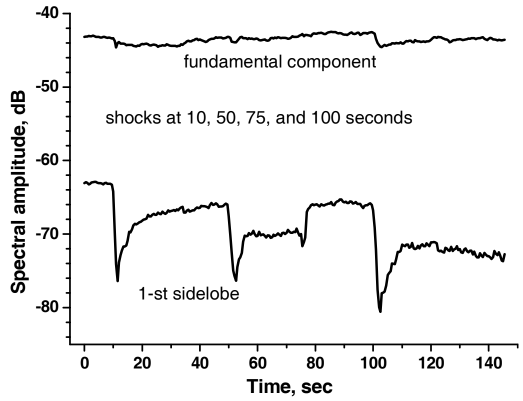

Figure 4: Temporal slice of a waterfall-record similar to Figures 2,3. The 1st sidelobe of the probe wave exhibits much higher sensitivity than the fundamental line. Slow post-shock dynamics of the sidelobe is clearly visible.

Figure 2 presents the waterfall spectrum for the pump wave with 0.5-second step between the sequential spectra. The simultaneous waterfall record for the received initially sinusoidal probe wave is shown in Figure 3, in which the cross-modulation sidelobes (up to 3-4th orders) produced by the pump wave are clearly visible. The moment of the "seismic event" produced by the additional shaker is indicated by the arrow in the figures. Figure 3 demonstrates that, under the action of the pulse, the variations in the probe wave amplitude at the fundamental frequency were hardly noticeable, whereas the modulation sidelobes exhibited 10-15 dB perturbation. The next Figure 4 presents a slice of the a similar waterfall record the amplitudes of the fundamental line and the 1st modulation sidelobe of the probe wave as function of time. In the course of the record a series of shocks was produced by the shaker (times are indicated in the figure). Figure 4 shows that the shocks hardly manifested themselves in the amplitude of the fundamental (only at 100 sec the variation of the fundamental amplitude is better distinguishable at the noise level). In contrast, the sidelobes exhibit strong 10-15 dB variations. It is interesting to note that a kind of slow dynamics with 5-10 sec characteristic scale is clearly visible in the time dependence of the post-shock behaviour of the sidelobes. Evidently this phenomenon is connected to relaxation (re-arrangement of the weakest contacts perturbed by the pulse action). Returning to Figure 2 it should be noted that the higher-order sidelobes of the pump wave are also high sensitive to the shocks, since these sidelobes arose during the pump propagation in the medium (in contrast to 1st order sidelobes of the electrical origin). In the experiment, amplitude dependencies for the sidelobes have been studied, as well as the self-action of the pump wave. The respective results will be published elsewhere.

Conclusion

The results obtained clearly demonstrate that the nonlinear cross-modulation of the LG-type for interacting elastic waves is quite pronounced in contact-containing media with grainy structure. Physically the origin of the effect is connected to the high-nonlinear fraction of the weakest contacts [2-5]. The sensitivity of the induced modulation sidelobes to perturbations of the material state has proven to be much higher than that of the linearly propagated fundamental component. The effect looks promising for diagnostic applications, for example, for monitoring is seismic engineering and non-destructive testing.

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References

[1] A.L. Bagmet, V.E. Nazarov, A.V. Nikolaev, A.M. Polikarpov, A.P. Reznichenko, Doklady: Earth Sciences, **346** (1996) 135.

[2] V. Zaitsev, V. Gusev, B.Castagnede, Phys. Rev. Lett., **89** (2002), 105502.

[3] V.Yu. Zaitsev, Acoust. Physics, **41**(3), (1995) 385-391.

[4] V.Y. Zaitsev, A. B. Kolpakov, and V. E. Nazarov, Acoust. Phys. **45**, Pt. I, 235 (1999); **45**, Pt. II, 347 (1999).

[5] V. Tournat, V. Zaitsev, V. Gusev, V. Nazarov, P. Bequin, B. Castagnede, Phys. Rev. Lett. **92**, 085502 (2004)