EUROPHYSICS
LETTERS

OFFPRINT

Vol. 70 • Number 5 • pp. 607–613

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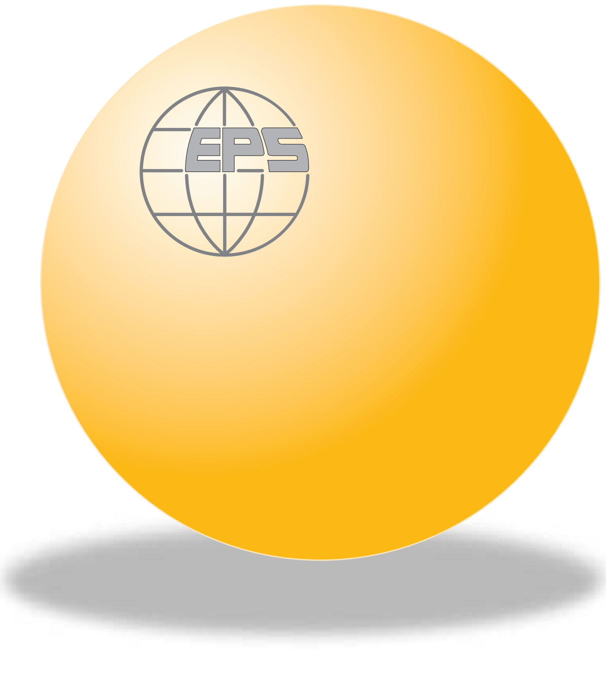

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EUROPHYSICS LETTERS

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24 issues - Vol. 69-72 (6 issues per vol.)

ISSN: 0295-5075 - ISSN electronic: 1286-4854

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EUROPHYSICS LETTERS 1 June 2005

Europhys. Lett., **70** (5), pp. 607–613 (2005)
DOI: `10.1209/epl/i2005-10023-5`

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

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received 3 January 2005; accepted in final form 31 March 2005

PACS. `43.25.+y` – Nonlinear acoustics.
PACS. `83.80.Fg` – Granular solids.
PACS. `81.05.Rm` – Porous materials; granular materials.

Abstract. – A nonlinear effect consisting of transfer of modulation from one amplitude-modulated elastic wave, the "pump" wave, to the second initially monochromatic probe wave has been recently introduced in nonlinear acoustics by analogy with radio waves. For the first time, this effect is applied to probe perturbations of the state of a granular material induced by shocks, "seismic events". The experiments indicate a much stronger variability of the nonlinearity-induced modulation sidelobes in comparison with changes in the components at the fundamental frequencies of the probe and pump waves. Another new feature revealed in the experiments is that the transitional shock-induced variations in the amplitudes of the modulation sidelobes are several times stronger than the relaxed, residual values of the changes. The effects observed suggest interesting possibilities to application in active acoustic/seismic monitoring schemes.

Studies of nonlinear acoustic (NA) effects in solids with complex structure attract ever increasing attention due to both the interesting, "non-classical", character of the observed phenomena and to promising applications of these effects as a new diagnostic tool [1]. Nonlinear acoustics, by definition, deals with deviations of the material stress-strain relationship from the linear Hooke law that nearly perfectly describes homogeneous solids up to strains 10^{-5} and even higher. In contrast, the presence of even a small amount of "weak features" (disbonds, cracks, contacts and other defects with locally strongly increased stress and strain) leads to a drastic increase of the material nonlinearity. This results in the break of the superposition principle for elastic waves, so that the increased level of nonlinearity-induced wave spectral components may serve as a sensitive indicator of the presence of such "weak features" and thus can be used for damage detection and material characterization [2–9]. In particular, NA methods have been used as a diagnostic tool for diffusion bonds [3, 4], for monitoring of metal processing and fatigue [6, 8], and detection of cracks [2, 5, 9]. In many cases, the variability of the nonlinearity-induced components of the sounding fields exhibits much higher sensitivity to

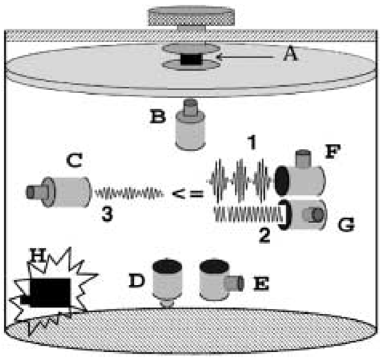

Fig. 1 – Sketch of the experimental apparatus and the cross-modulation process. 1: modulated pump wave; 2: initially monochromatic probe wave; 3: received probe wave with nonlinearity-induced modulation; A: force cell; B, C: receivers; D, E and F, G: sources of the pump and probe waves; H: shaker.

different-type imperfections of the material in comparison with the variability of linear elastic parameters. However, it is only recently that NA methods have been applied to probe *in situ* transient processes in materials, such as fatigue and crack growth during continuous cycling loading [8, 9]. These experiments have confirmed that NA effects (as compared to their linear counterparts) can be effectively used to diagnose earlier stages of fatigue damage.

In the present letter, we describe experiments demonstrating that NA methods are much more sensitive in the diagnostics of transient processes in granular packings than conventionally exploited linear acoustic effects. We utilize the nonlinear transfer of the modulation spectrum from one elastic wave, a "pump" wave, to a probe wave having a different carrier frequency. Such modulation transfer was recently observed for resonant standing waves in solid samples containing cracks [10]. The effect consists in the generation of sidelobes in the spectrum of an initially monochromatic probe wave arising from the interaction with the amplitude-modulated pump due to the material nonlinearities (see fig. 1). This phenomenon is an elastic-wave analog of the so-called Luxemburg-Gorky (LG) effect of cross-modulation of radio waves in the ionosphere. Note that a related nonlinear phenomenon has been observed in field seismic experiments [11]. Namely, a weaker sinusoidal seismo-acoustic wave at 44 Hz, propagating from a surface vibrator over a 200 m path in a sandy soil, experienced up to 20% variations in amplitude under the action of periodic (several seconds) bursts of a stronger wave at 20 Hz radiated by another source located in the middle of the path. Here we report the first observation of the acoustic nonlinear cross-modulation effect in a granular packing of glass beads, the conditions for the generation of which differ significantly from those given in refs. [10, 11], which demonstrates the ubiquity of the phenomenon in virtually any contact-containing structures and materials. Furthermore, we report the complementary variability of the nonlinearly induced modulation sidelobes and the fundamental (linear) component of the probe wave under the action on the medium of short acoustic bursts emitted by an additional shaker, which modeled "seismic events". The resultant transient variations in the amplitude of the modulation sidelobes typically exceed, by an order of magnitude, the complementary variations of the fundamental harmonics —the variations in the latter being frequently undetectable.

Granular media represent a bright example of complex materials intrinsically combining the relatively rigid component (grain bulk) with much softer inter-grain contacts, which results in their strongly increased acoustic nonlinearity compared with homogeneous solids [1].

As is elucidated in [12–14], nonlinear effects are especially sensitive to the presence of weakest contacts. Just this weakest-contact fraction, on the one hand, is primarily affected by variations of the material strain, but, on the other hand, these contacts hardly manifest themselves in the linear elasticity of the material. Consequently, such early stages of re-arrangements of granular packing as those caused by weak strain waves, which are unable to influence the average- and strongly-loaded contacts, are difficult to evaluate based on observations of linear sound propagation. In contrast, nonlinear effects such as self-demodulation of high-frequency pulses [13, 15, 16] or higher-harmonics generation [12, 14] exhibit higher structure sensitivity. However, practical application of these effects for monitoring material state is complicated by rather low generation efficiency and by increased dissipation of the nonlinearity-induced higher harmonics. Besides, the harmonic generation technique intrinsically requires highly monochromatic primary excitation. For the self-demodulation effect, similar drawbacks are typical, which is especially limiting for possible field applications of these effects in seismic monitoring. In this respect, the exploitation of the cross-modulation effect of the LG-type may be rather advantageous. The presence of parasitic higher harmonics in the initial spectra of both pump and probe waves does not prevent altogether the observation of the modulation transfer; besides, the modulation sidelobes have practically the same attenuation as the primary frequencies. The collinearity of the pump and probe waves is also not necessary, since the effect is related to the amplitude-dependent dissipation and does not require spatial synchronism.

The experiments were carried out using both longitudinal (L) and shear (S) elastic waves in glass beads of 2 mm in diameter packed in a plastic cylindrical container 40 cm in diameter and 50 cm in height (see fig. 1). The vertical loading via a rigid plastic cover was controlled by a force cell producing static stress in the range of 10–50 kPa, which corresponded to the strain in the range of $(1–5) \times 10^{-4}$. We used piezo-transducers Panametrics V3052 (L-type, 40 mm in diameter) and V1548 (S-type, 25 mm diameter) in order to generate L- and S-waves, respectively. Either of them (marked by letters D, E, F, G in fig. 1) could be utilized as the pump or probe wave source. The characteristic strain amplitude of the pump wave was roughly an order of magnitude smaller than the static strain. The same type of L-transducers were used for reception. In view of their better sensitivity to normal strain, mostly L-transducers were also chosen to excite the probe wave. We tested both orthogonal orientation of the pump and probe waves (when F, G and D, E transducers were used in different combinations) and collinear orientation, as is shown schematically in fig. 1. The observed phenomena were rather robust and the resultant cross-modulation effect was roughly the same for different polarizations and orientations of the waves. However, since the collinear variant allowed for a more simple simultaneous reception of both pump and probe waves using one receiving transducer, below we discuss the results obtained for the collinear pump and probe wave propagation. An additional small electromagnetic shaker (B&K 4810) was buried at the bottom of the container and produced short seismic events, bursts of 4–10 periods at 1 kHz. Its peak force of 3–5 N provided strain perturbations of the order of 10^{-6} at the propagation path of the probe wave, so that the most part of grains remained consolidated and only weakest inter-grain contacts were essentially perturbed by these pulses.

Figure 2 shows the “waterfall record” of spectra for the 100% amplitude-modulated pump wave. The sequential spectra were recorded in 0.5 second steps before and after the short seismic event. The simultaneous spectral waterfall record for the received probe wave, which was initially monochromatic, is shown in fig. 3. The pump-induced cross-modulation sidelobes (up to 3rd-4th orders) are clearly visible. The moment of the seismic event produced by the additional shaker is indicated by arrows in the figures.

Figure 3 shows that, after the action of the shaker pulse, the variations in the probe wave amplitude at the fundamental frequency were hardly noticeable, whereas the modulation

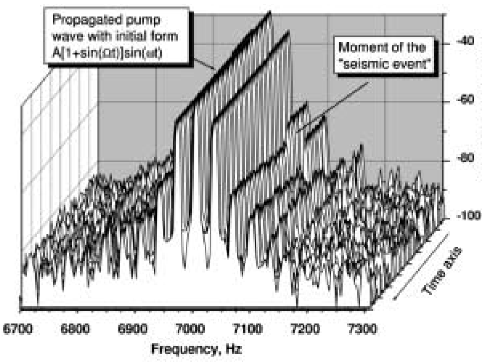

Fig. 2

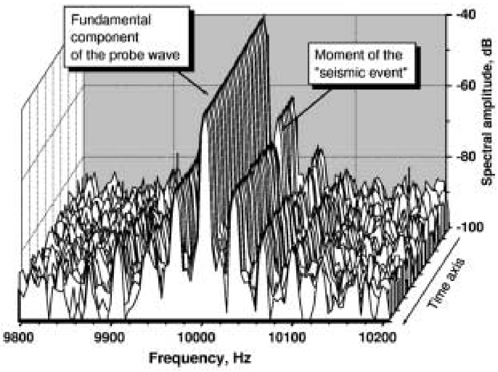

Fig. 3

Fig. 2 – Spectral waterfall record (with 0.5 s temporal step) of the initially 100% amplitude modulated pump wave received after propagation through the material.

Fig. 3 – Spectral waterfall record (synchronous with that in fig. 2) of the induced modulation of the received probe wave, which was initially monochromatic.

sidelobes exhibited 10–15 dB perturbation. Returning to fig. 2, it should be noted that the higher-order (2nd and 3rd) sidelobes of the pump wave are also sensitive to the shocks, since these sidelobes are generated during pump propagation in the medium, in contrast to the fundamental component and the 1st-order sidelobes that were initially formed by the generator and directly fed to the transducer.

Figure 4 presents temporal slices for the amplitudes of the fundamental component and the first modulation sidelobe of the probe wave using a waterfall record similar to that in fig. 3. In the course of the recording, a series of shocks was produced by the shaker as indicated in the figure. Figure 4 shows that the shocks only weakly manifest themselves in the amplitude of the fundamental: only at the 100 second point in fig. 4 is the variation of the amplitude of the fundamental distinguishable from the background. In contrast, the nonlinearity-induced sidelobes persistently exhibit strong, 10–15 dB, variations.

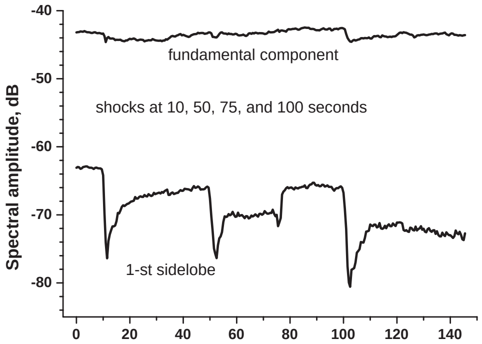

Fig. 4 – Time dependences of the amplitudes for the fundamental component (at 10 kHz) and for the modulation sidelobe at +30 Hz from the fundamental component of the probe wave (that is constant-frequency slices of a waterfall spectral record similar to that in fig. 3). The sidelobe exhibits much higher sensitivity to shocks than the fundamental component. The slow post-shock dynamics of the sidelobe is clearly visible.

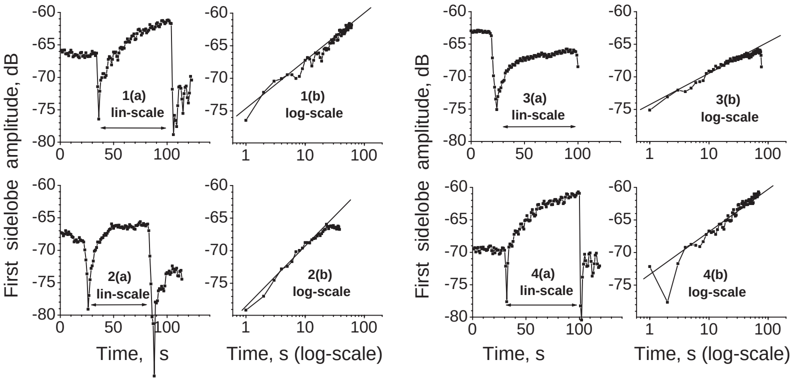

Fig. 5 – Time dependences of the 1st sidelobe of the probe wave. Parts (a): in linear scale; parts (b): post-shock fragments marked by arrows are replotted on a logarithmic scale with superimposed straight lines indicating the log-time character of the transient behavior of the nonlinearity-induced modulation.

A remarkable feature of this transitional response of the cross-modulation to the seismic shocks is a kind of nearly logarithm of time slow dynamics with a 10–100 s characteristic scale in the time dependencies of the post-shock behavior of the sidelobes (see examples in fig. 5 obtained for several records similar to that in fig. 4). Such a log-time dynamic response is remarkably common to many different systems with complex microstructures, *e.g.* rocks and granular solids [17]. In some cases such slow dynamics exhibits pronounced symmetry between the stages of the material perturbation and relaxation, the phenomenon being readily explained by the symmetry of the acoustical heating and the subsequent cooling of cracks [18]. In the present case, the dynamics of the modulation is strongly asymmetrical, with an abrupt reaction to the shock and a slow, nearly log-time relaxation after the termination of the shock. This behavior seems to have much in common with the effect recently reported in ref. [19]: when shearing of a granular material was suddenly stopped, stress relaxation occurred with a logarithmic functional form that is attributed to force network/particle rearrangements. Thus, the selective sensitivity of the nonlinear signal components to the weakest intergranular contacts is favorable for the observation of fine transitional changes in the material microstructure, which are rather indirectly related to the mean stress.

The previous plots shown in figs. 3-5 were obtained at fixed pump and probe wave amplitudes, but in the presence of the shocks perturbing the material. The next fig. 6, in contrast, is obtained for the same relaxed state of the material and for a fixed probe wave excitation, but at different levels of the pump wave. The pump amplitudes and the simultaneously recorded amplitudes of the fundamental and the first sidelobe of the probe wave are superimposed on the plot. Figure 6 indicates that the probe wave modulation sidelobe amplitude is not simply proportional to the pump wave amplitude (that varied in steps within a 45 dB range). The level of the induced modulation of the probe wave varied significantly (within a 18 dB range) exhibiting the trend to saturation at higher pump level. The fundamental component of the probe wave exhibits much smaller (~ 1 dB) complementary variation in its amplitude under the influence of the pump. This variation in the fundamental component agrees well with the depth (typically $-25\ldots-35$ dB relative to the fundamental component) of the induced modulation of the probe wave, and corroborates that this is rather an amplitude- than phase-type modulation. Physically, it may be attributed to the changes in the probe wave dissipation caused by the action of the pump on the loose contacts in the material. A detailed discussion of

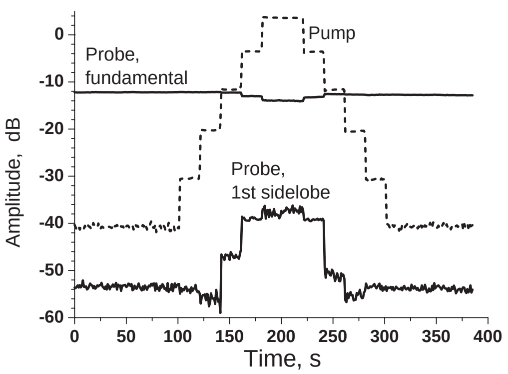

Fig. 6

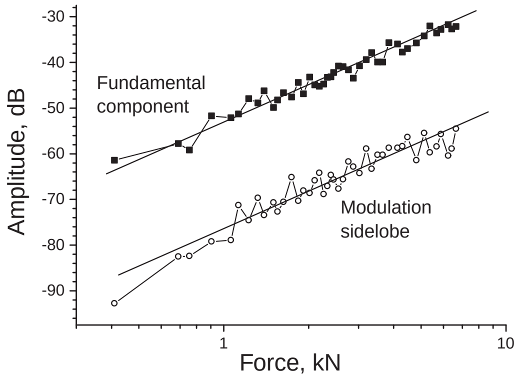

Fig. 7

Fig. 6 – Complementary records of the pump wave amplitude, fundamental component of the probe wave and its cross-modulation sidelobe obtained for a relaxed state of the material.

Fig. 7 – Dependences of the fundamental component and the 1st modulation sidelobe amplitudes of the probe wave on the mean static force applied to the material.

the possible mechanism(s) of the variation of dissipation at the contacts is beyond the scope of the present communication and will be published elsewhere. Figure 6 demonstrates in its own way the aforementioned strong difference in the complementary variability of the fundamental ($\sim 1\,\text{dB}$) and the cross-modulation sidelobe ($\sim 18\,\text{dB}$ variation) of the probe wave. The difference from figs. 3 and 4 is that here the material state is affected by the strong pump wave itself, but not via additional "seismic shocks". Generically, the observed variety of nonlinear-dissipative manifestations agrees well with our previous data on self-demodulation [13, 15, 16] and harmonic generation [12, 14] in granular media confirming the strongly dominant role of loose inter-grain contacts in the material nonlinearity. Unlike predominantly nonlinear elastic effects studied in [12–16] in the considered case the loose contacts manifest themselves in the nonlinear transfer of the modulation from the modulated pump wave to the initially monochromatic probe via the pump-induced variations in the dissipation of the probe wave.

Finally, fig. 7, for the same experimental conditions as for records shown in figs. 3, 4, shows the dependence of the first modulation sidelobe of the probe wave and its fundamental component as a function of the mean static force applied to the material, which was changed in steps every 1–2 minutes in order to let the material to relax after each change in the applied static force. The levels of the complementary fluctuations of the fundamental harmonic and the modulation sidelobe are comparable, but are much smaller than the transitional post-shock variations of the sidelobes shown in figs. 4 and 5. On average, the modulation depth remained nearly constant over the whole pressure range.

The results obtained in these experiments clearly show that the sensitivity of the cross-modulation sidelobes to perturbations of the material state is much higher than that of the linearly propagated fundamental component. Physically, the origin of the effect arises from the high nonlinearity of weak (loose) contacts [12–16]. A remarkable feature of the cross-modulation effect is the enhanced sensitivity to transitional variations in the material state, which suggests its use as a promising monitoring tool in laboratory studies, non-destructive testing in industrial conditions and for seismic engineering.

In a certain sense the cross-modulation effect (as well as other mentioned nonlinear-acoustic effects) can be considered as a complementary approach to monitoring of materials' state based on acoustic-emission technique [20], since the acoustic emission much like the microstructure-induced acoustic nonlinearity is also directly related to the weakest (loosest) regions in the material and transitional processes of rupture in these places. As is clearly shown in examples presented in figs. 4 and 5, the advantage of the cross-modulation technique is that it allows one to monitor both the transitional effects and the residual structural changes in the material. Besides, the frequency band for the acoustic-emission technique is pre-determined by the physics of the phenomenon and normally falls in the range from tens kHz to MHz frequencies. Rather high dissipation for such high-frequency signals often strongly limits the operation distances for the acoustic emission technique. In contrast, for the proposed method, the operation frequencies could be readily chosen much lower, from kHz range like in our model experiment down to hundreds and tens of Hz, so that the spatially averaged monitoring could be feasible at much larger distances (compare to [11]).

* * *

The study was supported by DGA contracts No. 00.34.026, 00.470.75.65, PECO-NEI 16366, the Russian Science Support Foundation and RFBR (grant No. 05.02.17355).

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