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NONLINEAR ACOUSTIC EFFECTS IN UNCONSOLIDATED GRANULAR MEDIA

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This paper deals with various manifestations of classical and non classical nonlinear acoustic effects that have been observed recently in unconsolidated assemblages of glass beads: operation of the parametric antenna with shear pump waves, non monotonous amplitude dynamics of the longitudinal second harmonic generated from a shear fundamental wave, cross-modulation of propagating waves. Theoretical interpretations of each of these non linear effects demonstrate the important role of the so-called weak contacts, i.e. contacts that support weaker static loads than the average one in the medium. In contrast, the linear wave propagation is mainly affected by the average and strong contacts. As a consequence, nonlinear acoustic methods are found to be much more sensitive than the linear methods for the evaluation of the granular materials in general, and may contribute to a better understanding of their peculiar properties.

1. Introduction

Granular assemblages can be found in many situations on Earth (sediments, sand, cereals ...), in industrial products, providing interesting applications. But also, the physics and the mechanics of the granular materials are quite often intriguing. Granular materials behave sometimes like solids, liquids or gaz, depending on the external and internal conditions. Their behaviors are not well understood yet, even the simplest macroscopic mechanical behavior.

From the point of vue of non linear acoustics, unconsolidated granular materials are very interesting due to their extremely high quadratic non linearity [1], that can exceed by a factor of 1000 the classical quadratic nonlinearity of homogeneous solids or liquids. They also are interesting because of the opportunity to modify easily their external and internal characteristics, by varying the applied static stress, by shaking the container, by changing the size of the beads ... However the difficulties in such situations are that many of their acoustical (linear and non linear) properties can be modified at the same time: absorption, velocity dispersion, non linearity, scattering ... They also exhibit very peculiar features such as the formation of force chains under static stress, i.e. chains of beads formed by the highly pre-stressed contacts. In a disordered granular medium, all the contacts are not equivalent due to the geometrical disorder. This ensures that all the contacts in the medium do not support the same load. Instead, a so-called distribution of contacts exists, with a given number of weak contacts (contacts that support a smaller static force than the average static force in the medium) and strong contacts (contacts that support a higher static force than the average one). From the theoretical point of vue, the strong contacts determine the linear acoustic properties of the medium while the weak contacts (and the "weak holes") play a minor role. However, the weak contacts exhibiting a higher acoustic non linearity than the strong contacts, they rule the nonlinear properties of the medium. The number of weak contacts in a granular material can be higher than the number of strong contacts [1].

2. Experimental observations

Several non linear effects have been observed in different configurations of granular materials, most of the time exhibiting new features. These effects are the self-demodulation [1], the harmonic generation [2], the subharmonic generation and route to chaos [3] and the transfer of modulation [4] (also called the Luxembourg-Gorky effect by analogy to the same effect observed in radiophysics more than 70 years ago). The experimental setup was presented in the papers cited above and is shortly recalled here. Glass beads are *2* mm in diameter. The cylindrical container is 50 cm in diameter and 40 cm high. A vertical static stress can be applied and measured up to 300 Mpa. In the medium, we introduced some longitudinal and shear piezo-electric transducers in different configurations, as well as a low-frequency shaker (~100 Hz).

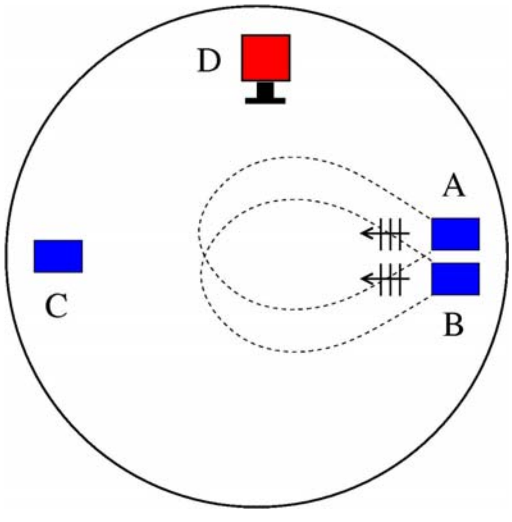

Fig. 1. S Schematic representation of the experimental setup. A, B are longitudinal or shear transducers depending on the experiment and C is a longitudinal receiver. D is a low-frequency shaker. The propagation direction is orthogonal to the (vertical) symmetry axis of the cylindrical container.

Transition in the amplitude dynamics of the self-demodulated signals

In this experiment, only one shear emitter (A or B for example) is used at one time. It emits a sine wave at frequency ω =85 kHz modulated in amplitude at Ω = 5kHz (these are the so-called pump waves). The longitudinal receiver C is used to record the nonlinearly self-demodulated signal at 5 kHz. The study consists in increasing the emitted pump amplitude A_ω and monitoring the received demodulated amplitude A_Ω. We observed, as shown on figure 2, that the slope is initially quadratic ($\sim A_\omega^2$) and becomes, at a given excitation amplitude, proportional to $\sim A_\omega^{3/2}$. This dependence is associated with the clapping of the contacts, i.e. the opening and closing of the contacts under the action of the acoustic wave [1]. In Figure 2, this dependence is presented for two different polarizations of the shear wave emitter. Actually we used identical shear transducers A and B, one oriented along the vertical axis of the cylindrical container (along which the static stress is imposed), and the other being oriented horizontally.

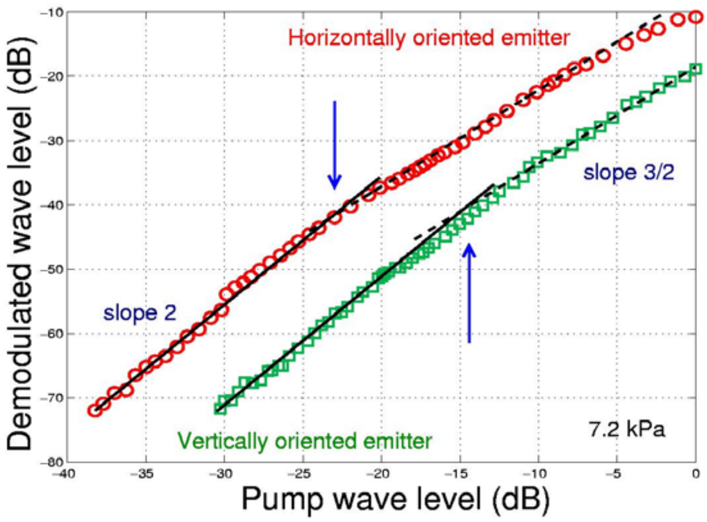

Fig 2. Amplitude dynamics of the demodulated signal for two polarizations of the emitted pump waves. The static pressure of 7.2 kPa is applied.

An important difference can be seen between the demodulated signal amplitudes generated by identical shear transducers having different polarizations. This relative difference, of the order of 10 to 15 dB, can be explained by the difference in the nonlinear parameter seen by the different polarizations of shear pump waves. Actually, the static stress is applied vertically (i.e. it is a uni-axial stress), which produces an anisotropy of the static stress, the vertical contacts being stronger in average than the horizontal contacts [1]. The strong contacts have a lower quadratic nonlinear parameter than the weak contacts, as a consequence, the nonlinearity seen by the vertical polarization shear wave is lower in average than the nonlinearity seen by the horizontal polarization. The difference in the amplitude transition between a slope 2 and a slope 3/2 can also be explained by the anisotropy of the granular material created by the uniaxial stress. The slope 2 (a quadratic dependence in fundamental wave amplitude) is the classical slope for homogeneous solids or fluids. It corresponds also to the expected dependence in granular materials where there is no clapping, i.e. the contacts remain effective. When there is a sufficient amount of contacts that are clapping, the amplitude dependence becomes a 3/2 power law. Thus, the transition between a quadratic to a 3/2 power law occurs in a granular medium when the acoustic wave amplitude is sufficiently high to allow the weaker contacts to clap. The vertical contacts being stronger in average than the horizontal contacts, the transition between a quadratic and a 3/2 power law for the vertical polarization is at a higher acoustic amplitude than for the horizontal polarization. Another important point is that this transition occurs for acoustic deformations much lower (one order of magnitude) than the average static deformation of the contacts, which means that only weak contacts are clapping at the transition $2 \rightarrow 3/2$. Their contribution to the nonlinearity of the medium is more important than the contribution of the strong contacts.

Non-monotonous amplitude dynamics of the super-harmonics as a function of the fundamental wave amplitude

Another interesting effect was observed in the same experimental configuration. This time, longitudinal second harmonic generation from shear fundamental wave was studied as a function of the excitation amplitude [2]. As it is shown in figure 3, the amplitude dynamics of the longitudinal second harmonic is non monotonous with the fundamental excitation amplitude, which is non classical. The dependences exhibit several extrema. In Ref. [2], the theoretical description of the effect and the associated interpretations show that the succession of maxima and minima is a process involving the velocity difference between the shear fundamental wave and the longitudinal second harmonic wave, as well as the changes in the source spatial distribution with excitation amplitude (changes in the characteristic length of the region of nonlinear interaction). The phase between the nonlinear source and the nonlinear signal at the end of the interaction region is changing if the length of the interaction region is modified, because the source velocity is different from the nonlinear signal velocity. When the nonlinear sources and the nonlinear signal are out of phase at the end of the interaction region the received amplitude exhibits a local minimum.

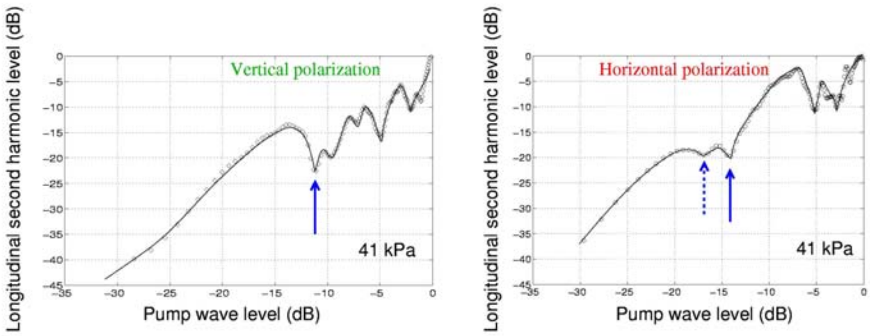

Fig 3. Amplitude dynamics of the longitudinal second harmonic as a function of the fundamental shear wave amplitude for two polarizations of the shear wave.

The first obtained minimum in amplitude is related to the clapping of some contacts in the medium. Consequently, it is also an indicator of the static stress in the medium [2]. In figure 3, the anisotropy of the medium is well probed by the two different polarizations of shear waves: for the vertical polarization of shear pump wave, the first minimum is around -11 dB while for the horizontal polarization, it is around -17 dB. Consequently, this new manifestation is also useful to probe the anisotropy of the static stress in granular media. Once again, the occurrence of the clapping effect for acoustic deformations much lower than the average static deformation of the contacts is observed: the weak contacts play a major role in the nonlinear acoustic properties.

Extreme sensitivity of the transferred modulation signal to small perturbations of the medium

The last experiment described here concerns the modulation transfer effect or the so-called Luxembourg-Gorky effect. A pump wave composed of frequencies ω_1, $\omega_1+\Omega$, and $\omega_1-\Omega$ is launched in the medium. Due to several phenomena like thermal heating, the acoustic dissipation in the medium is modulated at the frequency Ω. Then, the transmission of a probe wave at frequency ω_2 propagating through this modulated region, is modulated at frequency Ω. Sidelobes are consequently observed around the probe wave frequency, due to the nonlinear effects. As a result, the modulation of the pump wave has been transferred to the probe wave. For elastic waves, this effect of transfer of modulation was first observed in a resonant type experiment for damaged glass rods. The experiments reported here are the first observation of the effect for elastic propagating waves. In figure 4, the sidelobe levels, around the probe wave at 10 kHz, are monitored as a function of time. At several times of the temporal scan, some low frequency shocks (bursts of 5-10 periods of 1 kHz) are generated in the medium by the shaker D (see figure 1). The fundamental component of the probe wave is practically unchanged by these shocks, as seen in figure 4. This means that the linear properties are weekly modified by the small perturbations of the medium. However, the sidelobe level is strongly affected by the shocks, demonstrating an extreme sensitivity of the nonlinear effect Luxembourg-Gorky to the small perturbations of the medium.

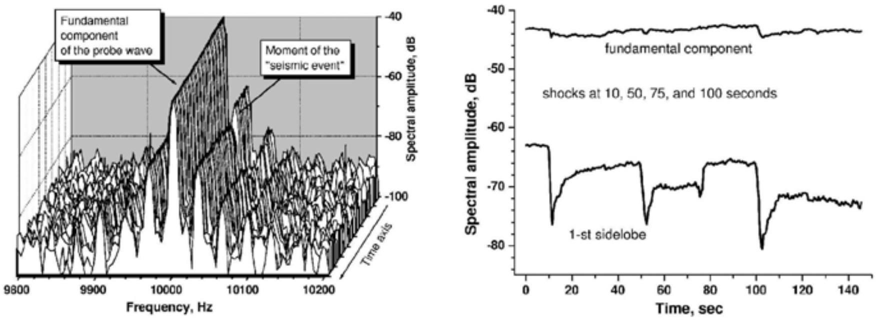

Fig 4. Waterfall representation of the time evolution of the spectrum around the probe wave frequency (left). Spectral amplitude of the probe wave and the first sidelobe as a function of time when small perturbations of the medium are imposed by the shaker (right).

The interpretation of this effect is qualitatively not different from the other mentioned effects described above. The weak contacts of the granular assemblage play an important role in the nonlinear dissipation of the acoustic waves and are easily modified by small perturbations of the medium. As a consequence, the modulation transfer effect, associated to the nonlinear dissipation in the medium, is strongly sensitive to small perturbations, which is not the case of the linear acoustic propagation.

3. Conclusions

The different experimental observations reported in this paper demonstrate the important role of the so-called weak contacts in the nonlinear acoustic properties of the unconsolidated granular materials. The higher sensitivity of the nonlinear effects compared to the linear effects for the probing of the weak contacts and consequently for the probing of the weak perturbations of the medium is promising for the evaluation of granular assemblages. Some effects described here, provide also powerful tools in order to probe the anisotropy of the average static stress supported by the contacts.

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REFERENCES

1. Tournat V., Zaitsev V.Yu., Gusev V.E., Nazarov V.E., Béquin P., and Castagnède B. Probing weak forces in granular media through nonlinear dynamic dilatancy: clapping contacts and polarization anisotropy // Phys. Rev. Lett. 2004. V.92 (8); P. 085502.
2. Tournat V., Gusev V.E., Zaitsev V.Yu., and Castagnède B. Acoustic second harmonic generation with shear to longitudinal mode conversion in granular media // Europhys. Lett. 2004. V. 66 (6); P. 798-804.
3. Tournat V., Gusev V.E., and Castagnède B. Subharmonics and noise excitation in transmission of acoustic wave through unconsolidated granular medium // Phys. Lett. A 2004. V.326 (5-6), P. 340-348.
4. Zaitsev V.Yu., Nazarov V.E., Tournat V., Gusev V.E., and Castagnède B. Luxembourg-Gorky effect in a granular medium: probing perturbations of the material state via cross-modulation of elastic waves // Europhys. Lett. 2005. V. 70 (5), P. 607-613.

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DIRECT AND INVERSE SCATTERING PROBLEM IN CANCELLOUS BONE: APPLICATION OF BIOT THEORY

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In this paper direct and inverse scattering problems of ultrasonic pulses from cancellous bone are investigated. Reflection and transmission coefficients are derived for a slab of cancellous bone having an elastic frame using Biot's theory. The inverse problem for waves transmitted by cancellous bone is solved at normal incidence. Experimental results for slow and fast waves transmitted through cancellous bone samples are given and compared with theoretical predictions.

1. Introduction

Osteoporosis is a disease caused by biochemical and hormonal changes, affecting the equilibrium between the resorption and deposition of new bony tissue. It leads to modification of the structure (porosity and thickness of trabeculae) and composition (mineral density) of this material. There has been much discussion on changes in trabecular pattern due to osteoporosis, but general indications are that the trabeculae grow thinner, possibly disappearing, and are therefore more widely spaced. Early clinical detection of this pathology via ultrasonic characterization would be of fundamental interest. Since trabecular bone is an inhomogeneous porous medium, the interaction between ultrasound and bone will be highly complex. Modelling ultrasonic propagation through trabecular tissue has been considered using porous media theories, such as Biot's theory (1). Applications of Biot's theory to trabecular bone have enjoyed varying degrees of success (2)-(4). The theory predicts two compressional waves: a fast wave, where the fluid (blood and marrow) and solid (calcified tissue) move in phase, and a slow wave where fluid and solid move out of phase. Fast and slow waves were identified independently in bovine trabecular bone in the late 1990s by Hosokawa and Otani (4).